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# ASPECTS OF THE MICROPALAEONTOLOGY AND STRATIGRAPHY OF CRETACEOUS SHELF CARBONATES FROM THE OMAN MOUNTAINS

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University of Plymouth

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**ASPECTS OF THE MICROPALAEONTOLOGY AND  
STRATIGRAPHY OF CRETACEOUS  
SHELF CARBONATES FROM THE OMAN MOUNTAINS**

**MICHAEL DEREK SIMMONS B.Sc (Hons.)**

**Thesis submitted to the Council for National Academic Awards in partial  
fulfillment of the requirements for the Degree of Doctor of Philosophy.**

**Sponsoring Establishment:  
Polytechnic South West**

**Department of Geological Sciences**

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**Earth Sciences Resources Institute at University College of Wales, Swansea and University of South Carolina,  
USA**

**AMOCO Petroleum Company Limited, Houston, USA**

**"Even in a perfect world where everyone was equal  
I'd still hold the film rights and be working on the sequel"**

**Elvis Costello: "Everyday I write the book"**

**"There are no calculations more doubtful than those of the geologist"**

**Hugh Miller: "The Old Red Sandstone or New walks in an old field"**

**DECLARATION**

This is to certify that this work submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy under the title "Aspects of the Micropalaentology and Stratigraphy of Cretaceous Shelf Carbonates from the Oman Mountains" is the result of original work.

All authors and works consulted are fully acknowledged. No part of the work has been accepted in substance for any other degree and is not being concurrently submitted in candidature for any other degree.

CANDIDATE



MICHAEL D. SIMMONS

RESEARCH SUPERVISOR



PROF. M.B. HART

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### DECLARATION

During the course of this research six papers have been published on the results obtained.

1. Simmons, M.D. & Hart, M.B. 1987. The biostratigraphy and microfacies of the Early to mid-Cretaceous carbonates of Wadi Mi'aidin, Central Oman Mountains. *In: Hart, M.B. (ed.), Micropalaeontology of Carbonate Environments*, Ellis Horwood, Chichester, 176-207.
2. Simmons, M.D. 1988. Early-mid Cretaceous Larger Foraminifera in Middle Eastern biostratigraphy. *Revue de Paléobiologie*, Vol. Spec. 2, 465.
3. Schroeder, R. & Simmons, M.D. 1988. Case 2663. *Orbitolina* d'Orbigny, 1850 (Foraminiferida): proposed confirmation of *Orbulites concava* Lamarck, 1816 as the type species. *Bull. Zool. Nomenclat.*, 45, 254-261.
4. Schroeder, R. & Simmons, M.D. 1989. The type species of the genus *Orbitolina* d'Orbigny, 1850 (Foraminifera). *J. Micropalaeont.*, 8, 87-90.
5. Banner, F.T., Finch, E.M. & Simmons, M.D. In press. On *Lithocodium* Elliott: Its Palaeobiological Significance. Submitted to *Journal of Micropalaeontology*.
6. Smith, A.B., Simmons, M.D. & Racey, A. In press. Cenomanian echinoids, larger foraminifera and calcareous algae from the Natih Formation, Central Oman Mountains. Submitted to *Cretaceous Research*.

Copies of these papers form Appendix 2 of this thesis, and are to be found in the back pocket of this volume.

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## **ABSTRACT**

### **Aspects of the Micropalaeontology and Stratigraphy of Cretaceous Shelf Carbonates from the Oman Mountains**

by

**Michael Derek Simmons B.Sc (Hons.)**

Five outcrop sections (Wadi Mi'aidin, Wadi Bani Kharus, Jebel Madar, Jebel Madamar and Jebel Salak), exposing Thamama and Wasia Group sediments were sedimentologically logged and sampled. Thin sections of each of the Thamama Group samples were prepared for micropalaeontological and microfacies analysis. The foraminifera, calcareous algae and calpionellids in each sample were recorded in order to provide a means of biostratigraphic subdivision, and together with microfacies analysis and sedimentological observations made in the field, provide a means of elucidating the depositional environments of the Thamama Group in the study area. Correlation between outcrop sections has been attempted using a biozonation scheme developed in the course of this project, and also by graphic correlation techniques. The taxonomy of 39 genera including 56 species of key foraminifera, calcareous algae and calpionellids is reviewed in detail.

A complete revision of Cretaceous Middle Eastern lithostratigraphic nomenclature is required. Some recommendations for such a revision are proposed.

Within the Thamama Group, 13 biozones/subzones are recognised using the extinction and inception events for key taxa. Both biozonal correlation and graphic correlation demonstrate that most Thamama Group formations are diachronous and may also be condensed at some localities. Biostratigraphic studies demonstrate that in the Central Oman Mountains region the Thamama Group formations are of the following ages: The Rayda Formation is of Early Berriasian age. It possibly extends into the earliest Valanginian at some localities (eg. Wadi Bani Kharus). The Salil Formation is of Berriasian - Valanginian age, possibly Hauterivian in age in its upper part at some localities. The Habshan Formation is of Hauterivian age everywhere, with possible extension into the Late Valanginian in its lower part. The Lekhwair Formation is essentially of Hauterivian - Barremian age (often largely Hauterivian). The Kharab Formation is of typically Late Barremian - Early Aptian age, whilst the Shuaiba Formation is of Early Aptian age.

Thamama Group deposition took place on an initially downwarped carbonate ramp, prograding towards the Tethyan Ocean (towards the north and east). Offshore palaeowinds precluded the development of reefs, but an oolitic shoal was located at the margin of the ramp, at least during Hauterivian times.

## ACKNOWLEDGEMENTS

I make no apology for the length of this acknowledgements section. It would have not been possible to complete this thesis without the help and advice of many friends and scientific colleagues. I am therefore grateful for the opportunity to record my sincere thanks to the many individuals who have helped me over the years. However, I must stress that all the views expressed in this work are my own, thus the errors are also mine alone.

First and foremost I wish to thank Prof. Malcolm Hart for asking me to undertake the project, finding the funding and for all his advice along the way. I would also like to thank the Earth Science Resources Unit (as was) of University College Wales, Swansea and the University of South Carolina and AMOCO Petroleum Co., for providing funding, samples and logistical support in a number of ways. In particular, I would like to thank Dr. John Smewing, Dr. Bob Scott and Tom Connelly Jr, who initially showed me the outcrops in Oman and subsequently provided valuable advice and data.

Whilst at Plymouth Polytechnic (now Polytechnic South West), I received support from all the lecturing, research and technical staff in the Department of Geological Sciences. Thanks are also due to the Library (LRC) staff for helping me amass my collection of references.

I owe a special mention to my fellow Ph.Ders: Mike Bidgood, Chris Pound, Colin Williams and last, but not least, Chris Dodd. All have helped me in more ways than they probably realise. In particular, Chris Dodd undertook the fieldwork with me and provided valuable scientific discussion throughout our time at Plymouth. Theresa Blank helped me by translating various French articles and assisting with the drafting of some of the early text-figures.

Since joining BP I have received much help and encouragement from the staff and management of Stratigraphy Branch. I have also received technical support from the EPD drawing office team (led by John Ager) and from the word processing unit (led by Tina Cooper) who kindly formatted the final version of the thesis. I would like to particularly thank my fellow micropalaeontologists Bob Jones and Toine Wonders who have tried to teach me how to be an industrial (and research!) micropalaeontologist, and to my current manager Steve Lowe who has allowed me every opportunity to complete this thesis. Dominic Emery and Dave Casey of BP Exploration helped in discussions of the geological setting of the Thamama Group. Phil Smith of Drillings and Completions Branch kindly lent me his portable PC which enabled me to finish writing up the text of this thesis.

I am very grateful for the micropalaeontological advice given by Prof F.T. Banner, Dr. A. Arnaud-Vanneau, Prof. R. Schroeder, Dr. G.F. Elliott, Dr. M.A. Conrad, Dr. J.-P. Masse and Dr. J.E. Whittaker. I am grateful to Dr. P.W. Skelton, Dr. W.J. Kennedy, Dr. E.F.P. Rose and Dr. A.B. Smith for identification of the macrofauna collected during the fieldwork.

Finally, I wish to thank my wife Jayne for helping with the diagram drafting and reference collation, but more than anything else, her constant encouragement and for putting up with my bad moods and absence from home working on "the thesis".

## **CHAPTER 1: INTRODUCTION**

### **1.1: Aims and Scope**

Despite an upsurge in research over the last 15-20 years, including extensive hydrocarbon exploration, the geology of the Oman Mountains is still poorly known. There are virtually no published accounts concerning the micropalaeontology and biostratigraphy of the autochthonous Early - mid Cretaceous shelf carbonates. Indeed, the occurrence of Cretaceous microfossils in the Middle East region is still poorly documented.

This study considers various aspects of the stratigraphy and micropalaeontology of the Early - mid Cretaceous shelf carbonates of the Oman Mountains. The lithostratigraphy of both the Early Cretaceous ["Thamama Group"] and mid-Cretaceous ["Wasia Group"] is considered in detail. This is followed by details of micropalaeontological studies which focus on the calcareous microfossils of the Early Cretaceous Thamama Group alone.

A major aim of this study was to record the foraminifera, calcareous algae and calpionellids present within the Early Cretaceous shelf carbonates of the Oman Mountains and to document their stratigraphic range. A biozonation scheme has been developed and suitable correlation methods have been considered.

In addition, the taxonomy of certain microfossils has been studied in detail, and the palaeoenvironmental significance of the microfossils and sediments has also been examined.

The project has been sponsored by AMOCO Petroleum Co. via the Earth Science Resource Institute (ESRI) of the University of South Carolina and the University of Swansea. It forms part of AMOCOs' exploration programme in Oman. Certain aspects of this study have therefore been conducted with hydrocarbon exploration in mind.

## **1.2: Fieldwork Area**

The rock samples examined in this study are from a number of localities in the Oman Mountains area (see Figure 1.1). The Oman Mountains are on the southeastern edge of the Arabian Peninsula where they form a spectacular arcuate barrier stretching for almost 700km. from the Straits of Hormuz in the north to the Ras al Hadd area in the southeast. Plate 1.1 shows a LANDSAT photograph of the central part of the mountains which is the area from which most of the studied samples were collected.

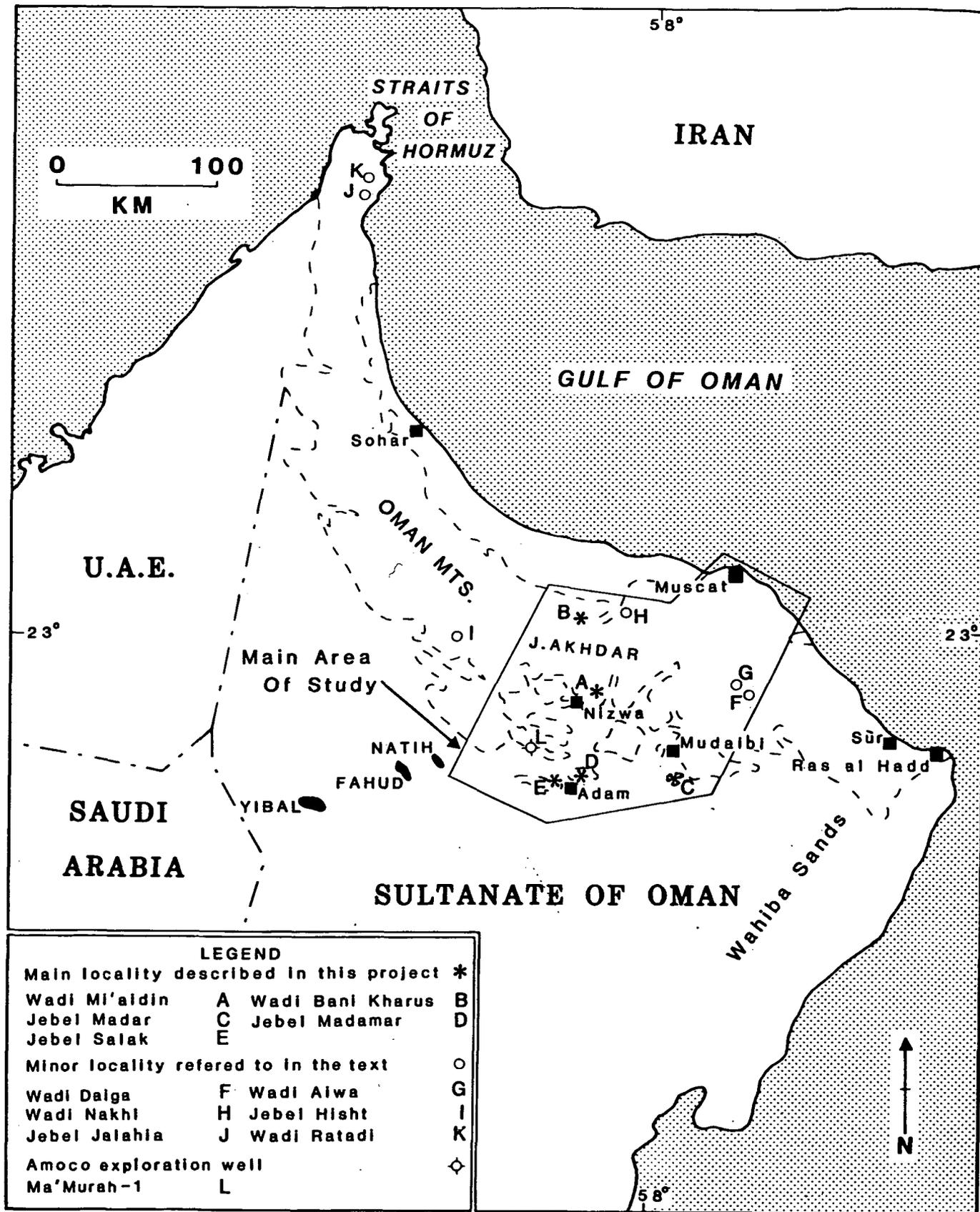
The mountain belt is approximately 30 - 130km. wide. The highest peak, Jebel Akhdar, reaches a height of approximately 3000m. To the northeast the mountains are bounded by the Trucial Oman coastal plain and the Gulf of Oman. To the southwest there is a vast gravel plain of deflation lag deposits which passes into the Rub al Khali erg. The smaller erg of the Wahiba Sands borders directly on to the Eastern Oman Mountains.

The mountains are rugged, but in recent years a number of roads have been built through them which allows reasonable access. Four wheel drive vehicles are essential for field work when the gravel plain needs to be crossed, or when access into the numerous wadis which cut into the mountain range and outlying jebels is required. It is these deep, gorge - like wadis which afford the best sections of outcrop. Exposure is frequently 100% with little vegetation cover. The central mountains and outlying jebels are elongate domes with a NW - SE axis. The wadis tend to flow NE - SW off these domes providing dip sections at right angles to the regional strike. Temperatures often exceed 38 ° C and rainfall is extremely rare. However sudden rainfall often results in flash floods which disrupt transport and are a hazard to geologists working in the field.

The samples studied in the course of this project are from outcrops in the Central Oman Mountains, an area lying between Muscat, the Omani capital city, to the northeast and the Fahud oil field to the southwest (see Figure 1.1).

## **1.3: Sample Collection and Analysis**

Fieldwork was carried out in Oman for six weeks during the months of February and March 1983. The majority of this time was spent logging and sampling Cretaceous shelf carbonate successions.



Map illustrating the position of the main localities mentioned in the text

Figure 1.1

This fieldwork was carried out in association with a team of geologists funded by AMOCO Petroleum Co. and ESRI. This research team has been studying many different aspects of the geology of Oman. My part in this project has been the investigation of the Early - mid Cretaceous shelf carbonates of the Oman Mountains, and in particular their microbiostratigraphy.

I was assisted in the field by Dr. J.D. Smewing of ESRI and also by Professor M.B. Hart and Mr. C.D.L. Dodd of Plymouth Polytechnic, and by Dr. R.W. Scott and T.C. Connally of AMOCO Production Co.

The initial samples for this study were collected by Professor M.B. Hart, Dr. S. Crittenden and Dr. J.D. Smewing during March 1982. These samples were collected from three localities; Wadi Mi'aidin, Wadi Bani Kharus and Jebel Madamar (see Figure 1.1). These samples proved to contain a good microfauna and flora, so during the 1983 field season these localities were relogged and sampled further by the author. In addition, the localities of Jebel Salak and Jebel Madar (see Figure 1.1) were investigated for the first time.

On account of the thickness of the successions and the limited time available to study them, it was not possible to carry out detailed sedimentary logging. Instead, typical field work procedure involved the broad scale logging of successions with a Jacob staff, although as many sedimentary features as possible were recorded. Generally samples were taken at 10m. intervals, although very often at critical parts of the successions (marked lithological breaks, rapid facies changes, zones with prolific larger Foraminifera, etc) samples were taken at much closer intervals. Wherever possible, macrofossils were collected, although because of time constraints it was not always possible to make a detailed search.

The samples collected for micropalaeontological analysis were roughly hand specimen sized (15 - 25 cms<sup>3</sup>). From each sample at least one standard thin - section (25x30mm, 30 microns thick) has been produced. All the microfossils studied in this project have been studied in thin - section.

This is because:

- (i) The limestones are particularly well indurated so virtually none of the samples would disaggregate.
- (ii) The microfossils involved in this study (larger Foraminifera, calcareous algae and calpionellids) are much easier to identify in cross - sectional views on account of their complex internal structure

which is used in their classification. It is often impossible to identify free specimens of larger Foraminifera to even generic level, since the critical internal structure is not visible.

There are several problems to overcome when identifying microfossils in thin - section. Initially it takes time to become accustomed to identifying three dimensional objects in only two dimensions. Most importantly, a number of random sections through a fossil may not produce the critical section needed for identification. Since no individual specimens of microfossils were obtained it was not possible to make orientated sections through single specimens. Therefore from a sample which contained a form which needed to be identified precisely, a number of thin - sections had to be made until suitable cross - sections were seen.

An advantage of working with microfossils in thin - section is that one is bound to consider the fossil - sediment relationship. By considering the entire assemblage preserved in the thin - section and the enclosing sediments, palaeoenvironmental conclusions can readily be drawn.

In addition to the many thin - sections prepared from the author's samples, thin - sections were also made available for study from the collections of ESRI. These included material from the five localities visited by the author and also other localities such as Jebel Nakhl and a number of localities in the Saih Hatat area.

Material held by AMOCO Production Co. in Houston, Texas has been studied and samples from an AMOCO well (Ma'Murah -1) in the Oman Mountains concession held by Robertson Research International Ltd., Llandudno, U.K. has also been examined. Figure 1.1 shows the approximate position of this well. Finally a large number of thin - sections of Cretaceous shelf carbonates from a number of localities in the Oman Mountains and the Musandam Peninsula which were collected by Drs. K.W. Glennie and W.F.H. Pillar of Shell KSPHEL were studied. These are held in Leiden Museum at present. The material is from the following localities; Wadi Nakhl, Wadi Aiwa, Wadi Ratadi, Jebel Misht, Jebel Jalahia and Wadi Daiga (see Figure 1.1).

In total approximately 1100 thin sections of Cretaceous shelf carbonates from the Oman Mountains have been examined in the course of this study. It should be pointed out however that attention has been focused on the five localities visited by the author, and in particular the three localities with good exposures of the Early Cretaceous Thamama Group (Wadi Mi'aidin, Wadi Bani Kharus and Jebel Madar). The other material has largely been used to provide various background information and help confirm general stratigraphic and palaeoenvironmental conclusions.

As well as identification of microfossils from the thin - sections, the sedimentary microfacies of the samples has been studied. Occasionally this required the staining of sections with Alizarin Red-S solution to determine the presence of dolomite.

#### Index of Sample Numbers.

As mentioned above, during the course of this study a large number of samples from a variety of sources have been examined. To clarify the location and source of a sample when it is mentioned in the text, the following index of sample/thin - section numbers is provided.

Samples prefixed with the letters 'Plr.' are the property of the Rijksmuseum van Geologie en Mineralogie, Hooglandse Kerkgracht, Leiden, The Netherlands. The samples are held in the museums 'Oman Mountains Collection' and are also given Rijksmuseum van Geologie en Mineralogie registration numbers prefixed with the letters RGM. The following thin - sections were studied:

Plr 798 - 813	(RGM 237785 - 237800)	Jebel Misht
Plr 828 - 829	(RGM 237814 - 237815)	Jebel Misht
Plr 1360 - 1384	(RGM 238345 - 238369)	Wadi Daiga
Plr 1390 - 1396	(RGM 238375 - 238381)	Wadi Aiwa
Plr 1425 - 1428	(RGM 238410 - 238413)	Wadi Aiwa
Plr 1429 - 1431	(RGM 238414 - 238416)	Wadi Daiga
Plr 1504	(RGM 238489)	Wadi Nakhil
Plr 1507 - 1539	(RGM 238492 - 238524)	Wadi Nakhil
Plr 1608 - 1623	(RGM 238593 - 238608)	Wadi Aiwa
Plr 1691 - 1694	(RGM 238676 - 238679)	Jebel Jalahia
Plr 1889 - 1893	(RGM 238874 - 238878)	Wadi Ratadi

The following samples belong to the collections of ESRI and are held by Dr. J.D. Smewing, Department of Geology (ERI), University College, Singleton Park, Swansea, U.K.:

Prefix 'BK' - Wadi Bani Kharus	(BK1 - 88)
Prefix 'JM' - Jebel Madamar (South side)	(JM1 - 10)
Prefix 'WM' - Jebel Madamar (North side - also called Wadi Madamar)	(WM1 - 29)
No prefix - Wadi Mi'aidin	(1 - 263)

The following samples belong to the collections of the author and are at present located at the BP Research Centre (Stratigraphy Branch), Chertsey Road, Sunbury on Thames, Middlesex, TW16 7LN, U.K. (duplicates of some samples are held by Prof. M.B. Hart, Polytechnic South West) :

Prefix 'JM' - Jebel Madamar	(JM1 - 13)
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N.B prefix as for ESRI collections.

Prefix 'WMA' - Jebel Madamar (North side - also called Wadi Madamar)	(WMA1 - 14)
Prefix 'JSN' - Jebel Salak	(JSN1 - 22)
Prefix 'JS' - Jebel Salak	(JS1 - 7)
Prefix 'JSX' - Jebel Salak	(JSX2 - 5)
Prefix 'WM' - Wadi Mi'aidin	(WM1 - 107)

N.B confusion with ESRI 'WM' series from Jebel Madamar.

Prefix 'WMX' - Wadi Mi'aidin	(WMX2 - 20)
Prefix 'NU' - Wadi Mi'aidin	(NU1 - 29)
Prefix 'B' - Wadi Bani Kharus	(B1 - 100)
Prefix 'K' - Wadi Bani Kharus	(K1 - 35)
Prefix 'JMD' - Jebel Madar	(JMD1-1 - 2-22)
Prefix 'MR' - Jebel Madar	(MRJ - MR1 - 16)
Prefix 'MS' - Jebel Madar	(MS1 - 91.4)

Prefix 'NM' - Jebel Madar

(NM1 - 30)

Prefix 'N' - Jebel Madar

(N1 -16)

#### **1.4: Geological Investigations in Oman.**

It is not possible to document the details of all the geological investigations that have taken place in Oman. Therefore within this section two aspects of the geology of Oman will be highlighted. These are firstly, the arguments concerning the role of thrust tectonics in the geological history of Oman, and secondly, observations and ideas about the Cretaceous shelf carbonates involved in this study and in particular, their micropalaeontology.

There are a few reports about the geology of Oman in publications of the 19th century, and it was not until 1908 that the first serious study of Oman geology was published. This paper by Pilgrim (1908) gave a brief outline of the geology of Oman; a result of his explorations in 1904 and 1905. The hostile nature of the local tribes prevented him from reaching many parts of the mountain range, including the Jebel Akhdar area, around which there are considerable outcrops of Cretaceous shelf carbonates. Pilgrim divided the successions he saw into two units; an "Oman Series" which included all sedimentary formations from Palaeozoic to Cretaceous age, and a "Basic Igneous Series", which is now known as the Semail Ophiolite.

Lees (1928) made a major contribution to our knowledge of the geology of Oman, although he, like Pilgrim, was unable to visit Jebel Akhdar. Lees was the first geologist to recognize the major rock units present in Oman. He also recognized the importance of thrust tectonics in the geological history of Oman. He made a detailed description of some of the fossils he collected during his study. A number of Early and mid-Cretaceous macrofossils (largely molluscs) are described, together with the first record of the larger foraminiferid *Orbitolina*, from the shelf carbonates of Cretaceous age.

Many of the fossils collected by Lees were further described by the Austrian palaeontologist Kuhn (1929), who made a detailed study of some of the molluscs and corals of Cretaceous age.

Lees recognized the following major rock units in Oman (from base to top):

- (i) Pre - Permian quartzites, limestones, phyllites, etc.

- (ii) Permian limestones
- (iii) Triassic Eliphinstone Beds (largely limestones)
- (iv) Musandam Limestone (Jurassic - Early Cretaceous in age)
- (v) Hawasina Series - shales, radiolarites. (Jurassic - Early Cretaceous in age)
- (vi) Semail Igneous Series
- (vii) Unconformable Late Cretaceous and Eocene sediments
- (viii) Miocene shales, sandstones and coals

This sequence has been recognized by all following workers as the basic sub-division of the rock units in Oman.

Lees believed that the Hawasina and Semail Series had been thrust into their present position in the rock sequence, and were in fact, the age equivalents of the Musandam Limestone which underlies them. The ideas of thrust tectonics and age equivalence concerning these rock units has been the subject of considerable disagreement in publications on Oman geology, but most geologists now agree that Lees' model of thrust emplacement for the Hawasina and Semail Series is correct.

The 'Musandam Limestone' of Lees partially includes the Early - mid- Cretaceous carbonates of this study.

Between 1949 and 1960 geologists of the Iraq Petroleum Company carried out extensive field surveys for Petroleum Development (Oman) Ltd. (PDO). This resulted in the publications of Morton (1959), Hudson (1960) and Hudson *et al.* (1954a,b) and Hudson and Chatton (1959).

Hudson and Chatton (1959) described in detail the Musandam Limestone (Jurassic - Early Cretaceous) of the Musandam Peninsula. However, they do not refer to the equivalent and almost identical beds of the Central Oman Mountains. As well as describing the lithology of the Musandam Limestone, they correlate the sections in Musandam to wells in the Qatar Peninsula, thus placing the Lower Cretaceous part of the succession within the Thamama Group, a lithostratigraphic unit used to describe Lower Cretaceous carbonate sediments across the Middle East.

Hudson and Chatton (*op. cit.*) divided the Musandam Limestone into a number of lithological units which are dated on the basis of Foraminifera, calcareous algae and calpionellids, supported by macrofossil evidence (although they found no ammonites).

They believed the Upper Musandam Limestone to be of Berriasian - Early Aptian age (age equivalent to the Thamama Group in the Oman Mountains). Their lithological succession is the same as that in the Oman Mountains. This includes a lower shale unit with radiolaria and *Calpionella alpina* Lorenz 1902 and upper shelly and peloidal limestone units with common Foraminifera. Among the Foraminifera they record are; *Orbitolina* sp. cf. *O. discoidea* Gras 1852, *Orbitolina* sp. cf. *O. lenticularis* (Blumenbach 1805), *Dictyoconus arabicus* Henson 1948, *Choffatella decipiens* Schlumberger 1904, *Trocholina* spp., *Pseudochrysalidina* sp., *Pseudocyclammina lituus* (Yokoyama 1890) and *Pseudocyclammina kelleri* Henson 1948.

Morton (1959) described the geology of most of the Oman Mountains range, including Jebel Akhdar, and presented a geological map of Oman. As well as describing the rock units present in Oman, his paper presents palaeontological evidence for the age of parts of the succession, including the Cretaceous shelf carbonates. In this respect there is mention of the larger Foraminifera *Praealveolina cretacea* d'Archiac 1837, *Orbitolina* sp. cf. *O. discoidea*, *Orbitolina* sp. cf. *O. concava* (Lamarck 1801) and the calpionellid *Calpionella alpina*.

The most important aspect of Morton's paper is that in direct opposition to Lees, he believed both the Hawasina and Semail Series to be autochthonous. He states that the contact between the Hawasina Series and the underlying mid Cretaceous carbonates is "sharp but concordant, while that between the Hawasina and Semail is also concordant but slightly sheared to a degree which does not indicate important thrusting". He also claims that "the Semail extrusions are deep - rooted *in situ*", although he remarks that the evidence for the actual 'roots' is undiscovered.

Morton thus believed that the whole Oman Mountains succession is a normal younging upwards sequence and autochthonous. He was later supported in this view by Tschopp (1967a) and Wilson (1969).

During the 1960s considerable field work was carried out by Shell geologists for PD(Oman) Ltd. During this time field surveys and exploration wells were carried out by other oil companies for the first time. A result of the exploration studies by PD(Oman) Ltd. were the publications of Tschopp (1967a,b) and Wilson (1969).

These authors supported Morton's hypothesis that the Hawasina and Semail Series were autochthonous. One of the strongest reasons for their doing so is that the Hawasina turbidites are underlain by similar looking turbidites containing not only reworked fossils of Early Cretaceous and Jurassic age, but also globotruncanids (planktonic foraminifera) of Late Cretaceous age. However as Glennie *et al.* (1973a,b;1974) have shown, these lower turbidites belong to a separate autochthonous unit; the Muti Formation. The Hawasina Series contains no Late Cretaceous fossils only contemporaneous Jurassic and Early Cretaceous faunas in normal younging upwards sequences repeated imbricately as a result of thrusting. By excluding the Muti Formation from the Hawasina Series, the Hawasina Series must be considered to be allochthonous.

Wilson (1969) believed that the Semail Series represented autochthonous extrusive deposits and he placed a possible zone of submarine fissure eruptions to the north and east of the present Oman coast (Wilson, 1969, Fig.24).

Wilson placed the Early and mid-Cretaceous shelf carbonates within the Musandam Limestone. These carbonates are divided into a, lower, Thamama Group of Berriasian - Aptian age, and an, upper, Wasia Group, of Late Albian - Cenomanian age.

Tschopp (1967b) documented the exploration history and the geology of the Fahud oil field which is located approximately 50km. southwest of the Oman Mountains (see Figures 1.1 and 1.2).

Three giant oil fields occur southwest of the Oman Mountains; Yibal, Natih and Fahud (see Figures 1.1 and 1.2). Fahud-1 was the first well to be drilled in Oman and was spudded in 1956. Oil was discovered in commercial quantities at Natih in 1960. The oil reservoir was in Cenomanian shelf carbonates of the Wasia Group. An anticlinal structure at Fahud was drilled by Fahud-2 in 1963 and oil discovered in commercial quantities, also in limestones of the Wasia Group. Since this time oil has continued to be discovered in this area. In 1983 production from the Yibal field was approximately 38 million barrels, from Fahud 24 million barrels and from Natih 10 million barrels (Hemer and Pickford, 1984).

Tschopp discussed the stratigraphy of the Fahud field and divided the Cretaceous shelf carbonates into an, upper, Wasia Group, and a, lower, Thamama Group. The Wasia Group was divided into an, upper, Wasia Limestone Formation, (= Natih Formation of other authors), and a, lower, Nahr Umr Formation. Tschopp defined seven members within the Wasia Limestone Formation, lettered a - g, on the basis of lithology and log



response. These have since been recognized in other wells in the Oman area, and attempts have been made to recognize them in the field, although all members are not always present.

The first geologists to abandon Morton's ideas on the age and autochthonicity of the Hawasina and Semail Series were Hareboure and Horstink in an unpublished PD(Oman) report (see Glennie *et al.*, 1974). Like Lees (1928) they believed that the Semail and Hawasina Series were thrust into their present position. Their ideas were soon supported in papers by Reinhardt (1969) and Allemann and Peters (1972) on the Semail Ophiolite.

During the late 1960s Shell KSPeL carried out a detailed geological survey of the Oman Mountains under the supervision of K.W. Glennie. This survey team produced a number of publications on the geology of Oman, notably Glennie *et al.* (1973a,b;1974) and Glennie (1977). The publication of 'The Geology of the Oman Mountains' by Glennie *et al.* (1974) is the most comprehensive study of this area to date and it is impossible to summarize here all the data and interpretations presented in this work.

Glennie *et al.* (1973a) presented evidence that the Hawasina and Semail Series are allochthonous. Although Wilson (1973) attempted to defend the idea that they are autochthonous, his arguments are not convincing. In particular, he could not explain the total lack of Late Cretaceous microfossils within the Hawasina Series. As part of his argument, Wilson figured what he believed to be specimens of *Orbitolina*, (Wilson, 1973, figure 1). However, these are in fact specimens of the Early Jurassic species *Meyendorffina* (*Lucasella?*) *cayeuxi* (Lucas). Glennie *et al.* (1973b;1974) rejected Wilson's arguments and showed convincing evidence that the Hawasina and Semail units are a series of allochthonous nappes.

Glennie *et al.* (1974) produced an extremely accurate geological map of Oman, a simplified version of which is shown here as Figure 1.3, and also gave very detailed descriptions of the rock units present. They were able to divide the succession in Oman into a large number of units, groups, formations, etc. A summary table of the rock units they determined is presented in Figure 1.4. A schematic cross - section through the Oman Mountains as drawn by Glennie *et al.* (1974) is shown as Figure 1.5.

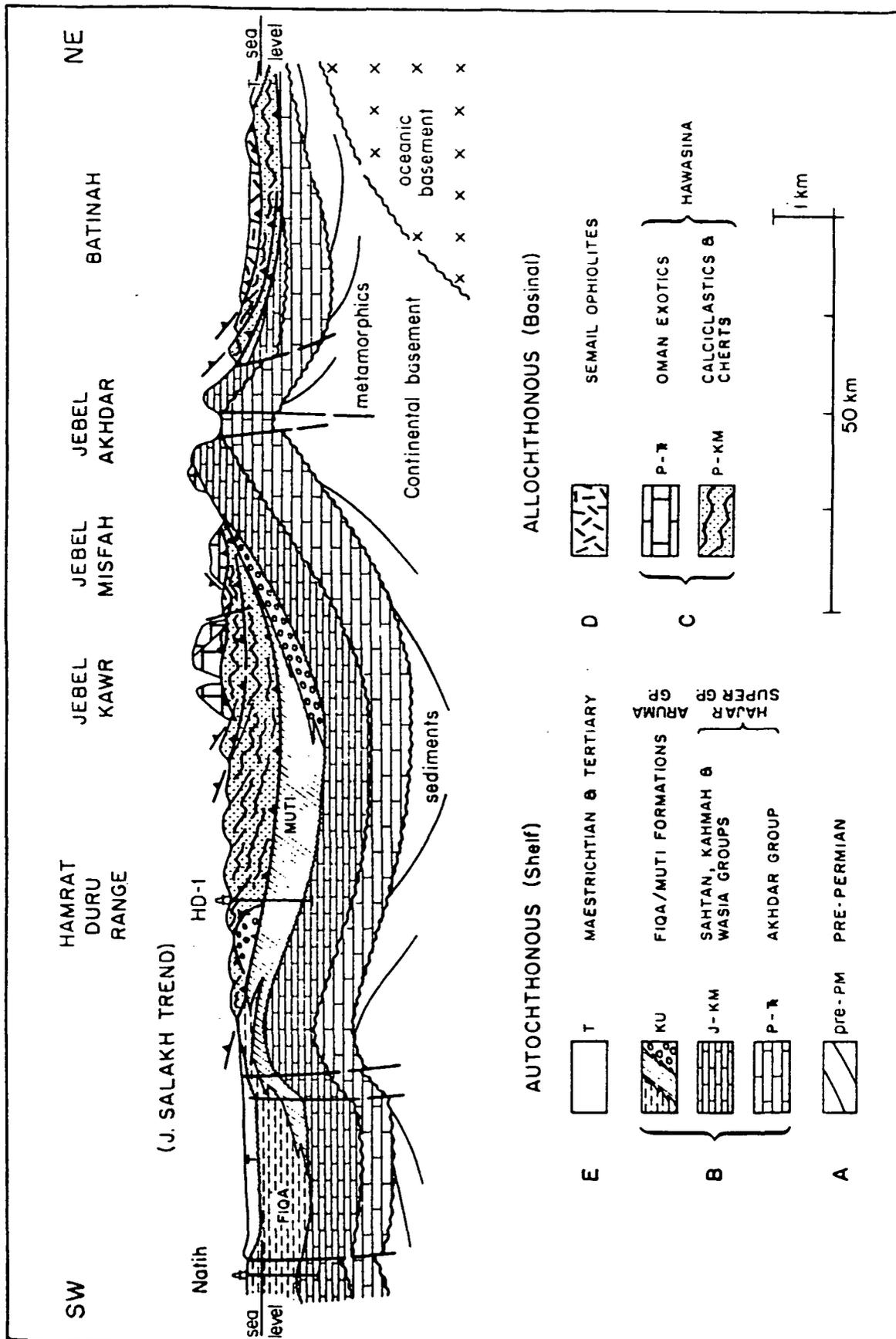
Glennie *et al.* (1974) recognized that the Semail Igneous Series represented an ophiolite (i.e a fragment of obducted mantle and oceanic crust). They recognized the pillow lavas, sheeted dykes, layered gabbros and ultramafics, which form a classic ophiolite succession.

	LITHOLOGY	FORMATION		FAUNA and FLORA	PROVEN AGES	
F		MAASTR.-TERTIARY			Latest Cretaceous to Early Tertiary	
E		SEMAIL NAPPE		GLOBOTRUNCANA, ROTALIPORA	Mid to Late Cretaceous	
D		OMAN EXOTICS	HAWASINA ALLOCTH. UNITS	CORALS, ALGAE MEGALODONTIDS FUSULINIDS ETC.	Mid to Late Permian and Late Triassic	
		HALIW FM		RADIOLARIA	Early Jurassic ? to Early Cretaceous ?	
		AL ARIDH FM		PELAGIC LAMELLIBRANCHS INVOLUTINIDS	Permian ?, Triassic to Early Jurassic	
		HALFA FM		RADIOLARIA PELAGIC LAMELLIBRANCHS	Triassic to Early Cretaceous ?	
		AL AYN FM		PELAGIC LAMELLIBRANCHS INVOLUTINIDS	Late Triassic to Early Jurassic	
		WAHRAH FM		CUNEOLINA, TINTINNIDS PFENDERINIDS, INVOLUTINIDS	(Late Triassic) Mid Jurassic to Mid Cretaceous	
		NAYID Lst Fm		HAMRAT DURU GP	PRAEALVEOLINA, ORBITOLINA	Early to Mid Cretaceous
		SID'R Chert Fm			RADIOLARIA, TINTINNIDS	Late Jurassic to Early Cret.
		SUWAYZA FM Lst Mbr			PROTOPENEROPLIS PFENDERINIDS	Early to Late Jurassic
		SUWAYZA FM Sst Mbr			HAURANIA INVOLUTINIDS	Late Triassic to Early Jurassic
C		MUTI FM QUMAYRAH and RIYAMAH FAC.	ARUMA GP	GLOBOTRUNCANA	Late Cretaceous	
		MAYHAH FM	SUMEINI GP	PRAEALVEOLINA ORBITOLINA PROTOPENEROPLIS INVOLUTINA	Late Triassic to Early and Mid Cretaceous	
		MAQAM FM	JEBEL WASIA FM	CORALS CALCISPONGES ALPINOPHRAGMIUM PELAGIC LAMELLIBRANCHS	Triassic (and Late Permian ?)	
B		MUTI FM	ARUMA GP	GLOBOTRUNCANA	Late Cretaceous	
		WASIA GP	HAJAR SUPER-GROUP	PRAEALVEOLINA, ORBITOLINA	Mid Cretaceous	
		KAHMAH		ORBITOLINA, CHOF FATELLA TINTINNIDS	Late Jurassic to Early Cretaceous	
		SAHTAN		PFENDERINIDS, HAURANIA ORBITOPSELLA	Early to Late Jurassic	
		MAHIL FM		ALGAE INVOLUTINIDS	Triassic	
	SAIQ FM	CORALS FUSULINIDS ETC.		Mid to Late Permian		
A		PRE - PERMIAN	PRE-PERMIAN BASEMENT			

Division of rock units present in Oman by Glennie *et al.* (1974).

From Glennie *et al.* (1974)

Figure 1.6



**Geological cross-section through the Central Oman Mountains.**

Line of section follows that shown as "Figure 2.2.1" on Figure 2.

From Glennie et al (1974)

Figure 1.5

TIME STRATIGRAPHY		DHO FAR - HUQF DESERT PLAINS	EASTERN OMAN MTNS	CENTRAL OMAN MTNS	NORTHERN OMAN MTNS
CENOZOIC	RECENT PLEISTOCENE	LOWER FARIS Fm desert gravels, sands, Sabha evaporites and deflation lag deposits			
	PLIOCENE				
	MIOCENE				
	OLIGOCENE				
	Eocene				
MESOZOIC	PALEOCENE	DANMAM Fm (limestone) RUS Fm (anhydrite, limestone, dolomite) LOWER RHADZINA Fm (limestone)			
	MAASTRICHTIAN	JUWEIZA Fm (conglomerates, sandstones, shales)	SEMAIL NAPPE (opholites) 1500-2000m QALHAM Fm (congl) 1500-2000m	SEMAIL NAPPE (opholites) 1500-2000m QALHAM Fm (congl) 1500-2000m	SEMAIL NAPPE (opholites) 1500-2000m QALHAM Fm (congl) 1500-2000m
	CAMPANIAN	FIQA Fm (marl)	MUTRI Fm (limestone conglomerate and shale) 0-300m	MUTRI Fm (limestone conglomerate and shale) 0-600m	MUTRI Fm (limestone conglomerate and shale) 0-300m
	SANTONIAN				
	CONIACIAN				
	TURONIAN				
	CENOMANIAN				
	ALBIAN	NATIH Fm (limestone) 650m RUHR LMR Fm (limestone and shale)	NATIH Fm (limestone) 0-100m RUHR LMR Fm (limestone and shale)	NATIH Fm (limestone) 450m RUHR LMR Fm (limestone and shale)	
	APTIAN	SHUAIBA Fm KHARIB Fm LEKHWAIR Fm HABSHAN Fm SALIL Fm	limestones 0-100m porcellanitic limestone	limestones 700m porcellanitic limestone 80m	limestones porcellanitic limestone 1500m
	VALANGINIAN	RAYDA Fm			
KIMMERIDGIAN	JUBAILA Fm HANIFA Fm TUWAIQ Fm 300m DHRUMA Fm ADIGRAT (MARRAT) Fm	limestone, basal sandstones 300m	limestone, basal sandstones 400m	limestones	
PALAEOZOIC	LIASSIC	JILH Fm SUDAIR Fm	MAHIL Fm (dolomite) 1200m	MAHIL Fm 250m	GHALAM Fm sandstone and limestone 400m MILAH Fm limestone and dolomite
	PERMIAN	KHUFF Fm (limestone and dolomite)	SAIQ Fm (limestone and dolomite) 200-700m	SAIQ Fm (limestone and dolomite) 460m	GHAIL Fm dolomite HAGIL Fm limestone and dolomite 900m BIM Fm dolomite and limestone
	CARBONIFEROUS	HAUSHI Fm (conglomerate, sst, shale, limestone) 300m			
	DEVONIAN				
	SILURIAN	MISFAR Fm			
PRE-CAMBRIAN	ORDOVICIAN	MAHATTA HUMAID Fm 7000m			
	LATE CAMBRIAN	ARA (limestone, dolomite, halite, anhydrite)			
	CAMBRO- PRE-CAMBRIAN	BUAH Fm (dolomite) SHURAM Fm (siltstone, shale, limestone) KHUFAI Fm (dolomite) ABU MAHARA Fm (sandstone and shale) 1200m	HJAM Fm (dolomite) AMDEH Fm (quartzites) (HATAI and QALHAT METAMORPHICS)	KHARUS Fm (limestone and dolomite) MI'ADIN Fm (siltstone) HAJIR Fm (limestone) MISTAL Fm (conglomerate and sandstone) 1750m	
PRE-CAMBRIAN		GNEISS and GRANITE			

Table of lithostratigraphic units present in the Oman Mountains.

From Glennie (1977)

Figure 1.4



The Semail Igneous Series is perhaps the best example of an ophiolite in the world and since the advent of plate tectonics in the late 1960's, it has been extensively studied. Major publications concerning the Oman ophiolite include Reinhardt (1969), Allemann and Peters (1972), and the special issue on the Oman ophiolite in *Journal of Geophysical Research* (V.86, 1981). In the late 1970's a team from the Open University under the supervision of Prof. I.G. Gass and Dr. J.D. Smewing conducted an extensive mapping study of the ophiolite, and a number of maps have been produced.

Glennie *et al.* (1974) divided the entire Oman succession into six major rock units lettered A - F (see Figure 1.6). From base to top they are:

- (A) A basement of granites, gneisses, partly metamorphosed sediments and metavolcanics. This basement was folded in a pre-Permian orogeny.
- (B) A sequence of mainly shallow marine carbonates that ranges from mid - Permian to Late Cretaceous in age. This is largely the Hajar Super - group (see Figure 1.6), and the rocks studied in this project occur in this unit.
- (C) The Sumeni Group; local thrust sedimentary sequences of Permian to mid - Cretaceous age. These include carbonates, boundstones and conglomerates. These are overlain by Late Cretaceous silicified conglomerates, grainstones and cherts of the Aruma Group. The Sumeni Group was rarely mentioned by previous workers and was usually placed in unit D.
- (D) The Hawasina Series; a complex association of folded and faulted turbidites, limestones and cherts of Triassic to Cenomanian age, and shallow marine limestones of Permo - Triassic age sometimes associated with basaltic pillow lavas.
- (E) A thick sheet of basic and ultrabasic rocks (the Semail ophiolite) with a discordant contact with the underlying Hawasina Series.
- (F) A sequence of shallow marine Maastrichtian and Early Tertiary carbonates and conglomerates, that overlie all older sequences unconformably.

Glennie *et al.* (1974) deduced that the three major sedimentary units [the Hajar Super - group (unit B), the Sumeni Group (unit C) and the Hawasina Series (unit D)] were all deposited within the same mid - Permian to Cenomanian time span. The Hajar Super - group was deposited in shallow water environments on the Arabian

continental margin. The Sumeni Group was deposited on the continental edge and at the foot of the continental slope, and the Hawasina Series on the continental rise and oceanic basin that lay to the northeast of the continental margin. During the Late Cretaceous the Sumeni Group, the Hawasina Series and the Semail Ophiolite were tectonically emplaced above the Hajar Super - group.

Glennie *et al.* (1974) also defined ten microfossil zones (I - X) within the mid - Permian to Late Cretaceous sequences. The Early - mid Cretaceous sediments studied here fall into zone VI (the 'tintinnid/*Cuneolina* Zone'), zone VII (the '*Orbitolina* Zone') and zone VIII (the '*Praealveolina* Zone'). From each zone Glennie *et al.* (1974) documented a reasonable microfauna and microflora which enabled them to accurately date the succession.

As stated above the Cretaceous carbonates of this study fall within the autochthonous Hajar Super - group. The Cretaceous part of the Hajar Super - group (partly synonymous with the Musandam Limestone of Lees (1928)), is divided by Glennie *et al.* (1974) into a, lower, Kahmah Group and an, upper, Wasia Group (see Figure 1.4).

The Kahmah Group as defined by Glennie *et al.* (1974) is a thick (c.750m) carbonate sequence with porcellanites in the lower part conformably overlying the Jurassic Sahtan Group. The upper limestones have a marked disconformity with the overlying Wasia Group. The age range for the Kahmah Group was thought to be Tithonian to Aptian. Glennie *et al.* (1974) introduced the term Kahmah Group to replace the term Thamama Group, which is in part defined by the presence of the underlying Hith Anhydrite, which is missing in Oman. However the term Thamama Group has been retained by some workers, including the author, and it is still used in sub - surface work in Oman.

The Wasia Group was recognized by Glennie *et al.* (1974) as a succession of limestones and shales in the lower part overlain by more massive limestones. Total thickness is 400m. The upper surface was described as a marked disconformity with the overlying Aruma Group. The age span of this unit was thought to be Albian - Cenomanian (? Early Turonian).

Glennie *et al.* (1974) did not originally divide the Wasia and Kahmah Groups into formations. However Glennie (1977) (see Figure 1.4) suggested correlation with formations recognized in Dhofar and elsewhere in the Arabian Peninsula. These formations are (from top to base):

Natih Fm.

= Wasia Group

Nahr Umr Fm.

---

Shuaiba Fm.

Kharaib Fm.

Lekhwair Fm.

= Kahmah Group (Thamama Group)

Habshan Fm.

Salil Fm.

Rayda Fm.

These terms have since been widely used by geologists working in Oman and are used in this study.

Despite the above remarks, the publications of Glennie *et al.* (1973,b; 1974) do not go into great detail concerning the Kahmah and Wasia Groups. Although the basic lithology is described and a number of measured sections presented (Glennie *et al.*, 1974, enclosure 3), there is little detail, and the micropalaeontological content is limited to the mention of a few common or stratigraphically important genera.

Since the publication of 'The Geology of the Oman Mountains' by Glennie *et al.* (1974), geological investigations in Oman have been expanding dramatically. As mentioned above there has been considerable work conducted on the Semail ophiolite in recent years.

Oil company interest in the geology of Oman has expanded in the 1970's and 1980's with a number of companies now holding concessions within Oman (Figure 1.2 shows a map of oil company concessions and oil fields in Oman). However publications resulting from this exploration have been limited. Elf Aquitaine geologists Ricateau and Riche (1980) published a useful account of the geology of the Musandam Peninsula and surrounding areas. This included details of offshore wells and evidence that the Nahr Umr Formation occurs in this area. Micropalaeontological evidence for the age of the succession is presented.

Gulf Oil geologists Harris and Frost (1984) published an account of the nature of the mid - Cretaceous carbonate reservoirs in Oman, including the Fahud field. This included a depositional model for the Wasia Group, and details of porosity and permeability. Harris and Frost prefer to use 'Mishrif Formation' and

'Mauddud Formation' in place of the term Natih Formation. These equate with similar Mishrif and Mauddud facies seen elsewhere within the Arabian Peninsula (see also Chapter 2.1).

Geologists working for the ESRI research team, sponsored by Amoco, have produced a number of publications on aspects of the geology of Oman (eg. Searle *et al.*, 1983; Searle, 1985). Hopefully many more publications will be forthcoming. However oil company restrictions may delay publication.

Oil exploration continues apace in Oman. In 1983 thirty seven exploratory wells were drilled, twenty of which recorded hydrocarbons. 24,260km. of land seismic lines were shot and crude production totaled 140,162,000 bbl., an increase of 19.3% on 1982 (Hemer and Pickford, 1984).

There have been many publications on the overall geology of the Middle East which mention Oman, and in particular, details of the Cretaceous geology of this area. It would be impossible to document all these publications but some of the major papers include Henson (1951), Dunnington (1967), Sampo (1969), El-Naggar and Al-Rifay (1972, 1973), Saint-Marc (1978), Murriss (1981) and Harris *et al.* (1984).

Henson (1951) published an early account of the geology and nature of petroleum occurrences in the Middle East and included notes on the stratigraphy of Oman. Dunnington (1967) provided details of the stratigraphic distribution of oilfields in the Iraq - Iran - Arabia Basin. Detailed descriptions of the lithology, stratigraphy and palaeontology of the Cretaceous geology of this region were given, including notes on the correct use of the term 'Wasia Group'. Sampo (1969) described the microfacies and micropalaeontology of Southwest Iran, which includes descriptions of microfossils that are also recorded from Oman. El-Naggar and Al-Rifay (1972, 1973) provided details of the biostratigraphy and microfacies of the Cenomanian Magwa Formation of Kuwait. The Magwa Formation is partly equivalent with the Natih Formation in Oman and the papers deal with the arguments concerning Wasia Group lithostratigraphic nomenclature. They also provided numerous photomicrographs of microfossils from this Cenomanian succession, many of which are also found in Oman. Saint-Marc (1978) provided a good introduction to the geology of the Arabian Peninsula and a synthesis of ideas concerning the palaeogeography of this region. A correlation chart of Cretaceous formations in the Arabian Peninsula is given.

The paper by Murriss (1981) is a summary of the geologic evolution of the Middle East and how this evolution relates to oil habitat. A series of palaeogeographic maps illustrate the environments of deposition.

Two main styles of deposition are recognized, related to sea level change: (i) Ramp - type mixed carbonate - clastic units related to regressions resulting in 'layer - cake' formations, and (ii) differentiated carbonate shelves related to transgressions producing time transgressive surfaces. The tectonic framework is also discussed.

A recent paper by Harris *et al.* (1984) discussed regional unconformities and depositional cycles within the Cretaceous of the Arabian Peninsula. The paper relates these cycles to world - wide and local sea level changes and gives a palaeodepth curve for the study area. Details of the lithostratigraphy and biostratigraphy of the region are provided, and a calcareous nannofossil - planktonic Foraminifera - larger benthonic Foraminifera biostratigraphic zonation is given. Much of the work of Harris *et al.* is based on outcrop and well samples from Oman and thus has great relevance to this study.

## **CHAPTER 2: LITHOSTRATIGRAPHY AND SEDIMENTOLOGY**

### **2.1: Lithostratigraphic Nomenclature**

The lithostratigraphic nomenclature used in this study is largely that of Glennie (1977), (see Figures 1.4 and 2.1). However the term Thamama Group is preferred to Glennie's term Kahmah Group (for explanation see below). The eight formations recognized by Glennie (see Figures 1.4 and 2.1) in Dhofar (Rayda - Natih Formations), and tentatively correlated by him to the Oman Mountains, are used in this study. Although there is no published description of these formations in Oman, it has been oil company practice to apply these terms to outcrop and well sections for the last few years (eg. unpublished AMOCO and BP reports).

The lithostratigraphic nomenclature used to describe the Lower to mid-Cretaceous shelf carbonates in Oman has been created in an unsystematic way. Almost every author who has described these sediments has developed a different system of nomenclature, resulting in a large number of lithostratigraphic terms being used. Figure 2.1 summarizes most of the lithostratigraphic schemes available. Furthermore, many terms are invalid or improperly used according to the rules of lithostratigraphic nomenclature. This is true of lithostratigraphy not only in Oman, but also elsewhere in the Middle East. For example, many formational names are now used to describe rock units that bear little apparent sedimentological relation to the same formations as described in their type sections. A revision of Middle Eastern lithostratigraphic nomenclature, including that used in Oman, is required, but this is outside the scope of the present study. Indeed such a revision is probably impracticable since oil company geologists have been using some of the existing terms for many years.

The remainder of this sub-chapter discusses some of the problems of lithostratigraphic nomenclature of the Cretaceous in Oman. These include use of the terms 'Musandam Limestone', 'Thamama Group' and 'Wasia Group', overlap and duplication of lithostratigraphic terms used in Oman, and correlation of lithostratigraphic units used in Oman with those used in other areas of the Middle East.

Lees (1928) introduced the term 'Musandam Limestone' to describe the Jurassic and Lower Cretaceous shelf carbonates outcropping in the Musandam Peninsula, and the Oman Mountains. This definition does not include the Upper Albian - Upper Cenomanian/?Turonian shelf carbonates outcropping in the Central Oman



Mountains which were placed by Glennie *et al.* (1974) within the Wasia Group. However, these sediments have now also been recognized in the Musandam area (Ricateau and Riche, 1980). The term 'Musandam Limestone' is still applied to the Jurassic and Lower Cretaceous shelf carbonates which outcrop in the Musandam Peninsula, despite obvious similarities to the formations recognized in the the Central Oman Mountains.

Glennie (1977) preferred to use the term 'Musandam Group' to describe the Jurassic and Lower Cretaceous carbonates of the Northern Oman Mountains, rather than the terms 'Sahtan Group' and 'Kahmah Group' which he used for their equivalents in the Central Oman Mountains.

Ricateau and Riche (1980) introduced the term 'Musandam Super-group', which is equivalent to Glennies' Musandam Group (see Figure 2.1). They divided this into 9 units lettered A - I. Units G - I represent the Lower Cretaceous which is unconformably overlain by sediments of the Wasia Formation (= Wasia Group of this study). However, units G - I could be replaced by the formational terms used in the Central Oman Mountains in this study (Rayda Formation, Salil Formation, etc.). In offshore well sections Ricateau and Riche used the terms Fahiliyan Formation, Gadvan Formation and Dariyah Formation, which are used in onshore southern Iran, instead of units G, H and I respectively (see Figure 2.1).

Allermann and Peters (1972) included 'the Musandam Limestone' within their Ruus al Jibal unit. The latter unit comprises some 4000 metres of Permian - Campanian para-autochthonous carbonates outcropping in the Musandam Peninsula. They tentatively correlated this unit to the Jebel Akhdar and Saih Hatat areas.

Hudson and Chatton (1959) produced an extremely detailed description of the Musandam Limestone in the Musandam Peninsula. They divided the limestone into Lower (Jurassic) and Upper (Jurassic - Lower Cretaceous) units. They correlated the Upper (largely Cretaceous) unit with formations in Central Arabia and the Thamama Group of the Dukham wells of the Qatar area. This is the first mention of the term 'Thamama Group' in connection with the Cretaceous shelf carbonates of the Oman Mountains.

The term 'Musandam Limestone' was used by Tschopp (1967a) and Wilson (1969). In both cases it was applied to sediments both in the Musandam Peninsula, and the Central Oman Mountains. Both authors divided the Cretaceous part of the Musandam Limestone into a lower, Thamama Group, and an upper, Wasia Group (see Figure 2.1). However, in accordance with the original definition of the Musandam Limestone by Lees (1928), both Tschopp and Wilson are wrong to place their 'Wasia Group' sediments within the Musandam

Limestone. Lees recognized no Wasia Group equivalent sediments in his type description of the Musandam Limestone.

Tschopp (1967a) was the first to divide the Cretaceous shelf carbonates of the Central Oman Mountains into Thamama and Wasia Groups. He was also the first to introduce formational terms for these sediments. He divided the Wasia Group into an upper, Wasia Limestone Formation, and a lower, Nahr Umr Formation (see Figure 2.1). The Wasia Limestone Formation is equivalent to the term 'Natih Formation', first used by Glennie *et al.* (1974) and used in this study.

The Wasia Limestone Formation was subdivided by Tschopp (1967a;b) into seven members lettered a - g from top to base. The members are recognized on the basis of lithology and log response. They are usually separated by shale layers or marly intercalations. The lithology of the seven members is as follows:

Member (a) (thickness approx. 65m, youngest member) consists of chalky wackestones and packstones. The allochems are either skeletal fragments (including rudists) or benthonic foraminifera.

Member (b) (thickness approx. 90m) is typically bituminous with argillaceous packstones and wackestones. Allochems are mainly planktonic foraminifera with whole and broken molluscan shells.

Member (c) (thickness approx. 50m) is mainly a chalky and argillaceous wackestone with abundant planktonic foraminifera. The lower part is partly dolomitized and most of the member is slightly bituminous with thin shale intercalations.

Member (d) (thickness approx. 45m) comprises a bioclastic peloidal chalky packstone. The top 5 metres are often bioclastic wackestones with rudist debris.

Member (e) (thickness approx. 180m) largely consists of peloidal wackestones. At the base cherts occur, whilst towards the top the member is sometimes slightly dolomitic.

Member (f) (thickness approx. 30m) consists of partly chalky and dolomitic wackestones, with some argillaceous intervals.

Member (g) (thickness approx. 20m) comprises chalky lime mudstones which develop into bioclastic and peloidal wackestones towards the top of the unit.

All seven members are oil producing. Members (a), (c), (d) and (e) are particularly good reservoir intervals, and is from these sediments that the oil of the Fahudd and Natih fields is produced (Tschopp 1967b,

Harris and Frost 1984). According to Harris and Frost (*op. cit.*), the reason for this is the presence of good interparticle porosity in grainstones, and, more importantly, the development of moldic porosity after fine rudist debris, associated with meteoric water lenses. These authors believe these lenses are related to the development of islands and subaerial exposure during sea level lows. The shales of the lower Fiqqa Formation provide an effective seal. Average porosities in the main reservoir intervals ranges from 25 - 32%, with permeabilities as high as 10 - 20,000md (Harris and Frost, *op. cit.*).

Member (b) is thought to be a potential hydrocarbon source rock (Tschopp, 1967b). However it cannot be the source of the Fahudd and Natih fields, since it would not have reached maturation until the Middle Eocene. The source for these fields is thought to be Palaeozoic or Early Mesozoic (Harris and Frost, 1984).

The members defined by Tschopp (1967a;b) are still used as working terms by geologists in Oman, particularly with reference to subsurface sections southwest of the main Oman Mountains range (eg. Harris and Frost, 1984).

Where possible these members are recognised in the sediments studied in this project. However, as pointed out by Harris and Frost (1984), the use of these terms is not satisfactory for outcrop sections in the Oman Mountains. This is because; (a) the shale and marl intervals that separate the members are absent, (b) several of the upper members can be missing due to erosion or non-deposition, and (c) chalky, pelagic limestones of intrashelf basin origin occur as lateral facies equivalents.

Glennie *et al.* (1974) formally described a number of lithostratigraphic terms which they applied to the Cretaceous shelf carbonates of the Oman Mountains. As mentioned in the previous chapter, they placed these sediments within the Hajar Super-group, which encompasses all the autochthonous sediments of Permian to mid-Cretaceous age in the Oman Mountains.

The Cretaceous part of this succession in the Central Oman Mountains was divided by Glennie *et al.* into two groups; the Kahmah Group and the Wasia Group. The Kahmah Group equivalent sediments of the Musandam Peninsula were placed within the Musandam Group (see Figure 2.1). As mentioned above, Glennie *et al.* (1974) and Glennie (1977) did not feel justified in using the term Kahmah Group to describe the sediments of the Musandam Peninsula, despite remarks that the Kahmah Group and the upper Musandam Group are very

similar and can be correlated. The Musandam Group of Glennie *et al.* (1974) includes Jurassic sediments equivalent to the Sahtan Group of the Central Oman Mountains.

The name Kahmah Group was introduced by Glennie *et al.* (1974) as a new term synonymous with 'Thamama Group' as used by Tschopp (1967a;b) and Wilson (1969). Glennie *et al.* argued that at its type locality in Saudi Arabia, the Thamama Group is in part defined by the presence of the underlying Hith Anhydrite. Since this does not occur in the Oman Mountains, the name Thamama Group cannot be used. Curiously, Glennie *et al.* remarked that the name 'Thamama' could be retained in Oman for sub-surface work. It has been oil company practice to do this, and to apply the name to outcrop sections, despite the comments of Glennie *et al.*

The name Thamama Group is maintained in this project for both the description of outcrop and sub-surface sections. This is partly because it is oil company practice to do so, and also because the absence of an underlying lithology (i.e the Hith Anhydrite) should not prevent a lithostratigraphic term being used, if the lithology of the unit being described is comparable to that of the type section. Neither the International Stratigraphic Code (Hedberg, 1976), nor the North American Stratigraphic Code (NACSN, 1983), mention the need for a lithostratigraphic unit to be constantly underlain by one lithology (or another lithostratigraphic unit). It seems impractical to expect this. In any case, the prime consideration for defining a lithostratigraphic unit must be the lithology of that unit, not that of the underlying rocks. Therefore, the term Kahmah Group as used by Glennie *et al.* (1974) and Glennie (1977) is synonymous with Thamama Group as used in this study (see Figure 2.1). Glennie *et al.*'s original description of the Kahmah Group is thus a useful introductory description of the Thamama Group in Oman.

Glennie *et al.* (1974) described the Kahmah Group as a carbonate sequence of 750 metres maximum thickness, ranging from deeper marine pelagic porcellanites and cherts at the base of the succession, to shallow marine limestones at the top. It was thought to be Tithonian - Aptian in age, which can now be slightly revised (see subsequent chapters). A stratigraphic thinning to the east and northeast, recognized in this study, was noted.

It is worth repeating Glennie *et al.*'s full description of the Kahmah Group here, as it provides an accurate description of the Thamama Group in Oman.

"The unit consists of a lower part of thin to thick bedded, microbioclastic mudstone and wackestone with very fine, thin bedded, porcellaneous mudstones ('porcellanites') containing black chert nodules at the base; and an upper part of predominantly thick bedded bioclastic and peloidal wackestone and packstone, alternating with thinner bedded, bioclastic mudstones and thick bedded, skeletal, oolitic and pelletal grainstone, the later being commonly fossiliferous (e.g. *Orbitolina*). In the upper part of the sequence the wackestone contains rudists (monopleurids and caprinids), while foraminiferal grainstone bands and coquina beds of thick shelled molluscs become increasingly abundant toward the top." (Glennie *et al.*, 1974, p. 140-1).

Glennie *et al.* remarked that it is possible to subdivide the Kahmah Group in the field into smaller lithostratigraphic units (i.e. formations), especially along the southern flank of Jebel Akhdar (eg. at Wadi Mi'aidin). However, they stated that towards the north across Jebel Akhdar, these units become inseparable in the field. In the experience of this author this is not the case. For example, at Wadi Bani Kharus on the northern edge of Jebel Akhdar (see Figure 1.1), all the formations used in this study (see Figures 2.1 and 2.2) are recognizable. However, the boundaries between the formations are sometimes unclear and the condensed nature of the formations may make them difficult to recognize initially (see Chapter 2.3). Glennie *et al.* did not define, or name, any formational units within the Kahmah Group, because they thought them not recognizable across the entire Oman Mountains area.

In this project the formations noted by Glennie (1977) in the Dhofar region and correlated to the Oman Mountains are used. This follows nomenclature originally used by Petroleum Development (Oman) in an internal report in 1971. Most of these formations are widely recognized across the Arabian Peninsula. Descriptions of these formations are given in the subsequent subchapter.

Glennie *et al.* (1974) thought that the Kahmah Group was conformable with the underlying Jurassic Sahtan Group, whilst the contact with the overlying Wasia Group was a disconformity.

The Cretaceous shelf carbonates overlying the Kahmah Group are placed within the Wasia Group by Glennie *et al.* (1974), following the practice of Tschopp (1967a;b) and Wilson (1969). The Wasia Group was originally defined by Owen and Nasr (1958) in the subsurface of Kuwait (although see below for a discussion of problems with this nomenclature).



Glennie *et al.*'s description of the Wasia Group is a useful introductory account of this unit in Oman, and can be repeated here. According to Glennie *et al.* the Wasia Group is a sequence of shallow - marine sediments, some 300 - 400 metres thick, thought to be of Albian - Cenomanian (?Turonian) age. The top and bottom of the unit are defined by region-wide disconformities. The thickness of the unit reduces to the northwest and increases to the southwest.

According to Glennie *et al.* (1974, p. 219); "The lower quarter of the unit is a varyingly argillaceous muddy carbonate interval with a uniform larger foraminiferal content (*Orbitolina*). Above this, the major part of the unit is a series of shoaling-up carbonate cycles each having a variably terrigenous thin basal interval. The shallow marine carbonates show lateral variations through a variety of facies, the most striking comprising biostromes of caprinid and radiolitid rudists".

The base of the Wasia Group is a region-wide disconformity with the carbonates of the Thamama Group. Glennie *et al.* (1974) did not record the temporal extent of this disconformity, but the results of this study indicate that sediments of Late Aptian - Early Albian age are absent.

The disconformity with the Aruma Group at the top of the Wasia Group omits strata from the major part of the Turonian stage from this region (see Figure 2.1).

Glennie *et al.* noted that the Wasia Group can be divided into the Nahr Umr and Natih Formations, equal to the the Nahr Umr and Wasia Limestone Formations of Tschopp (1967a)(see Figure 2.1). However, the seven members defined by Tschopp (1967b) are not recognized.

Harris and Frost (1984) and Harris *et al.* (1984) divide the uppermost carbonates of the Wasia Group equivalent to the Natih Formation (*sensu* Glennie (1977) and this study) into three lithological units (see Figure 2.1). These are shallow shelf limestones of the Mauddud and Mishrif Formations, and the intrashelf basinal facies of the Rumaila/Khatiyah Formation. The lower unit, the Mauddud Formation, is equivalent to Natih Members E - G of Tschopp (1967b), whilst the upper, Mishrif Formation is equivalent to Natih Members A - D of Tschopp. Sediments of the Rumaila/Khatiyah Formation usually overly the Mishrif Formation, according to Harris and Frost (1984) (but see below). Harris and Frost introduced the above lithostratigraphic terms because they are widely used across the Persian Gulf area. In this study the term Natih Formation is preferred because it has a useful local stratigraphic significance. However, reference will be made to the terms 'Mauddud',

'Mishrif' and 'Rumaila/Khatiyah', particularly in the context of the correlation of the Natih Formation with these units elsewhere in the Middle East.

Brennan (1985) in a discussion of Harris and Frost (1984) argued that the Rumaila/Khatiyah Formation should be referred to only as the Khatiyah Formation. This is correct since the term 'Rumaila' describes a basinal facies commonly encountered in Kuwait and southeast Iraq. The term 'Khatiyah' describes a 'deep-water' facies encountered in the Trucial Coast region and Iran. Furthermore, Brennan states that the Khatiyah Formation should always lie between the Mauddud and Mishrif Formations (Brennan (1985, figure 3), rather than above the Mishrif Formation as stated by Harris and Frost (1984, figure 7). Brennan also states that the Mauddud and Khatiyah Formations are Cenomanian in age, whilst the Mishrif is Turonian. These ages are somewhat incorrect for the Oman Mountains area, although this may be a function of diachronism.

With respect to the position of the Khatiyah Formation, this will occur within a sequence wherever intrashelf basin facies are developed. In the Oman Mountains, this is at the top of the Natih Formation (= top of the Mishrif Formation - Natih members b and a?) and is of Late Cenomanian - Early Turonian age (e.g. Jebel Salak). It can also develop in the lower Natih Formation (Mauddud Formation equivalent - Natih member e?) (e.g. Jebel Madamar).

The variable position of this formation makes it at odds with the International Stratigraphic Guide's rules for the use of the term 'formation' (Hedberg, 1976). Elsewhere in the Arabian Peninsula sediments of the Khatiyah Formation and its equivalents are commonly encountered between those of the Mishrif and Mauddud Formations (Burchette and Britton, 1985; El-Naggar and Al-Rifay, 1972; T.C. Connally Jr., pers. comm., 1985), therefore its use in these areas is correct. However in Oman the names Rumaila or Khatiyah Formation should not be used, and if required, a new formation introduced to describe the intrashelf basinal sediments that overly the Mishrif Formation equivalent sediments. In this study all these sediments are included within the Natih Formation.

Some authors have questioned the use of the term 'Wasia Group' to describe sediments occurring in Oman and elsewhere in the Arabian Peninsula.

According to Dunnington (1967) the *Wasia Formation* as defined by Steineke and Brankamp (1952) at outcrop in Saudi Arabia, is a marine sandstone unit of Cenomanian age which rests upon the eroded top of

terrestrial sands of the Albian Biyadh Formation. Correlation of this unit to Kuwait places it directly above limestones of the Mauddud Formation. Its top is placed by Dunnington at the unconformity with the overlying Aruma shales and equivalents.

Owen and Nasr (1958) in their definition of the Wasia *Group* placed the upper boundary at the unconformity with the Aruma Group and its equivalents. They also chose to carry the group downwards to include the Mauddud and Nahr Umr Formations. Dunnington (1967) correctly notes that this application of the same name to a group and to a formation which is part of that group is inadmissible under the rules of lithostratigraphic nomenclature. Despite this, the term Wasia Group quickly achieved widespread usage.

Further confusion arose when oil companies operating in Abu Dhabi defined the Wasia Group as comprising only the lateral equivalents of the Mauddud and Nahr Umr Formations. These units soon became known as the "Wasia Limestone" and "Wasia Shale" respectively. In Oman the Natih Formation became known as the "Wasia Limestone" (e.g Tschopp, 1967a). This practice was incorrect since it meant that the "Wasia Limestone" and "Wasia Shale" were in a stratigraphic position *underlying* the equivalents of the type Wasia Formation. Because of this confusion Dunnington recommended that:

- (1) The name Wasia should be restricted to the Cenomanian sandstone unit that is mapped over much of Saudi Arabia.
- (2) A new group name should be introduced to accommodate the Cenomanian limestone and shale formations from Iraq to Oman.
- (3) Another new group name should be introduced for the Albian Mauddud Limestone and Nahr Umr Shale Formations and their equivalents.
- (4) Use of the terms 'Wasia Limestone' and 'Wasia Shale' should be discontinued.

El-Naggar and Al-Rifay (1972) noted that the recommendations of Dunnington (1967), although technically correct, are at variance with the current usage of the term 'Wasia'. They believed that the problems created by using the term Wasia could be overcome by inclusion of the succession between the top of the Thamama Group and the base of the Aruma Group into one major rock unit; the Wasia Group. The term Wasia Formation should be dropped. El-Naggar and Al-Rifay state that further subdivision of the Wasia Group into

formations and members in both marginal and marine (limestone) facies is possible, and achieved the following subdivision for the marine facies.

They divide the Wasia Group occurring in the subsurface of the Kuwait area into the following formations and members:

- Mishrif Member

MAGWA Fm.

- Rumaila Member

WASIA

GROUP

AMMADI Fm.

WARA Fm.

MAUDDUD Fm.

BURGAN Fm.

Although the recommendations of Dunnington (1967) are more in line with the rules of lithostratigraphic nomenclature, the use of the term Wasia Group, as defined by El-Naggar and Al-Rifay (1972) has become widely accepted across the Middle East. However not all the formations listed by El-Naggar and Al-Rifay for the Wasia Group of Kuwait have been recognized elsewhere (see Figure 2.2, and Brennan (1985, figure 2)).

The Burgan Formation is equivalent to the Nahr Umr Formation and the Wara and Ahmadi Formations are not recognized outside the eastern Arabian Gulf. The Mishrif and Rumaila are usually described as formations, rather than members, the term Magwa Formation not being used. All the equivalents of the formations described in Kuwait by El-Naggar and Al-Rifay above the Burgan Formation are placed within the Natih Formation in this study (see Figure 2.2).

From the above discussion of the usage of lithostratigraphic nomenclature for the Cretaceous carbonates in Oman, several conclusions can be drawn. These are:

- (1) The terms 'Musandam Limestone', 'Musandam Group' and 'Musandam Super-group' should not be used, and the relevant sediments be redefined into Sahtan Group (for the Jurassic), and Thamama Group and subsequent formations (for the Early Cretaceous).

- (2) The divisions of the Natih Formation defined by Tschopp (1967a,b), cannot easily be recognized in the field outcrops of the Oman Mountains.
- (3) The term Thamama Group should be preferred to the term 'Kahmah Group' introduced by Glennie *et al.* (1974).
- (4) The terms Mauddud Formation and Mishrif Formation, although valid, are not used in this study, the term Natih Formation being preferred.
- (5) The term Khatiyah Formation is invalid in Oman, and new terms should be defined (if required) - perhaps at the member level - to describe the intrashelf basin sediments that occur within the Natih Formation.
- (6) The term Wasia Group has a confused origin, and does not wholly comply with the rules of lithostratigraphic nomenclature. However, it now has a well established meaning (eg. in Oman it incorporates the Natih and Nahr Umr Formations), and is therefore impractical to revise.

The lithostratigraphic nomenclature used in Oman in this study can be correlated with the nomenclature used for the equivalent sediments in other parts of the Middle East. Figure 2.2 summarizes this correlation. It should be emphasized that these correlations are only approximate. Difficulties arise because of the diachronous nature of some of the units, and where different authors use a name for different meanings. Where this is the case the scheme with the most common usage, or the most practical scheme has been chosen.

It can be seen that on one hand a large number of names are used to describe equivalent and similar sediments, whilst on the other, some lithostratigraphic terms are used across the Arabian Peninsula despite changes in lithology. Clearly, a revision of the lithostratigraphy of the Middle East is required, but as mentioned earlier this is probably impracticable.

## **2.2: Descriptions of the Lithostratigraphic Units**

The eight formations recognized in the Early to mid-Cretaceous shelf carbonates of the Oman Mountains in this study have never been fully described. This is particularly true of outcrop sections in the Oman Mountains. These eight formations (Rayda - Natih; see Figure 2.1) are now briefly described. In the following

sub-chapter more detailed descriptions of the formations are given as part of the sedimentological descriptions of the localities visited and logged by the author. Note that between localities in the Oman Mountains individual formations may show considerable small-scale variation.

**RAYDA FORMATION:** This formation is the basal formation of the Thamama Group and was originally defined by Hassan *et al.* (1975) as a deep water equivalent of the basal part of their Habshan Formation described from Abu Dhabi and Oman. This deep water facies occurs in Oman and the eastern United Arab Emirates. The name Rayda is derived from 'Irq Rayda, a sand and gravel area near Lekhwair in Oman. The lithology of the Rayda Formation in Oman is very similar to that described by Hassan *et al.* for Abu Dhabi.

In Oman the Rayda Formation usually overlies the Jurassic Sahtan Group with a disconformity of variable stratigraphic magnitude. The Sahtan Group generally consists of interbedded lime mudstones and ooid grainstones.

The Rayda Formation has an average thickness of approximately 80 - 90 metres. At the base there is sometimes a thin peloidal and bioclastic grainstone, but this rapidly passes up into light grey and pale pink thinly to medium-bedded lime mudstones. Because of their extremely fine grained nature they are often referred to as 'porcellanites'. Chert nodules are common throughout this formation and form a diagnostic feature. At some localities there is a zone of dolomitization in the middle of the formation. This is most likely a late, post diagenetic feature. Radiolarians are common throughout the formation. These often appear to have been altered to calcite. Calpionellids and rare planktonic foraminifera are other typical components of the microfauna. Occasionally abundant belemnites are the only macrofauna recorded from this formation. Bioturbation is common. The age of this formation is probably Berriasian.

**SALIL FORMATION:** The Salil Formation, like the Rayda Formation, was defined by Hassan *et al.* (1975) as a deep water facies equivalent of the their Habshan Formation (lying above the Rayda Formation). The name of this unit is derived from Wadi as Salil near Lekhwair in Oman.

In the outcrop sections of the Oman Mountains, the Salil Formation is represented by approximately 110 metres (at Jebel Madar and Wadi Bani Kharus) to approximately 250 metres (at Wadi Mi'aidin) of light -

medium grey lime mudstones and occasional bioclastic and peloidal wackestones. These sediments are usually thinly bedded and often intensely bioturbated. The uppermost 20 metres of the formation consists of bioclastic wackestones with bivalve and gastropod shells at some localities. Belemnites occur rarely in the lower part of formation. Radiolarians are rarer in this formation than the underlying Rayda Formation, and a lack of cherts in the Salil Formation distinguishes the two lithostratigraphic units. In all six sections, the Salil Formation is the thickest of the six Early Cretaceous formations of the Thamama Group. Slight intraformational unconformities occur within the Salil Formation, notably at Wadi Bani Kharus.

The Salil Formation is generally poorly exposed and is often strongly tectonically deformed. At Wadi Bani Kharus a strong cleavage has developed at a low angle to bedding, and bedding planes are frequently lined with hydrothermal calcite.

As well as rare radiolarians, the microfauna consists of rare calpionellids in the lower half of the formation, sponge spicules and sporadic benthonic and planktonic foraminifera. This fauna suggests a ?Late Berriasian - Valanginian age for the formation.

**HABSHAN FORMATION:** The Habshan Formation was defined by Hassan *et al.* (1975) in Abu Dhabi in the Bab -2 well. There the formation consists largely of mudstones and wackestones probably deposited in very shallow water. Some grainstones are also present. In the Oman Mountains the Habshan Formation is represented by fossil rich bioclastic - peloidal wackestones and packstones, and most typically oolitic grainstones. These are probably correlative with the Yamama Formation of the Saudi Arabia - Qatar region (see Figure 2.2). The type description of the Habshan Formation by Hassan *et al.* (1975) only applies to that formation as seen in central and western Abu Dhabi. A reference section for the Habshan Formation needs to be formally described from the Oman Mountains.

The formation is approximately 60 metres thick and lies with a slight unconformity on the Salil Formation.

In the Oman Mountains the Habshan Formation contains a macrofauna of molluscs, echinoids, corals, stromatoporoids and sponges. Some units, especially the oolitic grainstones show trough cross bedding and small scale channel structures. Oncoidal wackestones also occur within this formation.

The microfauna includes smaller benthonic foraminifera and often abundant calcareous algae (notably encrusting forms). The age of this unit is thought to be ?Valanginian - Hauterivian, and like all the Thamama Group formations in the Oman Mountains is clearly diachronous.

**LEKHWAIR FORMATION:** As defined by Hassan *et al.* (1975), the type locality of this formation is the Lekhwair -6 well in western Oman. It is equivalent to the fine grained limestones and shales of the Ratawi Formation of the Hasa Coast (see Figure 2.2), which, east of Qatar, are replaced by shallow water limestones.

In Abu Dhabi Hasan *et al.* (1975) reported that the upper and lower limits of the Lekhwair Formation are bounded by slight unconformities. No evidence of these unconformities was seen in the Oman Mountains succession during this study.

The oil producing Zakum Member defined by Hassan *et al.* (1975) at the base of the Lekhwair Formation in Abu Dhabi, has not been recognised in the Oman Mountains during this study. Hassan *et al.* noted that this unit thins to the east in the Abu Dhabi area, which suggests that it is indeed likely to be absent in the Oman Mountains.

Hassan *et al.* (1975) and Harris *et al.* (1984) record that the Lekhwair Formation in Abu Dhabi consists of a series of sedimentary cycles, resulting in alternations between dense argillaceous lime mudstones and clean porous peloidal wackestones and packstones. However, this cyclic sedimentation was not seen by this author in the Oman Mountains.

In the Oman Mountains the Lekhwair Formation is approximately 120 metres thick at localities south of Jebel Akhdar, and about 65 - 70 metres thick at localities to the north. It is medium - thickly bedded and includes a number of limestone facies. Bioclastic wackestones and packstones are common, as are intraclastic and oolitic grainstones and packstones. The presence of intraclasts is a particularly diagnostic feature. Cross - bedding, channel structures and bioturbation are common. Sometimes cryptalgal laminates with mudcracks occur in the upper part of the formation.

Macrofauna is common, but is rarely in life position. Often it is concentrated into storm lags. Bivalves and gastropods are common throughout, as are tucasid rudists. Large corals and stromatoporoids are also present in parts of the sequence.

Microfauna/flora includes larger foraminifera, but is dominated by calcareous (mainly dasyclad) algae of a number of genera. This unit has an age range of Hauterivian - Early Barremian, and is clearly diachronous.

**KHARAIB FORMATION:** According to Hassan *et al.* (1975), the type locality of this formation is the Kharaib -1 well in central Qatar. In Abu Dhabi a distinctive shale unit occurs at the top of the formation, known as the Hawar Member (see Figure 2.2). In Qatar this is termed the Hawar Formation (see Figure 2.2). During this study this unit could not be clearly recognised in the outcrop sections of the Oman Mountains, although at Wadi Mi'aidin an upper shale unit is recognizable within the Kharaib Formation.

A major feature of the lithology of the Kharaib Formation is a cyclic sedimentation style (Hassan *et al.*, 1975; Johnson and Budd, 1975; Harris *et al.* 1968; 1984). Two scales of cyclicity are present: Large scale cycles resulting in the development of two massive lime wackestone - packstone units, the upper being underlain and overlain by recessive argillaceous lime mudstone - wackestone units (i.e 4 units in total; 2 massive, 2 recessive); within each of the larger units smaller sub-cycles are present. In the massive units upwards coarsening cycles of mudstones grading to grainstones overlain by further mudstones occur. In the argillaceous units *Palorbitolina* rich packstones grade into mudstones with burrows. This cyclic sedimentation is present in the Kharaib Formation of the Oman Mountains and can most clearly be seen in the section at Wadi Mi'aidin.

The larger foraminiferid *Palorbitolina* is very common in this formation and forms a diagnostic feature. *Palorbitolina* is virtually the only allochem in the recessive argillaceous units, whilst in the more massive units microbivalves and intraclasts are also present. Corals, rudists and other molluscs are occasionally present in the massive units. Bioturbation is common and stylolitization is also a common feature.

The thickness of the Kharaib Formation varies across the Oman Mountains from approximately 40 metres at Wadi Bani Kharus, to approximately 120 metres at Wadi Mi'aidin.

Besides *Palorbitolina*, other larger foraminifera and calcareous algae are sporadically present. This formation is thought to be of Early Barremian - Early Aptian age.

SHUAIBA FORMATION: The name "Shuaiba" for the uppermost formation of the Thamama Group is widely used in the Arabian Gulf area (see Figure 2.2). Originally described by Owen and Nasr (1958) and amended by Dunnington *et al.* (1959), the type section is in the Zubair -3 well in southern Iraq. The lithology of this unit is remarkably constant throughout the Arabian Gulf area, and the formation, as it is represented in the Oman Mountains, is very similar to that recorded by Owen and Nasr (1958) in Iraq. However, in Abu Dhabi, Hassan *et al.* (1975) recorded a three phase depositional series within the Shuaiba Formation. This is as follows: Initially shallow shelf limestones were laid down across the entire Abu Dhabi area. These sediments are referred to as "Zone A". In the north these sediments were followed by deeper open marine sediments, whilst in the south an algal platform developed overlain by rudist build-ups and shallow shelf sediments. The open marine sediments to the north are referred to as the "Bab Member". In Oman the Bab Member is probably absent due to erosion or non-deposition, since no 'deep-water' Shuaiba sediments occur. Hassan *et al.* (1975) record an ammonite assemblage from the Bab Member which they thought to indicate a Late Aptian age for these sediments. Dr. W.J. Kennedy of Oxford University (pers. comm., 1985) confirms that this ammonite assemblage is of Late Aptian age. No Shuaiba Formation sediments of this age occur in Oman based on microfossil evidence.

The Shuaiba Formation of the Oman Mountains consists of a massively bedded limestone unit with stylonitic bedding. It is predominantly a microbioclastic lime mudstone - wackestone with *Palorbitolina*, miliolids, bivalves, gastropods and rudists, although in the lower part extensive *Bacinella - Lithocodium* algal boundstones may be developed. In parts, foraminifera - peloidal packstones and grainstones are common. In the upper part biostromes of caprinid rudists are a diagnostic feature. Bioturbation is common. The thickness of this unit is no greater than 45 metres.

In the Oman Mountains the Shuaiba Formation is of Early Aptian age.

The contact of the Shuaiba Formation with the overlying Nahr Umr Formation is a significant region - wide disconformity. The conformable contact recorded between these two formations in southern Iraq by Owen and Nasr (1958) is almost certainly incorrect. In the Oman Mountains this unconformity omits strata of Late Aptian - Early Albian age, although elsewhere in the Arabian Gulf, the unconformity may be of variable extent.

**NAHR UMR FORMATION:** The Nahr Umr Formation is the basal formation of the Wasia Group and was first defined by Owen and Nasr (1958). The type locality is in the Nahr Umr -2 well in southern Iraq. This formation, like the Shuaiba Formation, is recognised across much of the Arabian Gulf area (see Figure 2.2) and displays a consistent lithology, although the carbonate content increases to the east. In the type section in southern Iraq the lithology consists of interbedded shales and sandstones with few limestones. In Oman thinly bedded limestones and calcareous shales are dominant.

In the Oman Mountains outcrops, the Nahr Umr Formation consists of recessive, orange weathering argillaceous lime wackestones and packstones with abundant *Orbitolina* and macrofauna. This includes gastropods, bivalves and rare ammonites. Small scale cyclicity is present with shaley *Orbitolina* packstones being repeatedly overlain by slightly thicker bedded muddy wackestones with macrofauna. Slight disconformities occur throughout the formation. The thickness of this formation varies from 70 metres to 120 metres in the sections measured.

Apart from *Orbitolina* and a few other larger foraminifera, little other microfauna/flora was recorded from this formation in the course of this study. However in disaggregated micropalaeontological preparations, ostracods are known to occur, sometimes in abundance (Dr. J. Athersuch, BP Research Centre, pers. comm., 1985). On micropalaeontological evidence this formation is thought to be of late Early Albian - Late Albian age.

**NATIH FORMATION:** The term Natih Formation was first used by Glennie *et al.* (1974), and as mentioned in the preceding sub-chapter, has been used in Oman to describe sediments equivalent to the Mauddud, Mishrif and Khadiyah Formations (see Figures 2.1 and 2.2). No type description of the Natih Formation exists in the published literature, although since the term has been used by oil company geologists for the last 15 years, type descriptions probably exist in unpublished oil company reports. The description of Tschopp (1967b) of the Wasia Limestone Formation (= Natih Formation) in the Fahudd oilfield, in which he divides that unit into seven members (see Chapter 2.1), could be used as a temporary type description. However, as mentioned in the preceding sub-chapter, the Natih Formation in the outcrop sections differs from the section described by

Tschopp in that the marl horizons between members are absent, and the upper members are often missing due to erosion or non-deposition. Also intrashelf basin sediments occur as local lateral facies equivalents.

In the outcrop sections of the Oman Mountains, the Natih Formation is distinct from the underlying orange weathering recessive limestones and marls of the Nahr Umr Formation, where the lower part of the Natih Formation is a massive grey limestone, which forms a prominent ridge above the poorly exposed Nahr Umr Formation. This lower unit is formed of bioclastic wackestones, interbedded with some argillaceous limestones. They contain a fauna of oysters and large *Orbitolina*. Above this is approximately 50 metres of thick, massive, shelly peloidal wackestone - packstone, with miliolids, large *Orbitolina*, oysters and small bioherms and biostromes of caprinid and radiolitid rudists together with corals. The remainder of the formation consists of medium - thickly bedded bioclastic - peloidal wackestones. About half way through the total thickness of the formation, a distinct Echinoid Marker Bed occurs with an abundant fauna of holoctypid echinoids, in association with radiolitid rudist - coral bioherms.

At Jebel Madamar 50 metres of shaley argillaceous limestones occur in the lower half of the formation. These contain planktonic foraminifera and represent a 'deep-water' facies not seen at other outcrop localities, although known to occur in sub-surface sections in Oman. This is equivalent to the Khatiyah Formation of the northern Arabian Peninsula, although as explained in Chapter 2.1, this term is not suitable for use in the Oman Mountains.

*Orbitolina* occurs in the lower third of this formation. In the upper two-thirds of the formation orbitolinids are replaced by alveolinids (notably *Praealveolina*) as the dominant larger foraminiferal component of the microfossil assemblage. A 5 metre maximum overlap occurs between the two foraminiferal groups. Larger foraminifera and calcareous algae are abundant throughout the formation.

Intraformational unconformities occur within this formation and are clearly marked by pyritized surfaces, and well developed phosphatic hardground surfaces. Cyclicality in this formation, although recorded by Harris and Frost (1984), is not clearly recognizable in the outcrop sections studied by this author, although small scale limestone/marl cycles are visible in the upper Natih Formation at Jebel Madar.

The maximum thickness of the formation is 300 metres, although no one outcrop section contains a complete sequence. The formation clearly thins to the north. At Jebel Salak the uppermost part of the

formation is present. These uppermost beds consist of dark grey bioclastic wackestones and mudstones with planktonic foraminifera, together with abundant ammonites at the top of the sequence.

The top of the Natih Formation (and thus the top of the Wasia Group) is a significant regional unconformity with the overlying Muti or Fiqa Formations of the Aruma Group. This unconformity omits strata of most of the Turonian stage.

On account of the abundant and varied microfauna/flora present in this formation, it can be accurately dated throughout. The age of the entire Natih Formation is Late Albian - Earliest Turonian.

### **Chapter 2.3: Lithology of Outcrop Sections**

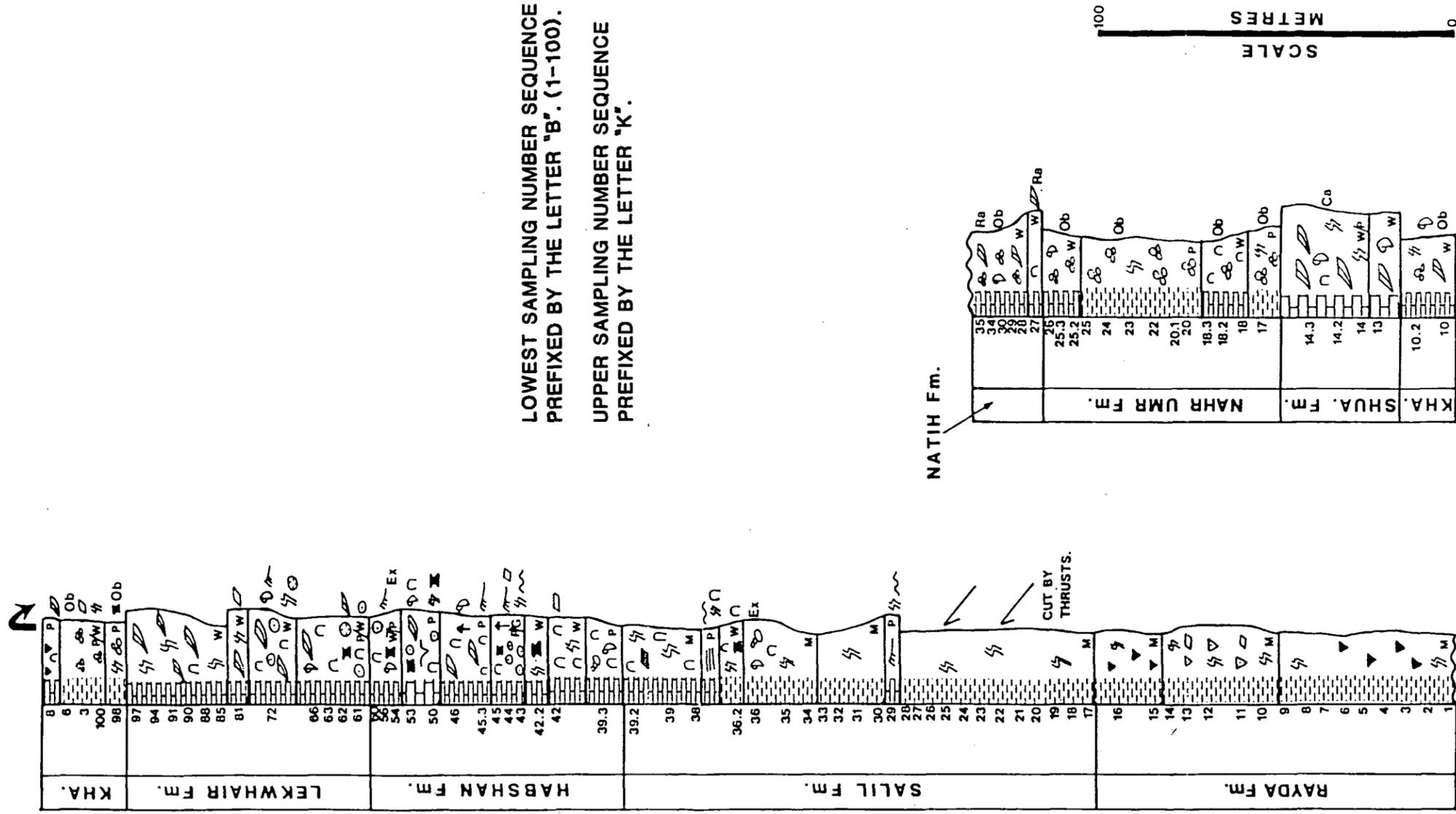
Five outcrop sections of Cretaceous shelf carbonates were examined in detail by the author during the course of field work in the Oman Mountains. These localities are Wadi Bani Kharus, Wadi Mi'aidin, Jebel Madar, Jebel Madamar and Jebel Salak (see Figure 1.1). A brief description of the section at Wadi Mi'aidin was given by Wilson (1969) and by Glennie *et al.* (1974), but no published descriptions of the other sections exist.

Within this sub-chapter lithological descriptions of all five localities are provided. Lithological logs of the localities are given (Figures 2.3 - 2.7), together with a key to the symbols used on these logs (Figure 2.8).

Whilst carrying out field work in the Oman Mountains, Cretaceous shelf carbonate outcrops other than those described below were briefly studied. Also thin sections of material from other localities (notably Saih Hataf) and from the Ma'Murah -1 well have been examined. Although the lithology of this material is not described here, the sedimentological information gained is incorporated in the interpretations made in the subsequent chapters and sub-chapters.

At all the localities rock exposure is very good allowing samples to be taken at regular intervals. Samples were taken, and logs constructed by the methods described in Chapter 1. The logs and descriptions given here are not to a very high sedimentological standard, and the logs are drawn at a small scale. This is because logging was done very quickly due to limited time available for field work. The Cretaceous carbonate succession is about 1500 metres thick in the Central Oman Mountains, and only a few weeks were available for

# SUCCESSION MEASURED AT WADI BANI KHARUS SHOWING SAMPLING POINTS



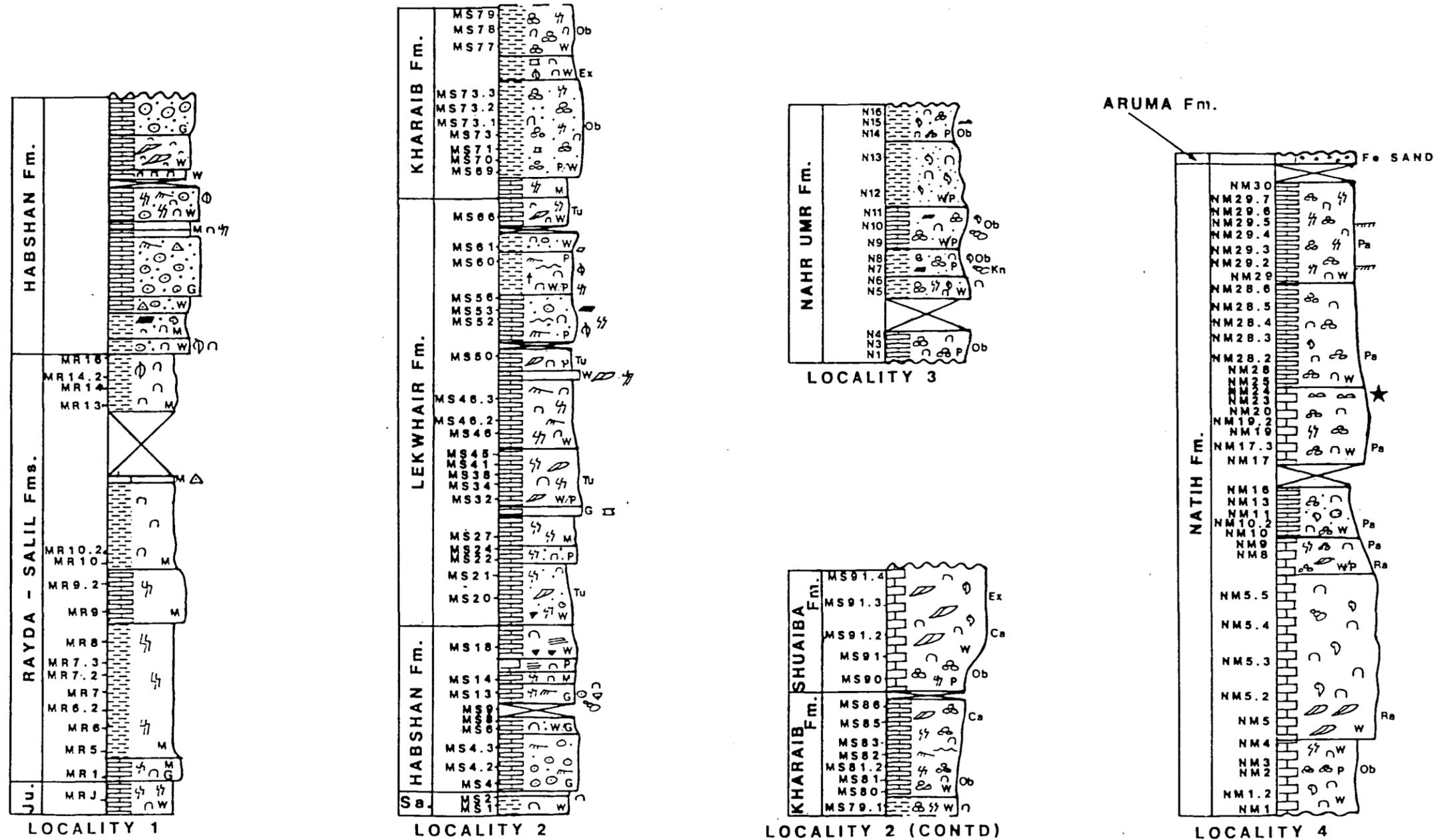
LOWEST SAMPLING NUMBER SEQUENCE  
PREFIXED BY THE LETTER "B". (1-100).

UPPER SAMPLING NUMBER SEQUENCE  
PREFIXED BY THE LETTER "K".

Figure 2.3



# SUCCESSION MEASURED AT JEBEL MADAR SHOWING SAMPLING POINTS



POSITIONS OF LOCALITIES IS SHOWN ON A SEPARATE MAP.

ALL FORMATIONS ARE VIRTUALLY ENTIRE.

Figure 2.5

# SUCCESSION MEASURED AT JEBEL MADAMAR SHOWING SAMPLE POINTS

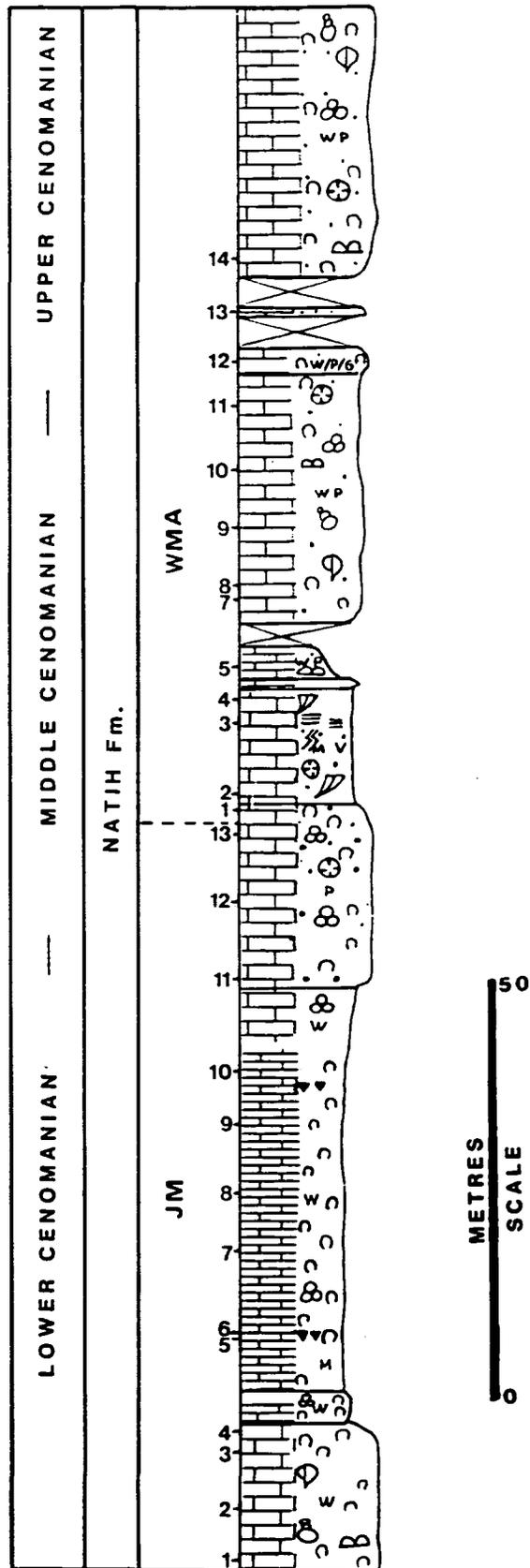


Figure 2.6



## KEY TO LOGS OF CRETACEOUS SUCCESSIONS MEASURED IN THE OMAN MTS.

 Thickly bedded	 Ammonites	 No or poor exposure
 Medium bedded	 Belemnites	 Base or top of unit obscured
 Thinly bedded	 Bivalves	 Unit continued on next log
M Lime mudstone	 Bryozoans	
W Lime wackestone	 Corals	
P Lime packstone	 Dasyclads	
G Lime grainstone	 Echinoids	
 Burrows	 Foraminifera	
 Cherts	 Gastropods	
 Dolomite	 Rudists	
 Pyrite	Ca Caprinid Rudists	
 Microbioclasts	Ex <i>Exogyra</i>	
 Ooids	Kn <i>Knemiceras</i>	
 Peloids	Mi <i>Milliolids</i>	
 Intraclasts	Ob <i>Orbitolina</i>	
 Cross-bedding	Pa <i>Prealveolina</i>	
 Plane bedding	Ra Radiolitid Rudists	
 Wave ripples	Tu Toucasid Rudists	
 Graded bedding	▲ Rudist Marker Bed	
 Channelling	★ Echinoid Marker Bed	
 Hardground	● Ammonite Marker Bed	

Figure 2.8

field work in which to study five localities in detail. Furthermore, sedimentological data acquisition was not the main aim of the project.

**WADI BANI KHARUS:** A log of the succession measured at Wadi Bani Kharus, showing sampling points, is provided as Figure 2.3.

Wadi Bani Kharus is a deeply incised valley which cuts into the northern edge of Jebel Akhdar. The mouth of the wadi is close to the town of Awabi and the wadi initially runs due south from here. The entire wadi is some 30km long and penetrates the exposed core of the Jebel Akhdar dome, where basement Cambrian/Precambrian beds outcrop. The Cretaceous shelf carbonates are exposed near the mouth of the wadi for approximately 2km. Exposure is very good on both sides of the wadi (see Plate 2.1), but the section described and illustrated here is from the west side. General dip of the Cretaceous carbonates is 30°N. This allows for a continuous succession to be measured along the floor of the wadi, although to obtain more exact measurement, the Salil, Nahr Umr and Natih Formations were measured in a continuous vertical section up the side of the wadi.

As originally noted by Glennie *et al.* (1974), Cretaceous carbonate sections on the north side of Jebel Akhdar, such as that at Wadi Bani Kharus, are rather different to those to the south. This is due to the condensed nature of the formations to the north, and the difficulty in defining boundaries between the formations.

The Sahtan Group/Thamama Group boundary is located where dark grey medium bedded lime wackestones and mudstones underlie thinly bedded light grey porcellanites (= very fine lime mudstones). The boundary appears to be somewhat gradational.

The Rayda Formation here is 102 metres thick and largely consists of bioturbated porcellanites with cherts (see Plate 2.2). Calcite veins occur along most bedding planes. The middle part of the formation (see Figure 2.3) shows evidence of dolomitization. Cherts are absent from this part of the formation and belemnites become quite common. Above this interval cherts occur again and belemnites are absent.

The last occurrence of cherts is taken to mark the top of the Rayda Formation. Above this the Salil Formation is estimated as being 134 metres thick. However, this formation is cut by a number of small thrusts, making its true thickness difficult to calculate. It is evident that the Salil Formation is much thinner here than at

any other locality. Indeed, all the Thamama Group formations are thinner here than at any of the other localities.

The lower part of the Salil Formation consists of bioturbated lime mudstones which are very thinly bedded (see Plate 2.3) and largely barren of macrofauna, although Dr. R.W. Scott of AMOCO, Tulsa (pers. comm., 1984) records a well preserved crinoid from this part of the sequence. Calcite veining is very common within these beds.

A thin bioclastic packstone occurs 55 metres up from the base of the formation. This displays ripple cross lamination and small asymmetrical current ripples. This bed is overlain by a further thick development of lime mudstones. These mudstones become fossiliferous about 95 metres from the base of the formation, and contain exogyrine oysters, gastropods and the bivalve *Lopha*. Above this, bioclastic wackestones and packstones develop with clear infill of burrows by intraclasts. Beds showing parallel lamination, flaser bedding and ripple cross lamination also develop, these being overlain by further bioturbated mudstone units.

The boundary between the Salil and Habshan Formations is gradational at this locality and somewhat difficult to define precisely. It is taken as occurring 234 metres from the base of the Cretaceous succession, where there is a gradual increase in macrofossils abundance and of allochems in general.

The Habshan Formation is 72 metres thick at this locality and consists of a variety of carbonate lithotypes (see Plates 2.4 - 2.6). The lower units are burrowed muddy wackestones and packstones with fairly common molluscs including *Exogyra* and nerineaid gastropods (see Plate 2.4). The rudists *Toucasia* and *Pachytraga paradoxa* (Pictet and Campiche) (Dr. P.W. Skelton, Open University, pers. comm., 1985) occur at this level and are common throughout the formation.

Dolomitization of these lower units is evident, particularly of burrows. Above this there is a 6.5 metre bed of intraclastic wackestone. Size of the intraclasts increases upwards to a maximum diameter of 1cm. *Thalassinoides* type burrows are common in this unit and are intraclast filled.

Overlying the intraclastic wackestone is a 9 metre thick unit of medium bedded, burrowed oolitic grainstone with some shell debris. Oolitic grainstones are diagnostic of the Habshan Formation in Oman, but the oolitic grainstones are not as well developed at Wadi Bani Kharus as at other localities.

The oolitic grainstone shows ripple cross lamination with sets 3cm thick in unburrowed oolite. The cross lamination indicates a palaeocurrent direction towards north - northwest and appears to be unidirectional. Small scale cyclicity is present with the grainstones repeatedly grading into thin mudstones. These mudstones are stylolitized. Within the mudstones faecal pellets can be seen to infill some *Thalassinoides*-type burrows. Shell debris is often accumulated into minor scours, whilst within the oolitic grainstones there are larger scours up to 1 metre across. Towards the top of the major grainstone unit large intraclasts are present. Fauna within the oolitic grainstone includes large gastropods, rare toucasid rudists and oysters.

The grainstone is overlain by a shell debris rich packstone. Fauna includes bivalves and caprinid rudists. Within this packstone 10cm thick cross sets are present which indicate a palaeocurrent direction towards the northeast. Shell debris is often concentrated into lag deposits. Rudist biostromes are evident in the upper part of this unit with ooids becoming less common. Above the rudist biostromes a burrowed dolomitic rudist debris wackestone is found. Small channels infilled with shell debris are also found.

These beds are overlain by a 0.5 metre thick bed rich in the oyster *Exogyra* sp. cf. *E. conica* (J. Sowerby). This is in turn overlain by a thin bed containing very large intraclasts. Above this oysters again occur in abundance. Ooids are increasingly common upwards together with rarer oncoids. The topmost Habshan Formation therefore consists of interbedded oolitic wackestones - packstones and oyster rich beds (see Plates 2.5 - 2.6). Bioturbation is common throughout. Some of the oolitic units show cross bedding with sets 5cm thick. A palaeocurrent direction towards the south is suggested.

The boundary between the Habshan and Lekhwair Formations is gradational and thus difficult to define. It is taken to be where there is an increase in macrofauna (both in terms of diversity and absolute numbers), and where ooids have become scarce. At this locality the Lekhwair Formation is 67 metres thick.

The basal bed of the formation is a bioclastic wackestone - packstone, with a fauna of stromatoporoids, rudists, bivalves, solitary corals and gastropods. Above this there is a series of beds alternating between shell rich wackestones and bioturbated mudstones. The shell beds are often laterally impersistent and have a fauna of bivalves and caprinid and toucasid rudists. Occasionally lenses of oolitic packstone occur. Cross bedding in some units indicates a palaeocurrent direction towards north (see Plate 2.7). Set thickness is 10cms. Small

oysters and branching corals occur 30 metres up from the base of the formation. Above this there are a number of rudist biostromes. Intraformational unconformities or emission surfaces can be seen within this formation.

The upper part of the formation consists largely of bioclastic wackestones and interbedded bioturbated mudstones and rudist biostromes. Bioturbation includes *Thalassinoides* type burrows. The rudist biostromes occur at approximately 1 metre intervals and are 0.5 - 1 metre thick. Caprinid rudists are dominant (see Plates 2.8 - 2.9).

The boundary between the Lekhwair and Kharaib Formations is clearly marked where there is a sudden change to thinly bedded nodular limestones (see Plate 2.10) with abundant *Palorbitolina*. At this locality the Kharaib Formation is 38 metres thick; considerably thinner than at localities south of the Jebel Akhdar dome.

The lowest unit of the formation consists of a *Palorbitolina* - intraclast packstone. This is overlain by a bioturbated wackestone/packstone with fine shell debris and *Palorbitolina*. Above these lower units repeated cycles of orbitolinid wackestone/packstone alternating with less fossiliferous mudstones and wackestones occur. Towards the top of the formation are biostromes of caprinid rudists and other bivalves. Dr. P.W. Skelton (pers. comm., 1985) records the rudist *Offneria* from this horizon. There are also rare chert nodules within this unit. Orbitolinids become rare towards the top of the formation. The rudist biostromes alternate with orbitolinid wackestones.

The boundary between the Shuaiba and Kharaib Formations is easily recognised where there is a sudden change from nodular bedded orbitolinid wackestones to massive biowackestones with common caprinid rudists. The Shuaiba Formation is 34 metres thick here and forms a distinctive 'wall' of dark grey limestone with large rudists on the western side of the wadi.

The lower part of the formation here is a 12 metre thick rudist - bivalve wackestone, although no biostromes are present. However, above this is a further massive wackestone, and within this there are very distinctive biostromes of caprinid rudists. *Caprina douvilleri* Paquier is the most common species within these biostromes, although *Glossomyophorus costatus* Masse, Skelton and Slisković, *Monopleura* and *Offneria* also occur (Dr. P.W. Skelton, pers. comm., 1985). The bivalve *Chondrondonta* is also present. Bioturbation is common throughout the formation and some burrows show pyrite infilling.

The boundary between the Shuaiba and Nahr Umr Formations is very clearly marked where there is a sudden change from massive rudist limestones to thinly bedded *Orbitolina* grainstones. The contact between the two formations is uneven, with the Nahr Umr Formation infilling the eroded surface of the Shuaiba Formation. At this locality the Nahr Umr Formation is 67 metres thick.

The majority of the Nahr Umr Formation is formed of orbitolinid packstones, although there are some alternations with orbitolinid - bioclastic wackestones. The entire formation distinctively weathers to an dull orange or brown colour. Macrofauna is scarce, although in the uppermost beds some oysters, toxasterid echinoids and bivalves occur. The orbitolinids in the upper beds of the formation are very large, with the largest examples having a diameter of 5cms.

The Natih Formation overlies the Nahr Umr Formation without any obvious disconformity. However, there is a marked change from orange, nodular thinly bedded orbitolinid wackestones and packstones to grey medium bedded biowackestones with rudists. The lower part of this formation is more resistant to weathering than the Nahr Umr Formation and forms a prominent overhang. The Natih Formation is not exposed on the floor of the wadi and can only be located by climbing the west side of the wadi, near the wadi entrance. 31 metres of Natih Formation are exposed, although only the basal beds of the formation crop out at this locality.

The lower part of the formation consists of radiolitid rudist biowackestones and occasional *Orbitolina*. Further up in the sequence radiolitid biostromes/bioherms alternate with oyster beds and orbitolinid packstones. Radiolitid rudist genera occurring in these beds include *Sphaerulites*, *Eoradiolites* and *Praeradiolites* (identifications by Dr. P.W. Skelton and Dr. R.W. Scott). The most common oyster species is *Exogyra flabellata* Goldfuss. At other localities orbitolinid wackestones occur at the base of the Natih Formation, with radiolitid rudists not present for the initial few metres. This is not the case here. Other macrofauna associated with the rudists includes bivalves and solitary corals.

The Natih Formation terminates at the top of the west ridge at the entrance to the wadi. The uppermost beds are strongly recrystallized almost to a marble, and these are overlain by unusual deep red feruginous sands. There is clear evidence for the tectonic deformation and removal of any stratigraphically higher Natih Formation beds that may have been deposited here.

Approximately 18km east of Wadi Bani Kharus, Wadi Mistal also cuts through Cretaceous shelf carbonates on the north side of Jebel Akhdar. Near the mouth of the wadi, Natih Formation sediments are exposed on both sides of the Wadi. At this locality structural deformation is quite intense with thrusting evident, and also a strong degree of recrystallization. However, Natih Formation beds containing common alveolinids were seen. Furthermore, some distance below this an overlap between orbitolinid and alveolinid occurrences was noted. This indicates that at least the lower half of the entire Natih Formation is exposed at this locality, which is considerably more than at Wadi Bani Kharus. Considering the close proximity of the two localities, it seems likely that a similar considerable thickness of Natih Formation was originally deposited at Wadi Bani Kharus but was subsequently removed by tectonic deformation and erosion. It is difficult to say if the upper half of the Natih Formation was ever deposited on the north side of Jebel Akhdar. No evidence for its deposition exists in outcrops, although it may have been removed by erosion or tectonic thinning.

At Wadi Mistal the Natih Formation includes alveolinid biowackestones and chrysalidinid wackestones. Above the last occurrence of *Orbitolina* caprinid - radiolitid rudist biostromes are common. No samples were collected from this locality on account of the highly recrystallized nature of the sediment.

**WADI MI'AIDIN:** Wadi Mi'aidin cuts into the southern side of the Jebel Akhdar dome 15km east of Nizwa and 10km west of Izki (see Figure 1.1). The wadi is clearly signposted from the main Muscat - Nizwa road.

In the section studied the wadi flows north to south. The wadi floor is approximately 400 metres wide and the wadi sides are up to 2000 metres high. The wadi cuts through a number of rock units from Cambrian basement beds near its source to Hawasina Series sediments at the mouth of the wadi. The wadi is particularly noted for its exposures of Mesozoic autochthonous sediments of the Hajar Super-group (see Plate 2.11). These are well exposed in a continuous section along the floor of the wadi and this has led the locality to be one of the most extensively studied in the Oman Mountains. Previously published descriptions of the locality are given by Wilson (1969) and Glennie *et al.* (1974).

Cretaceous shelf carbonates outcrop for 2-3km along the floor of the wadi directly below sediments of the Muti Formation, which are in turn overlain by the Hamrat Duru Group of the Hawasina Series. The boundary

between the Sahtan Group and the Thamama Group is approximately 5-6km north of the wadi mouth. Local dip is 35° S.

The section presented here is a composite taken from both sides of the wadi. A log of the succession measured at Wadi Mi'aidin showing sampling points is given as Figure 2.4. This log is based on an original log constructed by Dr. J.D. Smewing of ESRI and contains amendments noted by the present author during the course of his field work.

The contact between the Sahtan Group and the Thamama Group occurs close to a water pump on the west side of the wadi. Here light grey porcellanites of the Rayda Formation abruptly overlie dark grey shelly packstones of the Sahtan Group. The upper Sahtan Group bedding surface is covered in *Thalassinoides* type burrows (see Plate 2.12). Peloidal grainstones occur in the uppermost Sahtan Group. The boundary between the Sahtan Group and Rayda Formation is sharp but not clearly erosional.

At this locality the Rayda Formation is 63 metres thick and largely consists of thinly bedded, bioturbated radiolarian lime mudstones. These have a pinkish weathered appearance. Black nodular cherts are common throughout most of the formation (see Plate 2.13), although not in the top or bottom 10 metres. Belemnites often occur in abundance on bedding plane surfaces (see Plate 2.14).

The porcellanites of the Rayda Formation can be seen to be finely interbedded with silts. A typical cycle consists of 40cms porcellanite - 5cms silt - 5cm porcellanite - 5cms silt - 40cms porcellanite. The top of each porcellanite layer appears to be slightly erosional. Occasionally the porcellanite - silt intercalations form small mound like structures. The formation of these features may be related to secondary stylolitization.

The boundary between the Salil and Rayda Formations appears to be gradational and is difficult to define precisely. It is taken as occurring where burrowed recrystallized lime mudstones overlie porcellanites.

The Salil Formation is 313 metres thick at this locality. The lowest 90 metres consists of thinly bedded bioturbated lime mudstones with no macrofauna (see Plate 2.15). These beds are overlain by 32 metres of thinly bedded mudstones with some peloidal and intraclastic wackestones. Overlying this are 48 metres of massively bedded mudstones with fairly common belemnites. The topmost 143 metres of the formation consist of very thinly bedded bioturbated mudstones similar to the lower part of the formation.

The base of the Habshan Formation is marked where a ridge of slightly shelly mudstones overlies the thinly bedded mudstones of the Salil Formation. The Habshan Formation is 105 metres thick at this locality. The lowest part of the formation consists of burrowed shelly mudstones with rare corals and bivalves. Above this are a variety of carbonate lithologies, but dominantly shelly oolitic and peloidal wackestones and packstones. These are fairly rich in macrofauna especially bivalves, gastropods and echinoids. The caprotinid rudist *Pachytraga tubiconcha* Afre is present (Dr. P.W. Skelton, pers. comm., 1985). Bioturbation is common, and oolitic packstones can be seen to channel into shelly wackestones.

Directly above this channelling there are alternations between bioturbated mudstones and oolitic packstones. The burrows in this unit are sometimes infilled with shell debris. Overlying these units is a ridge of massively bedded sediments. The lower part consists of bivalve and gastropod rich intraclastic packstones, whilst the upper part is a 28 metres thick oolitic grainstone unit with layers of molluscs and stromatoporoids. The oolitic grainstone unit shows bimodal low angle planar cross bedding. Palaeocurrents are directed towards northeast and southwest. Some cross lamination appears to be large scale trough cross bedding.

The oolitic units appear to be slightly graded (i.e fining upwards). In places a sequence of cross bedded oolite - parallel laminated oolite - burrowed intraclastic packstone - cross bedded oolite can be seen.

The base of the Lekhwair Formation occurs where beds with abundant poorly sorted bivalves, gastropods and solitary corals overlie the oolitic grainstones of the Habshan Formation. The boundary between the two formations appears to be gradational. At this locality the Lekhwair Formation is 127 metres thick.

The lower part of the formation consists of medium bedded mollusc rich wackestones and mudstones with some intraclasts. Overlying these beds are massively bedded bioturbated mudstones with biostromes of bivalves and tucasid rudists. The rudists are usually selectively dolomitized. The topmost part of the formation consists of shelly intraclastic and peloidal wackestones, occasionally cross bedded.

The Kharai Formation is 125 metres thick at Wadi Mi'aidin. The base of the formation is marked where massively bedded shelly wackestones - packstones overlie thinly bedded wackestones of the Lekhwair Formation. The boundary between these two formations is gradational.

The lowest 48 metres of the Kharai Formation at this locality consist of bivalve rich bioturbated intraclastic wackestones and packstones (see Plate 2.16), usually massively bedded. Overlying this is 20 metres

of argillaceous packstones with abundant *Palorbitolina*. Twelve cycles of *Palorbitolina* bearing packstones grading into clean lime mudstone with burrows have been recognised in this unit (Dr. J.D. Smewing, pers. comm., 1984). This cyclicity is typical of the Kharai Formation. The upper part of the formation consists of a massive bioturbated lime mudstone with *Palorbitolina* being overlain by a further *Palorbitolina* rich argillaceous unit showing small scale cyclicity. Thus the large scale cyclicity thought to be typical of the Kharai Formation in the Arabian Gulf can be seen at this locality.

The Shuaiba Formation forms a 90 metre thick massively bedded limestone unit overlying the Kharai Formation. The boundary between the two formations is sharp but not erosional (see Plate 2.17). The Shuaiba Formation can be seen as a prominent cliff feature on either side of the wadi (see Plate 2.18). The majority of the formation consists of mudstones and wackestones with molluscs and occasional *Palorbitolina*. Pyrite nodules occur along some horizons. Towards the top of the formation caprinid rudist biostromes develop, but are not as prominent as those at Wadi Bani Kharus. The most common caprinid is *Caprina douvillei*, but the caprotinid *Glossomyophorus costatus* and the radiolitid *Eoradiolites* also occur (Dr. P.W. Skelton, pers. comm., 1985).

The top surface of the Shuaiba Formation is here covered in rudist bivalve debris. The surface is clearly an omission surface being strongly eroded and having numerous borings into it, these often being pyrite infilled. The topmost few centimetres of the formation appear to have developed into an ironpan deposit.

The Nahr Umr Formation is not well exposed at this locality (see Plates 2.19 - 2.20). Large parts of the succession are often covered by scree or vegetation. In general the formation forms a recessive unit composed largely of orange weathering, shaley *Orbitolina* grainstones and wackestones. The formation is 180 metres thick at this locality.

The lowest 5 metres of the formation are *Orbitolina* grainstones. These are overlain by thinly bedded shelly wackestones with *Orbitolina*. These are burrowed and contain gastropods (notably *Strombus* and *Luetia*) and bivalves (notably *Protocardium*). Overlying this are several metres of alternating *Orbitolina* wackestones and packstones. The wackestones often contain a well preserved mollusc fauna.

Towards the top of the formation the *Orbitolina* wackestones contain the oysters *Exogyra flabellata* Goldfuss and *E. conica*, together with bivalves, gastropods, corals, rudists and flat toxasterid echinoids. The

orbitolinids in this part of the succession are very large, up to 5cm in diameter. At the top of this formation, there are rare caprinid rudists.

The Natih Formation forms a prominent ridge of grey limestone overlying the thinly bedded orange limestones and marls of the Nahr Umr Formation (see Plates 2.19 - 2.20). The boundary between the two formations is sharp but not erosional. At this locality 310 metres of Natih Formation sediments are exposed.

The lowest 38 metres of the formation are formed of slightly shelly grey mudstones with occasional corals and *Orbitolina*. Overlying this is a prominent massively bedded unit 70 metres thick. This consists of orbitolinid mudstones alternating with bioclastic - intraclastic packstones and tucasid rudist biostromes. The hydrozoan *Parkeria* is also recorded from this unit (Dr. R.W. Scott, pers. comm., 1984). The packstones contain echinoid and radiolitid rudist debris. At the top of this unit there is an overlap in the occurrence of the larger foraminifera *Orbitolina* and *Praealveolina*. In the beds above this only *Praealveolina* is common.

Above the *Orbitolina* - *Praealveolina* overlap the formation consists of thickly bedded mudstones and bioclastic wackestones, with common *Praealveolina*. Laterally discontinuous radiolitid - caprinid rudist biostromes develop, but no bioherms were noted. Within the upper part of the succession several intraformational disconformities and hardground surfaces occur (see Plate 2.21), indicating parts of the formation deposited elsewhere may be absent here.

About 215 metres from the base of the formation, a bed with abundant echinoids of the species *Coenholectypus cenomanensis* (Gueranger) occurs. This is referred to as the "Echinoid Marker Bed", and can be traced to other localities (eg. Jebel Madar, Jebel Madamar).

The Natih Formation is terminated here by an erosive, unconformable contact with the overlying conglomerates of the Muti Formation.

**JEBEL MADAR:** Jebel Madar is an isolated dome located on the southern side of the Oman Mountains, 50km south of Ibra (see Figure 1.1 and Plate 2.22). The nearest village is Mudaybi, which is 20km to the north. No road runs close to the jebel and it is best reached by driving due south from Mudaybi across alluvial gravel plain deposits. The maximum elongation of the jebel is 8km in a SW - NE direction and it is 5km wide. The only

published information on the geology of Jebel Madar is that shown on the 1:500,000 scale geological map of Glennie *et al.* (1974).

Within the core of the dome, Triassic dolomitized grainstones of the Mahil Formation are exposed (Dr. J.D. Smewing, pers. comm., 1984). These are overlain by a thin sequence of Jurassic carbonates of the Sahtan Group, with Early - mid Cretaceous carbonates of the Thamama and Wasia Groups being exposed on the flanks of the dome.

The domal aspect of Jebel Madar has commonly been attributed to salt diapirism, although there are arguments that the dome developed by compressional tectonics (Dr. J.D. Smewing, pers. comm., 1984).

The Thamama and Wasia Groups are well exposed at Jebel Madar (see Plates 2.23 - 2.27), and a number of sections can be logged, although there is no one continuous section encompassing all the formations present. Four sections were logged and sampled by the author. The position of these is shown on the geological map of Jebel Madar presented as Figure 2.9. Logs of the measured sections are shown as Figure 2.5. Together these successions form a composite section through all the Thamama and Wasia Group sediments exposed at Jebel Madar.

The boundary between the Sahtan and Thamama Groups can be located near the core of the dome at locality one (see Figures 2.5 and 2.9). Here the upper Sahtan Group can be seen to be formed of dark grey, medium bedded, poorly fossiliferous lime wackestones, which are intensely bioturbated. The topmost Sahtan Group beds are coarse grainstones and oyster rich oolitic packstones. On the upper bedding plane surface of the Sahtan Group a coarse sand is plastered which infills depressions in this eroded surface. The topmost bedding plane is also iron stained and contains pyrite nodules. Therefore, there is some evidence that a disconformity separates the Sahtan and Thamama Groups at this locality.

Chert nodules which are a diagnostic feature of the Rayda Formation are not present at this locality. It is therefore impossible to distinguish between the Rayda and Salil Formations here. The combined thickness of the two formations is 154 metres.

The lowest 6 metres of the Rayda - Salil Formations are formed of light grey porcellanites with oyster and echinoid debris, and well developed *Thalassinoides* burrow systems. Belemnites are abundant. Dr. J.D. Smewing (pers. comm., 1984) records glauconite at the base of the Thamama Group. Above this there is a



monotonous sequence of poorly exposed, thinly bedded mudstones, porcellanous at the base, usually bioturbated and sometimes containing molluscan debris and rare belemnites. In the uppermost Salil Formation, shell debris occurs in abundance and beds become occasionally oolitic. At locality two (see Figures 2.5 and 2.9) belemnites, bivalves, gastropods and echinoids are quite common at the top of the Salil Formation.

The Rayda - Salil Formations are abruptly overlain by oolitic grainstones of the Habshan Formation (see Plate 2.28). The boundary between the two units is sharp but not erosive. The Habshan Formation was logged at both localities one and two.

At locality one it is some 63 metres thick and consists of thick oolitic grainstones at the base. This unit is highly stylolitized, is cross bedded and contains belemnites and shell lag deposits. Overlying this are highly burrowed (*Thalassinoides* type burrows) mudstones, overlain by a further oolitic grainstone unit. Above this are further burrowed mudstones and also macrofossil rich wackestones which contain bivalves, crinoid ossicles and echinoids. Tops of bedding surfaces are particularly well burrowed. Some beds contain toucasid rudist biostromes. Overlying the biostromes is a further oolitic grainstone unit.

At locality two the Habshan Formation is 43 metres thick and at the base there is a thick oolitic grainstone unit. This contains belemnites, *Exogyra* and large nerineaid gastropods. The unit displays a series of coarsening upwards cycles with ooid size increasing. There is also some cross bedding, with a palaeocurrent indicated towards the north and northeast. Above the grainstone unit there are a series of beds rich in macrofossils and bioclasts with occasional ooids. The shelly beds are often rich in oysters or toucasid rudists (see Plate 2.29). There are also small scale stromatoporoid and algal build-ups in the upper part of the Habshan Formation at this locality, a feature not noted elsewhere (see Plate 2.30). Channels of oolitic grainstone are noted cross-cutting algal bank developments. Cross bedding and parallel lamination are also common features in the upper part of the formation. Cross bedding indicates palaeocurrent directions towards the north and northeast. In the topmost unit of the formation chert nodules are developed. Dolomitization and micritization of ooids to peloids are features which are also recognized in this formation at locality two.

Localities one and two are only 1km apart, yet the Habshan Formation shows differences in lithology and thickness between the two. In particular, oolitic grainstones are better developed at locality one. These

differences can be explained by the fact that the Habshan Formation was deposited in a shelf margin environment (see subsequent chapters), in which distinct lateral facies variations are likely.

At locality one the contact of the Habshan Formation with the Lekhwair Formation is not exposed. However, at locality two intensely burrowed, poorly sorted bioclastic wackestones mark the base of the Lekhwair Formation. The boundary between the two formations is gradational. At locality two 136 metres of Lekhwair Formation sediments were recorded.

A wide variety of carbonate lithologies exist within the Lekhwair Formation (see Plates 2.31 - 2.32), especially burrowed bioclastic wackestones, peloidal grainstones, intraclastic packstones and oolitic grainstones. *Toucasid* rudists, gastropods and oysters are common macrofauna. Bioclastic debris is often concentrated into storm lags. Towards the top of the formation cryptalgal laminates with mudcracks occur. There are also biostromes with stromatoporoids. These are often dolomitized. Throughout the sequence burrows often appear to be preferentially dolomitized, and dolomitization is sometimes associated with stylolitization. Dolomitization is also particularly common towards the top of the formation.

Some units within the Lekhwair Formation at this locality display low angle cross bedding. Bimodal palaeocurrent directions are indicated in southwest - northeast directions. In association with the low angle cross bedding are symmetrical wave ripples. The cross bedding is usually concentrated in sand shoals. The algal laminates overlie these beds.

The sediments of the Lekhwair Formation pass into those of the Kharab Formation without any distinct boundary. The Kharab Formation is 102 metres thick at this locality. Neither the large scale or small scale cyclicity which is typical of the formation at other localities is clearly visible at Jebel Madar. The lower part of the formation consists of medium bedded grey mudstones with burrows. These are overlain by thinly bedded *Palorbitolina* packstones - grainstones. In these beds intraclasts and shell debris are also common. There are also layers with caprinid rudists. Overlying the grainstones are mudstones and wackestones with intraclasts, shell debris and sparse *Palorbitolina*. Within these beds an inverted whole stromatoporoid was noted. Towards the top of the formation there are beds of orbitolinid packstone. Some of the beds also display symmetrical wave ripples.

The Shuaiba Formation overlies the Kharai Formation as a massive light grey limestone. The boundary between the two beds is sharp but not erosive. At this locality the Shuaiba Formation is 40 metres thick although the top is not seen due to erosion.

The lower part of the formation contains a number of laterally discontinuous caprinid rudist biostromes. Overlying these are bioclastic wackestones with *Palorbitolina*. Rudist debris is common. The entire formation is bioturbated. Dr. J.D. Smewing (pers. comm., 1984) records *Rhizocorallium* burrows. Towards the top of the formation caprinid - toucasid rudist biostromes become common within a matrix of bioclastic wackestone. Oysters are also common.

The contact between the Shuaiba Formation and the Nahr Umr Formation was not observed at any locality in the Jebel Madar area. Exposure of the Nahr Umr Formation is very poor (see Plate 2.33) and the lowest beds of the formation are never seen. An 82 metre thick section through the Nahr Umr Formation was logged at locality three (see Figures 2.5 and 2.9). This section represents almost the entire formation since the Shuaiba Formation outcrops no more than 10 metres below the lowermost Nahr Umr Formation exposure, and the contact with the overlying Natih Formation is visible.

The main lithologies of the Nahr Umr Formation are orange coloured shales and argillaceous *Orbitolina* wackestones and packstones. The formation displays cyclicity with sandy orbitolinid packstones repeatedly grading into mudstones containing a fauna of whole macrofossils. This includes bivalves, gastropods, corals, echinoids and ammonites. This fauna is diverse including four species of echinoid, three species of gastropod and four species of bivalve. Identified taxa include the gastropod *Strombus*, the echinoid *Toxaster*, the bivalves *Exogyra flabellata* and *Protocardium*, and the ammonite *Knemiceras duberteri* Basse. Bioturbation is very common throughout the formation. Pyrite nodules and pyritization of macrofossils is also common.

The Natih Formation abruptly overlies the Nahr Umr Formation as a massive grey bioclastic wackestone. However the Natih Formation is not well exposed at locality three, where it is largely removed by recent erosion, so a full succession was measured at locality four (see Figures 2.5 and 2.9). Here 208 metres of Natih Formation were recorded.

The lowest part of the formation consists of alternations of bioclastic wackestones and recessive, bioclastic packstones (see Plate 2.34). Both lithologies are burrowed. Throughout the formation, but particularly in the lower part, fissures occur infilled by shales of the Aruma Group.

The alternating wackestones and packstones are overlain by a 50 metre thick chalky, massively bedded wackestone which forms a prominent cliff feature. Radiolitid rudists of the genus *Sphaerulites* are very common at the base of this unit. The majority of the unit consists of a bioclastic wackestone with bivalves, corals, rudists and oysters. *Orbitolina* is rare in this unit. Caprinid rudists become common towards the top of this unit.

Above the horizon rich in caprinids is a recessive microbioclastic wackestone which contains alveolinids. There is an overlap of about 5 metres in which both orbitolinids and alveolinids can be found. Within this zone of overlap a possible emission surface was noted showing karstification effects.

The beds above this have a diverse mollusc macrofauna with caprinid and radiolitid rudists (see Plate 2.35), oysters (*Exogyra flabellata*), *Protocardium*, *Lopha*, *Pecten* and gastropods. Because of the abundance of oysters these beds can be referred to as the "Exogyra Beds". The larger foraminifera *Praealveolina* is also common and becomes very large in size at the top of this recessive unit. Thin, pyrite rich sandstones are also present towards the top of this unit and may represent intraformational disconformities. These sandstones are clearly burrowed.

Overlying these units is a chalky massive bedded microbioclastic wackestone. Large *Praealveolina* are common in this unit, but other fauna is sparse. At the top of this unit is a distinctive red and white mottled bed (see Plate 2.36), overlain by a bed rich in large *Praealveolina* and the echinoid *Coenholectypus cenomanensis*. This is equivalent to the "Echinoid Marker Bed" noted at other localities in the Oman Mountains.

The uppermost 65 metres of the Natih Formation at this locality are medium bedded, microbioclastic wackestones (see Plate 2.37). These are burrowed and contain *Praealveolina*, occasional bivalves (including *Isogoman*), echinoids (including *Hemiaster*) and solitary corals. In the uppermost 25 metres a number of pyritic hardgrounds occur.

The contact of the Natih Formation with the overlying Aruma Group was not observed. However, basal beds of the Aruma Group were observed only 6 - 7 metres above exposed beds of the Natih Formation along the southeast flank of the Jebel. The basal Aruma Group here is formed of a ferruginous brown sand, overlain by red shales. The topmost exposed Natih Formation shows karst - like weathering features, and red mudstones infill fissures in the uppermost Natih Formation.

JEBEL MADAMAR: A log of the succession exposed at Jebel Madamar, showing sampling points is provided as Figure 2.6. This log was initially constructed by Dr. J.D. Smewing. The section is a composite measured at two localities on the north and south sides of the jebel.

Jebel Madamar is a small elongate structure measuring about 12km along its long axis. In effect it is an elongate anticline following the structural trend along which Jebel Salak and Jebel Hinqyd occur (see Glennie *et al.*, 1974, enclosure 2). The jebel is located about 1km north of the village of Adam (see Figure 1.1), and access to the locality can be gained by driving east from the main Muscat - Salalah road near this village.

Only beds of the Natih Formation are exposed at this locality (see Plate 2. 38). Almost 270 metres of Natih Formation sediments were measured. The contact with the underlying Nahr Umr Formation is not exposed, although the fauna and lithology suggest that the lowest Natih Formation beds exposed are close to the actual base of the formation. The lowest 30 metres of the exposed succession are thickly bedded bioclastic wackestones with exogyrine oysters, bivalves, echinoids and *Orbitolina*.

Overlying these beds are 70 metres of thinly bedded shaley mudstones and microbioclastic wackestones with occasional cherts. In thin section these sediments contain planktonic foraminifera. This facies is not seen at such a stratigraphically low level in the Natih Formation at any other locality. It appears to be very similar to the Khatiyah Formation (see Figures 2.1 and 2.2, and previous subchapter) or Members (b) and (c) of Tschopp (1967b). It's stratigraphic position suggest equivalence with Member e. This demonstrates the problems of trying to apply this previous lithostratigraphic nomenclature to the outcrop sections of the Oman Mountains as discussed in the previous subchapter.

The shaley beds are overlain by 30 metres of thickly bedded microbioclastic packstones. *Orbitolina* occurs in the lower part of the unit and *Praealveolina* in the upper part. An overlap of a few metres occurs

between the two genera. Overlying this unit are 35 metres of bioclastic wackestones and packstones with common caprinid rudists and corals.

The uppermost 100 metres of the formation largely consists of bioclastic wackestones and packstones with bivalves, gastropods and solitary corals (see Plate 2.39). 210 metres from the base of the succession a bed with abundant radiolitid rudists occurs which forms discontinuous bioherms in association with corals. Directly above this bed is a bed with abundant echinoids of the species *Coenholectypus cenomanensis* (Dr. E.F.P. Rose, University of London, pers. comm., 1983). The echinoid *Hetrodidemia lybicum* Agassiz and Desor also occurs in this bed, as well as large *Praealveolina*. These two horizons can be referred to the "Rudist Marker Bed" and "Echinoid Marker Bed" respectively, as seen elsewhere in the Oman Mountains.

The topmost Natih Formation exposed here is overlain by wadi gravels.

**JEBEL SALAK:** Jebel Salak is an elongate anticline that lies along the same structural trend as Jebel Madamar. Its long axis measures 30km. It lies 8km west of the village of Adam (see Figure 1.1), and can be reached by driving west from the main Muscat - Salalah road just south of this village.

A log of the section measured at Jebel Salak is provided as Figure 2.7. This log was measured at a locality on the north side of the jebel, about 20km from its western tip. Successions on the south side of the jebel and at other localities on the north side revealed similar lithologies. Only beds of the Natih Formation were recorded in the study carried out by the author. However, Dr. J.D. Smewing (pers. comm., 1984) believes he has located beds of the Nahr Umr Formation in the core of the anticline. A complete Natih Formation sequence exposed here would be the thickest in the Oman Mountains, and the most similar to that described by Tschopp (1967a;b) from the Fahud oilfield.

The lowest 15 metres of the succession logged consist of microbioclastic light grey mudstones with rare orbitolinids and chert nodules. Thin pyrite rich layers which may represent hardgrounds occur. Overlying this unit is a micritic unit containing common radiolitid rudists (see Plate 2.40). These form small bioherms. Above this there are partially dolomitized bioclastic wackestones with gastropods and corals. Overlying this is an 8 metre thick unit with abundant radiolitid rudists. The rudists are very large and appear to be in life position,

forming bioherms. They are associated with corals and occasional bivalves. This unit is thought to be equivalent to the "Rudist Marker Bed" seen at Jebel Madamar.

Above the "Rudist Marker Bed" is a bioclastic wackestone - packstone with *Protocardium* and coral and bivalve debris. The upper surface of this unit is highly burrowed. Directly overlying this is a unit thought to represent the "Echinoid Marker Bed". It contains abundant echinoids of the species *Coenholectypus cenomanensis*, together with rarer *Hetrodidemia lybicum*, *Salenia* and *Hemiaster*. Gastropods, corals and rudists also occur.

Overlying the "Echinoid Marker Bed" are 35 metres of thinly bedded bioclastic wackestones with abundant large *Praealveolina*, bivalves and corals (see Plate 2.41). There are also rare occurrences of ammonites and nautiloids. Possible hardground surfaces occur within this unit.

The upper 100 metres of the succession largely consists of bioclastic wackestones with occasional mudstone units (see Plate 2.42). *Exogyra flabellata* and corals are common in the lower part (see Plate 2.43), but bivalves (including *Protocardium*) and gastropods increase in abundance in the upper part of the succession. Some beds contain abundant fine comminuted bivalve debris. Within these beds ammonites are occasionally common. Identified taxa include *Turrilites prosticites*, *Neolobites* and *Acanthoceras* (Dr. W.J. Kennedy, Oxford University, pers. comm., 1984).

The topmost 35 metres of the formation is formed of thickly bedded lime mudstones which have only a sparse fauna. However, the uppermost Natih Formation sediments exposed (see Plate 2.44) contain abundant ammonites, including forms attributable to *Sagesia*, *Vascoeras* and *Pseudaspidoceras* (identifications by Dr. W.J. Kennedy). This bed can be termed the "Ammonite Marker Bed". These ammonites appear to represent a transported assemblage since the sediment is clearly winnowed. *Exogyra*, echinoids and large gastropods also occur within this bed.

The contact of the Natih Formation with the overlying red shales of the Aruma Group was not observed, but exposures of these sediments in the wadis surrounding the jebel suggest that the "Ammonite Marker Bed" is only a few metres below the lowest exposed sediments of the Aruma Group.

## **CHAPTER 3: TAXONOMY**

### **3.1: Introduction - Foraminiferida**

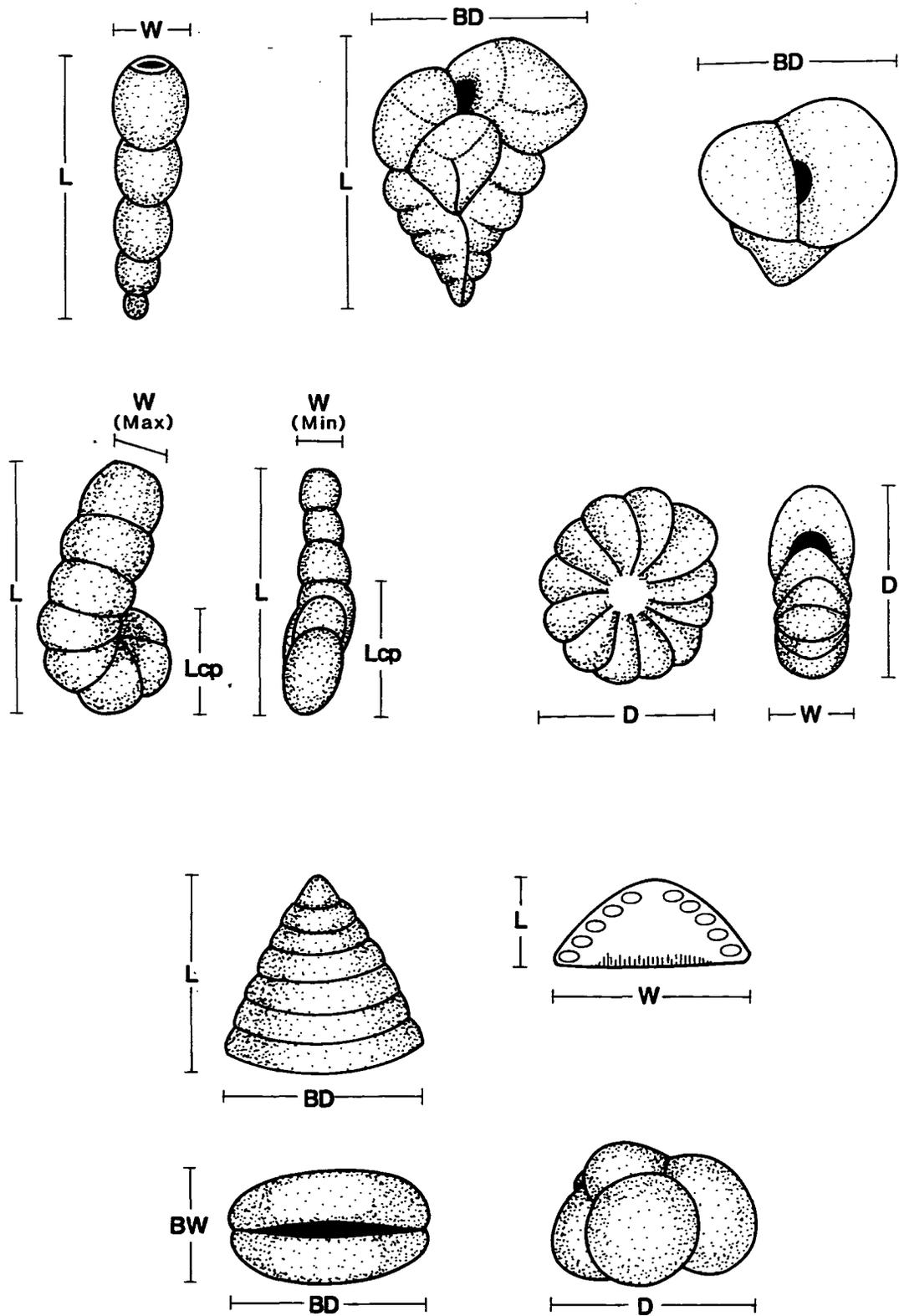
The foraminiferal classification used in this study is broadly based on that of Loeblich and Tappan (1964), together with the revised suprageneric classification proposed by Loeblich and Tappan (1984). These classifications are founded upon wall structure, and can lead to an "unnatural" grouping of taxa, with there being only limited account being made of the evolution and stratigraphic distribution of different taxonomic groups. Where appropriate the Loeblich and Tappan classification has been amended at generic and suprageneric level, both in the light of recent published data and as an outcome of research carried out in the course of this project. These changes are usually discussed in the text. Whilst this thesis was in the final stages of completion, the new monograph on foraminiferal genera and their classification by Loeblich and Tappan (1988) came to hand. Wherever possible, data and ideas from this important work have been incorporated or commented on in the foraminiferal taxonomy section below (Chapter 3.2).

The systematic descriptions are ordered following Loeblich and Tappan (1984). Suprageneric discussion is not usually included, although a description, discussion and comparison of genera and subgenera is provided. This is followed by the systematic description of species within a genus arranged in alphabetical order, unless the type species of a genus is present, which is always placed first.

For each species a synonymy is provided. The detail of this varies for different species. For those species which are stratigraphically useful, or have been taxonomically revised an attempt has been made to provide as full a synonymy as possible. This has often been necessary to establish the true stratigraphic and geographic range of a species. For certain less important species a more basic synonymy is given which outlines the type description, generic shifts and at least one recent well illustrated reference, if available. The letter "T" given before a taxonomic entry in the following synonymy lists refers to the type description of that species.

Following the synonymy a description of the species is given, followed by remarks concerning identification of the species, comparison with similar taxa, evolutionary relationships, etc. This is followed by a

**SCHEMATIC DIAGRAM TO ILLUSTRATE THE DIMENSIONS MEASURED ON THE VARIOUS FORAMINIFERAL GROUPS PRESENT IN THIS STUDY**



**L = Length (or height)**

**W = Width**

**BW = Basal Width**

**Lcp = Length of coiled portion**

**BD = Basal Diameter**

**D = Diameter**

**Figure 3.1**

statement of the species global distribution and stratigraphic range. The local occurrence of a species within the study area is given. Finally a statement of the palaeoecology of a species is given.

Figure 3.1 illustrates the terms used to describe various dimensions of the Foraminifera groups present, with the exception of the Orbitolinidae which are illustrated in more detail subsequently. The biozonation scheme referred to is further explained in Chapter 4.

Where possible the generic and specific descriptions are those given in the original designation of a taxon. In some cases this may be in the form of a translation. Where the original description is thought to be inadequate a more thorough recent one is given, or the original description revised herein.

### **3.2: Systematic Micropalaeontology - Foraminiferida**

Order FORAMINIFERIDA Eichwald, 1830

Suborder TEXTULARIINA Delage and Herouard, 1896

Superfamily HORMOSINACEA Haeckel, 1894

Family HORMOSINIDAE Haeckel, 1894

Genus *Reophax* de Montfort, 1808

Type Species *Reophax scorpiurus* de Montfort, 1808

#### **Diagnosis**

Test free, elongate, nearly straight or arcuate; chambers few, fusiform, pyriform or elongate, increasing in size as added; sutures oblique, obscure to moderately constricted; wall agglutinated, with comparatively little cement, surface rough; aperture simple, terminal, with or without neck (modified after Loeblich and Tappan, 1964 and Charnock and Jones, *in press*).

#### **Remarks**

*Reophax* differs from *Hormosina* Brady, by lacking the distinct globular chambers, pronounced apertural neck, smooth test and abundant cement of the latter. However, as shown by Schroeder (1986), there appears to be some intergradation between the two genera depending on the wall material utilized.

*Polychasmina* Loeblich and Tappan is similar to *Reophax*, but is flattened, and possess a more complex aperture.

*Adelungia* Suleymanov, known from the Late Jurassic and Early Cretaceous of the Asiatic USSR, differs from *Reophax* in having gradually enlarging and regular chambers, strongly oblique sutures, a distinctly arcuate test and a fine-grained agglutinated wall.

*Scherochorella* Loeblich and Tappan differs from *Reophax* in having broad, low and more regularly enlarging chambers and horizontal sutures.

Brönnimann and Whittaker (1980) provided an emended diagnosis of *Reophax*, but this is difficult to apply, particularly to thin-section specimens as examined in this study.

*Reophax* sp. A

Plate 3.1

Diagnosis

*Reophax* with a very slightly arcuate test, strongly compressed, chambers elongate, wall fairly coarsely agglutinated. Length *circa*. 0.7mm, width *circa*. 0.09mm max. 7-8 chambers in a typical specimen.

Remarks

It is possible that this species is a synonym of another previously described *Reophax* species. However, comparison to other *Reophax* species is difficult since the majority are described from isolated, solid specimens.

Global Distribution and Stratigraphic Range

Oman Mountains, Arabian Gulf (BP internal reports).

Late Barremian - Hauterivian/Valanginian.

Local Occurrence

Late Barremian - Hauterivian/Valanginian.

Paleodictyoconus arabicus Subzone - Buccicrenata hedbergi Subzone.

See range charts given in Chapter 4 for precise sample distribution.

### Palaeoecology

This species occurs in moderate - high energy outer shelf (circalittoral) facies, with relatively shallow water depths (c. 10-20m or less), for example proximal to the Habshan shoal (see chapter 5). It may also occur reworked into deeper slope environments.

Family THOMASINELLIDAE Loeblich and Tappan, 1984

Genus *Thomasinella* Schlumberger, 1893

Type Species *Thomasinella punica* Schlumberger, 1893

### Diagnosis

Test large, arborescent, large globular proloculus followed by uniserial broad and low cylindrical chambers in rectilinear or dichotomously branching series; wall thick, alveolar, coarsely agglutinated; aperture simple, rounded to ovoid, sometimes flattened into a slit, occasionally cribrate?, terminal at the end of the row of chambers, commonly single but less frequently with two openings, possibly just prior to bifurcation (after Loeblich and Tappan, 1988 and Arnaud-Vanneau and Prestat, 1984).

### Remarks

*Thomasinella* was first shown to possess an alveolar wall by Arnaud-Vanneau and Prestat (1984), who presented a complete review of the genus. Loeblich and Tappan (1988), without discussion, referred to the wall as "canaliculate" rather than alveolar. Without evidence to support the latter's assertion, the view of Arnaud-Vanneau and Prestat (1984) is upheld.

The bifurcating test and alveolar wall of this genus serve to distinguish it from most other homosinids. *Bireophax* Bolli is very similar but lacks an alveolar wall. Bifurcating specimens of *Polychasmina* Loeblich and Tappan can be distinguished by their simple wall and more complex aperture.

However, Arnaud-Vanneau and Prestat (1984) noted that the aperture of *Thomasinella* can vary with sexual and asexual generations, and that "juvenile" forms of the genus may be unbranched (see also Omara, 1956; Basha, 1978). This leads to some confusion with the genera *Polychasmina*, *Cribratina* Sample and "*Haplostiche*" Reuss. Arnaud-Vanneau and Prestat (1984) concluded that *Thomasinella* and *Polychasmina* were possible synonyms and were both associated with uniserial forms referable to "*Cribratina*" "*Haplostiche*". Unlike Loeblich and Tappan (1988) they considered *Polychasmina* to possess an alveolar wall. Thus, they tended to follow Omara (1956) in accepting a broad concept of *Thomasinella* to include branched and associated unbranched forms, and forms with cribrate and with simple apertures. This was refuted by Loeblich and Tappan (1988) who maintained *Cribratina* and *Haplostiche* as separate genera (whilst questioning the validity of *Haplostiche*), and argued that *Polychasmina* should be maintained as a separate genus because of its simple wall. This view is followed here (see above).

*Thomasinella punica* Schlumberger, 1893

Plate 3.2

- T 1893 *Thomasinella punica* n. sp. - Schlumberger, pl. 14.  
1956 *Thomasinella aegyptica* n. sp. - Omara, pl. 101, figs. 1-6.  
1956 *Thomasinella punica* Schlumberger - Omara, pl. 101, figs. 7-10.  
1956 *Thomasinella fragmentaria* n. sp. - Omara, pl. 101, fig. 11.  
1978 *Thomasinella aegyptica* Omara - Basha, pl. 1, figs. 1-5.  
1978 *Thomasinella fragmentaria* Omara - Basha, pl. 1, figs. 6-7.  
1978 *Thomasinella punica* Schlumberger - Basha, pl. 1, figs. 8-10.  
1984 *Thomasinella punica* Schlumberger - Arnaud-Vanneau and Prestat, pl. 1, figs. 1-9, pl. 2, figs. 1-2, 9-10.

Diagnosis

As for the genus, given above. The complete length of test is generally in the range 1-2mm, but can be as much as 3mm. Width of specimens is usually in the range 0.6-0.8mm.

Remarks

*Thomasinella punica* is herein considered to be the only species of the genus. This is in agreement with the opinions of Bolli (1962) and Gohrbandt (1966). Other species have been assigned to the genus, notably by Omara (1956): *Thomasinella aegyptica* and *Thomasinella fragmentaria*, but these forms are considered to be within the expected range of variation shown by *T. punica*. Basha (1978) maintained *T. aegyptica* and *T. fragmentaria* as separate species, but his reasons for doing so (thickness variation in the wall) are not considered to be of specific importance.

Bolli (1962) considered that his species *Bireophax quaricoensis* should be included within the concept of *T. punica*. However, this is rejected, because as shown by Loeblich and Tappan (1988) (see above), *B. quaricoensis* possesses simple, non-alveolar walls.

Global Distribution and Stratigraphic Range

Southern France, West Africa, North Africa, Near East and Middle East.

(Hauterivian) Albian - Cenomanian.

The probable specimen of this species recorded from the Oman Mountains in the course of this project is Hauterivian in age, and thus greatly extends the range of this species.

### Local Occurrence

Hauterivian.

Acroporella assurbanipali Zone.

See range charts given in Chapter 4 for precise sample distribution.

The single specimen of this species recovered during the course of this study (Plate 3.2) is rather small, and the typical alveolar wall is not shown well. However, it seems in all other respects to conform with the description of the species and is hence regarded as belonging to *T. punica*. In view of its age, which is remarkably older than any previous record of *T. punica*, it can be regarded as an early evolutionary form, which may account for its size.

### Palaeoecology

Basha (1978) suggested that *Thomassinella* was probably confined to lagoonal and nearshore environments. Butt (1982) noted its common occurrence in inner - middle shelf conditions in the Cenomanian of Morocco. These views are supported by the observations made in this study. *T. punica* occurs in low energy, back-shoal lagoonal environments, water depths being no greater than 10-20m.

Superfamily LITUOLACEA de Blainville, 1827

Family NAUTILOCULINIDAE Loeblich and Tappan, 1985

Genus *Nautiloculina* Mohler, 1938

Type Species *Nautiloculina oolithica* Mohler, 1938

### Diagnosis

Test free, lenticular, planispiral and involute, globular proloculus followed by numerous small chambers per whorl that increase gradually in size, umbonate test resulting from secondary thickening in the umbilical region; wall microgranular calcareous, agglutinated, simple and without exoskeletal or endoskeletal structures, single layered except for septa which are secondarily doubled; aperture interiomarginal, equatorial, single (based on Loeblich and Tappan, 1985; 1988).

### Remarks

*Nautiloculina* has previously been placed within a number of supergeneric groups, largely a result of misinterpreting diagenetic alteration of the wall. It was originally described by Mohler (1938) as being calcareous and imperforate, and compared to the porcelaneous *Planispirina*; hence it was placed in the suborder

Miliolina, family Fischerinidae by Loeblich and Tappan (1964). It was later described as having a "fibrous or pseudofibrous" microgranular wall and placed in the suborder Fusulinina, family Loeblichidae by Brönnimann (1968). However, this fibrous structure is visible only at a magnification of x500, whilst that of the Fusulinina is readily observable at magnifications of only x50. *Nautiloculina* was considered as calcareous microgranular and agglutinated by Neumann (1967) and Arnaud-Vanneau (1980) and placed in the family Lituolidae.

*Nautiloculina* was placed within a new (originally monogeneric) family (Nautiloculinidae) within the superfamily Lituolacea by Loeblich and Tappan (1985), on the basis that it differs from the Haplophragmoididae in having a microgranular agglutinated wall, from the Lituolidae in showing no tendency to uncoil, from the Mayncinidae in having a more nautiloid coil, and from all three families in having strong secondary umbilical thickening and secondarily doubled septa. Loeblich and Tappan (1988) also included the genus *Murgeina* Bilotte and Decrouez in the Nautiloculinidae. This genus differs from *Nautiloculina* by the presence of radial calcite forming a thickened umbonal region on both sides of the test. *Murgeina* is also very small, and possesses septa which curve back at the periphery of each whorl.

*Nautiloculina* can be distinguished from the superficially similar genus *Charentia* by its relatively simple wall structure, *Charentia* having a finely canaliculate "pseudalveolar" wall. *Charentia* also possesses relatively thin septa in comparison to *Nautiloculina*. This feature is distinctive in equatorial and sub-equatorial sections.

*Nautiloculina bronnimanni* Arnaud-Vanneau and Peybernes, 1978

Plates 3.3 - 3.4

- 1961 *Nautiloculina* sp. - Cuvillier, pl. 22, fig. 1.  
1967 *Nautiloculina oolithica* Mohler - Neumann, pl. 13, fig. 5.  
1969 *Nautiloculina* sp. 1 - Conrad, pl. 4, fig. 3.  
1973 *Nautiloculina* n. sp. - Moullade and Peybernes, pl. 3, figs. 3-4.  
1975 *Nautiloculina* sp. - Neagu, pl. 108, figs. 31-32.  
T 1978 *Nautiloculina bronnimanni* n. sp. - Arnaud-Vanneau and Peybernes, pl. 1, figs. 6-8, pl. 2, figs. 4-6.  
1980 *Nautiloculina bronnimanni* Arnaud-Vanneau and Peybernes - Arnaud-Vanneau, pl. 50, figs. 3-4, pl. 76, figs. 4-6.  
1987 *Nautiloculina bronnimanni* Arnaud-Vanneau and Peybernes - Simmons and Hart, pl. 10.1, fig. 7.

Diagnosis

External characters: Test globular, lobate, planispiral, involute, the last whorl sometimes having a tendency to uncoil. Test compressed in the equatorial plane and depressed along the axis of uncoiling. Surface smooth, the

wall is microgranular and agglutinated, rarely with quartz grains. The test outline is lobate because the sutures are depressed. The last whorl is composed of 11-16 chambers.

Ignoring uncoiling specimens, the diameter of individuals varies between 450 and 1250 microns, whilst the thickness varies between 250 and 500 microns.

Example measurements (all in microns):

	Diameter	Thickness
Holotype (microspheric)	1250	460
Macrospheric form	550	312.5
Uncoiled form	1950	700

In section: In equatorial section one can observe that the test consists of 3-4 whorls in primitive forms, and 5-6 whorls in more advanced forms.

In this species dimorphism is not greatly developed - proloculus diameters are in the order of 50 microns for microspheric forms and 70 microns for macrospheric forms. The dimensions of the chambers are greater for macrospheric forms.

In the equatorial plane the chambers are globular in the early whorls, then rectangular and finally "mushroom" shaped in the last whorl of adult specimens.

In axial section the the depression in the plane of enrollment is visible, although in subaxial sections it is not visible. The periphery appears to be subangular.

(Diagnosis freely translated from Arnaud-Vanneau and Peybernes (1978)).

#### Remarks

Although superficially very similar to other Early Cretaceous and Middle - Late Jurassic *Nautiloculina* species such as *N. circularis* (Said and Barakat), *N. oolithica* Mohler and *N. cretacea* Peybernes, *N. bronnimanni* can be distinguished by its external dimensions, number of chambers and whorls, proloculus size and peripheral shape. Table 3.1 below, reproduced from Arnaud-Vanneau and Peybernes (1978), outlines the differences between these species.

Espèces		<i>Nautiloculina circularis</i> (SAID & BARAKAT) 1959	<i>Nautiloculina colithica</i> NOHLER 1938	<i>Nautiloculina cretacea</i> PEYBERNES 1976	<i>Nautiloculina brönnimanni</i> n. sp.
Caractères	max.	880 µ	640 µ	2300 µ	1950 µ
	min.	360 µ	200 µ	600 µ	450 µ
Diamètre équatorial	max.	320 µ	380 µ	1225 µ	700 µ
	min.	200 µ	110 µ	400 µ	250 µ
Epaisseur	formes primitives	3 & 5	3 & 4	4	3 & 4
	formes évoluées			5 & 6	5 & 6
Nombre de loges dans le dernier tour (formes évoluées)		14 & 20	10 & 14	15 & 19	11 & 16
Taille du proloculus		26 & 40 µ	16 & 40 µ	80 & 125 µ	50 & 70 µ
Bord périphérique		aigü	arrondi	subaigü	subaigü
Répartition stratigraphique		Dogger - Malm inférieur ?	Malm	Berriasien à Bedoulien	Berriasien à Albien supérieur

Table 3.1. Comparative table for Late Jurassic - Early Cretaceous species of *Nautiloculina* (from Arnaud-Vanneau and Peybernes, 1978).

### Global Distribution and Stratigraphic Range

Western Mediterranean, Arabian Peninsula.

Berriasian - Albian.

In their review of this species Arnaud-Vanneau and Peybernes (1978) demonstrate that this species has a Late Berriasian - Late Albian range (although not fully confirmed by illustration) with the species being reported from Iberia, the Pyrenees, Southern France, and the Jura Mountains. The species is known to occur in the Arabian Peninsula (BP internal reports, Simmons and Hart (1987) and herein). Further research is needed to confirm the stratigraphic range of this species and complete records of its geographical distribution. It is expected that the species will be recorded from North Africa and the Eastern Mediterranean.

### Local Occurrence

Hauterivian - Early Aptian.

Cylindroporella arabica Zone - Palorbitolina lenticularis Subzone.

See range charts provided in Chapter 4 for precise sample distribution.

### Palaeoecology

According to Arnaud-Vanneau and Peybernes (1978) this species favours infralittoral environments with well oxygenated water and normal salinity. It is excluded from circalittoral facies and conditions of abnormal salinity. They noted that whilst *N. cretacea* favours conditions of higher energy, *N. bronnimanni* was commoner in lower energy conditions.

These observations are supported by those made during the course of this study. *N. bronnimanni* occurs in low energy, shallow water back-shoal sediments (mudstones - wackestones) in association with dasycladacean algae (eg. parts of the Lekhwair Formation), whilst *N. cretacea* occurs only in the high energy, packstone - grainstone sediments of the Habshan Formation.

### *Nautiloculina cretacea* Peybernes, 1976

Emend. Arnaud-Vanneau and Peybernes, 1978

Plates 3.5 - 3.7

- 1917 Rotalide - Blanchet, pl. 1, fig. 2.  
1953 *Nautiloculina* sp. aff. *oolithica* Mohler - Speck, pl. 9, fig. 6.  
1959 *Nautiloculina* sp. aff. *oolithica* Mohler - Thieuloy, pl. 15, fig. 8.  
1963 *Nautiloculina* aff. *oolithica* Mohler - Billiard and Deloffre, pl. 18, figs. 7-9.  
1969 *Nautiloculina* sp. 1 - Conrad, fig. 16e.  
1974 *Nautiloculina* n. sp. - Canerot, pl. 16, fig. 12.  
T 1976 *Nautiloculina cretacea* n. sp. - Peybernes, pl. 40, figs. 15-16 (non figs. 17-22 = *N. bronnimanni*).  
1976 *Nautiloculina* sp. - Masse, pl. 9, fig. 3.  
1978 *Nautiloculina cretacea* Peybernes - Arnaud-Vanneau and Peybernes, pl. 1, figs. 1-5, pl. 2, figs. 1-3.  
1980 *Nautiloculina cretacea* Peybernes - Arnaud-Vanneau, pl. 50, figs. 1-2, pl. 76, figs. 1-3.

### Diagnosis

External characters: Test globular, planispiral involute, compressed in the equatorial plane. The maximum thickness of the test is attained in the axis of enrollment. The test is microgranular, smooth surfaced, and often agglutinated with quartz grains. The suture lines form lines of slight relief on the surface of the test. Exceptionally, the suture lines of the last chambers of large individuals are clearly depressed. The last whorl is composed of 15-19 chambers. The diameter of this species varies between 500 and 2300 microns, whilst the thickness varies between 450 and 1200 microns.

In Section: In older forms of this species (eg. from Berriasian sediments of the Pyrenees) only 4 whorls are present. In younger forms (eg. from Aptian sediments in Vercors) 5-6 whorls are present, with the last whorl incomplete.

The proloculus is globular and has a diameter of 85-110 microns. In the equatorial plane the chambers are initially higher than wide, becoming trapezoid, then rhomboid in the later whorls.

In axial section the periphery appears subangular. In these sections, it can clearly be seen that there is a thickening of the test around the axis of enrollment. In sub-axial sections, traces of the chamber lumina are visible.

(Diagnosis freely translated from Arnaud-Vanneau and Peybernes (1978)).

#### Remarks

Although superficially very similar to other Early Cretaceous and Middle - Late Jurassic *Nautiloculina* species such as *N. circularis*, *N. oolithica* and *N. bronnimanni*, *N. cretacea* can be distinguished by its larger external dimensions, number of chambers and whorls, proloculus size, and chamber and peripheral shape. Table 3.1 above, reproduced from Arnaud-Vanneau and Peybernes (1978), outlines the differences between these species.

#### Global Distribution and Stratigraphic Range

Western Mediterranean, Arabian Peninsula.

Late (?) Berriasian - Early Aptian.

In their review of this species Arnaud-Vanneau and Peybernes (1978) demonstrate that this species has a Late Berriasian - Early Aptian range (although not fully confirmed by illustration) with the species being reported from Southern Spain, the Pyrenees, Southern France, and the Jura Mountains. The species is known to occur in the Arabian Peninsula (BP internal reports and herein). Further research is needed to confirm the stratigraphic range of this species and complete records of its geographical distribution. It is expected that the species will be recorded from North Africa and the Eastern Mediterranean.

#### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See ranges charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

According to Arnaud-Vanneau and Peybernes (1978) this species favours infralittoral environments with well oxygenated water and normal salinity. It is excluded from circalittoral facies and conditions of abnormal aslinity. They noted that *N. cretacea* favours conditions of higher energy, whilst *N. bronnimanni* favoured lower energy conditions.

These observations are in general agreement with those made in the course of this study. *N. cretacea* was only recorded from the high energy packstone - grainstone sediments of the Habshan Formation, representing deposition on a high energy, largely oolitic, shoal (see Chapter 5). Other fauna and flora recorded from these sediments suggest very shallow water depths and normal salinities.

Family LITUOLIDAE de Blainville, 1827

Genus *Lituola* Lamarck, 1804

Type species *Lituolites nautiloidea* Lamarck, 1804

#### Diagnosis

"Test free, large, early portion with three or more planispirally enrolled whorls, later uncoiling and rectilinear, chambers numerous, broad and low in the enrolled portion, sub-cylindrical in the rectilinear stage; wall agglutinated, interior simple and nonlabyrinthic; apertures multiple, in the face of the final chamber in the coil, terminal in the rectilinear portion" (Loeblich and Tappan, 1988).

#### Remarks

This is a long ranging genus with representatives known from Triassic - Recent sediments (Loeblich and Tappan, 1988).

In Early Cretaceous platform sediments specimens of *Lituola* in random thin- section may be confused with genera belonging to the superfamily Loftusiacea Brady (eg. *Pseudocyclammia* Yabe and Hanzawa). However, *Lituola* can be distinguished by its simple, non-alveolar wall.

*Ammobaculites* Cushman, *Ammomarginulina* Wiesner, *Ammotium* Loeblich and Tappan and *Sculptobaculites* Loeblich and Tappan, are all distinguished from *Lituola* by the presence of a simple, single aperture, rather than multiple aperture.

*Acactolituola* Loeblich and Tappan, known from the Early Cretaceous of Texas and Oklahoma, differs from *Lituola* in having only a slightly arcuate early stage of a few chambers, rather than a true coil with multiple whorls of numerous chambers each.

*Lituola? kelleri* (Henson, 1948)

Plate 3.8

T 1948 *Pseudocyclammina kelleri* n. sp. - Henson, pl. 9, figs. 4-5, 7.

Diagnosis

Test free, planispiral with short uncoiled portion, thick-walled, arenaceous, with much cement. Wall originally described as labyrinthic, but may be simple, non-alveolar (but see below). The spiral part of the test is involute, lenticular with two whorls and twelve to thirteen chambers in the last whorl; the uncoiled portion is somewhat elliptical in section with up to four chambers.

Remarks

Henson (1948) published the following dimensions for this species: Overall length 3.8mm, diameter of spiral part 1.4mm, thickness of spiral part 0.9mm.

Henson (1948) in his original description of this species considered it to possess an alveolar wall and multiple apertures. He thus referred it to the genus *Pseudocyclammina*.

However, close examination of the wall of the specimens illustrated by Henson suggests that the wall is not in fact alveolar, rather it is microgranular and solid, but agglutinates fine silt sized quartz and calcite particles and siliceous spicules, giving a false impression of an alveolar structure. Thus the presence of a simple wall and multiple apertures (the later described by Henson), suggests that this species should be referred to the genus *Lituola*. This view was first put forward by Prof. F.T. Banner in an internal BP report.

Whilst this report was in the final stages of completion Prof. F.T. Banner (pers. comm., 1988) suggested that on the basis of an examination of the many syntypes deposited by Henson in the British Museum (Natural History), the species may in fact possess a simple alveolar wall. However, rather than a multiple aperture, the species probably possess a simple single aperture, central in the apertural face. If this is the case, the species is referable to the genus *Everticyclammina* Redmond, and may form an evolutionary intermediate between the species *Everticyclammina virguliana* (Koechlin) and *Everticyclammina greigi* (Henson). However, this work was still in progress at the time of writing, hence the species is still tentatively referred to *Lituola*.

The suggestion that *Pseudocyclammina kelleri* may indeed possess an alveolar wall but single aperture is not completely new. Banner (1970) suggested that the species was the senior synonym of *Everticyclammina hensoni* Redmond, the type species of *Everticyclammina*. However, he also considered *Everticyclammina* to be a junior synonym of *Feurtillia* Maync. He thus referred *P. kelleri* to *Feurtillia*. However, *Feurtillia* possess alveolar septa, a feature not noted in *P. kelleri*, thus the species cannot be referred to that genus. Incidentally, the presence of alveolar septa distinguishes *Feurtillia* from *Everticyclammina*, thus the two genera should be regarded as distinct. The type species of *Everticyclammina*, *E. hensoni*, is thought to be a junior synonym of *Cyclammina greigi* Henson, regarded by Banner (1966; 1970) as the type species of his genus *Mayncella*, a genus which is thus a junior synonym of *Everticyclammina* (see below).

Gollesstaneh (1965) pointed out the similarity of *Pseudocyclammina kelleri* to *Pseudocyclammina virguliana* Koechlin, suggesting that two species were probably synonymous. *P. virguliana* is now regarded as a species of *Everticyclammina* (eg. Maync, 1965), thus Gollesstaneh's observations closely match those of Banner reported in the recent personal communication noted above. Indeed Gollesstaneh was echoing the words of some previous workers. Henson (1949) remarks that "*P. virguliana* is very similar in appearance to our *P. kelleri*. There are, however, sufficient differences of detail to separate the two species, though they may be closely allied". Redmond (1964) remarked "It would appear possible that *Pseudocyclammina virguliana* Koechlin 1943, *Pseudocyclammina kelleri* Henson, 1948.....might eventually be proved to fall within *Everticyclammina*".

If *P. kelleri*, does prove to possess an alveolar wall and simple aperture, thus placing it within *Everticyclammina*, it would be difficult to distinguish from *E. virguliana*, which would also be the senior synonym. The results of the further study of this species are eagerly anticipated, so that its problematic taxonomy can be resolved.

#### Global Distribution and Stratigraphic Range

Middle East.

Berriasian - Valanginian (?Hauterivian).

Henson (1948) in his original description of this species described its type locality as being "Argovian - Callovian limestones" from the Awasil-5 well in Iraq. Dunnington *et al.* (1959) demonstrated that these beds are in fact of Berriasian - Valanginian age.

The other records of this species from the Late Jurassic of Qatar and Lebanon by Henson (1948) are not thought to be of this species (Prof. F.T. Banner, pers. comm., 1988).

The species is often encountered in Berriasian - Valanginian platform carbonates in the Middle East region, especially in Iran and Iraq where the species is used as a biostratigraphic index form. Most of these records are unpublished in internal oil company reports.

#### Local Occurrence

Hauterivian.

*Cylindroporella arabica* Zone.

See range charts provided in Chapter 4 for precise sample distribution.

Only one questionable specimen of this species was recorded in the course of this study. In terms of its overall dimensions and chambers arrangement, etc., it is in quite close agreement with the syntypes figured by Henson (1948). However, the wall of this species is non-alveolar, and in view of the comments above and its high stratigraphic position it may be referable to another species.

#### Palaeoecology

The questionable specimen recovered in this study was recorded in relatively low energy, fore-shoal bioclastic wackestones, with common Lituolacea, reworked mollusc debris and calcareous algae. Water depths of a few tens of metres are envisaged.

Genus *Ammobaculites* Cushman, 1910

Type Species *Spirolina agglutinans* d'Orbigny, 1846

#### Diagnosis

Test free, early portion closely planispirally coiled, later uncoiled and rectilinear, rounded in section; wall agglutinated, interior simple, aperture terminal rounded (modified after Loeblich and Tappan, 1964).

#### Remarks

*Ammobaculites* differs from *Haplophragmium* Reuss in its early planispiral, rather than streptospiral coiling, from *Ammomarginulina* in its straight sutures and centrally placed aperture, and from *Lituola* in having a single rather than multiple aperture. It differs from *Flabellamina* Cushman which has compressed, equitant uniserial chambers and from *Haplophragmoides* Cushman which does not uncoil and has an aperture in the form of an equatorial interiomarginal slit. *Sculptobaculites* differs from *Ammobaculites* in having a somewhat evolute coil, deeply depressed and excavated umbilical region, angular periphery, and much reduced uniserial portion.

In some thin-sections from the Early Cretaceous of the Middle East, *Ammobaculites* may be confused with some members of the Choffatellidae and Hemicyclamminidae such as *Pseudocyclammina*, *Buccicrenata* Loeblich and Tappan and *Everticyclammina*. Although these genera can normally be distinguished by their alveolar wall, and in the case of *Pseudocyclammina*, multiple apertures, in certain oblique and/or micritised sections these features are not readily visible, and may cause misidentification.

*Ammobaculites* sp. A

Plates 3.9 - 3.13

1965 *Ammobaculites edgelli* n. sp. (*nomen nudum*) - Gollesstaneh, pl. 108, figs. 1-6.

1987 *Ammobaculites* sp. - Simmons and Hart, pl. 10.4, fig. 6.

Diagnosis

Early portion planispirally coiled (1 - 1.5 whorls) and composed of five to seven chambers. Later portion uncoiled, rectilinear or slightly curvilinear and usually composed of between two and five chambers. Wall and septa are coarsely agglutinated and typically exhibit considerable variation in the size and nature of agglutinated material. Proportionate chamber height increases with growth, and is most noticeable in the uncoiled portion. Final chamber is often distinctly pyriform.

Dimensions:     Total length - 0.85 - 2.10mm  
                      Diameter of coiled portion - 0.30 - 0.85mm  
                      Thickness - 0.35 - 0.40mm.

The above dimensions and description are based on those for *Ammobaculites "edgelli"* the invalid senior synonym of this species described by Gollesstaneh (1965).

Remarks

*Ammobaculites* sp. A. is the same form as *Ammobaculites "edgelli"* Gollesstaneh. However the later name is *nomen nudum*, since it was described in a thesis of limited circulation and without holotype. It is proposed to validate the name *A. "edgelli"* in a paper that is in preparation.

It is possible that this species is a synonym of another previously described *Ammobaculites* species. However, comparison to other *Ammobaculites* species is difficult since the majority are described from isolated, solid specimens.

Some specimens of this species contain aligned quartz particles within the walls and septa giving a "pseudo-alveolar" appearance, which may lead to confusion with loftusiids such as *Buccicrenata hedbergi* (Maync).

#### Global Distribution and Stratigraphic Range

Oman Mountains, Iran, Arabian Gulf (BP internal reports).

Valanginian/Hauterivian - Early Aptian.

#### Local Occurrence

Valanginian/Hauterivian - Early Aptian.

*Buccicrenata hedbergi* - *Palorbitolina lenticularis* Subzones.

See range charts provided with Chapter 4 for precise sample distribution.

#### Palaeoecology

This species appears to have had broad palaeoenvironmental tolerances. It is recorded in low energy fore-shoal wackestones of the upper Salil and basal Habshan Formation, in low energy lagoonal mudstones and wackestones of the Lekhwair Formation, but also high energy peri-shoal grainstones of the Habshan Formation, and outer shelf grainstones of the Kharaib Formation. Common factors are shallow water depths as evidenced by its association with micritised sediments, and normal salinities by its associated fauna and flora. The species is thus relatively common in most palaeoenvironments across the shallow carbonate shelf.

Superfamily LOFTUSIACEA Brady, 1884

Family CHOFFATELLIDAE Maync, 1958

*nom. transl.* herein ex subfamily Choffatellinae

The subfamilies Choffatellidae and Hemicyclammininae are raised to family level to indicate they are phylogenetically distinct from the Cenozoic and Recent Cyclamminidae.

Genus *Choffatella* Schlumberger, 1905

Type Species *Choffatella decipiens* Schlumberger, 1905

#### Diagnosis

"Test more or less discoidal, composed of chambers coiled in a spiral plane like a *Peneroplis*. The convex wall of the chambers is broken by numerous canals which constitute the openings. The exterior surface is covered in

a dense network of circular mesh. The test is finely arenaceous" (translated from original diagnosis of Schlumberger, 1905).

"Test planispiral, involute, chambers numerous, broad and low, tending to increase in breadth somewhat in adult so that whorls are higher; wall with imperforate outer layer and alveolar inner layer, regularly spaced partitions; aperture linear series of pores in slight depression extending vertically up apertural face" (Loeblich and Tappan, 1964).

"Test planispirally enrolled, compressed, partially evolute, whorls enlarging rapidly, chambers numerous, chamber lumen restricted to the peripheral area of the whorl so that in section it appears evolute, although the outer wall may somewhat overlap previous whorls, later chambers with a tendency to uncoil; wall exoskeleton with well developed sub-epidermal network, endoskeleton consists of thick and massive septa pierced by the large apertures in the median plane of the test, no pillars present; aperture a single areal row of large openings extending up the apertural face in the plane of coiling, those of successive chambers aligned in radial series as seen in axial section, with new series of apertures intercalated between these as the spire enlarges" (Loeblich and Tappan, 1988).

#### Remarks

Arnaud-Vanneau (1980) suggested that the aperture of *Choffatella* may be cribrate rather than a series of pores within an apertural groove. She found that in some topotypic specimens, particularly macrospheric forms, the apertures were dispersed across all the apertural face. If this is the case, the genus is difficult to distinguish from *Pseudocyclamma*. She noted four features which may still distinguish *Choffatella* from *Pseudocyclamma*:

- a) The alveoles of *Choffatella* are very regular, almost tubular, and do not distally thicken as is often the case in *Pseudocyclamma*.
- b) The flattened planispiral test has a rather acute periphery.
- c) The strongly curved, falciform chambers, resemble those of *Peneroplis*.
- d) The septa (crossed by numerous pores) do not appear to have an alveolar structure analogous to that seen in *Pseudocyclamma*.

However, in her diagnosis of *Choffatella decipiens*, the type species of the genus, she noted that this species often has a series of apertures aligned within a groove in the apertural face. This is a characteristic which she uses to distinguish it from her *Choffatella* n. sp. 1 (= *Choffatella cruciensis* (Pictet and Renevier)), which, according to her, typically has a true cribrate aperture. Furthermore and most importantly, she noted that the nature of the aperture varies between sexual and asexual generations for both the above species! (see also specific discussion below).

Clearly, the apertural characteristics of this genus need to be clarified by further study of type material. In the present study, it is accepted that the aperture is an aligned series within a groove. The paratype material figured by Loeblich and Tappan (1964) clearly illustrates this. This feature distinguishes the genus from other members of the Choffatellidae. However if the nature of the aperture does vary with generation, then the taxonomic problems of this genus and its constituent species may be difficult to resolve.

*Choffatella* may be distinguished from members of the Hemicyclamminidae (eg. *Hemicyclammina*, *Everticyclammina*, *Feurtillia* and *Buccicrenata*) which have only a single aperture.

The differences between *Choffatella* and *Pseudocyclammina* are noted above. In this respect, apertural characteristics notwithstanding, the most distinctive feature is the fine alveolar wall of *Choffatella*, in comparison to the coarsely alveolar wall of *Pseudocyclammina*.

*Alveosepta* may be distinguished from *Choffatella* by its low rather than high chambers, although this difference is somewhat minor. It may be that the two genera are effectively synonymous. Species now placed within *Alveosepta* were suggested by Banner (1970) as the ancestors of *Choffatella*.

The nature of the aperture/s of *Alveosepta* appears to be variable with generation, as in *Choffatella*.

*Pseudochoffatella*, *Torinosuella* and *Balkhania* may be distinguished from *Choffatella* by their flabelliform, complanate and annular tests respectively. In *Choffatella*, test morphology is typically planispiral, although it may occasionally be uncoiling or slightly flabelliform in adult microspheric forms. Furthermore, the septa of *Torinosuella* and *Balkhania* are thin and simplified, rather than complex and thick, as in *Choffatella*.

#### *Choffatella decipiens* Schlumberger, 1905

Plates 3.14 - 3.21

- ? 1858 *Operculina cruciensis* n. sp. Pictet and Renevier, fig. 4a-c. Early Cretaceous, Switzerland.
- T 1905 *Choffatella decipiens* n. sp. Schlumberger, pl. 18, figs. 1-6. "Gault (=Albian)" (dated as Barremian by Rey (1967)), Portugal.
- 1928 *Choffatella decipiens* Schlumberger - Tobler, pl. 34, figs. 4-6. Barremian, Swiss Jura.
- 1948 *Choffatella decipiens* Schlumberger - Henson, pl. 9, fig. 1. Early Cretaceous, Qatar.
- 1949 *Choffatella decipiens* Schlumberger - Maync, pl. 11, figs. 1-3, ?4, 5-15, pl. 12, figs. 1-4, 6-9 (non 5 = *C. pyrenaica*). Early Cretaceous, Venezuela (pl. 11, figs. 1-3, 5-9, 12-15, pl. 12, figs. 7, 9), Early

- Cretaceous, Florida (pl. 11, fig. 4, pl. 12, figs. 2, 6, 8), Late Aptian, Mexico (pl. 11, fig. 10, pl. 12, fig. 4), Barremian, Swiss Jura (pl. 11, fig. 11, pl. 12, fig. 1), Late Aptian, Cuba (pl. 12, fig. 3).
- 1952 *Choffatella decipiens* Schlumberger - Jordan and Applin, pl. 1, figs. 3-8, pl. 2, figs. 5-10. Early Cretaceous, Florida (pl. 1, figs. 3-4, 6-8, pl. 2, figs. 5-9) and Louisiana (pl. 1, fig. 5, pl. 2, fig. 10).
- 1952 *Choffatella decipiens* Schlumberger - Maync, pl. 11, figs. 9?, 10. Hauterivian, Algeria (fig. 9) and Aptian, Venezuela (fig. 10).
- 1956 *Choffatella decipiens* Schlumberger - Cuvillier, pl. 14, fig. 2., pl. 18, fig. 1, pl. 19, figs. 1-2. Neocomian (post Valanginian) (pl. 14, fig. 2) and Aptian, Western Aquitaine.
- 1958 *Choffatella decipiens* Schlumberger - Dufaure, pl. 2, fig. 12. Hauterivian?, Pyrenees.
- 1959 *Choffatella decipiens* Schlumberger - Maync, pl. 1, figs. 5, 15. Aptian, Languedoc (fig. 5), Barremian (Rey, 1967), Portugal (fig. 15).
- 1959 *Choffatella decipiens* Schlumberger - Sigal, pl. 29, figs. 1-8. Early Cretaceous, France.
- ? 1961 *Choffatella* sp. - Reiss, pl. 1, figs. 1-2, 14, pl. 3, fig. 45. Aptian, Israel.
- 1964 *Choffatella decipiens* Schlumberger - Loeblich and Tappan, pl. 143, figs. 3-6. Early Cretaceous, Portugal (fig. 3), Venezuela (figs. 4, 6) and Switzerland (fig. 5).
- 1964 *Choffatella decipiens* Schlumberger - Bozorgnia, pl. 67, fig. 2. Aptian, Iran.
- 1965 *Choffatella decipiens* Schlumberger - Gibson and Percival, pl. 1, fig. 1. Early Cretaceous, Somalia.
- 1967 *Choffatella decipiens* Schlumberger - Höttinger, text-figs. 32A-E, pl. 1, fig. 8, pl. 14, figs. 23-27. Early Cretaceous, Morocco.
- 1968 *Choffatella decipiens* Schlumberger - Kovatcheva, pl. 1, fig. 6. Early Aptian, Bulgaria.
- 1969 *Choffatella* sp. - Sampo, pl. 35, figs. 18-21. Barremian (figs. 18-19) and Valanginian - Hauterivian (figs. 20-21), Southwest Iran.
- 1969 *Choffatella decipiens* Schlumberger - Sampo, pl. 37, figs. 17-20. Aptian, Southwest Iran.
- 1970 *Choffatella decipiens* Schlumberger - Banner, pl. 4, figs. 1-5. Aptian, Persian Gulf.
- 1970 *Choffatella decipiens* Schlumberger - Saint-Marc, pl. 1, figs. 4-5. Early Aptian, Lebanon.
- 1972 *Choffatella decipiens* Schlumberger - Maync, pl. 2, figs. 4-6. Hauterivian, Israel (fig. 4) and Early Cretaceous, Senegal (figs. 5-6).
- 1972 *Choffatella decipiens* Schlumberger - Ramirez del Pozo, pl. 3, figs. 12-13. Early Aptian, Northern Spain.
- 1972 *Choffatella decipiens* Schlumberger - Ramirez del Pozo, pl. 3, figs. 10-13, pl. 6, figs. 1-3, 7. Late Barremian - Early Aptian, Northern Spain.
- ? 1974 *Choffatella decipiens* Schlumberger - Pastouret et al., pl. 1, fig. 4. Early Aptian, Bay of Biscay.
- 1975 *Choffatella decipiens* Schlumberger - Peybernes and Rey, pl. 2, fig. 18. Early Barremian, Portugal.
- 1975 *Choffatella decipiens* Schlumberger - Martinez and Quintero, pl. 3. Barremian - Early Aptian, Spain.
- 1976 *Choffatella decipiens* Schlumberger - Masse, pl. 9, fig. 6. Early Barremian, Provence.

- 1976 *Choffatella decipiens* Schlumberger - Leikine and Vila, pl. 3, figs. 9, 13. Barremian - Aptian, Algeria.
- 1977 *Choffatella decipiens* Schlumberger - Bartenstein and Bolli, pl. 1, fig. 32. Barremian - Aptian, Trinidad.
- 1979 *Choffatella decipiens* Schlumberger - Cherchi, pl. 24, fig. 7. Early Aptian, Sardinia.
- 1979 *Choffatella decipiens* Schlumberger - Luperto Sinni, pl. 32, figs. 8, 13-15. Barremian - Aptian, Southern Italy.
- 1979 *Choffatella decipiens* Schlumberger - Azema *et al.*, pl. 30, fig. 15. Early Aptian, Southern Spain.
- 1979 *Choffatella decipiens* Schlumberger - Kovatcheva, pl. 1, fig. 8. Early Aptian, Bulgaria.
- 1980 *Choffatella decipiens* Schlumberger - Arnaud-Vanneau, pl. 12, figs. 6-7, pl. 49, fig. 5. Barremian - Early Aptian, Vercors, France.
- ? 1980 *Choffatella cf. tingitana* Hottinger - Arnaud-Vanneau, pl. 49, figs. 6-7, pl. 75, figs. 3, 6-9. Barremian, Vercors, France.
- ? 1980 *Choffatella* n. sp. 1 Arnaud-Vanneau, pl. 49, figs. 1-4, pl. 75 figs. 1-2, 4-5. Late Barremian - Early Aptian, Vercors, France.
- ? 1981 *Choffatella cruciensis* (Pictet and Renevier) - Cherchi and Schroeder, pl. 1, figs. 1-2. Early Aptian, Switzerland.
- ? 1982 *Choffatella decipiens* Schlumberger - Dragastan, pl. 3, fig. 3. Early Aptian, Spain.
- 1982 *Choffatella cf. decipiens* Schlumberger - Altiner and Decrouez, pl. 3, figs. 20-21. Early Aptian, Turkey.
- 1982 *Choffatella decipiens* Schlumberger - Mouty and Saint-Marc, pl. 1, fig. 1. Early Aptian, Syria.
- 1982 *Choffatella decipiens* Schlumberger - Schroeder *et al.*, pl. 1, figs. 2-3. Barremian, Spanish Pyrenees.
- 1984 *Choffatella decipiens* Schlumberger - Canerot, pl. 2, fig. 1 (non pl. 1, figs. 3-4 = *C. pyrenaica*). Hauterivian, Southern Spain.
- 1984 *Choffatella decipiens* Schlumberger - Magniez-Jannin, pl. 1, figs. 14-15. Hauterivian - Barremian, Paris Basin.
- 1986 *Choffatella decipiens* Schlumberger - N'da Loukou, pl. 5, figs. 35-36. Early Aptian, Pyrenees.
- 1986 *Choffatella decipiens* Schlumberger - Kalantari, pl. 65, fig. 1, text-fig. 42/1-4. Barremian - Early Aptian, Iran.
- 1987 *Choffatella decipiens* Schlumberger - Simmons and Hart, pl. 10.4, fig. 4. Late Barremian - Early Aptian, Oman Mountains.

#### Diagnosis

"Plasmostracum planispiral, discoidal, generally involute; chambers in the adult arranged in crosier-shape; last whorl composed of 16-25 (on average 18-20) arcuate narrow chambers arranged in a *Peneroplis*-like spire with

coils progressively increasing in height (close coiled early chambers); about 8 chambers in straight portion; septa and lumina of chambers of about same breadth; the strongly forward recurved septa systematically pierced by numerous transverse, parallel-running channels which lead to the linear series of pores on the narrow apertural face;.....imperforate epidermal layer composed of both calcareous material and foreign particles.....; subepidermal layer with regular transverse (and subordinately parallel) partitions (delicate alveolar wall structure)...."

"The tendency of uncoiling is often evidenced in microspheric forms. The microspheric form differs from the megaspheric one by its very small proloculus, its closer coiled spire in the early stages, and its large size." (From the emended diagnosis of Maync (1949).

#### Remarks

According to Maync (1949) test diameter is in the order of 1.4mm for the type specimen. Proloculus diameter is typically in the range of 0.02 - 0.06mm.

Trimorphism has been recognised in this species (Sigal, 1959, Arnaud-Vanneau, 1980):

- a) **Microspheric forms:** The test is very large and strongly acute. The last whorl consists of 20-23 chambers and on the apertural face the apertures are aligned in a groove. Diameter = 1.885 - 3.875mm, Thickness = 0.2 - 0.4mm.
- b) **Macrospheric A1 forms:** The test is of intermediate size between microspheric and macrospheric A2 forms and as a somewhat less acute periphery than microspheric forms. The last whorl consists of 13-17 chambers and the apertural arrangement is similar to that of microspheric forms, but with two rows of apertures. Diameter = 0.675 - 1.875mm, Thickness = 0.125 - 0.3mm.
- c) **Macrospheric A2 forms:** Test small and more rounded. The last whorl contains 11-14 chambers, and the aperture is truly cribrate (i.e dispersed over the entire apertural face). Diameter = 0.725 - 0.85mm, Thickness = 0.225 - 0.35mm.

Note that the nature of the aperture varies depending on generation.

*Choffatella cruciensis* (Pictet and Renevier) (= *Choffatella* n. sp. 1 Arnaud-Vanneau, 1980) can be distinguished from *C. decipiens* by its larger size, slightly bulbous test and, according to Arnaud-Vanneau (1980), its true cribrate aperture. However, as noted above and in the generic remarks, apertural characteristics may vary with generation, and Arnaud-Vanneau notes that this species (*C. cruciensis*) has apertures aligned within a groove on

the apertural face in the microspheric generation. Taking this into account, there seems very little basis on which to separate the two species, since the size difference is only really noted in the microspheric generation. Cherchi and Schroeder (1981) separated the two species not only on size characteristics, but also on the basis of age. *C. cruciensis* is interpreted as the likely Aptian descendant of the Barremian species *C. decipiens*. This too, does not seem a particularly valid reason for separation of the two species, especially as Aptian forms of *C. decipiens* are well known from the literature. However pending further research, the two species are not placed in full synonymy, in which *C. cruciensis* would be the senior synonym and thus remove the well established species name *C. decipiens* from possible usage. If the two species are synonyms then there may be a case for the suppression of the name *C. cruciensis*.

*Choffatella tingitana* Hottinger described from the latest Jurassic of Morocco differs from *C. decipiens* in having a more coarsely alveolar hypodermis, more massive, less openly alveolar septa, and a more evolute test.

*Choffatella pyrenaica* Peybernes and Rey known from the Berriasian - Valanginian of the Western Mediterranean can be distinguished from *C. decipiens* by the presence of fewer chambers in the last whorl (on average 15 in generation A1 and 11 in generation A2), coarser septa, thicker chamber lumen and less tightly coiled test. It is thought to be an intermediate evolutionary form between *C. tingitana* and *C. decipiens*.

#### Global Distribution and Stratigraphic Range

Portugal, Southern Spain, Northern Spain, Pyrenees, Southern France, Bay of Biscay?, Paris Basin, Switzerland, Sardinia, Southern Italy, Bulgaria, Turkey, Morocco, Algeria, Somalia, Israel, Lebanon, Syria, Qatar, Persian Gulf, Iran, Oman Mountains, Venezuela, Mexico, Cuba, Trinidad, Florida, Louisiana, Senegal, Southern England.

#### Hauterivian - Aptian (Early Aptian?)

Records of this species are confined to a relatively narrow stratigraphic interval; i.e Hauterivian - Aptian times. Furthermore, the majority of records are from Barremian or Early Aptian sediments. It is likely that the species does not range into the Late Aptian, although Maync (1949) recorded it from "Late Aptian" sediments in Mexico and Cuba. The age of these sediments may be subject to revision, since no convincing evidence of their Late Aptian age was presented. The unillustrated record by Henson (1948) of *C. decipiens* from Vraconian (= Latest Albian) and Cenomanian sediments in the Middle East should be discounted. It is thought that the comment by Banner and Strank (1987), that this species has a Valanginian - Cenomanian range is unwarranted. Jaffrezo (1980) also concluded that this species has an Hauterivian - Aptian range. Records of the species from Valanginian sediments can either be assigned to *C. pyrenaica*, or in the case of "Valanginian - Hauterivian" records such as that of Simmons and Hart (1987) a Hauterivian age can be assigned.

Maync (1949) in his review of the genus *Choffatella* documents in detail, further unpublished or unillustrated occurrences of *C. decipiens* to which the reader is recommended.

#### Local Occurrence

Hauterivian - Early Aptian.

Cylindroporella arabica Zone - Choffatella decipiens Subzone.

See range charts provided with Chapter 4 for precise sample distribution.

#### Palaeoecology

Arnaud-Vanneau (1980; pers. comm., 1987), associates this species with sandy (terrigenous) sediments of the circalittoral - infralittoral environment. It is thought to occur in abundance following transgressive events (i.e. moving into vacant ecological niches). In this respect it is often associated with *Palorbitolina*. It is also particularly associated with platform channels.

These observations are supported by those made during the course of this study. *C. decipiens* was found to be common in high energy, shallow - moderate water depths of the outer platform environment. For example, the peri-shoal grainstones of the Habshan Formation, and outer platform ?channel grainstones - packstones of the Kharaib Formation. The species was found to be largely absent from low energy, lagoonal type sediments. The species was also particularly common in the the muddy wackestone intervals (cycles) within the Kharaib Formation. In particular the uppermost muddy cycle (referred to as the Hawar Member/Formation elsewhere in the Gulf region - see Chapter 1) contained common *Choffatella*. This interval is thought to be a period of relative water depth increase (eustatic sea level rise?) (see Chapter 5).

Genus *Bramkampella* Redmond, 1964

Type Species *Bramkampella arabica* Redmond, 1964

#### Diagnosis

"Test initially planispiral and involute with chambers increasing rapidly in volume as added, soon becoming evolute and passing into a prominent uniserial stage. Chambers in the uniserial stage of megalospheric individuals are small in cross-sectional area and moderately high; increases in volume of successive chambers in this generation are expressed as increases both in height and width of chamber. Chambers in the uniserial stage of microspheric individuals are saucer-shaped and of a minimal height throughout; increases in volume of successive chambers in this generation are expressed solely as progressive increases in diameter. It is this

feature which gives the adult microspheric test a conical shape. The chamber walls have a thick alveolar layer from which radially arranged transverse partitions project inward and backward to join the anterior wall of the preceeding chamber. Most of the radial partitions extend nearly to the axis of the test, their inner ends falling between the outermost pores of a small cribrate aperture. Thus, only a very small space in the centre of each chamber is left completely open" (Redmond, 1964).

#### Remarks

*Bramkampella* can be distinguished from outwardly similar members of the Lituolidae, notably *Haurania* and *Amijiella*, by its alveolar wall.

It is distinct from other members of the Loftusiacea, notably *Pseudocyclamina* and *Rectocyclamina*, by the conical test shape of the microspheric generation, its prominent system of radially arranged transverse partitions, and the restricted size and specialized nature of its cribrate aperture.

*Bramkampella* is presently a monospecific genus containing only *B. arabica*.

As pointed out by Banner (1970), the exact phylogenetic relationship of this genus is difficult to establish. He tentatively considered it to be an offshoot of *Pseudocyclamina*, which developed strong radial septulae. However it could also have developed from *Haurania* and *Amijiella* by the development of an alveolar wall. Further studies of this poorly described form are required.

*Bramkampella arabica* Redmond, 1964

Plate 3.22

T 1964 *Bramkampella arabica* n. sp. - Redmond, pl. 1, figs. 26-29, pl. 2, figs. 19-20.

#### Diagnosis

The characteristics of the species are outlined in the generic description above.

Redmond (1964) recorded the following dimensions for the species: "Holotype (microspheric individual), length 1.35mm, width 0.80mm. Paratype (megalospheric individual), length 0.91mm, width 0.63mm."..."Dimensions of exceptionally large individual, length 1.69mm, width 1.44mm."

#### Remarks

The differences between this distinctive species and other taxa are dealt with in the above generic remarks.

### Global Distribution and Stratigraphic Range

Saudi Arabia, Abu Dhabi (BP internal reports), Oman Mountains.

Earliest Cretaceous (Berriasian - Valanginian).

The only published record of this species is the original description of Redmond (1964). However the species is often referred to in internal oil company reports from the Middle East.

### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts provided with Chapter 4 for precise sample distribution.

Only poorly preserved, highly questionable specimens of this species were recorded during the course of this study (see Plate 3.22). They may be referable to other genera, if more specimens become available, eg. basal sections of *Cuneolina*.

### Palaeoecology

The specimens recovered in this study are from moderate energy, peri-shoal, outer shelf sediments of the Habshan Formation. Redmond (1964) gave no indication of the palaeoenvironmental conditions associated with *Bramkampella*, however the Sulaiy Formation from which he described it, is known to have been deposited in shallow shelf conditions.

Family HEMICYCLAMMINIDAE Banner, 1966

*nom. transl.* herein ex subfamily Hemicyclammininae

Genus *Everticyclammina* Redmond, 1964

Type Species *Everticyclammina hensoni* Redmond, 1964

### Diagnosis

"Test planispirally enrolled and involute, lenticular to slightly compressed, later with a slight tendency to uncoil, chambers wedgelike, sutures radial, slightly curved; wall agglutinated, alveolar, septa short, not alveolar, the elongate areal aperture resulting in very short septa with a triangular to rectangular thickened base of the septal face remaining against the previous whorl as seen in median section; aperture a short vertical areal slit"

(Loeblich and Tappan, 1985). The coalesced septal bases noted above were termed "basal layer" by Banner (1970).

#### Remarks

*Everticyclammina hensoni* Redmond, was designated by Redmond (1964) as the type species of his new genus *Everticyclammina*. This species is regarded as a junior synonym of *Everticyclammina greigi* (Henson).

Differs from *Haplophragmoides*, *Lituola* and *Ammobaculites* by its complex wall. Differs from *Pseudocyclammina*, *Choffatella* and related forms by having a single areal, rather than cribrate aperture. Differs from *Hemicyclammina* which has a high oval areal aperture in the septal face much reducing the septa, and from *Buccicrenata* in having a less compressed test, a simple slitlike aperture rather than an elongate zigzag slit, wedgelike rather than reniform chambers, and more extensive secondary deposits connecting the bases of successive septa against the previous whorl (better developed "basal layer").

Clearly, *Hemicyclammina* and *Everticyclammina* are closely related, and it is likely that *Everticyclammina* gave rise to *Hemicyclammina* during the Late Aptian - Early Albian. Banner (1966, 1970) recorded transitional forms in the Late Aptian of Abu Dhabi.

*Mayncella* Banner, 1966 is regarded as a junior synonym of *Everticyclammina*..

#### *Everticyclammina greigi* (Henson, 1948)

Plates 3.23 - 3.24

- T 1948 *Cyclammina greigi* n. sp. Henson, pl. 13, figs. 9, 11, 15-17. Early Cretaceous, Qatar.
- 1964 *Everticyclammina contorta* n. sp. Redmond, pl. 1, figs. 12-15, pl. 2, figs. 10-11. Early Cretaceous, Saudi Arabia.
- 1964 *Everticyclammina eccentrica* n. sp. Redmond, pl. 1, figs. 16-18, pl. 2, figs. 12-13. Early Cretaceous, Saudi Arabia.
- 1964 *Everticyclammina elegans* n. sp. Redmond, pl. 1, figs. 19-21, pl. 2, figs. 14-16. Early Cretaceous, Saudi Arabia.
- 1964 *Everticyclammina hensoni* n. sp. Redmond, pl. 1, figs. 22-25, pl. 2, figs. 17-18. Early Cretaceous, Saudi Arabia.
- 1965 *Haplophragmoides greigi* (Henson) - Hofker Jr., pl. 2, figs 1-7, pl. 3, figs. 1-3. Aptian - Albian (probably Aptian), Northern Spain.
- 1966 *Mayncella greigi* (Henson) - Banner, pl. 2, figs. 1-3, pl. 11, figs. 1-3, pl. 12, figs. 1-2. Early Cretaceous, Middle East.

- 1967 *Everticyclammina greigi* (Henson) - Höttinger, pl. 9, figs. 17-18. Hauterivian?, Saudi Arabia.
- non 1969 *Cyclammina greigi* Henson - Sampo, pl. 32, figs. 1-5.
- 1970 *Maynecella greigi* (Henson) - Banner, pl. 9, figs. 1-5. Neocomian, Persian Gulf (figs. 4-5).
- ? 1972 *Everticyclammina greigi* (Henson) - Ramirez del Pozo, pl. 7, figs. 1-2, pl. 9, fig. 3. Aptian, Northern Spain (pl. 7, figs. 1-2), Albian, Northern Spain (pl. 9, fig. 3).
- ? 1972 *Everticyclammina greigi* (Henson) - Ramirez del Pozo, pl. 3, figs. 14-16, pl. 6, figs. 3-4.
- 1975 *Everticyclammina virguliana* (Koechlin) - Brun and Rey, pl. 1, figs. 1, ?2-3, 4-7, pl. 2, figs. 1-5, ?6-8 (non 9), pl. 3, figs. 1-2, ?3, 5 (non 4), pl. 4, figs. 4, ?5, 6 (non 1-3, 7). Hauterivian, Portugal (pl. 1, figs. 1, ?2-3, 4-7, pl. 2, figs. ?7-8, pl. 3, figs. 1-2, ?3, 5), Hauterivian, Southern France (pl. 2, figs. 1-2), Neocomian, Iran (pl. 2, fig. 3), Neocomian, Morocco (pl. 2, figs. 4-5), Berriasian, Morocco (pl. 2, fig. 6), Barremian, Portugal (pl. 4, figs. 4, 6), Kimmeridgian?, Somalia (pl. 4, fig. ?5).
- 1982 *Melathrokerion greigi* (Henson) - Altiner and Decrouez, pl. 4, figs. 7-8?, 9, 10?. Early Aptian, Turkey.
- 1983 *Everticyclammina virguliana* (Koechlin) - Magniez-Jannin, pl. 1, figs. 1-3, ?6-7. Hauterivian - Barremian, Paris Basin.

#### Diagnosis

Features as for generic diagnosis. Also, test lenticular, bi-umbilicate in axial section, typically elongated in the direction of the last chamber; margin rounded, somewhat lobate; sutures straight, depressed, numbering six to eight in the last whorl; there are three rapidly opening involute whorls.

The dimensions of the holotype and paratypes figured by Henson (1948) are as follows:

	Max. Diameter	Thickness
Holotype	1.28mm	0.4mm
Paratypes	1.06mm	0.48mm

#### Remarks

May be confused with *Hemicyclammina sigali* which is of similar dimensions and internal structure. However *E. greigi* has a smaller aperture central in the septal face, with septal projections being present from both the inner and outer whorls.

In *E. greigi* there seems to be a trend to reduction of the number of chambers per whorl, together with a straightening of the septa and an increase in the average size of the septal aperture, throughout the Valanginian -

Aptian period, probably giving rise to *Hemicyclammina sigali* in the Late Aptian - Early Albian (see also comments above) (Banner, 1970). Some forms from the Aptian - Albian of northern Spain illustrated by Hofker Jr (1965) and Ramirez del Pozo (1972), appear to be transitional between *E. greigi* and *H. sigali*. These are in addition to the forms described by Banner (1966; 1970) mentioned above.

The four species of *Everticyclammina* described by Redmond (1964); *E. contorta*, *E. eccentrica*, *E. elegans* and *E. hensoni*, are all thought to be within the range of variation shown by *E. greigi*, and are therefore junior synonyms.

Brun and Rey (1975) placed *E. greigi* in synonymy with *Everticyclammina virguliana* (Koechlin). However *E. virguliana* differs from *E. greigi* by its much larger size (max. dia. = circa. 2mm), more prominent uncoiling portion and tendency for the lower parts of the septa to point forward, producing very convex septa, in which the aperture may be surrounded by a short thick neck. It is likely that that *E. virguliana* gave rise to *E. greigi*, by a gradual reduction of these features in the Early Cretaceous. Some Early Cretaceous forms illustrated by Brun and Rey (1975) from Portugal may be transitional between *E. virguliana* and *E. greigi*.

Whilst this thesis was in the final stages of completion, Prof. F.T. Banner (pers. comm.) suggested that *Pseudocyclammina kelleri* Henson, may be a species of *Everticyclammina*, and the evolutionary link between *E. virguliana* and *E. greigi*. This is further discussed in the section on *Lituola? kelleri* above.

#### Global Distribution and Stratigraphic Range

Qatar, Saudi Arabia, Arabian Gulf, Iran, Oman Mountains, Northern Spain, Paris Basin, Southern France, Morocco, ?Somalia, Blake Escarpment.

?Kimmeridgian, Berriasian - Albian.

The majority of the records of this species are from the Valanginian - Aptian interval.

#### Local Occurrence

Hauterivian - Late Barremian.

Cylindroporella arabica Zone - Paleodictyoconus arabicus Subzone.

See range charts provided in Chapter 4 for precise sample distribution.

### Palaeoecology

Upper circalittoral - mediolittoral (Brun and Rey, 1975). Brun and Rey further noted that the species is not particularly sensitive to photic and bathymetric conditions, but is sensitive to lithology of the substrate. They noted (in Portugal) that the species was most prolific and largest when associated with fine terrigenous sediments and clays. The species was found to be rarer and smaller in low energy carbonate environments, and totally absent from high energy carbonate environments. They considered it to be a useful marker for fine terrigenous sediments in the Estremadura Basin.

These observations are supported by those made during the course of this study. *E. greigi* was only recorded in outer shelf (circalittoral), moderate - high energy sediments of the peri-shoal Habshan Formation, or in the broad outer platform channels of the Kharab Formation. In the later instance the substrate would have been clay rich, analogous to the situation in Portugal described by Brun and Rey (1975).

Genus *Buccicrenata* Loeblich and Tappan, 1949

Type Species *Ammobaculites subgoodlandensis* Vanderpool, 1933

### Diagnosis

"Test planispirally enrolled, compressed, involute in the early stage, later with a tendency to uncoil and become rectilinear; wall agglutinated of calcareous particles mixed with quartz, a shallow alveolar layer in which the alveoles may bifurcate being covered by an imperforate epidermal layer, septa solid, the base of the septa against the previous whorl thickened to result in a triangular appearing mound at the position of the septum; aperture elongate, terminal, a straight to zigzag slit" (Loeblich and Tappan, 1985). Chambers are typically reniform in shape.

### Remarks

The type species, known for almost 50 years, was incompletely understood until the revision of the genus by Loeblich and Tappan (1985). In this revision they clearly illustrated the alveolar wall and the zigzag slit aperture of the genus. Maync (1952; 1955) suggested that *Buccicrenata* was non-alveolar and closely related to *Ammobaculites*. However, the alveolar wall of the genus was illustrated and described for *Buccicrenata libyca* Gohrbandt (1966, p. 67, pl. 1, fig. 11), but no specimens of that species were well enough preserved to show the aperture.

Because of the lobate periphery and reniform chambers of *Buccicrenata*, thin sections may intersect areas of the alveolar outer wall at the incised sutures, giving the false appearance of alveolar septa, but the alveolar character does not extend across the whorl to separate adjacent chambers, and the septa are solid beneath the surface (Loeblich and Tappan, 1985).

Differs from *Haplophragmoides*, *Lituola* and *Ammobaculites* by its complex wall. Differs from *Pseudocyclammina*, *Choffatella* and related forms by having a single terminal aperture, rather than cribrate or multiple apertures. Differs from *Hemicyclammina* which has a high oval areal aperture in the septal face much reducing the septa, and from *Everticyclammina* in having a more compressed test, an elongate zigzag slit rather than a simple slitlike aperture, reniform rather than wedgelike chambers, and less extensive secondary deposits connecting the bases of successive septa against the previous whorl (poorly developed "basal layer").

Loeblich and Tappan (1985) erected a new subfamily, the Buccicrenatinae, to include both *Everticyclammina* and *Buccicrenata*. However, it is considered herein that these genera are closely related to *Hemicyclammina*, thus *Buccicrenata* and *Everticyclammina* are considered to be members of the Hemicyclamminidae (=Hemicyclammininae, *sensu* Loeblich and Tappan, 1985; 1988). A paper on the suprageneric classification and phylogenetic relationships of the Cretaceous Loftusiacea is in preparation by the author.

*Buccicrenata hedbergi* (Maync, 1953)

Plates 3.25 - 3.28

- ? 1933 *Ammobaculites subgoodlandensis* n. sp. Vanderpool, pl. 49, figs. 1-3. Albian (?), Oklahoma.
- ? 1949 *Buccicrenata subgoodlandensis* (Vanderpool) - Loeblich and Tappan, pl. 47, figs. 5-15. Albian (?), Oklahoma.
- ? 1952 *Pseudocyclammina rugosa* (d'Orbigny) - Maync, pl.12, figs. 6-10. Cenomanian, France.
- T 1953 *Pseudocyclammina hedbergi* n. sp. Maync, pl. 16, figs. 1-8. "Aptian - Middle Albian" (possibly referable to Aptian only), Venezuela.
- 1956 *Pseudocyclammina hedbergi* Maync - Cuvillier, pl. 20, fig. 2. Aptian, Pyrenees.
- ? 1961 *Pseudocyclammina* sp. - Reiss, pl. 53. Late Aptian, Israel.
- ? 1964 *Pseudocyclammina hedbergi* Maync - Bozorgnia, pl. 72, fig. 2, pl. 83, fig. 2. Aptian - Albian, Iran.
- 1966 *Buccicrenata libyca* n. sp. Gohrbandt, pl. 1, figs. 11-16. Cenomanian, Libya.
- 1967 *Pseudocyclammina* cf. *P. rugosa* (d'Orbigny) - Arkin and Hamaoui, pl. 2, fig. 3. Cenomanian, Israel.
- 1968 *Lithocodium regularis* n. sp. - Johnson, pl. 2, fig. 3., pl. 4, figs. 6-7. Early Cretaceous, Blake Escarpment.
- 1969 *Pseudocyclammina rugosa* (d'Orbigny) - Sampo, pl. 39, figs. 6-8. Albian, Southwest Iran.
- 1970 *Pseudocyclammina* group *hedbergi* Maync - Banner, pl. 5, figs. 4-7. Cenomanian, Libya (fig. 4), Neocomian (fig. 6), Aptian (fig. 5) and Early Cenomanian (fig. 7), Persian Gulf.
- 1972 *Buccicrenata* sp. 1 - Magniez and Rat, pl. 2, fig. 21. Aptian, Northern Spain.
- ? 1973 *Pseudocyclammina rugosa* (d'Orbigny) - Bilotte, pl 3, fig. 15. Cenomanian, Pyrenees.

- 1975 *Everticyclammina virguliana* (Koechlin) - Gušić, pl. 5, fig. 2, pl. 6, figs. 3-4, pl. 7, figs. 1-3, pl. 8, figs. 1-5, pl. 9, figs. 1-5, pl. 10, figs. 2, 4. "Late Aptian - Early Albian" (now thought to be Late Aptian (Gušić, pers. comm., 1987)), Yugoslavia.
- ? 1978 *Pseudocyclammina hedbergi* Maync - Berthou and Schroeder, pl. 8, figs. 3-5. Late Albian, Portugal.
- 1979 *Pseudocyclammina* sp. ex. gr. *P. hedbergi* Maync - Azema *et al.*, pl. 32, fig. 20. Middle Albian, Southern Spain.
- ? 1979 *Pseudocyclammina hedbergi* Maync - Luperto Sinni, pl. 31, figs. 4-5. Barremian - Aptian, Southern Italy.
- 1980 *Everticyclammina hedbergi* (Maync) - Arnaud-Vanneau, text-fig. 178, pl. 40, fig. 5, pl. 63, figs. 3-4, pl. 65, fig. 1. Early Aptian, Vercors, France.
- 1982 *Pseudocyclammina hedbergi* Maync - Altiner and Decrouez, pl. 5, figs. 1-2. Early Aptian, Turkey.
- ? 1982 *Pseudocyclammina vasconica* Maync - Correia *et al.*, pl. 1, fig. 4. Early Aptian, Portugal.
- 1984 *Everticyclammina hedbergi* (Maync) - Canerot, pl. 1, fig. 5. Valanginian, Southern Spain.
- 1984 *Everticyclammina hedbergi* (Maync) - Chiocchini *et al.*, pl. 1, fig. 20. Early Aptian, Central Italy.
- ? 1985 *Buccicrenata subgoodlandensis* (Vanderpool) - Loeblich and Tappan, pl. 2, figs. 4-10. Early Cretaceous, Texas.
- 1986 *Pseudocyclammina lituus* (Yokoyama) - Kalantari, pl. 60, fig. 1-?2, pl. 61, fig. 2, text-fig. 42/6. Hauterivian - Valanginian, Iran.
- 1986 *Pseudocyclammina rugosa* (d'Orbigny) - Kalantari, pl. 71, fig. 1, text-fig. 42/8-9, ?10. Cenomanian, Iran.
- 1986 *Everticyclammina hedbergi* (Maync) - N'da Loukou, pl. 4, fig. 10. Late Aptian, Pyrenees.
- 1987 *Buccicrenata hedbergi* (Maync) - Simmons and Hart, pl. 10.4, figs. 2-3. Valanginian - ?Hauterivian, Oman Mountains.
- 1987 *Buccicrenata subgoodlandensis* (Vanderpool) - Simmons and Hart, pl. 10.5, fig. 1. Albian, Oman Mountains.
- 1987 *Buccicrenata? rugosa* (d'Orbigny) - Simmons and Hart, pl. 10.5, fig. 4. Early Cenomanian, Oman Mountains.

### Diagnosis

A *Buccicrenata* with a irregularly coarse alveolar wall, 4-5 chambers in the last whorl and often with an uncoiled portion consisting of 2, or occasionally more, large chambers. The outline of the test is lobate to sub-angular, with the chambers developing a strong reniform shape.

### Remarks

This species, commonly placed within the genera *Pseudocyclammina* or *Everticyclammina*, was first referred to the genus *Buccicrenata* by Loeblich and Tappan (1985).

Arnaud-Vanneau (1980) suggested that the aperture of this species may be variable with generation: a terminal slit in microspheric forms, and occasionally multiple in macrospheric forms.

This species is often coarsely agglutinated, obscuring the alveolar nature of the wall (eg. Plate 3.25). Arnaud-Vanneau (1980) has suggested that the early chambers of microspheric forms are in fact non-alveolar.

Dimensions of the original type specimens (all microspheric?) are as follows: Diameter: 1.6 - 2.16mm. Arnaud-Vanneau (1980) recorded diameters in the range of 0.975 - 3.525mm for macrospheric forms, with thicknesses of 0.675 - 1.575mm, and diameters of 2.4 - 4.2mm and thicknesses of 1.625 - 2.05mm for microspheric forms. Microspheric forms usually display 3 whorls, macrospheric forms only 1.

The species is thought to show considerable variation in size through time, becoming progressively larger, and also developing a thicker and more complex hypodermis. In this respect *Pseudocyclammina rugosa* (d'Orbigny) with its complex walls and large test may be the evolutionary descendant of *B. hedbergi*, and in fact be referable to *Buccicrenata*. However, until further research is undertaken on the aperture of *P. rugosa*, this cannot be confirmed. It is thought that many records of Cenomanian *P. rugosa* are referable to advanced forms of *B. hedbergi*.

*Buccicrenata subgoodlandensis* (Vanderpool) is difficult to distinguish from *B. hedbergi*. It has a similar number of chambers in the last whorl, with an identical chamber outline, although can be slightly larger in diameter, and have several chambers in its uncoiled portion. It probably forms part of the *B. hedbergi* - *B?. rugosa* evolutionary plexus, and is effectively synonymous with *B. hedbergi*. However, pending further research the two species are not placed in complete synonymy in this study. In such a synonymy *B. subgoodlandensis* would be the senior synonym.

Forms from the *B. hedbergi* - *B. subgoodlandensis* - *B?. rugosa* evolutionary plexus can be referred to under the common name of "*Buccicrenata* sp. ex. gr. *hedbergi*", although if full synonymy is established *B?. rugosa* has priority.

*Buccicrenata libyca* from the Cenomanian of Libya is thought to be identical with advanced forms of *B. hedbergi* and is treated as a junior synonym.

In random sections *B. hedbergi* may be confused with *Pseudocyclammia lituus* and *P. vasconica*. However, these species can be distinguished by having relatively numerous chambers in the last whorl, thicker and more complex alveolar walls, and by their cribrate aperture. *B. hedbergi* also has a distinctive reniform test outline.

#### Global Distribution and Stratigraphic Range

Venezuela, ?Texas, Oklahoma, ?Portugal, Northern Spain, Southern Spain, Pyrenees, ?Aquitaine, Southern France, Libya, ?Southern Italy, Central Italy, Yugoslavia, Turkey, Israel, Iran, Persian Gulf, Oman Mountains.

Valanginian - Cenomanian.

The relatively long range of this species is partially a result of placing advanced forms of the species previously recognised as *B. subgoodlandensis* and *P. rugosa* into synonymy. It is possible to recognize these advanced forms on the basis of wall structure and size, and thus allow for greater stratigraphic precision.

The species appears to be most commonly recorded in the Aptian - Albian. Valanginian records of the species are rare, and it is possible that these are subject to revision, with the inception of the species being within Hauterivian times. The top of the range of this species may be Early Cenomanian, although this is difficult to ascertain, as Cenomanian records of the species are imprecise.

#### Local Occurrence

Valanginian/Hauterivian - Late Barremian.

Buccicrenata hedbergi Subzone - Eopalorbitolina charollaisi Subzone

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

Arnaud-Vanneau (1980) recorded this species from platform channels influenced by terrigenous input, and in the euhaline infralittoral zone. In contrast N'da Loukou (1986) recorded it from various circalittoral and external platform environments.

In the course of this study the species was commonly recorded in various outer platform (circalittoral) environments. The species seems to be tolerant of various environmental conditions, and may also be recorded in slope sediments as a result of transport.

## Superfamily VERNEUILINACEA Cushman, 1911

The concept of this superfamily used herein follows that of Desai and Banner (1987) who demonstrated that taxa occur within this group with canaliculate walls, and that this feature should not be used for suprageneric classification. This view is in opposition to that expressed by Loeblich and Tappan (1984; 1988).

### Family CHRYSALIDINIDAE Neagu, 1968

Desai and Banner (1987) noted that this family can have canaliculate or solid walls. The presence of internal pillars was noted both by Loeblich & Tappan (1984; 1988) and Desai & Banner (1987) to be diagnostic of this family. However, the likely ancestral form within this group, *Praechrysalidina infracretacea*, does not possess true pillars.

### Genus *Praechrysalidina* Luperto Sinni, 1979

Type Species *Praechrysalidina infracretacea* Luperto Sinni, 1979

#### Diagnosis

Test conical, trochospiral, triserial, apical angle variable but always acute. The bulbous chambers are separated by marked sutures.

The initial stage is not well understood: the test probably begins with a spherical proloculus immediately followed by the three chambers of the first whorl. In the early part of the test there is probably a single simple aperture, situated on the internal side of the apertural face. In the following stage which is always triserial, the aperture is cribrate and covers the greater part of the apertural face. These apertures are disposed regularly across the apertural face. The apertural face ends in a sort of non-perforate large lip, which folds back within the shell, forming an apertural plate (?valvuline tooth). This plate, which is well seen in certain axial sections, may have its origin in the most external row of pores of the cribrate aperture.

In some cases one can see small "poutrelles" (*sensu* Reichel, 1964) on the internal surface of the apertural face of the last chambers of the test. The wall is thick and shows a complex structure: a very thin dark, dense, microgranular outer layer covers the exterior of the test, underlain by a thicker microgranular layer which is crossed by numerous fine tubes, giving the appearance of fibrous tissue. This is followed by a thin dark inner layer. Diagnosis freely translated from Luperto Sinni in Schroeder and Neumann (1985).

#### Remarks

The genus is currently monospecific (*Praechrysalidina infracretacea* Luperto Sinni).

The position of this genus within the Chrysalidinidae is questionable because it does not possess internal pillars. However as noted below *Praechrysalidina* may be ancestral to forms that do possess true internal pillars.

Five genera are similar to *Praechrysalidina*: *Valvulina* d'Orbigny, *Chrysalidina* d'Orbigny, *Dukhanina* Henson, *Pseudochrysalidina* Cole and *Minouxia* Marie.

*Valvulina* differs from *Praechrysalidina* in possessing a single interiomarginal/umbilical aperture rather than a cribrate aperture. It also has a distinct valvuline tooth.

*Chrysalidina* can be distinguished by its trematophore cribrate aperture, and in particular by its distinct canaliculate wall structure, and possession of pillars on the apertural plates present.

*Dukhanina* and *Pseudochrysalidina* have been considered by Höttinger and Drobne (1980) as synonyms of *Chrysalidina*. However *Dukhanina* does not possess a canaliculate wall structure like *Chrysalidina*, and differs from *Praechrysalidina* in possessing pillars on the apertural plates present.

*Pseudochrysalidina* can be distinguished from *Praechrysalidina* by the presence of pillars on the apertural plates and by a tendency to become biserial in the later stage of the test. The relationship of this genus to *Dukhanina* and *Chrysalidina* is uncertain. Henson (1949) regarded it as a synonym of *Dukhanina*, whilst Höttinger and Drobne (1980) regard it as a synonym of *Chrysalidina*. Further analysis of the wall structure of *Pseudochrysalidina* is required to determine its taxonomic position. Its isolated stratigraphic position (Eocene) suggests that it is phylogenetically distinct from the above named Cretaceous genera.

*Minouxia* is very similar to *Praechrysalidina*, although like *Chrysalidina* it has a distinct trematophore plate, which *Praechrysalidina* does not possess. Luperto Sinni (1979) suggested that the presence of very small "poutrelles" on the apertural face of *Praechrysalidina* distinguishes this genus from *Minouxia*. The wall structure of *Minouxia* is poorly known, although it is thought to be non-canaliculate like *Praechrysalidina*. Also like *Praechrysalidina*, no internal pillars are thought to be present. However, further studies of the internal structure of *Minouxia* are required to fully establish its distinction from *Praechrysalidina* and other members of the Chrysalidinidae.

*Praechrysalidina infracretacea* Luperto Sinni, 1979

Plate 3.29

? 1975 *Chrysalidina* cf. *gradata* d'Orbigny - Gušić, pl.4, fig. 1, pl. 9, fig. 2, pl. 10, figs. 1, 3-5.

- 1977 "*Pseudochrysalidina*" - Prestat, pl. 10, figs. 4-5.
- T 1979 *Praechrysalidina infracretacea* n. sp. - Luperto Sinni, pl. 1-3.
- 1984 *Praechrysalidina infracretacea* Luperto Sinni - Chiocchini *et al.*, pl. 1, figs. 23-24.
- 1985 *Praechrysalidina infracretacea* Luperto Sinni - Luperto Sinni *in* Schroeder and Neumann (eds), pl. 6, figs. 1-10.
- 1987 *Praechrysalidina infracretacea* Luperto Sinni - Simmons and Hart, pl. 10.1, fig. 5.

### Diagnosis

As for generic diagnosis above.

Holotype dimensions are as follows: Height 1.175mm, Basal diameter 0.85mm (not the dimensions published by Luperto Sinni (1985) which appear to be in error). These dimensions are of a rather small individual. Height can often exceed 2mm and basal diameter 1mm.

### Remarks

Four species may be confused with *P. infracretacea*: *Valvulina lugeoni* Septfontaine (?= *Pseudomarssonella plicata* Redmond), *Dukhania conica* Henson, *Dukhania arabica* Henson and *Chrysalidina gradata* d'Orbigny. The differences between these forms and *P. infracretacea* are covered within the above generic remarks. In addition species of *Minouxia* may be confused with *P. infracretacea*. The morphological differences between these forms and *P. infracretacea* are covered in the above generic remarks. Furthermore, *Minouxia* is a Late Cretaceous genus.

Luperto Sinni (1985) proposed the following phylogenetic lineage:

*Valvulina lugeoni* - *Praechrysalidina infracretacea* - *Chrysalidina gradata* - *Pseudochrysalidina floridana* Cole.

It is possible that *P. infracretacea* gave rise to *C. gradata*, by modification of the aperture and wall, and development of internal pillars. However it is also possible that iterative evolution of gross homeomorphs is taking place from a valvuline root stock giving rise to *Praechrysalidina*, *Dukhania*, *Chrysalidina*, etc. Another alternative, pending further research on the internal structure of *Minouxia*, is that *Praechrysalidina* gave rise to *Minouxia* by the addition of a trematophore plate, without any modifications to wall structure.

### Global Distribution and Stratigraphic Range

Hauterivian? - Late Albian.

Italy, ?Yugoslavia, Somalia, Oman Mountains, Arabian Gulf (BP internal records).

The records of Simmons and Hart (1987) and herein of this species from the Middle East greatly extend its stratigraphic and geographic range.

#### Local Occurrence

Hauterivian? - Late Barremian?

Cylindroporella arabica Zone - Palaeodictyoconus arabicus Subzone.

See range charts provided with Chapter 4 for precise sample distribution.

Only poorly preserved, questionable specimens of this species were recorded during the course of this study (see Plate 3.29). They be referable to other genera, if more specimens become available, eg. *Dukhania*, or as yet undescribed chrysalidinids.

#### Palaeoecology

In the present study, this species was recorded in the high energy, outer shelf grainstones and packstones of the Habshan and Kharaib Formations. No other descriptions of its palaeoecology are known.

Genus *Dukhania* Henson, 1948

Type Species *Dukhania conica* Henson, 1948

#### Diagnosis

Test calcareous, microgranular and non-caniculate. Test shape is conical, trochospiral, triserial following the initial stage, becoming biserial in advanced forms. Apical angle is typically fairly acute, base convex. Aperture cribrate. In section it can be seen that an interiomarginal apertural lip is extended across the umbilicus as a broad plate and that pillars are present on the apertural plates of the latter chambers.

#### Remarks

Since the description of this genus by Henson in 1948, it has usually been considered as a synonym of *Pseudochrysalidina* (eg. by Henson himself in 1949 and Loeblich and Tappan, 1964) or of *Chrysalidina* (eg. Höttinger and Drobne, 1980). However, it is recognised here as a distinct genus for the reasons outlined below. Recently, Loeblich and Tappan (1988) have also recognised it as a distinct genus.

Six genera may be confused with *Dukhania*: *Valvulina*, *Chrysalidina*, *Pseudochrysalidina*, *Praechrysalidina*, *Minouxia* and *Accordiella*.

*Valvulina* differs from *Dukhania* in possessing a single interiomarginal/umbilical aperture rather than a cribrate aperture. It also has a distinct valvuline tooth.

As stated above, *Dukhania* has been considered as a synonym of *Chrysalidina*. However *Chrysalidina* can be distinguished by its trematophore apertural plate and in particular by its distinct canaliculate wall structure which *Dukhania* does not possess. In all other respects *Dukhania* is a non-caliculate homeomorph of *Chrysalidina*.

*Dukhania* differs from *Praechrysalidina* in possessing pillars on the apertural plates present, otherwise the two genera are similar, both being non-caliculate.

*Pseudochrysalidina* is difficult to distinguish from *Dukhania*. Both genera possess pillars on the apertural plates and show a tendency to become biserial in the later stage of the test, although the latter is more strongly developed in *Pseudochrysalidina*. As stated above the two genera have been regarded as synonymous. Further analysis of the wall structure of *Pseudochrysalidina* is required to determine its taxonomic position, although some of the original illustrations of Cole (1941) suggest it may be canaliculate, which would refute any synonymy with *Dukhania*. Furthermore, the isolated stratigraphic position (Eocene) of *Pseudochrysalidina* suggests that it is phylogenetically distinct from the Cretaceous genera within the Chrysalidinidae.

*Minouxia*, like *Chrysalidina*, has a distinct trematophore plate, which *Dukhania* does not possess. Most importantly, no internal pillars are thought to be present. However, further studies of the internal structure of *Minouxia* are required to fully establish its distinction from *Dukhania* and other members of the Chrysalidinidae.

The Late Cretaceous genus *Accordiella* is very similar to *Dukhania* but has abundant rather than scattered pillars crowded centrally on the apertural plate. It may also have a canaliculate wall structure.

The phylogenetic relationships within the Chrysalidinidae and related taxa have been discussed above under the generic remarks of *Praechrysalidina* and specific remarks for *P. infracretacea*. The position of *Dukhania* in these relationships is unclear. It may have evolved from *Praechrysalidina* by the addition of pillars on the apertural plates, and given rise to *Chrysalidina* by the development of a canaliculate wall. Alternatively, it may be an iterative homeomorph of *Chrysalidina* developed from a valvuline root stock. Further study of the phylogenetic relationships of the Cretaceous Chrysalidinidae is required, but is outside the scope of this study.

*Dukhanian conica* Henson, 1948

Plates 3.30-3.32

- T 1948 *Dukhanian conica* n. sp. - Henson, pl. 15, figs. 2, 4-5, 8, pl. 18, figs. 2-3.  
1949 *Pseudochrysalidina conica* (Henson) - Henson, not figured.

Diagnosis

"Test calcareous, imperforate, microgranular, slightly arenaceous; form conical, acute to obtuse angled; base convex; chambers in a trochoid spire, each extending across the axis of the test, four or five to a coil in the early stages, becoming triserial and then biserial; sutures depressed; the last six chambers of the holotype average 0.24mm in depth at the cone surface; interseptal structures (pillars) in later chambers infrequent and irregular; apertures consisting of numerous small round perforations on the base of the test."

"The greatest observed height of the test is 2.0mm; the greatest observed diameter of the base is 2.2mm" (Henson, 1948).

Remarks

Two species of *Dukhanian* have been described: *Dukhanian conica*, the type species, and *Dukhanian arabica*. In *D. conica* the chambers are higher than in *D. arabica*, and there are fewer pillars. *D. conica* becomes biserial in the later stages whereas biserial chambers are not observed in *D. arabica* (thus questioning the position of this later species in the genus *Dukhanian*).

There appears to be some degree of variability in this species. In Cenomanian specimens quite numerous pillars are visible, whilst in Early Cretaceous specimens there are relatively few. Furthermore, some Cenomanian specimens show signs of developing a canaliculate wall, particularly in the later chambers. This suggests a phylogenetic lineage from ancestral forms of *Dukhanian conica* with few pillars, through advanced forms to *Chrysalidina gradata*. *D. conica* itself may be descended from *Praechrysalidina infracretacea* in such a lineage. The type material of *D. conica* shows some variation, and it is possible that ancestral Early Cretaceous forms such as those illustrated here could be regarded as a separate species. It is clear that the Cretaceous chrysalidinids are in need of a full taxonomic and phylogenetic study.

The differences between *D. conica* and species from other similar genera are dealt with under the above generic remarks.

### Global Distribution and Stratigraphic Range

Arabian Gulf, Israel, Iran, Oman Mountains.

Hauterivian - Cenomanian (?Turonian)

Described by Henson (1948) from Aptian, Cenomanian and Turonian sediments. Personal observations from Middle East sediments and BP internal records suggest a Hauterivian - Cenomanian range to be likely if the species is regarded *sensu lato*.

### Local Occurrence

Hauterivian - Early Aptian.

Cylindroporella arabica Zone - Palorbitolina lenticularis Subzone.

See range charts provided in Chapter 4 for precise distribution.

The specimens recorded in this study are ancestral forms, which differ from the holotype illustrated by Henson (1948), but are similar to some of the paratypes. The species is most common in the Early Aptian Shuaiba Formation.

### Palaeoecology

In this study, the species was recorded in a variety of shelf environments. It occurs most commonly in the deep lagoonal mudstones and wackestones of the Shuaiba Formation where it is associated with rudist biostromes. No other records of the species preferred palaeoecology are known. In Cenomanian limestones of Iraq, Reulet (1982) regarded the broadly homeomorphic species *C. gradata* to be typical of subtidal inner shelf lagoons.

Superfamily ATAXOPHRAGMIACEA Schwager, 1877

Family CUNEOLINIDAE Saidova, 1981

Genus *Cuneolina* d'Orbigny, 1839

Type Species *Cuneolina pavonia* d'Orbigny, 1846

Diagnosis

Test free, agglutinated, subcylindrical to flabelliform, trochospiral in early stage, rapidly becoming biserial, broad chambers compressed parallel to the plane of biseriality. The aperture is a series of aligned series of pores along the base of the septal face. The chambers are divided by radial partitions, and commonly by horizontal partitions.

Remarks

*Cuneolina* is very similar to *Vercorsella*, but can be distinguished by having an aperture in the form of an aligned series of pores rather than a basal slit. The aperture of *Cuneolina* also serves to distinguish it from the related genera *Sabaudia* (also distinguished by a hyaline wall surrounding the proloculus) and *Pseudotextulariella*.

Further comparison of *Cuneolina* with other Cretaceous members of the Cuneolinidae is provided in Figure 3.2.

*Cuneolina hensoni* Dalbiez, 1958

Not illustrated

- T 1958 *Cuneolina hensoni* n. sp. - Dalbiez, pl. 1, figs. 1-6, pl. 2, figs. 1-5. Valanginian?, Southwest France.
- 1969 *Cuneolina hensoni* Dalbiez - Conrad, text-figs. 12a-e. Barremian, Jura Mts.
- 1976 *Cuneolina hensoni* Dalbiez - Masse, pl. 10, figs. 9-10. Late Barremian - Early Aptian, Provence.
- 1980 *Cuneolina hensoni* Dalbiez - Arnaud-Vanneau, pl. 47, figs. 1-3, pl. 72, figs. 7-12, text-fig. 202. Late Barremian - Early Aptian, Vercors.

Diagnosis

Test variable in shape but usually strongly flabelliform. Apical angle is between 40-70°. Base of test convex. Average height is 1.1mm but can be as much as 2.5mm. Width is 0.8-1.5mm, but can occasionally reach 3.3mm. On average between 10 and 15 chamber layers are present. The chambers are divided by regular but not dense radial partitions, producing 8 chamberlets per 30° sector of an adult. Horizontal partitions are absent or very poorly developed in the final chambers. Basal sections appear elongate. The aperture is a series of small rectangular pores.

# IDENTIFICATION CHART FOR CRETACEOUS CUNEOLINIDAE

<p style="text-align: center;">Family CUNEOLINIDAE Saidova, 1981</p> <p style="text-align: center;">Subfamily CUNEOLININAE Saidova, 1981</p>	<p style="text-align: center;">Genus SABAUDIA Charollais and Bronnimann, 1965</p> <p>TEST BISERIAL, CONICAL COMPRESSED, WITH APERTURE A SLIT IN BASAL GROOVE. EMBRYONIC APPARATUS WITH PROLOCULUS AND POST EMBRYONIC CHAMBERS SURROUNDED BY A RADIAL HYALINE WALL. BISERIAL STAGE CHAMBERS REGULARLY SUBDIVIDED BY RADIAL PARTITIONS AND MORE IRREGULARLY, BY HORIZONTAL PARTITIONS.</p>	<p>MINUTA (Hofker) 1965 h=0.12-0.35mm w=0.15-0.36mm BROAD TRIANGULAR APICAL ANGLE (&gt;60°). BISERIAL STAGE OF 4-8 CHAMBER LAYERS. CONCAVE BASE PROLOCULUS FOLLOWED BY 2, RARELY 3, PERI-EMBRYONIC CHAMBERS. BASAL VIEW SUB-CIRCULAR. RADIAL PARTITIONS PRESENT. VERY RARELY HORIZONTAL PARTITIONS.</p>	<p>AURUNCENSIS (Chiocchini and Di Napoli Aliata) 1966 h=0.3-0.6mm w=0.33-0.42mm ACUTE APICAL ANGLE (35°-50°) 4-12 CHAMBER LAYERS. CONCAVE BASE. PROLOCULUS FOLLOWED BY 3 PERI-EMBRYONIC CHAMBERS. BASAL VIEW SUB-CIRCULAR. RADIAL PARTITIONS ARE PROMINANT AND ARE VISIBLE IN 3 ORDERS IN CIRCULAR BASAL SECTIONS.</p>	<p>BRIACENSIS Arnaud-Vanneau 1980 h=0.1-0.275mm w=0.2-0.5mm FLATLY CONICAL, APICAL ANGLE 80°-100°. 4-6 CHAMBER LAYERS. CONCAVE BASE. PROLOCULUS FOLLOWED BY 2 PERI-EMBRYONIC CHAMBERS. BASAL VIEW CIRCULAR. RADIAL PARTITIONS ARE PROMINANT AND ARE VISIBLE IN 3 ORDERS IN CIRCULAR BASAL SECTIONS.</p>	<p>CAPITATA Arnaud-Vanneau 1980 h=0.35-1.1mm w=0.3-1.2mm APICAL ANGLE 60°-80° 4-16 CHAMBER LAYERS. CONVEX BASE. PROLOCULUS FOLLOWED BY DEUTERCONCH AND 2 PERI-EMBRYONIC CHAMBERS. BASAL VIEW CIRCULAR-ELONGATE OVAL. NUMEROUS RADIAL PARTITIONS OF VARIABLE LENGTH. SOME HORIZONTAL PARTITIONS IN LATER CHAMBERS.</p>	<p>N.sp. Arnaud-Vanneau and Chiocchini 1985 h=0.25mm w=0.23mm VERY LARGE PROLOCULUS SURROUNDED BY 3 PERI-EMBRYONIC CHAMBERS. 3 CHAMBER LAYERS WITH RADIAL PARTITIONS.</p>	
	<p style="text-align: center;">Genus PSEUDOTEXTULARIELLA Barnard, 1953</p> <p>APERTURE AN INTERIOMARGINAL SLIT, INITIAL STAGE TROCHOSPIRAL, BECOMING TRISERIAL THEN BISERIAL. CHAMBERS DIVIDED BY RADIAL AND HORIZONTAL PARTITIONS.</p>	<p>CRETOSA (Cushman) 1932 h=0.6-1.4mm (usually &gt;1mm) w=0.6-1.2mm (usually c.1.1mm) TEST BROADLY TRIANGULAR, LARGE APICAL ANGLE. 5-6 CHAMBER LAYERS. BASAL SECTION OVAL. 3 ORDERS OF RADIAL AND HORIZONTAL PARTITIONS PRESENT.</p>	<p>SUBALPINA Arnaud-Vanneau 1980 h=0.6-1.3mm w=0.3-0.7mm TEST TRIANGULAR, APICAL ANGLE c.30°. 7 CHAMBER LAYERS. BASAL SECTION OVAL. FEW RADIAL PARTITIONS. CHAMBERLETS VERY UNEVEN IN SHAPE.</p>	<p>SALEVENSIS Charollais, Bronnimann and Zaninetti 1966 h=0.15-0.2mm w=0.12-0.2mm TEST LOW TRIANGULAR, LARGE APICAL ANGLE. DISTINCT INITIAL TROCHOSPIRE PASSES INTO 5-6 CHAMBER LAYERS. BASAL SECTION SUB-CIRCULAR. RADIAL PARTITIONS ONLY.</p>	<p>COURTIONENSIS Bronnimann 1967 h=0.48-0.8mm w=0.4-0.6mm TEST CONICAL-LOW TRIANGULAR, LARGE APICAL ANGLE. AN INITIAL TROCHOSPIRE PASSES INTO 10-11 CHAMBER LAYERS. BASAL SECTION SUB-CIRCULAR. NUMEROUS RADIAL PARTITIONS THROUGHOUT AND RARE HORIZONTAL PARTITIONS IN LATER CHAMBERS.</p>		
	<p style="text-align: center;">Genus VERCORSELLA Arnaud-Vanneau, 1980</p> <p>APERTURE A SIMPLE SLIT IN A BASAL GROOVE. CHAMBERS DIVIDED BY RADIAL PARTITIONS AND RARELY BY HORIZONTAL PARTITIONS.</p>	<p>ARENATA Arnaud-Vanneau 1980 h=0.5-0.72mm w=0.3-0.55mm APICAL ANGLE 30°-40° 8-10 REGULAR CHAMBER LAYERS. BASAL SECTION OVAL. FEW RADIAL PARTITIONS. TEST STRONGLY ARENACEOUS.</p>	<p>SCARSELLAI (De Castro) 1963 h=0.5-1.4mm (usually c.1mm) w=0.3-0.7mm ACUTE APICAL ANGLE. 20°-30°. 10-13 CHAMBER LAYERS. BASAL SECTION SUB-CIRCULAR. OVAL. RADIAL PARTITIONS OMITTED IN EARLY CHAMBERS. FEW IN LATER CHAMBERS AND OFTEN INCOMPLETE. USUALLY 4 VISIBLE IN BASAL SECTIONS.</p>				
	<p style="text-align: center;">Genus CUNEOLINA d'Orbigny, 1839</p> <p>APERTURE AN ALIGNED SERIES OF PORES ALONG THE BASE OF THE FINAL CHAMBER FACE. CHAMBERS DIVIDED BY BOTH VERTICAL AND HORIZONTAL PARTITIONS.</p>	<p>PAVONIA PRAVA Henson 1948 h=c.1.3mm (usually &gt;1mm) w=usually &gt;1mm TEST SHAPE VARIABLE USUALLY BROADLY CONICAL OR FLABELLIFORM. APICAL ANGLE 20°-96° (usually &gt;50°). 7-10 CHAMBER LAYERS FOLLOW A RELATIVELY LARGE PROLOCULUS. BASAL SECTION ELONGATE DISPLAYING NUMEROUS PARTITIONS. NUMEROUS RADIAL PARTITIONS PRODUCE DISTINCTIVE FINE CHAMBERLETS WHICH ARE RECTANGULAR. SOME HORIZONTAL PARTITIONS IN FINAL CHAMBERS.</p>	<p>CYLINDRICA Henson 1948 h=c.1.9mm w=0.4-0.6mm TEST ACUTELY TRIANGULAR WITH APICAL ANGLE 7°-14°. 16 CHAMBER LAYER FOLLOW RELATIVELY LARGE PROLOCULUS. BASAL SECTION OVAL. NUMEROUS RADIAL PARTITIONS PRODUCE FINE RECTANGULAR CHAMBERLETS. SOME HORIZONTAL PARTITIONS IN FINAL CHAMBERS.</p>	<p>AXINOIDES Arnaud-Vanneau 1980 h=0.83-1.6mm (usually c.1.3mm) w=0.53-0.85mm (usually c.0.75mm) TEST AXE SHAPED WITH EARLY CHAMBERS SUB-CYLINDRICAL. LATER CHAMBERS SLIGHTLY FLARED AND TRIANGULAR. INITIAL APICAL ANGLE 20°-25°. 10-12 CHAMBER LAYERS. BASAL SECTION ELONGATE. FEW RADIAL PARTITIONS. RARE HORIZONTAL PARTITIONS IN FINAL CHAMBERS.</p>	<p>HENSONI Dalbiez 1958 h=c.1.1mm (can reach 2.5mm) w=0.8-1.5mm (rarely 3.3mm) TEST VARIABLE IN SHAPE BUT USUALLY STRONGLY FLABELLIFORM. APICAL ANGLE 40°-70°. BASE CONVEX 10-15 CHAMBER LAYERS. BASAL SECTION ELONGATE. CHAMBERS DIVIDED BY REGULAR BUT NOT DENSE RADIAL PARTITIONS</p>	<p>TENUIS Velic and Gusic 1973 h=c.0.3mm w=0.3-0.4mm TEST TRIANGULAR. APICAL ANGLE c.45°. BASE CONVEX 8-9 CHAMBER LAYERS. BASAL SECTION OVAL FEW RADIAL PARTITIONS TEST AND SEPTA EXTREMELY FINE.</p>	<p>CAMPOSOURII Sartoni and Crescenti 1962 h=c.0.65mm w=c.0.34mm TEST TRIANGULAR, APICAL ANGLE 4°-60°. BASE CONVEX 7-10 CHAMBER LAYERS. BASAL SECTION OVAL QUITE NUMEROUS RADIAL PARTITIONS 10-14 MAY BE SEEN IN BASAL SECTIONS.</p>

Figure 3.2

### Remarks

*Cuneolina hensoni* is a particularly distinctive Early Cretaceous cuneolinid because of its flabelliform test shape. It is most similar to the Late Cretaceous species *Cuneolina pavonia parva* Henson. However the latter subspecies differs by the presence of a much denser network of radial partitions and by the more common occurrence of horizontal partitions.

The differences between *C. hensoni* and other Cretaceous members of the Cuneolinidae are further described in Figure 3.2.

### Global Distribution and Stratigraphic Range

Southern and western France, Oman Mountains.

Valanginian? - Early Aptian.

The geologically oldest record of this species (Dalbiez, 1958) is from questionable Valanginian sediments, which may even be as young as Barremian. Hence, the age of the origin of this species remains questioned.

The questionable record herein of this species greatly extends its geographic range. It had previously only been described from France.

### Local Occurrence

Hauterivian.

Acroporella assurbanipali Zone

See range charts provided in Chapter 4 for precise distribution.

Only questionable specimens of this species were recorded during the course of this study. None were considered suitable to use for illustration.

### Palaeoecology

Arnaud-Vanneau (1980) recorded this species from platform channel sands and from bioclastic sands deposited in the external region of the euhaline infralittoral zone. In this study the species was recorded from shallow inner shelf or lagoonal dasycladacean rich wackestones.

*Cuneolina laurentii* Sartoni and Crescenti, 1962

Plates 3.33 - 3.37

- T 1962 *Cuneolina laurentii* n. sp. - Sartoni and Crescenti, pl. 48, figs. 7-9, pl. 49, figs. 1, 3. Early Cretaceous, Central Italy.
- 1984 *Cuneolina* gr. *laurentii-camposaurii* Sartoni and Crescenti - Berthou, pl. 1, fig. 2. Late Albian, Portugal.
- 1987 *Cuneolina laurentii* Sartoni and Crescenti - Simmons and Hart, pl. 10.5, fig. 7. Valanginian - Hauterivian, Oman Mts.

Diagnosis

Test triangular with an apical angle of 35-50°. Base convex. Average test height is 0.75mm, average test width is 0.35mm. 7-8 chamber layers are developed divided by a few radial partitions, with 6-7 being visible in a basal section of an adult. Basal section is sub-circular or oval.

Remarks

This species is similar to *Vercorsella arenata* Arnaud-Vanneau and *Vercorsella scarsellai* (De Castro), but can be distinguished by its aperture (a series of pores rather than a basal slit) and relatively small proloculus.

*Cuneolina tenuis* Velić and Gušić is similar but has an extremely fine test wall and septa. *Cuneolina camposaurii* Sartoni and Crescenti is somewhat broader, has more chamber layers and more numerous radial partitions.

Further comparison of this species with other Cretaceous members of the Cuneolinidae is provided in Figure 3.2.

Global Distribution and Stratigraphic Range

Peri-Mediterranean, Middle East.

Valanginian - Late Albian.

Local Occurrence

Valanginian?/Hauterivian - Early Aptian.

Buccicrenata hedbergi - Palorbitolina lenticularis Subzones.

See range charts provided in Chapter 4 for precise distribution.

#### Palaeoecology

This species has been recorded by a number of authors (see above synonymy) across much of Tethys. It is typically recorded from infralittoral (=inner shelf) sediments of moderate energy. In this study it was found, although never in abundance, in a variety of environments across the Thamama ramp.

*Cuneolina camposaurii* Sartoni and Crescenti, 1962

Plates 3.38 - 3.39

T 1962 *Cuneolina camposaurii* n. sp. - Sartoni and Crescenti, pl. 24, fig. 1, pl. 48, figs. 1-6. Early Cretaceous, Central Italy.

#### Diagnosis

Test triangular - flabelliform in axial section with an apical angle of 40-60°. Base convex. Average test height is 0.65mm, average test width is 0.34mm. 7-10 chamber layers are developed divided by a numerous radial partitions, with 10-14 being visible in a basal section of an adult. Basal section is oval.

#### Remarks

This species is similar to *Cuneolina laurentii*, but is somewhat broader, has more chamber layers and more numerous radial partitions. *Cuneolina hensoni* has a distinctive more strongly flabelliform test shape, and is larger, whilst *Cuneolina pavonia parva* has numerous fine radial partitions.

Further comparison of this species with other Cretaceous members of the Cuneolinidae is provided in Figure 3.2.

#### Global Distribution and Stratigraphic Range

Peri-Mediterranean, Middle East.

Valanginian - Aptian.

#### Local Occurrence

Hauterivian.

Acroporella assurbanipali Zone.

See range charts provided in Chapter 4 for precise distribution.

#### Palaeoecology

This species was recorded by Sartoni and Crescenti (1962) from infralittoral (=inner shelf) sediments of moderate energy. In this study it was found, although never in abundance, in inner shelf or lagoonal environments of low energy.

Genus *Vercorsella* Arnaud-Vanneau, 1980

Type Species *Vercorsella arenata* Arnaud-Vanneau, 1980

#### Diagnosis

"Test free, agglutinated, of triangular form (in axial section) compressed parallel to the plane of symmetry of the biserial chambers, beginning with a brief uncoiled stage followed by a biserial stage and terminating with a basal apertural slit. The proloculus is partially visible at the surface of the test because of the very weak development of the initial spire. The chambers are divided by radial partitions sometimes associated with horizontal partitions" (translated from Arnaud-Vanneau, 1980).

#### Remarks

The genus *Vercorsella* is very similar to *Cuneolina*, but can be distinguished by having an aperture in the form of a basal slit, rather than an aperture consisting of an alignment of apertural pores situated at the base of the chambers. A further distinctive feature is the relatively large proloculus compared to that of *Cuneolina*.

Further distinctive features of the genus which distinguish it from other Cretaceous members of the Cuneolinidae are described in Figure 3.2.

*Vercorsella arenata* Arnaud-Vanneau, 1980

Plate 3.40

- 1966 *Cuneolina conica* d'Orbigny - Iocheva, pl. 1, figs. 20-21. Early Cretaceous, Bulgaria.
- ? 1973 *Cuneolina camposaurii* Sartoni and Crescenti - Velić, pl. 4, fig. 6 (Late Aptian), pl. 7, fig. 1-2 (Early Albian). Yugoslavia.
- 1976 *Cuneolina* cf. *hensoni* Dalbiez - Masse, pl. 10, fig. 11. Barremian, Provence.
- ? 1978 *Cuneolina* sp. - Babić and Gušić, pl. 2, fig. 8-9.
- T 1980 *Vercorsella arenata* n. sp. - Arnaud-Vanneau, pl. 46, figs. 1-2, pl. 71, figs. 1-7. Early Aptian, Vercors.

1987 *Vercorsella arenata* Arnaud-Vanneau - Simmons and Hart, pl. 10.5, fig. 8. Hauterivian, Oman Mountains.

#### Diagnosis

Small *Vercorsella*, test very arenaceous with a fairly acute apical angle (30-40°). The chambers are divided by radial partitions and rare horizontal partitions only visible in the last formed chambers. Five or six radial partitions are typically developed in the last chamber. The basal section appears oval. The sharp apex contains a proloculus visible through the sides of the test. The biserial stage consists of 18-20 slightly bulbous chambers, always wider than high and separated by straight depressed sutures. The progressive increase in chambers is regular. The aperture is a basal slit occupying almost the whole width of the chamber (freely translated from Arnaud-Vanneau, 1980).

#### Remarks

The following dimensions were recorded by Arnaud-Vanneau (1980):

Height - 0.5-0.725mm

Width - 0.3-0.55mm

Thickness - 0.2-0.3mm

Proloculus Diameter - 90-130 microns.

Examination of topotype specimens suggests that often less than 18-20 chambers are present. More typically there are 8-10.

Three Early Cretaceous species are very similar in general form to *V. arenata*: *Vercorsella scarsellai* (De Castro), *Cuneolina tenuis* Velić and Gusić and *Cuneolina camposaurii* Sartoni and Crescenti.

*V. scarsellai* can be distinguished by its very acute apical angle, generally larger size and radial partitions that are often incomplete and sinuous. *C. tenuis* can be distinguished by its finer test structure and apertural arrangement. *C. camposaurii* can be distinguished by its apertural arrangement, broader apical angle, higher number of radial partitions, and smaller proloculus.

The differences between *V. arenata* and other members of the Cuneolinidae are further described in Figure 3.2.

#### Global Distribution and Stratigraphic Range

Southern France, Yugoslavia, Bulgaria, Oman Mountains.

Hauterivian - Early Aptian (?Early Albian).

The Late Aptian and Early Albian records of this species (Velic, 1973) are questionable. They may be species of *Cuneolina*.

The records of this species from the Middle East (Simmons and Hart, 1987 and herein) extend the geographical and stratigraphic range of this species. It is thought that further research may reveal new records of this species previously identified as a *Cuneolina*.

#### Local Occurrence

Hauterivian.

*Cylindroporella arabica* - *Acroporella assurbanipali* Zones.

See range charts provided in Chapter 4 for precise details.

#### Palaeoecology

Arnaud-Vanneau (1980) noted that this species was abundant in terrigenous channel sands and bioclastic sands with quartz of the Vercors Urgonian Platform. This equates to euhaline sedimentation in the infralittoral zone. In this study the species was recorded in lagoonal packstones and wackestones deposited behind an oolitic shoal.

#### *Vercorsella scarsellai* (De Castro, 1964)

Plates 3.41 - 3.43

- T 1964 *Cuneolina scarsellai* n. sp. - De Castro, pl. 1, figs. 1-10, pl. 2, figs. 1-4. Aptian - Albian, Central Italy.
- 1966 *Cuneolina scarsellai* De Castro - Chiocchini and Di Napoli Alliata, pl. 3, fig. 1, pl. 6, fig. 1?, 2, pl. 7, fig. 2? Late Aptian - Early Albian, Central Italy.
- 1966 *Textulariella* or *Pseudotextulariella* sp. - Ferrer, text-figs. 10, 16. Aptian - Albian, Northern Spain.
- 1968 *Pseudotextulariella? scarsellai* (De Castro) - Brönnimann and Conrad, text-figs. 1-4, pl. 1, figs. 1-8, pl. 2, figs. 1-10. Barremian - Early Aptian, Jura Mts.
- 1980 *Vercorsella* aff. *scarsellai* (De Castro) - Arnaud-Vanneau, pl. 46, fig. 3, pl. 71, fig. 8. Early Barremian - Early Aptian, Vercors.

### Diagnosis

Relatively large *Vercorsella* with few, and often incomplete radial partitions usually only present in the later chambers. No horizontal partitions. Apical angle 20-30°. Between 10-13 chamber layers visible. Basal section oval, with typically four radial partitions visible. The aperture is a basal slit.

### Remarks

The morphology, internal structure and occurrence of this species have been reviewed in detail by Brönnimann and Conrad (1968).

Comparison of this species to similar members of the Cuneolinidae is shown in Figure 3.2.

### Global Distribution and Stratigraphic Range

Western Mediterranean, Oman Mountains.

Valanginian - Middle (?) Albian.

The record herein of this species from the Middle East extends its geographical and stratigraphical range. The species is thought likely to occur in other suitable Central Tethyan sediments (eg. from the Near East) but has not yet been recorded.

### Local Occurrence

Valanginian?/Hauterivian - Barremian.

Buccicrenata hedbergi Subzone - Permocalculus inopinatus Zone.

See range charts provided with Figure 4 for precise distribution.

### Palaeoecology

Arnaud-Vanneau (1980) recorded this species from infralittoral bioclastic sands in the Vercors region. Brönnimann and Conrad (1968) also recorded a similar environmental distribution, suggesting that *V. scarsellai* occurs in biomicrites deposited in a very shallow environment, protected from strong currents. They noted that the species prefers low energy environments. In this study the species was recorded from a variety of palaeoenvironments across the Thamama ramp.

Superfamily ORBITOLINACEA Martin, 1890  
Family ORBITOLINIDAE Martin, 1890  
Genus *Palorbitolina* Schroeder, 1963  
Type Species *Madreporites lenticularis* Blumenbach, 1805

Diagnosis

Flatly conical orbitolinid, beginning with a relatively simple, apically situated, embryonic apparatus consisting of a spherical embryonic chamber (combined proloculus and deuteroconch), and in advanced specimens, periembryonic chamberlets. The original proloculus may be distinguished in some specimens by a chitinous wall. The deuteroconch and periembryonic chambers typically show a surface division by septa. The chambers can be divided into a marginal zone partitioned by horizontal and vertical septa, and a central zone comprising a radial part and a central part with a complex reticulum. In the central zone, the oblique apertural pores are disposed in diagonal lines. The septa alternate from one chamber to another.

Macrospheric forms have a somewhat flatly conical test, with an apical angle usually greater than 90°, and a large apical embryonic apparatus. Microspheric forms have a very large test, highly flattened, and a very small embryonic apparatus situated slightly eccentrically.

For further details see also the specific remarks below for *Palorbitolina lenticularis*. Figure 3.3 illustrates the morphological features of the Orbitolinidae referred to in this study. For details of some of these features the reader is recommended to Schroeder (1975) and Arnaud-Vanneau (1980).

Remarks

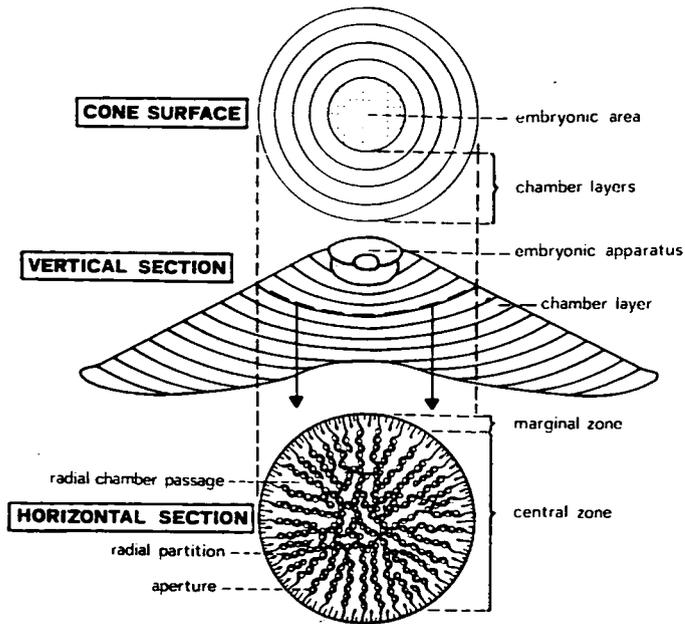
*Palorbitolina* can be distinguished from *Eopalorbitolina* Schroeder and Conrad in having an larger, apically placed embryonic apparatus, as opposed to one eccentrically placed. Arnaud-Vanneau (1980) placed *Eopalorbitolina* as a subgenus within *Palorbitolina*. This practice is not followed here, the two taxa being considered generically distinct (see section on *Eopalorbitolina*).

*Palorbitolina* differs from *Orbitolina* and *Praeorbitolina* by lacking a subembryonic zone within the embryonic apparatus. It differs from *Simplorbitolina*, *Palaeodictyoconus* and *Paracoskinolina* by possessing radially placed or labyrinthically arranged septula within the central zone of the chamber layers instead of pillars, and also a larger apically situated embryonic apparatus, with periembryonic chamberlets in advanced forms. *Orbitolinopsis* has a smaller, simpler embryonic apparatus, and only a weakly developed radial zone (if at all).

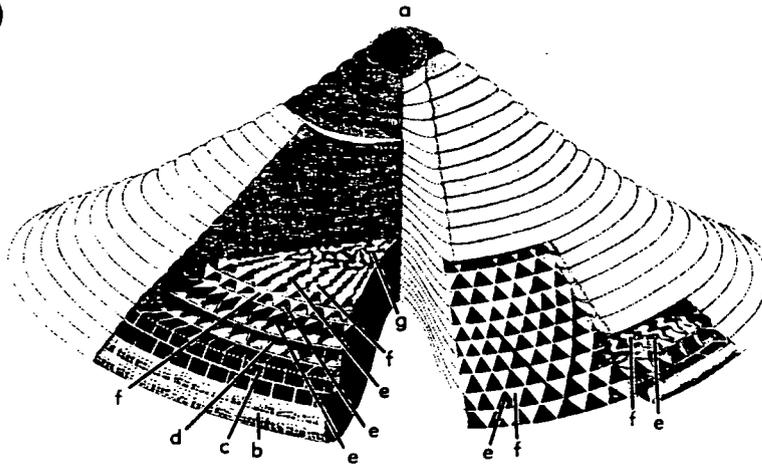
# MAIN MORPHOLOGICAL ELEMENTS OF THE ORBITOLINIDAE WITH PARTICULAR REFERENCE TO PALORBITOLINA/ ORBITOLINA

(a) From Schroeder (1975); (b) From Douglass, Loeblich and Tappan (1964); (c) From Arnaud-Vanneau (1980)

(a)



(b)



(c)

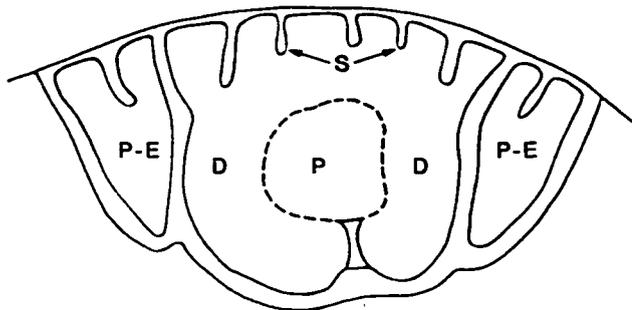


Figure 3.3

KEY FOR FIGURE 3.3

Figure (b): a = Megalospheric embryonic apparatus  
b = Slightly abraded surface showing cellules  
c = Marginal zone beneath cut-away surface  
d = Inframarginal zone exposing chamberlets  
e = Radial passages between chambers  
f = Slightly zigzag main radial partitions showing triangular cross-section  
g = Central complex.

Figure (c): Embryonic apparatus of Palorbitolina.

P = Proloculus  
D = Deuteroconch  
S = Septa  
P-E = Peri-embryonic chamberlets

# IDENTIFICATION TABLE FOR EARLY CRETACEOUS ORBITOLINIDAE (From Arnaud-Vanneau, 1980)

PORES	NATURE DES DIVISIONS DE LA ZONE CENTRALE	ZONE MARGINALE		LES CLOISONS DE LA Z.M. N'ALTERNENT PAS D'UNE LOGE A L'AUTRE		LES CLOISONS DE LA ZONE MARGINALE ALTERNENT D'UNE LOGE A L'AUTRE				
						P.P. INDIVISE	PARTIE PERIPHERIQUE DE LA ZONE MARGINALE DIVISEE			
PORES OBLIQUES	Cloisons méandriiformes sans partie centrale  Z.M. P.R.	 Z.M. P.R.						<i>Palorbitolina</i>	<i>Orbitolina</i>	<i>Praeorbitolina</i>
	Cloisons méandriiformes avec partie centrale  Z.M. P.R. P.C.	 Z.M. P.R.					<i>Valserina</i> <i>Simplorbitolina</i>	<i>Neorbitolinopsis</i>	<i>Neorbitolina</i> <i>Alpillina</i>	
	Cloisons piliers et pilaroides  Z.M. Z.C.	 Z.M. Z.C.					<i>Paleo-dictyoconus</i> <i>Valdanchella</i>			
	Cupules  Z.M. Z.C.	 Z.M. Z.C.					<i>Orbitolinopsis</i>			
PORES VERTICAUX	"Cloisons"  Z.M. Z.C.	 Z.M. Z.C.				<i>Falsurgonina</i>				
	Cloisons non méandriiformes  Z.M. Z.C.	 Z.M. Z.C.					<i>Cribellopsis</i>	<i>Abrardia</i>		
	Piliers  Z.M. Z.C.	 Z.M. Z.C.	<i>Paracoskinolina</i>	<i>Dictyorbitolina</i>	<i>Urgonina</i>	<i>Dictyoconus</i>	<i>Recto-dictyoconus</i>			
	Zone centrale en partie divisée  Z.M. Z.C.	 Z.M. Z.C.					<i>Hetero-coskinolina</i>			
	Zone centrale indivise  Z.M. Z.C.	 Z.M. Z.C.					<i>Coskinolinoides</i>			
	SECTION TRANSVERSE	SECTION AXIALE	SIMPLE	COMPLEXE	SIMPLE		COMPLEXE			
			APPAREIL			EMBRYONNAIRE				
						P. + D. DIVISEE	P. + D. + ZONE PERIEMBRYON.	APICAL	EXCENTRE	
							P. + D. + Z. SUBEMBRYONNAIRE			

Figure 3.4

According to Cherchi and Schroeder (1980) *Palorbitolina* evolved from *Eopalorbitolina* in the Late Barremian and evolved into *Palorbitolinoides* at the base of the Late Aptian. *Palorbitolinoides* differs from *Palorbitolina* in having a more complex embryonic apparatus in which a periembryonic ring of chamberlets is developed.

Figure 3.4 taken from Arnaud-Vanneau (1980) presents a table for distinguishing Early Cretaceous Orbitolinidae, and effectively demonstrates the differences between *Palorbitolina* and some of the related genera mentioned above.

There is some uncertainty as to the validity of the genus *Palorbitolina*, since the type species is, according to some authors, also that of *Orbitolina*. In order to clarify this issue, I have reviewed the problem in detail below. This review forms the essence of two papers, both recently published (Schroeder and Simmons, 1988, 1989). The decision of the ICZN on the recommendations made is awaited.

#### Comments on the type species of *Orbitolina* and the validity of the genus *Palorbitolina*

The genus *Orbitolina* was erected by d'Orbigny in 1850. Because of uncertainty in the original designation of a type species for this genus, a number of species have since been referred to as "type species". This has led to some confusion concerning the taxonomic concept of the genus and may have rendered other genera invalid because of problems with type species priority. In particular, the commonly used generic name *Palorbitolina* Schroeder, 1963 has been thought by some to be invalid, because the type species of that genus, *Madreporites lenticularis* Blumenbach, 1805, has been described, e.g. by Douglass, Loeblich and Tappan (1964), as the type species of *Orbitolina*. If this were the case it would have tremendous taxonomic implications. Not only would the name *Palorbitolina* be unavailable, but most species commonly regarded as belonging to *Orbitolina* would have to be assigned to a new genus. This is because Schroeder (1964a,b; 1975) has shown that *Palorbitolina* is morphologically and phylogenetically distinct from *Orbitolina*. Therefore if the true nature of *Orbitolina* is that commonly regarded as *Palorbitolina* (i.e. that of the species *lenticularis*), then other species thought today to be *Orbitolina* (e.g. *O. concava* (Lamarck, 1816) (*Orbulites*) or *O. texana* (Roemer, 1849) (*Orbitulites*)) could not belong to that genus because of the observations of Schroeder (*op. cit.*)

To clarify these problems a detailed examination of the original description of the genus *Orbitolina* and subsequent type species designations has been carried out.

#### **Original designation**

The first problem to address in this review is to establish if d'Orbigny designated a type species for *Orbitolina* in his original 1850 description.

*Orbitolina* is first mentioned on page 143 of volume 2 of the "Prodrome de Paléontologie stratigraphique universelle des animaux mollusques & rayonnés faisant suite au cours élémentaire de Paléontologie et de Géologie stratigraphiques". There is no mention of *Orbitolina* in either volume 1 or 3 of this book.

The entry on page 143 reads:

"ORBITOLINA, d'Orb., 1847. Ce sont des Orbitolites a côtés inégaux, l'un encroûte, l'autre avec des loges.

\*342. *lenticulata*, d'Orb., 1847. *Orbitolites lenticulata*,

Lamarck, 1816; Lamouroux, 1821, pl. 72, fig. 13-16. Perte-du-Rhône (Ain), St-Paul-de-Fenouillet (Aude)."

In this text "d'Orb., 1847" refers to the manuscript date. *Orbitolites lenticulata* Lamarck 1816 is synonymous with *Madreporites lenticularis* Blumenbach, 1805, variously referred to *Orbitolina* or *Palorbitolina*.

It is important to note that this volume is arranged in stratigraphic order. Hence the first species mentioned under *Orbitolina* is *lenticulata* in the section "Foraminifères", within the chapter "19e étage - Albien".

Within the subsequent chapters the following species are listed:

20e étage - Cenomanien; pages 184 - 185:

"ORBITOLINA, d'Orb., 1847. Voy. t.2, p.148.

\*743. *plana*, d'Archiac, 1837, Mém. Soc. géol. de France, t.2., p.178. France, Fouras, La Malle (Var).

\*744. *mamillata*, d'Archiac, 1837, id., t.2, p.178. Fouras.

\*745. *concava*, Lamarck, 1816. Anim. sans vert., 2, Michelin, 1842, Icon. zoophyt., p.28, pl.7, fig. 9 (mala).

*Orbitolina conica*, d'Archiac. France, Ballon, St-Paulet, près le Pont-St-Esprit, Fouras."

22e étage - Senonien; pages 279 - 280:

"ORBITOLINA, d'Orb., 1847. Voy. p.148.

\*1350. *gigantea*. d'Orb., 1847. Espèce qui atteint jusqu'à 10 centimètres de diamètre; concave en dessous, convexe en dessus. France, Royan, Pérignac (Charente-Inférieure)

\*1351. *radiata* d'Orb., 1847. Espèce pourvue de rayons qui convergent du bord au centre. France, Royan."

In total six species are listed under the genus *Orbitolina* in stratigraphic order. D'Orbigny does not indicate any particular species to be the type, and the stratigraphic nature of the volume implies that the first mentioned species under a genus is not necessarily the type.

It is clear, therefore, that no type species was designated for *Orbitolina* by d'Orbigny, and that *lenticulata* (= *lenticularis*) is not automatically the type species simply because it is listed first. This was first noted by Schroeder (1963) in a paper which established *lenticularis* as type species of the new subgenus (later genus) *Palorbitolina*.

Unfortunately, Douglass (1960a,b), Hofker (1963; 1966a,b) and most importantly Douglass, Loeblich and Tappan (1964) in the definitive "Treatise on Invertebrate Paleontology" regard *Madreporites lenticularis* Blumenbach, 1805 as type species. According to the last-named authors (page C309); *Orbulites lenticulata* Lamarck, 1816 (= *Madreporites lenticularis* Blumenbach, 1805) is the type species of the genus by original designation (monotypy).

As demonstrated above there is neither an original type species designation by d'Orbigny, nor is the genus monotypic in the reference containing the original description.

#### Subsequent designation

All six species recorded by d'Orbigny (1850) under *Orbitolina* have equal claim as type species. According to Article 69(a) of the International Code of Zoological Nomenclature (ICZN) (Ride *et al.*, 1985), the first published designation of a type species subsequent to the original publication of the genus should be regarded as the only valid one.

There are, in fact, several subsequent quotations which could be regarded as designations of a type species for *Orbitolina*.

- (i) According to Parker and Jones (1860:35) "the conical, hemispherical and flattened forms of *Orbitolina* so common in the Cretaceous deposits, and known under twelve or more different names, are referable to one specific type, namely the *O. concava*, Lamarck, sp. and to this type not only these large..." However, this quotation, nor any that follow it in the text, is really valid as a type designation, as these authors were not using type in the sense of "type species of a genus", but rather as an indication of the "typical form of a species." Indeed on page 38 one can read "we regard it (*O. concava*) as the type of a species including numerous varieties". In their recent monograph of foraminifera genera, Loeblich and Tappan (1988:166) cited this reference by Parker

and Jones (*op. cit.*), as a valid subsequent designation of a type species, and thus regarded *Orbulites concava* Lamarck, 1816, as the correct type species of *Orbitolina*. As noted above, one cannot agree with their opinion that the Parker and Jones reference is a valid subsequent designation, although for different reasons, as will be shown, it is recommended that *O. concava* be regarded as type species.

- (ii) Ellis and Messina (1940 *et seq.*) reported that *Orbitolina lenticularis* Blumenbach, 1805 was designated as type species by Dollfus (1905). They regarded this designation as invalid because a species named *lenticularis* was "not among the species originally included under the generic name by d'Orbigny." In fact d'Orbigny (1850:143) cited *Orbitolites lenticulata* Lamarck, 1816, which is synonymous with *Madreporites lenticularis* Blumenbach, 1805.

The reference "Dollfus, 1905" of Ellis and Messina relates to a review by that author on a paper published by Prever (*in* Prever and Silvestri, 1905). In this review Dollfus (1905:232) pointed out: "Il (= Prever) considère que le Genre *Dictyocornis* (he means *Dictyoconus*) Blackenhorh, fondé pour quelques espèces d'Egypte, est bien rigoureusement synonyme (with *Orbitolina*); il le compare aux Genres voisins et commence par établir que le type du G. *Orbitolina* est *O. lenticularis* Blum. sp. (*Madreporites*) 1796, espèce de la Perte du Rhône." However, the second half of this statement made by Dollfus is wrong; Prever has never designated *O. lenticularis* as type species of *Orbitolina*. On the contrary, *O. lenticularis* belongs to the species which were eliminated by this latter author (1905:469; "il lavoro di revisione compiuto, mi ha obbligato a distruggere parecchie delle specie già istituite ed anche di quelle or nominate, ed in cambio a crearne delle nuove").

- (iii) Cushman (1928:182) designated *Orbitolina gigantea* d'Orbigny as type species of *Orbitolina*. Subsequently Douvillé (1933:199) demonstrated that this species is a coral belonging to the genus *Cyclolites* Lamarck.
- (iv) Davies (1939:786) pointed out that "*O. concava* seems to be the form best indicated in the "Prodrome" itself. It is also the best for studying the genus, being usually better preserved as well as much larger than *O. lenticularis*. It should obviously, in my opinion, be taken as the type of *Orbitolina*."

Davies (*op. cit.*) therefore selected *O. concava* as type species. By doing so he hoped to alleviate the taxonomic problems caused by Cushman's designation of the coral *O. gigantea* (= *Cyclolites*) as type species. In fact Cushman in the 1950 edition of his text, named *O. concava* as the type

species. A number of other workers have also agreed with Davies's opinion that *O. concava* should be regarded as the type species of *Orbitolina*. These include Henson (1948) and Sahni and Sastri (1957).

- (v) Thalmann (1950:509) proposed *Orbitolina texana* (Roemer, 1849) (= *Orbitulites texanus* Roemer, 1849) as a substitute type species in place of *Orbitolina concava*. However, since this species is not among those originally included under the generic name by d'Orbigny, it can be immediately excluded from consideration as a type species (ICZN Article 69a).
  
- (vi) Douglass (1960a:28) and Douglass, Loeblich and Tappan (1964:C309) considered *Orbitolina lenticularis* to be the type species of the genus. Douglass (*op. cit.*) is of the opinion that "only one species is referred to the genus in this, the original description. The genus as described is therefore monotypic, even though five other species are referred to it in later sections of the volume." As demonstrated above, the stratigraphic nature of the "Prodrome" implies that the first mentioned species under a genus is not necessarily the type. For this reason, the arguments of Douglass and Douglass *et al.* (*op. cit.*), which were also followed by Hofker (1963:220; 1966b:9), are invalid (see also Schroeder, 1963:351).

### Conclusions and Recommendations

It is clear that despite the arguments of Douglass (1960a), Hofker (1963) and Douglass, Loeblich and Tappan (1964), no original designation of a type species of *Orbitolina* was made by d'Orbigny (1850), nor was the genus monotypic in the original description. Hence, *Madreporites lenticularis* (= *Orbitolina lenticularis*) is not automatically the type species.

The first designation of a type species is that of Cushman (1928), who nominated *Orbitolina gigantea* d'Orbigny, 1850. According to Douvillé (1933) this taxon is a species of the coral genus *Cyclolites*. In strict observance of the International Code of Zoological Nomenclature, *Orbitolina* d'Orbigny, 1850 is a synonym of *Cyclolites* Lamarck, 1801 (see Wells, 1956:F386).

If one accepts this situation, then the numerous species regarded as belonging to *Orbitolina* would have to be assigned to a new genus. Therefore it is recommended that *Orbitolina gigantea* be suppressed as type species and the recognition of *Orbitolina concava* as replacement type species of *Orbitolina*, as originally suggested by Davies (1939). This will negate the need for a major revision of orbitolinid taxonomy and allow the genus *Palorbitolina* to remain valid. In this context an official application is being made to the International

Commission on Zoological Nomenclature to implement the above recommendations (Schroeder and Simmons, 1988).

It is worth noting that *Orbitolina concava* (= *Orbulites concava* Lamarck, 1816) is not the same taxon as *Orbitolites concava* Lamarck, 1801. As demonstrated by Parker and Jones (1860) and Schroeder (1962), the earlier named species (in fact a bryozoan) cannot be considered as the type of *Orbitolina concava*. Hence it is *Orbitolina concava* (Lamarck, 1816) that should be regarded as the valid type species of the genus *Orbitolina*.

*Palorbitolina lenticularis* (Blumenbach, 1805)

Plates 3.44 - 3.54

- T 1805 *Madreporites lenticularis* n. sp. - Blumenbach, pl. 80, fig. 1-6.  
1816 *Orbulites lenticulata* - Lamarck, p. 197.  
1821 *Orbulites lenticulata* - Lamouroux, pl. 72, figs. 13-16.  
? 1840 *Orbitolites bulgarica* n. sp. - Boue, p. 239.  
1850 *Orbitolina lenticulata* (Lamarck) - d'Orbigny, p. 184.  
? 1852 *Orbitolina conoidea* n. sp. - Gras, pl. 1, figs. 4-6.  
? 1852 *Orbitolina discoidea* n. sp. - Gras, pl. 1, figs. 7-9.  
1858 *Orbitolina lenticularis* (Lamarck) - Pictet and Renevier, p. 1.  
1912 *Orbitolina lenticularis* (Blumenbach) - Douville', p. 570.  
1929 *Orbitolina tibetica* n. sp. - Cotter, pl. 27, fig. 12.  
1948 *Orbitolina kurdica* n. sp. - Henson, pl. 1, figs. 9-15.  
1948 *Orbitolina* cf. *discoidea* Gras - Henson, pl. 2, figs. 1-3.  
1948 *Orbitolina discoidea* Gras var. *delicata* var. nov. - Henson, pl. 2, figs. 13-14.  
1960 *Orbitolina lenticularis* (Blumenbach) - Douglass, pl. 1, figs. 1-26.  
1960 *Orbitolina lenticularis* (Blumenbach) - Douglass, pl. 1, figs. 1-11.  
1961 *Orbitolina conoidea discoidea* Gras - Chevalier, pl. 10, figs. 60-62.  
1963 *Orbitolina lenticularis* (Blumenbach) "Form group I" - Hofker, pl. 1, figs. 1-17, pl. 2, figs. 1-15, pl. 3, figs. 1-15, pl. 4, figs. 1-13, pl. 5, figs. 1-8, pl. 6, figs. 1-17, pl. 7, figs. 1-12.  
1963 *Orbitolina (Palorbitolina) lenticularis* (Blumenbach) - Schroeder, pl. 23, figs. 1-9, pl. 24, figs. 1-10.  
1964 *Orbitolina lenticularis* (Blumenbach) - Mehes, pl. 2, fig. 1-2.  
1964 *Orbitolina praecursor* n. sp. - Montanari, pl. 19, figs. 1-9; pl. 20, figs. 1-8; pl. 21, figs. 1-5.  
1964 *Palorbitolina lenticularis* (Blumenbach) - Schroeder, p. 465, not figured.  
1964 *Orbitolina lenticularis* (Blumenbach) - Douglass *et al.*, Text-Fig. 220.1, ?220.2-4.  
1965 *Orbitolina praecursor* Montanari - Montanari, pl. 6, figs. 4-5.

- 1966 *Palorbitolina lenticularis* (Blumenbach) - Moullade, pl. 12, figs. 13-15.
- 1966 *Orbitolina lenticularis* (Blumenbach) "Form group I" - Hofker, pl. 1, figs. 9-10.
- 1966 *Orbitolina lenticularis* (Blumenbach) - Fulop, pl. 14, fig. 8.
- 1966 *Palorbitolina lenticularis* (Blumenbach) - Schroeder and Charollais, pl. 3, figs. 1, 6.
- 1969 *Orbitolina (Palorbitolina) lenticularis* (Blumenbach) - Mehes, pl. 1, figs. 4-6.
- 1969 *Palorbitolina lenticularis* (Blumenbach) - Conrad, text-fig. 13c.
- 1969 *Palorbitolina lenticularis* (Blumenbach) - Arnaud-Vanneau, pl. 1, figs. 1-5.
- 1970 *Palorbitolina lenticularis* (Blumenbach) - Fourcade, pl. 35, fig. 4.
- 1970 *Palorbitolina lenticularis* (Blumenbach) - Saint-Marc, pl. 1, figs. 1-3.
- 1971 *Orbitolina conoidea* Gras - Sen Gupta and Grant, text-figs. 3a,b.
- 1971 *Palorbitolina lenticularis* (Blumenbach) - Ramirez del Pozo, pl. 32.
- 1972 *Palorbitolina lenticularis* (Blumenbach) - Rey, pl. 12, fig. 3.
- 1972 *Orbitolina* sp. - Campobasso *et al.*, pl. 9, fig. 3.
- 1972 *Palorbitolina lenticularis* (Blumenbach) - Fourcade *et al.*, pl. 5, figs. 1-2.
- 1973 *Palorbitolina lenticularis* (Blumenbach) - Fourcade and Raoult, pl. 1, figs. 4-5.
- 1973 *Palorbitolina lenticularis* (Blumenbach) - Mehrmusch, fig. 14.
- 1974 *Palorbitolina lenticularis* (Blumenbach) - Canerot, pl. 24, fig. 6-7.
- ? 1975 *Palorbitolina lenticularis* (Blumenbach) - Gušić, pl. 31, figs. 1-8.
- 1976 *Palorbitolina lenticularis* (Blumenbach) - Peybernes, pl. 22, fig. 14.
- 1976 *Palorbitolina lenticularis* (Blumenbach) - Masse, pl. 13, fig. 16.
- 1977 *Palorbitolina lenticularis* (Blumenbach) - Velić, pl. 22, figs. 1-3.
- 1978 *Palorbitolina lenticularis* (Blumenbach) - Velić and Sokač, pl. 4, fig. 4, pl. 6, figs. 1-6.
- 1978 *Palorbitolina lenticularis* (Blumenbach) - Garcia-Hernandez, pl. 26, figs. 2-3, 7.
- 1978 *Palorbitolina lenticularis* (Blumenbach) - Cherchi *et al.*, pl. 3, figs. 1-3.
- 1979 *Palorbitolina lenticularis* (Blumenbach) - Schroeder et Cherchi, pl. 1, fig. 1-2, pl. 2, fig. 3.
- 1979 *Palorbitolina lenticularis* (Blumenbach) - Decrouez and Kunzle, pl. 1, fig. 3.
- 1979 *Palorbitolina lenticularis* (Blumenbach) - Luperto Sinni, pl. 3, fig. 1, 4, 5-8, ?pl. 4, figs. 1-8, ?pl. 5, figs. 1-8.
- 1980 *Palorbitolina (Palorbitolina) lenticularis* (Blumenbach) - Arnaud-Vanneau, pl. 62, figs. 1-5, pl. 104, figs. 1-7, pl. 105, figs. 1-3.
- 1981 *Palorbitolina lenticularis* (Blumenbach) - Gušić, pls. 3-4.
- 1982 *Palorbitolina lenticularis* (Blumenbach) - Flügel, pl. 19, fig. 7.
- 1984 *Palorbitolina lenticularis* (Blumenbach) - Chiocchini *et al.*, pl. 1, figs. 1-2.
- 1987 *Palorbitolina lenticularis* (Blumenbach) - Simmons and Hart, text-fig. 10.8e, pl. 10.2, figs. 1, 7.

The above synonymy is by no means complete. It serves to illustrate the stratigraphic and palaeogeographic range of the species, mention important nomenclatural changes and record useful illustrations of the embryonic apparatus of the species. For more detail, particularly of 19th century and early 20th century records, the reader is recommended to examine the paper by Schroeder (1963).

#### Diagnosis

As for generic diagnosis. Arnaud-Vanneau (1980) has made the following additional observations on the species *P. lenticularis*: "In both generations the base is convex to concave and with a subcircular or undulating periphery. The oral face shows a much reduced smooth marginal zone; in the central zone, the clearly visible radial part is comprised of radial ridges which correspond to the chamberlets, and radial grooves which correspond to the radial septa. On the sides of these grooves the apertural pores are obliquely situated. The central part forms a more or less clear reticulum according to the nature and the size of agglutinated grains.

The chambers which make up the test increase regularly in size. They become annular and then their diameter increases more rapidly than the height of the chambers. Sometimes the test is damaged and broken, but a phenomenon of regeneration allows the growth of new chambers which cover the broken periphery. The chambers are subdivided by horizontal and vertical septulae which form a rectangular pattern on the surface of the test. After slight abrasion of the test, the horizontal septulae disappear and the vertical septulae indicate the chambers which are higher than broad. When the test is more worn, the triangular sections of the septa of the radial part are visible. At the base of these septa, the oblique apertural pores occur, which are arranged in diagonal lines."

In axial thin-sections, it can be seen that each chamber in the marginal zone is divided by one or two horizontal septa. In the central zone, the radial and central parts can be distinguished by the nature and size of agglutinating grains.

In horizontal cross-sections, the marginal zone is subdivided by septa which become thicker towards the centre. Between the septa, there are two or three vertical septulae whose ends are rounded; the middle septulae is generally larger than the others. In the central zone, the ease with which the radial part can be distinguished depends on the nature and size of the agglutinating grains. The central part is always obscured by agglutinating material.

Arnaud-Vanneau (1980) recorded the following measurements for *P. lenticularis*:

- Microspheric forms

Height: 0.520 - 2.470mm

Diameter: 2.520 - 7.240mm

- Macrospheric forms

Height: 0.210 - 2.070mm

Diameter: 0.520 - 5.200mm

Height of adult chamber: circa. 40 microns

Number of adult chambers per 0.5mm measured perpendicular to the base of the test: 10-15.

Remarks

The distinction between *P. lenticularis* and other Early Cretaceous orbitolinid species is covered in the above generic remarks.

Henson (1948) described a number of orbitolinid species from the Middle East. Some of these are regarded as synonyms or questionable synonyms of *P. lenticularis*. A thorough examination of the syntypic material of Henson, now housed in the British Museum (Natural History), with special regard to embryonic apparatus characteristics is required to establish the true synonymy of Henson's taxa. Henson was one of the first palaeontologists to recognize the stratigraphic value of the orbitolinids if they were subdivided on internal characteristics, rather than ecologically controlled external features such as general test shape. However, he did not fully appreciate the significance of the embryonic apparatus in taxonomic subdivision. It was not until the work of Schroeder (eg. 1963, 1975) that the value of this feature was recognised.

Arnaud-Vanneau (1980) recognised three subspecies within *P. lenticularis*: *P. lenticularis lenticularis*, *P. lenticularis praecursor* (Montanari) and *P. lenticularis* s. sp. 1. These subspecies were differentiated on the basis of test shape, and nature of agglutinating material incorporated within the test. Whilst accepting that these ecologically controlled features may have some value in recognising subspecies which may be useful in palaeoenvironmental studies, these subspecies have not been differentiated during the course of this study.

Gušić (1981) working on successive populations of *P. lenticularis* from the Dinaric Mountains of Yugoslavia, noted that progressive increases in the size and complexity of the embryonic apparatus (particularly the diameter of the fused proloculus/deuteroconch) could be used to distinguish different evolutionary stages within the phyletic lineage. These in turn, enabled a subdivision of the Late Barremian - Early Aptian time-span.

It should be noted that Gušić was not the first to note the gradual increase in the size of the embryonic apparatus within *P. lenticularis*. Henson (1948) noted that three species recorded by him from the Middle East, *O. cf. discoidea*, *O. discoidea* var. *delicata* and *O. kurdica* (all synonyms of *P. lenticularis*), formed a continuous

gradational series. In particular the size of the embryonic apparatus increased in diameter from *O. kurdica* (0.12mm) through to *O. cf. discoidea* (0.3-0.4mm). Hofker (1963) also noted the gradual increase in embryonic apparatus size within his "*Orbitolina lenticularis* Form Group I" (= *P. lenticularis*). However he drew the conclusion that this represented a gradation into his "*O. lenticularis* Form Group II", which I (following the works of Schroeder) consider to be the phylogenetically unrelated *Orbitolina* (*Mesorbitolina*) group. Schroeder (1975) stated that "The diameter of the embryonic areas....increases gradually from the Upper Barremian to the boundary Lower Aptian/Upper Aptian...." However, none of the above named workers recognised the stratigraphic significance of the trends they saw, in the manner of Gusić (1981).

A similar fine stratigraphic subdivision using *P. lenticularis* has also been suggested for the Early Cretaceous carbonates of the Oman Mountains by Simmons and Hart (1987). However, further detailed work carried out using tens of thin-sections per sample in the course of this study, have shown that it is difficult to consistently recognise any trend in the increase in size and complexity of the embryonic apparatus of populations of *P. lenticularis* from the Early Cretaceous of the Oman Mountains. Although simple forms with a relatively small embryonic apparatus and no peri-embryonic chamberlets occur (eg. Plates 3.44, 3.45 & 3.47) as do advanced forms with relatively large embryonic apparatus and peri-embryonic chamberlets (eg. Plates 3.49 - 3.52), there appears to be no consistent pattern to their occurrence, with advanced forms occurring in the Late Barremian basal Kharai Formation, and primitive forms occurring in the Early Aptian Shuaiba Formation. This is highlighted by Plate 3.54 which shows an advanced form co-occurring with a primitive form, perhaps a transitional form between *P. lenticularis* and *E. charollaisi*. The sample is from the Late Barremian lower Kharai Formation. It is possible, however, to state that the dominant form in the Early Aptian is the "advanced" form, whilst that in the Late Barremian is the "primitive" form, although this is only possible using numerous specimens. Extreme care must be exercised in drawing conclusions from isolated specimens, which may not be typical of the entire population.

#### Global Distribution and Stratigraphic Range

Pan-Tethyan (see Figure 3.5).

Late Barremian - Early Aptian (?earliest Late Aptian).

#### Local Occurrence

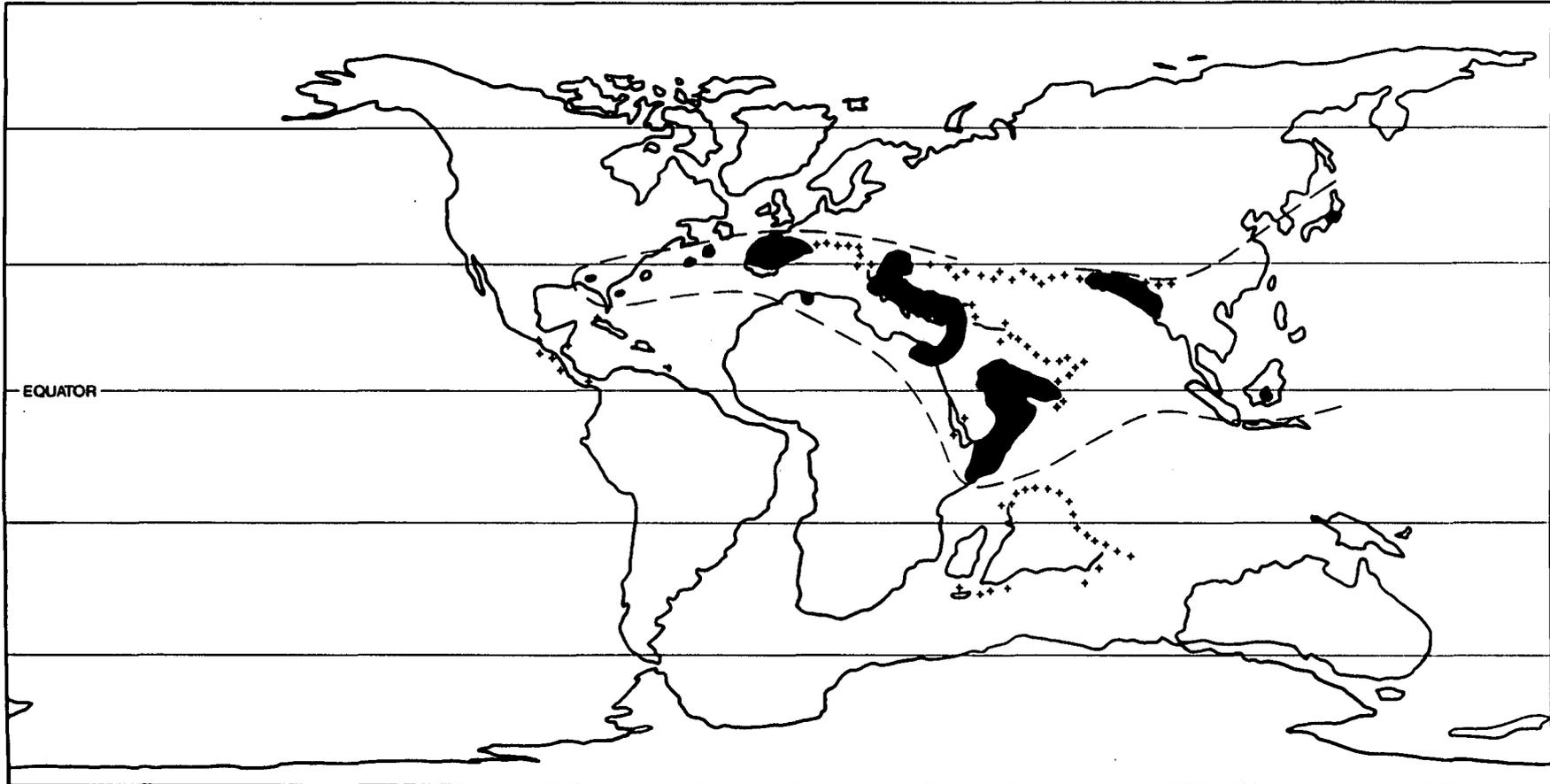
Late Barremian - Early Aptian.

*Eopalorbitolina charollaisi* - *Palorbitolina lenticularis* Subzones.

See range charts provided with Chapter 4 for precise distribution.

# GLOBAL DISTRIBUTION OF PALORBITOLINA LENTICULARIS

Mid-Cretaceous palaeogeography after Smith, Hurley and Briden, 1981



Probable extent of occurrence - - - -

Figure 3.5

Numerous well preserved specimens of this species were identified during the course of this study. Some of the better axial sections are illustrated in Plates 3.44 - 3.54. As discussed above, both "primitive" and "advanced" forms were recognised, together with forms possibly transitional to *E. charollaisi* (Plate 3.54). Also of note were the unusual forms of the species such as that illustrated in Plate 3.53. These occur in the Early Aptian Shuaiba Formation and have a weakly developed peri-embryonic ring suggesting that they are transitional to *Palorbitolinoides hedini*. *P. hedini* does occur in the Middle East, although not in the Central Oman Mountains, so it is possible that the phylogenetic lineage *Eopalorbitolina* - *Palorbitolina* - *Palorbitolinoides* can be seen in the Early Cretaceous of the Middle East with all transitional forms present.

#### Palaeoecology

Although encountered in a wide range of palaeoenvironments from infralittoral - circalittoral, Arnaud-Vanneau (1980; pers. comm., 1987) particularly associates this species with sands of the circalittoral zone. It is thought to occur in abundance following transgressive events (i.e moving into vacant ecological niches). In this respect it is often associated with *Choffatella*. It is also particularly associated with platform channels. *P. lenticularis* is known (Arnaud-Vanneau, 1975; 1980) to be an epiphytic species associated with udoteacean algae.

In the course of this study, *P. lenticularis* was found to be common in the the outer shelf packstones and grainstones of the Kharai Formation. These represent high energy sedimentation in broad outer shelf channels. On this shelf which possessed little sea-floor topography, eustatic sea-level changes played an important role, and sea-level rises are represented by mudstone or wackestone deposition. In these sediments, *P. lenticularis* is particularly common and is associated with *Choffatella* (for example the muddy unit at the top of the Kharai Formation, which is equivalent to the Hawar Shale of Qatar). Elsewhere in the Gulf region these units may contain rare planktonic foraminifera, which also suggest increasing water depth. Thus *P. lenticularis* does appear to occur in abundance in sediments relating to transgressive events. However, it is also found in quiet water lagoonal wackestones such as those of the Shuaiba Formation.

Genus *Eopalorbitolina* Schroeder and Conrad, 1968

Type Species *Eopalorbitolina charollaisi* Schroeder and Conrad, 1968

#### Diagnosis

"A member of the Orbitolinidae which has an eccentrically lying embryonic apparatus formed of a more or less spherical embryonic chamber (combined proloculus and deuteroconch) and an adjacent, semi-annular, lateral chamber with supra-embryonic subdivision (periembryonic zone). The spherical section of the embryonic apparatus sometimes shows traces of the original subdivision into two chambers. The chambers of the test can be divided into a marginal and central zone, in which the marginal zone is well developed with major radial

septa being present, whereas those of the inner part are probably arranged in a labyrinthic manner" (freely translated from the original diagnosis of Schroeder and Conrad, 1968).

Figure 3.3 illustrates the morphological features of the Orbitolinidae referred to in this study. For details of some of these features the reader is recommended to Schroeder (1975) and Arnaud-Vanneau (1980).

#### Remarks

The genus is presently monospecific.

Schroeder and Conrad (1968) considered *Eopalorbitolina* to be the direct ancestor of *Palorbitolina*. Following this argument, Arnaud-Vanneau (1980) placed *Eopalorbitolina* as a sub-genus within *Palorbitolina*, on the grounds that she had observed transitional forms between *E. charollaisi* and *P. lenticularis*. However, the generic status of *Eopalorbitolina* is retained here as it appears distinct enough from *Palorbitolina* in the eccentric position of its embryonic apparatus, *Palorbitolina* having a apically placed embryonic apparatus. This practice has also been followed by Loeblich and Tappan (1988).

*Eopalorbitolina* differs from *Orbitolina* and *Praeorbitolina* by lacking a subembryonic zone within the embryonic apparatus. It differs from *Simplorbitolina*, *Palaeodictyoconus* and *Paracoskinolina* by possessing radially placed or labyrinthically arranged septula within the central zone of the chamber layers instead of pillars, and also a more complex embryonic apparatus. *Orbitolinopsis* has a simpler embryonic apparatus, and only a weakly developed radial zone (if at all).

#### *Eopalorbitolina charollaisi* Schroeder and Conrad, 1968

Plates 3.55 - 3.56

- T 1968 *Eopalorbitolina charollaisi* n. sp. - Schroeder and Conrad, pl. 1, figs. 1-5, pl. 2, figs. 1-7, pl. 3, figs. 1-3, pl. 4, figs. 1-5. Late Barremian, Jura Mountains.
- 1969 *Eopalorbitolina charollaisi* Schroeder and Conrad - Conrad, text-fig. 13d, pl. 6, fig. 1. Late Barremian, Jura Mountains.
- 1980 *Palorbitolina (Eopalorbitolina) charollaisi* Schroeder and Conrad - Arnaud-Vanneau, pl. 103, figs. 3-6. Late Barremian, Vercors, France.
- non 1986 *Eopalorbitolina charollaisi* Schroeder and Conrad - Zhang, pl. 1, fig. 1.
- 1987 *Eopalorbitolina charollaisi* Schroeder and Conrad - Simmons and Hart, pl. 10.2, fig. 6. Late Barremian, Oman Mountains.

### Diagnosis

As for the generic diagnosis.

### Remarks

"*E. charollaisi* has similar external shape and dimensions to *P. lenticularis*. Adult specimens have a width of 2.4-2.8mm and a height of 0.7-0.9mm. The tests have the form of a rather flat and blunted cone of which the base is typically convex.

In the holotype the maximum height of the embryonic chamber is 0.1mm with a maximum width of 0.11mm. Adult individuals consist of ca. 30 dish shaped chambers. The height of these chambers increases in the course of ontogeny.

The septules in this species are relatively thick, and this feature together with the correspondingly narrow chamber passages, help to distinguish the species from other orbitolinids" (based on remarks in Schroeder and Conrad, 1968).

### Global Distribution and Stratigraphic Range

Jura Mountains, Eastern France, Oman Mountains.

Late Barremian.

Until Simmons and Hart (1987) recorded this species from the Middle East, it was thought to be endemic to the Western Alps (Moullade *et al.*, 1985). It is thought likely that the species occurs elsewhere in the Peri-mediterranean and Middle Eastern regions, but has been overlooked. The restricted range of this species makes it a useful stratigraphic marker.

### Local Occurrence

Late Barremian.

*Eopalorbitolina charollaisi* Subzone.

See range charts provided with Chapter 4 for precise distribution.

This species is used as a zonal marker for the Late Barremian in this study. It is often associated with *Palaeodictyoconus arabicus*, another Late Barremian marker.

Depending on the angle of section, it is not always possible to see that the embryonic apparatus is eccentrically situated (eg. Plate 3.56). Specimens like this may have previously been misidentified as *P. lenticularis*, resulting in the current apparently restricted distribution of the species.

#### Palaeoecology

Arnaud-Vanneau (1980 and pers. comm., 1987) recorded this species in abundance in sediments deposited in euhaline circalittoral environments, in platform talus deposits and in sands associated with transgressive episodes. The species has been recorded from similar palaeoenvironments in this study, particularly from wackestones and mudstones relating to eustatic sea-level rises on a broad outer shelf setting (lower Kharaib Formation).

Genus *Orbitolinopsis* Henson, 1948

Type Species *Orbitolinopsis kiliani* Henson, 1948

#### Diagnosis

Orbitolinid with a simple, globular proloculus situated slightly eccentrically. A rectilinear uniserial growth of circular chambers follows a short trochospire. Chambers delimited by wavy septa, which come into mutual contact, giving an indented appearance to chambers in vertical section. In transverse sections, the wavy appearance of septa produces structures resembling the central rectilium of *Orbitolina*. The marginal zone may either be simple (without subepidermal partitions) or subdivided by vertical and, in advanced species, horizontal subepidermal partitions (eg. in the "genus" *Iraqia* Henson).

Figure 3.3 illustrates the morphological features of the Orbitolinidae referred to in this study. For further details of some of these features the reader is recommended to Schroeder (1975) and Arnaud-Vanneau (1980).

Figure 3.6 is an illustration of the internal structure of *Orbitolinopsis* from Arnaud-Vanneau (1980).

#### Remarks

The status and authorship of this genus and the type species have been incorrectly cited in the past. According to Loeblich and Tappan (1988), Prever, in Prever and Silvestri (1905) cited the species name *Chapmania kiliani* without description hence not making it available. Silvestri (1932) referred *Chapmania kiliani* Prever to *Orbitolinopsis? kiliani* (Prever) and also mentioned *Orbitolinopsis? silvestrii* (Prever). Silvestri did not validate either species and did not indicate a type species for the genus *Orbitolinopsis*, thus also rendering that invalid. Cushman (1940) stated erroneously that "Silvestri has proposed a generic name, *Orbitolinopsis* with the genotype *Orbitolina conulus* Douville" but gave no definition of the genus which remained invalid. Henson (1948) described the genus and also described *O. kiliani* indicating the type species as *Orbitolinopsis kiliani*

**INTERNAL STRUCTURE OF ORBITOLINOPSIS**  
(From Arnaud-Vanneau, 1980)

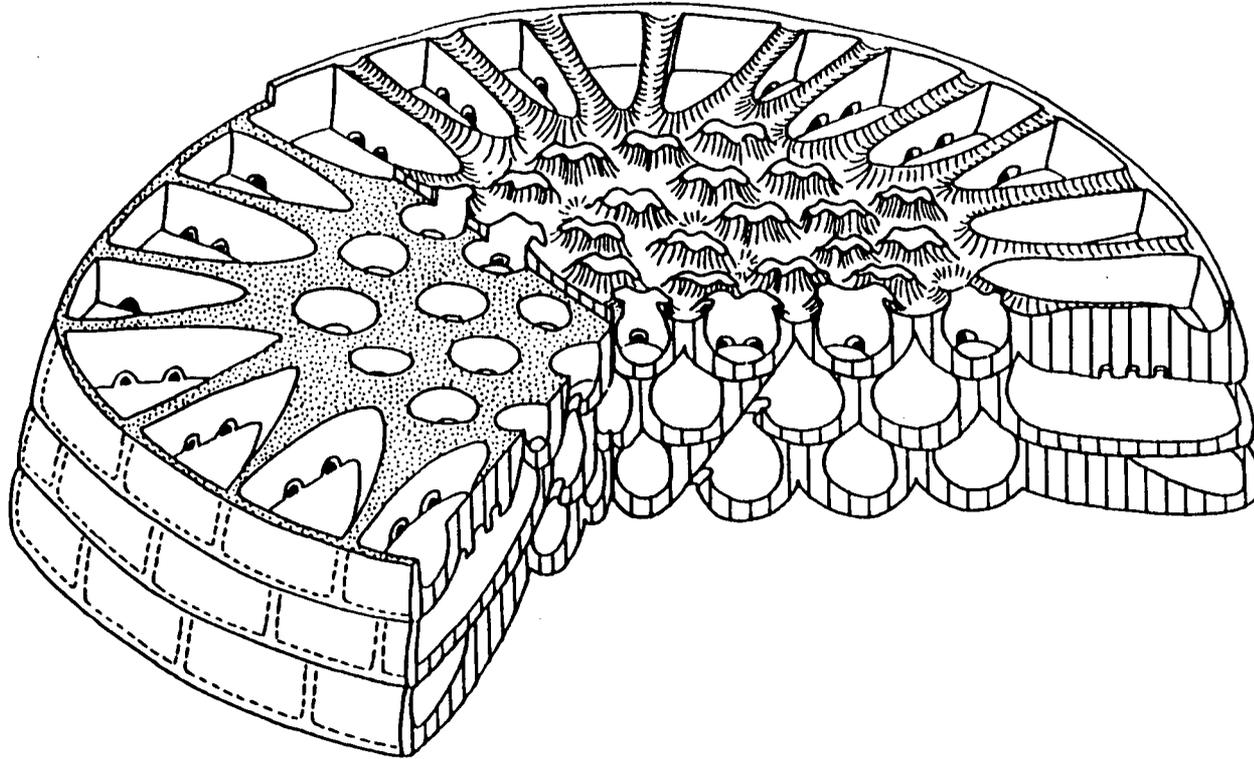


Figure 3.6

(Prever). As no earlier references meet the basic requirements for validation, both genus and species were invalid prior to Henson's description and type designation, and both must be credited to Henson.

A large number of Early Cretaceous taxa have been assigned to this genus. However, comparatively few species are sufficiently well described to be recognised unambiguously. Confusion has arisen by the description and naming of new species from random sections or relying only on outer shape. The entire group is in need of taxonomic revision.

Following Schroeder (1963; 1964; 1965), *Iraqia* is considered to be a junior synonym of *Orbitolinopsis* with species assigned to this genus (eg. *Orbitolinopsis simplex* (Henson)) being advanced forms in which a complex marginal zone with both vertical and horizontal subepidermal partitions have developed. In contrast, Douglass *et al.* in Loeblich and Tappan (1964) and Loeblich and Tappan (1988) have maintained *Iraqia* as a separate genus.

Douglass (1960), Douglass *et al.* in Loeblich and Tappan (1964) and Hofker (1966) considered *Orbitolinopsis* to be synonymous with *Orbitolina* d'Orbigny, a result of their broad concept of the later genus. However for the reasons stated below *Orbitolinopsis* is clearly distinct.

*Orbitolina*, and similar, although not necessarily related forms, such as *Palorbitolina* Schroeder and *Praeorbitolina* Schroeder (see section on *Palorbitolina*), possess a considerably more complex internal structure than *Orbitolinopsis*. In these forms, chamberlets may be present in two or more series, a marginal zone and central zone are distinct, the later being divided into a central reticulate area and radial area, and in all forms, but most noticeably *Orbitolina*, the embryonic apparatus is much more complex than that of *Orbitolinopsis*.

Moullade (1963; 1965) suggested that *Simplorbitolina* Ciry and Rat might be a synonym of *Orbitolinopsis*. *Orbitolinopsis* is similar to *Simplorbitolina* but differs in having a reticulate-like central zone.

*Neorbitolinopsis* Schroeder is very similar to advanced forms of *Orbitolinopsis* such as *O. simplex*, but can be distinguished by an apically situated embryonic apparatus and by the possession of tiers of peripheral chamberlets. Schroeder (1965) considered *O. simplex* to be the direct ancestor of *Neorbitolinopsis*.

*Paracoskinolina* Moullade and *Paleodictyoconus* Moullade, can be distinguished from *Orbitolinopsis* by possessing radial partitions which become broken up to form distinctive pillars in the central zone.

Figure 3.4 taken from Arnaud-Vanneau (1980) presents a table for distinguishing Early Cretaceous Orbitolinidae, and effectively demonstrates the differences between *Orbitolinopsis* and some of the related genera mentioned above.

For further discussion of the genus *Orbitolinopsis*, the reader is recommended to examine the detailed review of Arnaud-Vanneau (1980).

*Orbitolinopsis simplex* (Henson, 1948)

Not illustrated

- |   |      |   |
|---|------|---|
| T | 1948 | <i>Iraqia simplex</i> n. sp. - Henson, pl. 1, figs.   |
|   | 1962 | <i>Iraqia simplex</i> Henson - Bassoullet and Moullade, pl. 1, figs. 16-19.                                   |
|   | 1962 | <i>Iraqia rubiensis</i> n. sp. - Bassoullet and Moullade, pl. 1, figs. 8-12.                                  |
|   | 1962 | <i>Iraqia</i> sp. a n. sp. - Bassoullet and Moullade, pl. 2, figs. 1-2.                                       |
|   | ?    | 1962 <i>Iraqia</i> sp. - Bassoullet and Moullade, pl. 1, fig. 13, pl. 2, figs. 3-7, 11-13, pl. 3, figs. 1-13. |
|   | ?    | 1962 <i>Dictyoconus</i> sp. - Bassoullet and Moullade, pl. 3, fig. 14.  |
|   | ?    | 1964 <i>Iraqia simplex</i> Henson - Billiard and Moullade, pl. 1, fig. 15.                                    |
|   | ?    | 1964 <i>Iraqia minima</i> n. sp. - Billiard and Moullade, pl. 1, figs. 1-5.                                   |
|   | 1964 | <i>Iraqia rubiensis</i> Bassoullet and Moullade - Billiard and Moullade, pl. 1, figs. 6-7.                    |
|   | 1964 | <i>Iraqia flandrini</i> n. sp. - Billiard and Moullade, pl. 1, figs. 16-17.                                   |
|   | 1966 | <i>Orbitolina simplex</i> (Henson) - Hofker, pl. 4, figs. 10-14.  |

Diagnosis

An advanced form of *Orbitolinopsis*, which is characterised by the presence of both vertical and horizontal subepidermal partitions in the marginal zone. Shape usually regularly conico-convex or conical, with more than 25 circular chambers in fully grown specimens. Height usually exceeds 1mm, and basal diameter is usually slightly less than height.

Remarks

*Orbitolinopsis simplex* can be distinguished from other species of *Orbitolinopsis* by the presence of both vertical and horizontal subepidermal partitions in the marginal zone, and to a lesser extent by its high conical shape and relatively large size. *Cribellopsis neolongata*, and *Orbitolinopsis praesimplex* are broadly similar to *O. simplex* in test shape and size, but neither possess a complex marginal zone. *O. praesimplex* lacks horizontal subepidermal partitions and is considered to be ancestral to *O. simplex*.

The distinction between *O. simplex* and other Early Cretaceous orbitolinid species is dealt with in the above generic remarks.

Bassoullet and Moullade (1962) and Billiard and Moullade (1964) described populations of abundant "*Iraqia*" and *Orbitolinopsis* from the Early Aptian of the Spanish Pyrenees, including several new taxa. Almost all these forms are either clearly synonyms of *O. simplex*, or are in fact indeterminate, since they are described only from oblique sections.

#### Global Distribution and Stratigraphic Range

Iran, Iraq, Abu Dhabi (BP internal reports), Oman Mountains, Pyrenees.

Latest Early Aptian - Earliest Late Aptian.

This species has a very restricted stratigraphic range as reported by a number of workers (eg. Schroeder, 1964; Moullade *et al.*, 1985).

#### Local Occurrence

Early Aptian.

Palorbitolina lenticularis Subzone.

See range charts provided in Chapter 4 for precise distribution.

Only rare poorly preserved and somewhat questionable specimens of this species were recorded during the course of this study.

#### Palaeoecology

Champetier and Moullade (1970) concluded that orbitolinids of the *O. simplex* type preferred quiet back-reef environments and even adapted themselves to hyposaline conditions, as evident from their co-occurrence with charophytes (although the later could be transported into a marine setting). The specimens recorded in this study were from lagoonal mudstones and wackestones of the Shuaiba Formation associated with caprinid rudist biostromes.

Genus *Cribellopsis* Arnaud-Vanneau, 1980

Type Species *Orbitolinopsis? neolongata* Cherchi and Schroeder, 1978

Diagnosis

Test conical to subcylindrical, with simple embryonic apparatus followed by evolute sub-apical trochospire, later uncoiled with uniserial discoidal chambers, with marginal zone subdivided into rectangular chamberlets by alternating longer and shorter radial beams, the longer beams continuing into the central zone and secondary ones limited to the marginal zone, beams of successive chambers in vertical alignment; apertural face flat to convex, with smooth marginal zone and central zone that may have approximately radially arranged grooves, apertural pores with small collars, forming a circlet at the junction of the marginal and central zones, as well as scattered over the surface in the central zone, either obliquely piercing the radial plates or passing vertically through the the septa between the radial plates (after Loeblich and Tappan, 1988).

Figure 3.3 illustrates the morphological features of the Orbitolinidae referred to in this study. For details of some of these features the reader is recommended to Schroeder (1975) and Arnaud-Vanneau (1980).

Remarks

*Cribellopsis* can be distinguished from superficially similar genera such as *Orbitolinopsis*, *Paleodictyoconus*, *Simplorbitolina* and *Urgonina* by the presence of a highly subdivided marginal zone, chamberlets which are somewhat rectangular in form and the distinctive apertural arrangement in the central zone (see above). It differs from *Orbitolina*, *Neorbitolinopsis*, etc., by possessing a simple embryonic apparatus.

Figure 3.4 taken from Arnaud-Vanneau (1980) presents a table for distinguishing Early Cretaceous Orbitolinidae, and effectively demonstrates the differences between *Cribellopsis* and some of the related genera mentioned above.

*Cribellopsis elongata* (Dieni, Massari and Moullade, 1963)

Plates 3.57 - 3.58

- T 1963 *Orbitolinopsis elongatus* n. sp. - Dieni, Massari and Moullade, pl. 1, figs. 1-2, 4.  
1980 *Cribellopsis elongata* (Dieni, Massari and Moullade) - Arnaud-Vanneau, pl. 96, figs. 3-8.

Diagnosis

A small, cylindro-conical *Cribellopsis* characterised by a rather conspicuous trochospiral portion and a central zone which is somewhat reduced in size.

### Remarks

Cherchi and Schroeder (1978) placed *Orbitolinopsis elongata* (= *Cribellopsis elongata*) and *Orbitolinopsis subkilianii* Dieni, Massari and Moullade in synonymy, believing that the former was just a peculiar section of the latter. However, Arnaud-Vanneau (1980) was able to show that the internal structure of the two species is completely different.

There are similarities between *C. elongata* and *Cribellopsis neoelongata* (Cherchi and Schroeder). According to Arnaud-Vanneau (1980) it seems likely that the former could be the ancestor of the latter. The differences between these two species not only relate to size (*C. neoelongata* is larger), but also to the central zone which is relatively larger and more complex in *C. neoelongata*.

### Global Distribution and Stratigraphic Range

Sardinia, Southern France, Oman Mountains.

Late Hauterivian - Early Barremian.

### Local Occurrence

Hauterivian.

Acroporella assurbanipali Zone.

See range charts provided in Chapter 4 for precise distribution.

### Palaeoecology

According to Arnaud-Vanneau (1980) this species occurs in sands and muddy sands forming shoals at the edge of platforms. These represent infralittoral to circalittoral conditions, probably euhaline.

In this study, rare specimens of the species were found in muddy back-shoal lagoonal wackestones, in association with common dasycladacean algae. This, together with the often micritised condition of the specimens (eg. Plate 3.58) suggests very shallow water conditions.

Genus *Paleodictyoconus* Moullade, 1965  
Type Species *Dictyoconus cuvillieri* Foury, 1963

Diagnosis

Test conical, diameter usually equalling or exceeding height, usually obtuse owing to a rather strongly developed initial trochospiral stage. This later feature is gradually reduced in the course of phylogeny. Megalospheric embryonic apparatus simple, consisting of a more or less spherical fused proloculus and deuteroconch. In the conical stage three zones can be distinguished in the interior of each chamber layer: a marginal zone, subdivided by both vertical and horizontal subepidermal partitions; a central zone composed in the lower part of each chamber layer of numerous densely and irregularly arranged "half-pillars", which thicken upward and merge to form a more or less reticulate meshwork (this specific type of pillar was termed "pilaroïde" by Moullade (1965) and Arnaud-Vanneau (1980), and "halbpfeiler" by Schroeder (1964)) and also alternate in position from one chamber layer to another; and a radial zone, variously developed which lies between the marginal and central zones. In advanced forms the final growth stages may be represented by annular chambers.

The marginal zone is divided by both horizontal and vertical partitions.

The central zone is perforated by the apertural pores which are disposed obliquely along diagonal lines.

Figure 3.3 illustrates the morphological features of the Orbitolinidae referred to in this study. For details of some of these features the reader is recommended to Schroeder (1975) and Arnaud-Vanneau (1980).

Remarks

*Paleodictyoconus* was erected as a subgenus of *Dictyoconus* by Moullade (1965). It was elevated to generic status by Schroeder and Charollais (1966).

*Paleodictyoconus* is very similar to the Cretaceous (?) - Tertiary genus *Dictyoconus*. However, the latter genus has a central zone with clearly individualized pillars, rather than "half-pillars", which extend through the entire height of each chamber. In addition, the radial zone is not usually developed. Thus a central zone with pillars is clearly delimited and a narrow annular space inserted between central and marginal zones, through which the main radial partitions project inwardly, often referred to as the "marginal canal" in Tertiary *Dictyoconus*. Two Cretaceous species are commonly assigned to *Dictyoconus*: *D. walnutensis* (Carsey) from the Aptian - Albian of Texas, and *D. reicheli* Guillaume from the Barremian of Switzerland. However this assignment is questionable, and this group, like *Orbitolinopsis*, is in need of taxonomic revision, outside the scope of this study.

The genus *Valdanchella* Canerot and Moullade is identical to *Palaedictyoconus* in internal structure, with the exception that the embryonic apparatus is situated apically.

*Rectodictyoconus* Schroeder is also very similar to *Paleodictyoconus*, but possess an apical embryonic apparatus that is complex and also has true pillars in the central zone. *Rectodictyoconus giganteus* Schroeder is considered to be the direct descendant of *Paleodictyoconus arabicus* by Schroeder (1964) and Correia *et al.* (1982).

*Orbitolina* and the similar, although not necessarily related forms *Palorbitolina*, *Praeorbitolina*, etc. can be distinguished from *Paleodictyoconus* by possessing radially placed or labyrinthically arranged septula within the central zone of chamber layers rather than pillars (strictly "half-pillars"). This also serves to distinguish *Orbitolinopsis*, *Valserina* Schroeder and Conrad and *Simplorbitolina*, the latter also having an apically situated embryonic apparatus.

*Paracoskinolina* Moullade can be distinguished from *Paleodictyoconus* in that the partitions in the marginal zone do not alternate in position from one chamber layer to the next. Also this genus possesses true pillars.

Figure 3.4 taken from Arnaud-Vanneau (1980) presents a table for distinguishing Early Cretaceous Orbitolinidae, and effectively demonstrates the differences between *Paleodictyoconus* and some of the related genera mentioned above.

For further discussion of the genus *Paleodictyoconus*, the reader is recommended to examine the detailed review of Arnaud-Vanneau (1980).

*Paleodictyoconus arabicus* (Henson, 1948)

Plates 3.59 - 3.62

- T 1948 *Dictyoconus arabicus* n. sp. - Henson, pl. 1, figs. 5-8, pl. 14, figs. 1-12.  
1960 *Simplorbitolina arabicus* (Henson) - Douglass, not figured.
- ? 1966 *Dictyoconus arabicus* Henson - Hofker, pl. 6, figs. 5-6.  
1968 *Paleodictyoconus arabicus* (Henson) - Schroeder *et al.*, not figured.
- non 1970 *Paleodictyoconus arabicus* (Henson) - Saint-Marc, pl. 1, fig. 13. (= *Rectodictyoconus giganteus* Schroeder)  
1974 *Paleodictyoconus arabicus* (Henson) - Schroeder *et al.*, pl. 1, figs. 8-9, pl. 2, figs. 9-10.  
1979 *Paleodictyoconus arabicus* (Henson) - Schroeder and Cherchi, pl. 1, figs. 3-7, pl. 2, figs. 1-2, 4-5.  
1982 *Paleodictyoconus arabicus* (Henson) - Correia *et al.*, pl. 1, figs. 1-2, 6-7.

### Diagnosis

Test acutely to broadly conical; initial trochospire is relatively slight and marginal, radial and central zones are rather distinct. Fully grown specimens can have more than 20 chamber layers with height 1-2mm; basal diameter 1-3mm.

### Remarks

This species was first attributed to *Paleodictyoconus* by Schroeder *et al.* (1968), on the basis of the presence of interseptal pillars merging into rudimentary partitions in the upper part of the chambers ("half-pillars" -see generic description).

In certain specimens of *P. arabicus*, nannoconids have been found in great abundance as agglutinated particles within the septal walls. These include the records of the species by Schroeder and Cherchi (1979) from the Grand Banks, and Correia *et al.* (1982) from Portugal.

*P. arabicus* can be distinguished from *Paleodictyoconus cuvillieri* (Foury) which has a very strongly developed initial trochospiral stage, which encloses the nepiont from all sides, and hence an obtuse conical shape. The latter species is also smaller than *P. arabicus*, with fewer chamber layers and a poorly defined radial zone. *Paleodictyoconus actinostoma* Arnaud-Vanneau and Schroeder is the most advanced form of *Paleodictyoconus* yet recorded having a very large size (height up to 3mm, basal diameter up to 6mm), a slightly developed initial trochospire, complex radial zone and annular chambers in the final growth stages.

The distinction between *P. arabicus* and other Early Cretaceous orbitolinid species is dealt with in the above generic remarks.

Henson (1948) and Hofker (1963) considered it possible that *P. arabicus* represented a transitional form between *Dictyoconus* and *Orbitolina* (= *Palorbitolina sensu* Schroeder and this study). However this suggestion is clearly refutable, since the internal structure of *P. arabicus* and its supposed descendant, *Palorbitolina lenticularis*, are very different (see above).

Douglass (1960) considered *P. arabicus* to belong within *Simplorbitolina*, which according to him, represented a group of orbitolinids transitional between *Dictyoconus* and *Orbitolina*. However, *P. arabicus* possess an internal structure which clearly excludes it from *Simplorbitolina*.

### Global Distribution and Stratigraphic Range

Arabian Gulf, Oman Mountains, Iran, Lebanon, Bulgaria, Yugoslavia, Greece, Southern Italy, Algeria, Portugal, Grand Banks continental rise.

Late Barremian - ??Earliest Aptian.

It is likely that this species is restricted to the Late Barremian, since the Early Aptian records of this species are doubtful. This view was also expressed by Schroeder and Cherchi (1979). Henson (1948) in his original description of the species considered it to be have a "maximum development" in the Barremian.

Cherchi *et al.* (1981) discuss the geographic distribution of *P. arabicus*, which has been incorporated in the above global distribution summary.

#### Local Occurrence

Late Barremian.

Paleodictyoconus arabicus Subzone.

See range charts provided in Chapter 4 for precise distribution.

The restricted range of this species makes it a useful Late Barremian marker in the Oman Mountains area.

#### Palaeoecology

Like *Palorbitolina lenticularis*, appears to occur in the greatest numbers in high energy, often channelized environments of the outer shelf (Arnaud-Vanneau 1980 and pers. comm. 1987). This may relate to the colonization of environmental niches directly following a transgression (in turn related to a eustatic sea-level rise?). In this study the species was encountered in the outer platform packstones and grainstones of the Kharai Formation.

Suborder INVOLUTININA Hohenegger and Piller, 1977

Family TROCHOLINIDAE Kristan-Tollmann, 1963

Genus *Trocholina* Paalzow, 1922

Type Species *Involutina conica* Schlumberger, 1898

#### Diagnosis

"Test free, conical, with a base which may be flat, convex or rounded. A proloculus is followed by a trochospirally enrolled tubular chamber. On the dorsal face which has rarely preserved perforations, all the whorls are visible. On the ventral face which shows slight relief, only the last whorl is visible and this terminates in a simple aperture. In the umbilical area a reticulate zone is visible, in the form of an irregular

meshwork, formed by slightly depressed grooves isolating pseudopillars. A marginal zone, smooth or crossed by radial grooves, can be separated from an umbilical zone by a marginal groove. In axial section, the pseudopillars and grooves (which may be of two size orders) are interrupted at each whorl. The test, which is always recrystallised, is generally formed by a crystal mosaic, clear in colour, probably originally aragonite." (translated from Arnaud-Vanneau *et al.*, in press).

#### Remarks

Reichel (1955) erected the genus *Neotrocholina* to incorporate trocholinids characterised by a test formed of radial hyaline calcite, often amber in colour. In most other respects *Neotrocholina* is identical to *Trocholina*. Subsequent authors have disagreed over the validity of *Neotrocholina*. Some (eg. Loeblich and Tappan, 1964, 1988; Dessauvage, 1968) have placed *Neotrocholina* in synonymy with *Trocholina*. Others (eg. Arnaud-Vanneau, 1980; Arnaud-Vanneau *et al.*, in press) have maintained that the two genera are distinct. In this account the two genera are considered distinct for the following reasons (mostly after Arnaud-Vanneau *et al.*, in press):

- (1) The test of *Trocholina* was probably originally aragonite, now recrystallized to coarse clear calcite, a phenomenon also observed in originally aragonitic gastropods and dasyclad algae. The test of *Neotrocholina* was originally magnesian calcite, now recrystallized to amber tinted radial calcite. X-ray spectroscopic analysis reported by Arnaud-Vanneau *et al.* (in press) has confirmed a significant magnesium content in *Neotrocholina*, but not in *Trocholina*. A primary difference in mineralogy between the two genera was first suggested by Reichel (1955). The difference in wall structure and colour permits the most direct distinction between the genera, although Arnaud-Vanneau *et al.* (in press) recorded true *Trocholina* from Crimea which have an amber tint and partially radial wall structure.
- (2) The ventral face of *Neotrocholina* has considerably more relief than *Trocholina*. In the central zone large pillars are formed separated by coarse grooves. In axial section these pillars are not interrupted by the chamber whorls as in *Trocholina*. The pillars also increase regularly in size with each progressive whorl.
- (3) The two genera do not have a coincident palaeoecological distribution. *Trocholina* seems to be common in infralittoral sediments, whilst *Neotrocholina* is common in circalittoral sediments (Arnaud-Vanneau, 1979; 1980).

It appears that the two genera are homeomorphs developed in separate phylogenetic lineages. The suprageneric classification of *Neotrocholina* is uncertain since its originally magnesium calcite test may exclude it from the Involutinina.

The genus *Hottingerella* was erected by Piller (1983) to describe trocholines with an umbilical canal system. The type species of this genus is the Early Cretaceous form *Trocholina chouberti* Höttinger, 1976. However, Arnaud-Vanneau *et al.* (in press) have shown that such an umbilical canal system does not occur in this species, rather the structure represents a network of grooves in the central zone. The genus *Hottingerella* is therefore considered to be synonymous with *Trocholina*.

*Coscinoconus* Leupold and Bigler variously described as a foraminiferid (Leupold and Bigler, 1935) or a dasyclad alga (Maslov, 1958; Harlan Johnson, 1969) is clearly a synonym of *Trocholina*, as first pointed out by Henson (1948).

Moullade and Peybernes (1973) erected the genus *Hensonina* for planispiral and ornamented "trocholines". They cited *Trocholina lenticularis* Henson, 1948 as the type species of this genus. Henson, in his description of *T. lenticularis*, noted that two separate morphological forms existed which he both assigned to the one species. However, the holotype of *T. lenticularis* is clearly a *Trocholina*, thus rendering *Hensonina* synonymous with *Trocholina*, although the planispiral, ornamented forms as described by Moullade and Peybernes were also described by Henson as *T. lenticularis*. A new specific and possibly a new generic name (the forms may be attributable to *Involutina*) is thus required for these forms.

*Ichnusella* Dieni and Massari (1966) is probably a synonym of *Trocholina* because the test structure is not monocrystalline and the calcite (which was probably originally aragonite) on the outer surface of the test can also be present in *Trocholina* (Piller, 1983).

A large number of specific names have been assigned to *Trocholina* or synonymous genera. However, some workers have used comparatively few names tending to lump species into two or three main morphotypes (eg. "*Trocholina elongata*" and "*Trocholina alpina*"). On the other hand, some workers have maintained that a wide variety of species existed.

Whilst recognizing that there is probably considerable ecophenotypic variation within individual species in the trocholinid group, there certainly exist a reasonable number of species which can be recognised on a variety of morphological characters and which have distinct stratigraphic ranges. Arnaud Vanneau *et al.* (in press) have demonstrated this in some detail. They recognize three major groups of trocholines in the Cretaceous. The first

are those of the Berriasian - Valanginian which have thin tests; the second, those of the Hauterivian - Albian have thick tests; the third, those of the Late Albian - Cenomanian have an ornamented dorsal face.

In this study an attempt has been made to rationalize the existing taxonomy of Early Cretaceous trocholinas, drawing strongly on the recent review of Arnaud-Vanneau *et al.* (in press). The results of this study are presented in Figure 3.7, and in further detail below for those species occurring in Oman.

The following features can be used to define species within *Trocholina*:

- (i) Test height
- (ii) Test width
- (iii) Height:width ratio
- (iv) Apical angle
- (v) Number of whorls
- (vi) Test thickness
- (vii) Shape of ventral face
- (viii) Relief and ornamentation on ventral face
- (ix) Length and depth of ventral grooves
- (x) Chamber shape in cross-section
- (xi) Chamber diameter

The results of a comparison of these features is shown in Figure 3.7 and in the notes below.

For further details of the morphology and taxonomy of Cretaceous trocholinids the reader is referred to the excellent paper by Arnaud-Vanneau *et al.* (in press).

*Trocholina sagittaria* Arnaud-Vanneau, Darsac and Boisseau (in press)

Plates 3.63 - 3.65

1959 *Neotrocholina*(?) sp. aff. *elongata* (Leupold) - Thieuloy, pl. 21, figs. 18-19.

1980 *Trocholina* aff. *elongata* (Leupold) - Arnaud-Vanneau, pl. 79, figs. 18-20.

T In press *Trocholina sagittaria* n. sp. - Arnaud-Vanneau, Darsac and Boisseau, pl. 1, fig. 5, pl. 6, figs. 1-10.

#### Diagnosis

"This species has a slender test, with a moderately thick wall, conical to cylindro-conical, with a pointed apex and a plane or very slightly convex oral face. The apical angle is relatively sharp (35 - 52°). The tubular

SPECIES	Published Range	Height mm	Width mm	H:W Ratio	Apical Angle	Number whorls	Test thickness	Ventral Face Shape	Relief + ornament	Ventral Grooves	Chamber Shape	Comments
T. MOLESTA Gorbatchik, 1959	Berrs.- Barr.	0.09- 0.34	0.3- 0.68	0.3- 0.5	90°- 125°	4-6	Fine/ Smooth	Plane- Convex	Distinct marginal + central zone	weak	Oval- subrectangular	Can all be considered to be within the range of variation of <i>T. molesta</i> . <i>T. krzyzanowiensis</i> has priority but is poorly understood.
T. ACUTA Antonova, 1964	Berr.- Apt.	0.1- 0.2	0.2- 0.35	0.5- 0.6	80°- 85°	5-7	?	Plane	Fine marginal groove	?	Oval	
T. KRZYZANOWIENSIS Sztejn, 1957	Valg.	0.09	0.13- 0.2	0.45- 0.7	?	5-7	Smooth?	Plane	Reticulate	?	?	
T. MICRA Dulub, 1972	E. Cret.	0.1	0.25	0.4	c. 130°	7	?	Plane- Convex	Reticulate	?	?	
T. SILVAI Petri, 1962	L.Alb	0.09- 0.23	0.21- 0.4	0.4- 0.5	80°	6	Smooth?	Plane	Reticulate	?	?	
T. ELONGATA (Leupold, 1935)	Berrs.- Valg.	0.64- 1.76	0.2- 0.45	3.2- 3.9	22°- 25°	9-13	Fine/ Smooth	Convex	slight reticulation	only in last whorl	Semi-circular -semi rectangular	
T. CHERCHIAE Arnaud-Vanneau et al. in press	Berrs.- Valg.	0.8- 2.3	0.45- 0.84	1.8- 2.7	40°- 55°	8-12	Fine/ Smooth	Convex	strong reticulation	only in last whorl	Triangular dissected towards base	
T. SAGITTARIA Arnaud-Vanneau et al. in press	Berrs.- Barr.	0.42- 0.86	0.26- 0.47	1.6- 1.8	36°- 53°	9-12	Slight thickening smooth	Plane- Convex	Fine	weak	Rectangular	
T. ALTISPIRA Henson, 1948	L.Alb- E.Cenom.	1.0- 2.0	0.52- 0.77	1.9- 2.6	28°- 45°	10-13	Fine/ Striatic	very Convex	Fine	very short	Triangular dissected towards base	
T. DELPHINENSIS Arnaud-Vanneau et al. in press	Berrs.- Valg.	0.57- 1.4	0.43- 0.95	1.3- 1.5	50°- 63°	8-9	Fine/ Smooth	Convex	Fine	only in last whorl	Semi-oval - marginal dissected towards Apex	
T. CAMPANELLA Arnaud-Vanneau et al. in press	Berrs.- Valg.	0.8- 1.5	0.78- 1.2	1- 1.25	57°- 85°	6-8	Fine/ Smooth	Convex	Fine	only in last whorl	Triangular dissected towards base	
T. ARABICA Henson, 1948	L.Alb.- E. Cenom.	0.49- 1.2	0.62- 1.3	0.8- 0.9	75°- 90°	6-8	Fine/ Punctate	Convex	Medium	medium	Triangular dissected towards base	
T. ALPINA (Leupold, 1935)	Berrs.- Valg.	0.42- 1.13	0.5- 1.06	0.8- 1.0	80°- 95°	5-6	Fine/ Smooth	Convex	irregular reticulum	To last but one whorl	Semi-circular - Triangular	
T. BURGERI Emberger, 1955	Valg.	0.33- 0.56	0.5- 0.7	0.5- 1.0	c. 70°	5-6	?	Plane- Convex	Reticulum +marginal groove	?	?	Probable junior synonym of <i>T. alpina</i>
T. ODUKPAIENSIS Dessauvage, 1968	Berrs.- Cenom.	0.31- 0.98	0.44- 1.15	0.7- 0.85	90°- 110°	5-7	Thick/ Smooth	Plane- Convex	strong- distinct marginal central zone	Strong	Oval- Triangular	
T. GIGANTEA Gorbatchik + Mentsurova 1982	E. Berrs.	0.42- 0.58	1.02- 1.12	0.4- 0.5	130°	4	Fine/ Smooth	Convex	very fine Reticulum	Weak	semi- circular	
T. CHOUBERTI Hottinger, 1976	Valang.	0.42- 0.72	1.53- 2.0	0.27- 0.36	120°- 140°	5-6	Fine/ Smooth	Convex	Dense Reticulum	Strong	Triangular dissected to base	
T. LENTICULARIS Henson, 1948	L. Alb.- E. Cenom.	0.37- 0.79	0.65- 1.27	0.57- 0.6	120°- 130°	5-9	Fine/ Ornate	Convex	Strong	Strong	Oval- Triangular	
T. FLORIDANA Cushman + Applin, 1947	E. Cret.	0.32- 0.45	0.67- 1.0	0.45	140°	5-6	Fine/ Smooth?	Plane- Convex	Reticulum Present	?	?	Poorly Described. Possible senior synonym of <i>T. lenticularis</i>

COMPARISON OF CRETACEOUS TROCHOLINA SPECIES

Figure 3.7

chamber is enrolled in 9-12 whorls, and in axial section appears rectangular. For the entire height of the test, the tubular chamber always occupies half or slightly more than half of the width of the test. In axial section, some rare grooves appear only in the last whorl." Translated from Arnaud-Vanneau *et al.* (in press).

Height: 0.425-0.86mm.

Width: 0.26-0.475mm.

#### Remarks

*T. sagittaria* is superficially similar to other cylindro-conical Cretaceous trocholines (*Trocholina altispira* Henson, *Trocholina elongata* (Leupold) and *Trocholina cherchiaie* Arnaud-Vanneau *et al.*). However it can be distinguished by its smooth test, rectangular chambers in axial section and apical angle.

The differences between this species and other Cretaceous trocholines are fully documented in Figure 3.7.

#### Global Distribution and Stratigraphic Range

Southern France, Oman Mountains.

Berriasian - Barremian

Until the records herein, this species has only been recorded from the Vercors region of Southern France.

According to Arnaud-Vanneau *et al.* (in press) this species is rare in the Berriasian and Valanginian, and becomes increasingly common in the Hauterivian and Barremian.

#### Local Occurrence

Hauterivian.

Cylindroporella arabica - Acroporella assurbanipali Zones.

See range charts given in Chapter 4 for precise sample distribution.

#### Palaeoecology

According to Arnaud-Vanneau *et al.* (in press), this species occurs in a variety of infralittoral palaeoenvironments. In this study the species was recorded from shoal and shallow back-shoal lagoonal environments.

*Trocholina* sp. aff. *T. sagittaria* Arnaud-Vanneau, Darsac and Boisseau

(in press)

Plate 3.66 - 3.67

Diagnosis

This species is similar in all respects except height and width to *T. sagittaria* as described above. The height and width of this form is considerably smaller than that of *T. sagittaria* s. s. although the ratio of these dimensions remains identical.

Height: 0.43 - 0.35mm

Width: 0.28 - 0.20mm

Remarks

This species differs from *T. sagittaria* s. s. by its smaller external dimensions. It differs from other cylindrical Cretaceous trocholines by the same features as *T. sagittaria* described above.

It is possible that this species is a sexual dimorph of *T. sagittaria* s. s.

Global Distribution and Stratigraphic Range

Oman Mountains.

Hauterivian - ?Barremian.

Local Occurrence

Hauterivian - ?Barremian.

*Cylindroporella arabica* - *Permocalculus inopinatus* Zones.

See range charts given in Chapter 4 for precise sample distribution.

Palaeoecology

According to Arnaud-Vanneau *et al.* (in press), this species occurs in a variety of infralittoral palaeoenvironments. In this study the species was recorded from shoal and shallow back-shoal lagoonal environments.

*Trocholina molesta* Gorbachik, 1959

Plate 3.68

- ? 1957 *Trocholina krzyzanowiensis* n. sp. - Szejn, pl. 10, figs. 91a-b.  
T 1959 *Trocholina molesta* n. sp. - Gorbachik, pl. 4, figs. 1-2.  
? 1962 *Trocholina silvai* n. sp. - Petri, pl. 13, figs. 6-7.  
1963 *Trocholina molesta* Gorbachik - Guillaume, pl. 2, figs. 13-16?, 17-18.  
? 1964 *Trocholina acuta* n. sp. - Antonova *et al.*, pl. 13, figs. 10-11.  
? 1972 *Trocholina micra* n. sp. - Dulub, pl. 9, figs. 5a-c.  
1982 *Trocholina molesta* Gorbachik - Mantsurova and Gorbachik, pl. 1, fig. 1, *non* 2 (= *T. odukpaniensis*), pl. 3, fig. 5?  
1985 *Trocholina molesta* Gorbachik - Kutnetsova and Gorbachik, pl. 12, fig. 1.  
in press *Trocholina molesta* Gorbachik - Arnaud-Vanneau *et al.*, pl. 6, figs. 11-21.

Diagnosis

"This species is of small size, with a test of moderate thickness, in the form of a regular cone with a open apical angle (80-125°). The base is either plane or convex. The tubular chamber is enrolled in 4-6 whorls, and in axial section appears oval or subrectangular. The oral face clearly shows two parts separated by a marginal groove: a marginal zone, striate, plane or very slightly convex and an umbilical zone, sometimes plane but often convex with a small number of pseudopillars. The grooves in the marginal zone are few in number and not deep." Translated from Arnaud-Vanneau *et al.* (in press),

Height: 0.09 - 0.34mm

Width: 0.30 - 0.68mm

Remarks

Two other Cretaceous trocholines are similar in general appearance to *T. molesta*: *Trocholina odukpaniensis* Dessauvage and *Trocholina alpina* (Leupold). *T. molesta* can be distinguished from *T. odukpaniensis* by its smaller size and thinner wall. It can be distinguished from *T. alpina* by its smaller size, thicker wall and chamber shape (those of *T. alpina* appear triangular in axial section).

The differences between this species and other Cretaceous trocholines are fully described in Figure 3.7.

*T. silvai* Petri is considered to be a synonym of *T. molesta* herein (after Arnaud-Vanneau *et al.*, in press), although having been recorded in somewhat younger sediments than *T. molesta* s. s.

*T. micra* Dulub and *T. acuta* Antonova *et al.* from the Early Cretaceous of Eastern Europe are considered junior synonyms, although with some reservation because the original figures of these species are unclear and do not illustrate all the features required for specific determination. However external dimensions, apical angle and number of whorls are comparable.

*T. krzyzanowiensis* Szejn is questionably a senior synonym of *T. molesta*. It is of similar dimensions, although the apical angle is less broad. The original illustrations of *T. krzyzanowiensis* do not permit a complete comparison of the two species. The original description of *T. krzyzanowiensis* mentions the test having a cream colour, a feature which may indicate that this species belongs in the genus *Neotrocholina*.

#### Global Distribution and Stratigraphic Range

Crimea, Caucasus, Poland?, Brazil?, Southern France, Switzerland, Oman Mountains.

Berriasian - Barremian (?Late Albian)

Placing *T. silvai* in synonymy extends the range of this species into the Late Albian, although there are no Aptian or Early-Middle Albian records.

The record herein of this species extends its geographic range into the Middle East.

#### Local Occurrence

Hauterivian.

*Cylindroporella arabica* - *Acroporella assurbanipali* Zones.

See range charts given in Chapter 4 for precise sample distribution.

#### Palaeoecology

According to Arnaud-Vanneau *et al.* (in press), this species occurs in a variety of infralittoral palaeoenvironments. In this study the species was recorded from shoal and shallow back-shoal lagoonal environments.

*Trocholina odukpaniensis* Dessauvagie, 1968

Plate 3.69

- 1947 *Trocholina* sp. 1 - Henson, pl. 13, figs. 1-4.  
1963 *Trocholina* sp. 1 - Guillaume, pl. 6, figs. 111-118.  
1966 *Trocholina* sp. aff. *friburgensis* (Guillaume and Reichel) - Moullade, pl. 12, figs. 17-18.  
T 1968 *Trocholina odukpaniensis* n. sp. - Dessauvagie, pl. 1, figs. 1-4, pl. 2, figs. 3-5, 7.  
1969 *Trocholina* cf. *friburgensis* (Guillaume and Reichel) - Conrad, text-figs. 18c-d.  
1976 *Trocholina aptiensis* Iocheva - Masse, pl. 14, fig. 13.  
1976 *Trocholina* sp. - Masse, pl. 14, fig. 14.  
1980 *Trocholina* sp. - Arnaud-Vanneau, pl. 79, figs. 1-5.  
1982 *Trocholina molesta* Gorbatchik - Mantsurova and Gorbatchik, pl. 1, fig. 2, non 1 (= *T. molesta*), pl. 3, fig. 5?  
in press *Trocholina odukpaniensis* Dessauvagie - Arnaud-Vanneau *et al.*, pl. 5, figs. 7-22.

Diagnosis

This species has a thick test wall, and is a moderately large cone with a plane or slightly convex base. The apical angle varies from 90° to 110°. The tubular chamber is enrolled in 5-7 whorls. In the early whorls the appearance of this chamber in axial section is oval; in the later whorls it is triangular, with the apex being rounded, and may also appear subrectangular. In the later cases the internal wall of the chamber is pointed towards the base of the test. The oral face possesses a strong marginal groove which separates a marginal zone with radial grooves, from the umbilical zone which is flat or slightly rounded and covered with large grooves. Occasionally, these grooves are preserved in the preceding whorl. Freely translated from Arnaud-Vanneau *et al.* (in press).

Height: 0.31 - 0.98mm

Width: 0.44 - 1.15mm

Remarks

Two other Cretaceous trocholines are similar in general appearance to *T. odukpaniensis*: *T. molesta* and *T. alpina*. *T. molesta* can be distinguished from *T. odukpaniensis* by its smaller size and thinner wall. *T. alpina* can be distinguished by its finer wall, and distinctive triangular chambers when seen in axial section.

The differences between this species and other Cretaceous trocholines are fully described in Figure 3.7.

### Global Distribution and Stratigraphic Range

West Africa, Pyrenees, Southern France, Switzerland, Sardinia, Crimea, Arabian Gulf, Southern Iran, Oman Mountains.

Berriasian - Early Cenomanian.

This species is rare in the Berriasian and Valanginian, becoming more frequent in the Hauterivian and Barremian. It is not recorded from Aptian and Early-Middle Albian strata, although occurs in the Late Albian and Early Cenomanian.

### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts given in Chapter 4 for precise sample distribution.

### Palaeoecology

According to Arnaud-Vanneau *et al.* (in press), this species occurs in a variety of infralittoral palaeoenvironments. In this study the species was recorded from shoal and shallow back-shoal lagoonal environments.

*Trocholina chouberti* Höttinger, 1976

Plate 3.70

- T 1976 *Trocholina chouberti* n. sp. - Höttinger, pl. 1, figs. 1-15.  
1983 *Hottingerella chouberti* - Piller, p.197, not illustrated.  
in press *Trocholina chouberti* Höttinger - Arnaud-Vanneau *et al.*, pl. 5, figs. 1-2.

### Diagnosis

This species has a fine walled test of large size, flatly conical, and particularly distinctive is the often concave oral face. The apical angle is very broad and varies between 120° and 140°. The tubular chamber is enrolled in 5-6 whorls. In axial section this chamber appears triangular. The side of this triangle opposite the apex is rather concave, whilst that opposite the base is flat and lies parallel to the base. In the juvenile stage the chamber occupies half the width of the test, in the adult stage it occupies no more than a fifth. The grooves of first and second order form a dense reticulum on the oral face. In axial and subaxial sections, the partitions parallel to the

oral face are more or less continuous in the last whorl. This structure has been interpreted by Höttinger as a marginal canal system. This interpretation is difficult to accept because the structure can be seen in tangential and subaxial sections as well as axial ones. It is possible that the structure is a complex marginal canal system, rather different to that described by Höttinger. Freely translated from Arnaud-Vanneau *et al.* (in press).

Height: 0.42 - 0.72mm

Width: 1.43 - 2.00mm

#### Remarks

This species is easily distinguished from other Cretaceous trocholines by its complex basal "canal" network, concave base, and size.

The differences between this species and other Cretaceous trocholines are fully described in Figure 3.7.

#### Global Distribution and Stratigraphic Range

Morocco, Southern France, Oman Mountains.

Valanginian.

The record of the species herein from the Middle East, greatly extends its geographic range.

#### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts given in Chapter 4 for precise sample distribution.

#### Palaeoecology

According to Arnaud-Vanneau *et al.* (in press), this species occurs in a variety of infralittoral palaeoenvironments. In this study the species was recorded from shoal and shallow back-shoal lagoonal environments.

Suborder GLOBIGERININA Delage and Herouard, 1896  
Superfamily ROTALIPORACEA Sigal, 1958  
Family GLOBULIGERINIDAE Loeblich and Tappan, 1984  
Genus *Globuligerina* Bignot and Guyader, 1971 emend. Stam, 1986  
Type Species *Globuligerina oxfordiana* Grigelis, 1958

#### Diagnosis

"Test free, chambers coiled in a trochospiral, the height of which may vary from low to high; chambers spherical to ovate; wall calcareous, perforate, radial, bilamellar. Chamber surface may be pitted, cancellated or hispid; Aperture umbilical-extraumbilical, and may vary from semicircular to looped arch either narrow and high to broad and low, bordered with a lip. Previous apertures, when visible, are usually open to the umbilicus" (from Stam, 1986).

#### Remarks

Loeblich and Tappan (1984) and Riegraf (1987) regard *Globuligerina* as the only valid genus of the family Globuligeridae. All Jurassic and earliest Cretaceous planktonic foraminifera described to date can probably be assigned to this genus. However, Loeblich and Tappan (1988) also recognise the Jurassic genus *Conoglobuligerina* Morozova, which is extremely similar to *Globuligerina*, differing in that it constantly possesses a low, arched, virtually symmetrical intraumbilical aperture. In thin-section (as in this study) the genera are impossible to tell apart.

Early Cretaceous species of *Globuligerina* develop a reticular structure reminiscent of the Barremian - Albian genus *Favusella* Michael, 1973 (Riegraf, 1987). However, in *Favusella* the cellular pores are separated by a distinct imperforate reticulum, whilst in *Globuligerina* they are separated only by pustules. It is this feature which excludes *Globuligerina* from the family Favusellidae Longoria, 1974.

*Globuligerina* differs from other Mesozoic planktonic foraminifera by its umbilical-extraumbilical aperture position, apertural lip and wall structure.

*Polskanella* Fuchs, 1973 and *Caucasella* Longoria, 1974 are synonyms of *Globuligerina* (Grigelis and Gorbachik, 1980b; Caron, 1985).

*Globuligerina hoterivica* (Subbotina, 1953)

Plates 3.71 - 3.74

- T 1953 *Globigerina hoterivica* n. sp. - Subbotina, pl. 1, figs. 1a-c, 4a-c. Hauterivian, Caucasus.
- ? 1958 *Globigerina oxfordiana* n. sp. - Grigelis, text-figs. a-c. Early Oxfordian, Lithuania.
- 1959 *Globigerina kugleri* n. sp. - Bolli, pl. 23, figs. 3a-5. Late Barremian, Trinidad.
- 1961 *Globigerina terquemi* n. sp. - Iovceva and Trifonova, pl. 2, figs. 9-14. Tithonian, Bulgaria.
- 1966 *Hedbergella hoterivica* (Subbotina) - Salaj and Samuel, pl. 8, figs. 7a-c. Barremian, Czechoslovakia.
- ? 1971 *Globigerina (Globuligerina) oxfordiana* Grigelis - Bignot and Guyader, pl. 1, figs. 1-4, pl. 2, figs. 3-4. Late Jurassic, France.
- 1971 *Globigerina (Globuligerina) hoterivica* Subbotina - Bignot and Guyader, not figured.
- 1979 *Globuligerina gulekhensis* n. sp. - Gorbachik and Poroshina, pl. 1, figs. 1-2, text-fig. 1. Berriasian, Caucasus.
- 1979 *Globuligerina caucasica* n. sp. - Gorbachik and Poroshina, text-figs. 2-3. Berriasian, Caucasus.
- 1980 *Globuligerina hoterivica* (Subbotina) - Grigelis and Gorbachik, pl. 2, fig. 3. Hauterivian, Caucasus.
- 1985 *Globuligerina hoterivica* (Subbotina) - Caron, pl. 25, figs. 1 (holotype), 2-3 (Early Barremian, Canary Islands).
- 1985 *Globigerina hoterivica* Subbotina - Connally and Scott, pl. 6, fig. F. Berriasian - Valanginian, Oman Mountains.
- 1987 *Globuligerina hoterivica* (Subbotina) - Simmons and Hart, pl. 10.5, fig. 2. Berriasian - Valanginian, Oman Mountains.

Diagnosis

"Shell small, strongly convex, turret shaped, consisting of 3 whorls, the last of which contains 4-5 strongly inflated round chambers which are very closely packed together so that the shell has the appearance of a chaotic accumulation of spherical chambers. The chambers increase in size very gradually so that the last whorl is of almost uniform dimensions. Sutures short, slightly curved or almost straight. Umbilical orifices represented by a large notch around the umbilicus. Orifices with small lips in the form of a narrow border. Walls smooth, with fine pores. Mean dimensions: diameter 0.15mm, greatest breadth 0.1mm" (Subbotina, 1953).

Remarks

"The increase in size among the chambers of the last whorl is a variable characteristic. Thus together with the individuals in which the chambers are almost uniform in size there are others in which the size increases so

rapidly that the last chamber is approximately half the total volume of the shell. Certain individuals have a vesicular structure in the umbilical region" (Subbotina, 1953).

This species has also been placed within a number of different genera. Bignot and Guyader (1971) were the first to assign it to *Globuligerina* (then a subgenus).

The concept of this species has varied considerably amongst previous workers. Some such as Grigelis and Gorbachik (1980a;b) have taken a very narrow view of the species, others such as Masters (1977) have taken a broader view. In this study a rather broad concept of the species is followed, because the specimens studied are in thin-section and pending further research into the taxonomy and phylogeny of Late Jurassic - Early Cretaceous planktonic foraminifera (see also Appendix 1).

It is possible that *G. oxfordiana* (Grigelis) is a junior synonym of *G. hoterivica*, as argued by Masters (1977). However, this synonymy is not confirmed here pending further research. *G. oxfordiana* does have fewer chambers and whorls, and is smaller, although these features may relate to it being a "primitive" form of *G. hoterivica* from which *G. hoterivica s. s.* evolved.

*Globigerina kugleri* Bolli, *Globigerina terquemi* Iovceva and Trifonova, *Globuligerina gulekhensis* Gorbachik and Poroshina and *Globuligerina caucasus* Gorbachik and Poroshina, are all regarded as being with the range of variability, or identical to, *G. hoterivica* and thus are treated as junior synonyms.

*G. hoterivica* differs from *Globuligerina jurassica* (Hofman) by its much lower spire height. Masters (1977) suggests that *G. hoterivica* evolved from *G. jurassica* by a reduction of the spire height.

#### Global Distribution and Stratigraphic Range

Pan-Tethyan.

(?Oxfordian) Kimmeridgian - Barremian (?Aptian).

Published global and stratigraphic ranges of this species have varied considerably depending on the authors concept of the species. Grigelis and Gorbachik (1980a;b) restrict it to the Hauterivian, whilst Caron (1985) erected a Hauterivian *G. hoterivica* Zone based on an inception of the species at the base of the Hauterivian, although according to her the species ranges into the Aptian. Masters (1977) gave the species a mid-Bathonian to mid-Aptian range. Given the broad concept of the species employed here the later range noted above seem most likely. At present the records of this species are rather patchy across the Tethyan region. It is expected that the species will be recorded from most Early Cretaceous Tethyan sediments in favorable facies.

### Local Occurrence

All occurrences of *G. hoterivica* recorded in this study have been observed in thin-section. Because random thin-sections of planktonic foraminifera do not permit complete recognition of wall structure, or in some cases, number of chambers and apertural characteristics, identification to specific level cannot be made with full certainty. However, given the restrictions imposed by only thin-section study, the specimens cited below seem to be in close agreement with the description of *G. hoterivica*.

Early Berriasian - Valanginian/Hauterivian.

*Globuligerina hoterivica* Zone.

See range charts given in Chapter 4 for precise sample distribution.

The occurrence of this species in the Rayda and Salil Formations makes it useful as a local biozonal marker.

### Palaeoecology

Riegraf (1987) regarded *Globuligerina* as a genus typical of the margins of Tethys. He noted further that:

- a) The genus displays patchy distributions, mostly in large numbers, stratigraphically followed by radiolaria.
- b) The palaeolatitudinal distribution of the genus seems to be concentrated in the northern hemisphere at palaeolatitudes of 20-30° N, although records from outside this zone and in the southern hemisphere are known.
- c) Globuligeridae did not occur in true open ocean environments, rather they were associated with open marine conditions on the edges of carbonate platforms (circalittoral environments). Caron and Homewood (1983) supported this hypothesis and suggested that calpionellids may have prevented these early planktonic foraminifera from entering the open oceans.

In this study, the species has been recorded in the periodically anoxic basinal - toe of slope Rayda Formation, and in the slope sediments of the Sail Formation. It is associated with common calpionellids or radiolaria, although rarely occurs in the same sediments as them. This suggests the above statements by Riegraf (1987) are likely to be correct, and that the species was typical of platform slope, rather than basinal conditions. Water depths may have been in the order of 50 - 200m.

### 3.3: Introduction - Calcareous Algae

The hierarchical classification of calcareous algae used in this study follows that of Wray (1977) and Wray *in Haq* and Boersma (1978). It should be noted however, that Early Cretaceous calcareous algae are in need of thorough taxonomic revision at the specific and generic level, and indeed at the suprageneric level. Clearly this task is beyond the scope of the present study, so concepts of taxa following previous workers have been used. In particular, the concept of Dasycladaceae taxa follows that of Bassoullet *et al.* (1978) and Elliott (1968), with a few amendments. For other algal groups taxonomic classification usually follows that of Elliott, the pioneering worker on Early Cretaceous Middle Eastern microfloras.

In the following section suprageneric discussion is not usually included, although a description, discussion and comparison of genera and subgenera is provided. This is followed by the systematic description of species within a genus arranged in alphabetical order, unless the type species of a genus is present, which is always placed first.

For each species a synonymy is provided. The detail of this varies for different species. For those species which are stratigraphically useful, or have been taxonomically revised an attempt has been made to provide as full a synonymy as possible. This has often been necessary to establish the true stratigraphic and geographic range of a species. For certain less important species a more basic synonymy is given which outlines the type description, generic shifts and at least one recent well illustrated reference, if available.

Following the synonymy a description of the species is given, followed by remarks concerning identification of the species, comparison with similar taxa, evolutionary relationships, etc. This is followed by a statement of the species global distribution and stratigraphic range. The local occurrence of a species within the study area is given. Finally a statement of the palaeoecology of a species is given.

Where possible the generic and specific descriptions are those given in the original designation of a taxon. In some cases this may be in the form of a translation. Where the original description is thought to be inadequate a more thorough recent one is given, or the original description revised herein.

The letter "T" before a record of a species in the following synonymy lists indicates the type description of that species.

### 3.4 Systematic Micropalaeontology - Calcareous Algae

Phylum CYANOPHYTA Sachs, 1874  
Class CYANOPHYCEAE Sachs, 1874  
Order NOSTOCALES Geitler, 1925  
Family RIVULARIACEAE Rabenhorst, 1865  
Genus *Rivularia* Roth, 1802  
Type Species *Rivularia dura* Roth, 1802

#### Diagnosis

"Globular or hemispherical thallus with erect growth, mono-, bi- or multi-digitate, crossed by trichoms or pseudobifurcate filaments of sympodial type. Inner diameter of filaments (lumen) of type species is 4-9 microns and usually varies between 2-70 microns. The angle of divergence between filaments varies between 2-20°. It may or may not show zonal structure". (Description by Dragastan (1985)).

#### Remarks

Dragastan (1985) introduced this extant genus to describe various species of fossil Cyanophyta. These had previously been referred to genera such as *Cayeuxia* Frollo, *Diversocallis* Dragastan and *Pycnoporidium* Yabe and Toyama, which according to Dragastan (1985) are all synonyms of *Rivularia* (although see section below on *Ethelia* for discussion of *Diversocallis*). These genera have had a somewhat varied taxonomic history sometimes being placed within the Codiaceae as encrusting forms (eg. Frollo, 1938). Banner *et al.* (in press) have shown that these forms are distinct from true encrusting Codiaceae belonging to the subfamily Lithocodioidea.

Dragastan (1985) provides a complete review of the genus *Rivularia* in the fossil record, which need not be repeated here. However, of particular note is the comment that most well known Mesozoic species of *Cayeuxia*

(eg. *Cayeuxia moldavica* Frollo) are in fact synonyms of *Rivularia lissaviensis* (Bornemann) (= *Zonotrichites lissaviensis* Bornemann).

The angle of divergence of the filaments distinguishes *Rivularia* from *Ortonella* Garwood. In *Rivularia* it is 2-20°, in *Ortonella* it is 30-60°. Dragastan (1975) also describes intermediate forms.

*Rivularia lissaviensis* (Bornemann, 1887)

Plate 3.75 - 3.76

- T 1887 *Zonotrichites lissaviensis* n. sp. - Bornemann, pl. 5, figs. 1-2, pl. 6, figs. 1-2.  
1985 *Rivularia lissaviensis* (Bornemann) - Dragastan, text-figs. 1-2, pl. 1, figs. 1-3, pl. 3, figs. 1-2, pl. 4, figs. 1-6, pl. 5, figs. 1-5, pl. 6, figs. 1-2, pl. 7, figs. 1-4, pl. 8, fig. 1-5. Also complete synonymy until 1985.

Diagnosis

"Thallus with wide morphological variability, varying in size from 2.2 x 8mm to 1 x 6cm. Subspherical, hemispherical, columnar-erect or fanlike nodules with more or less flaring borders. Thallus crossed by filament-like pseudobifurcate cells, sympodially V-shaped, with the angles of divergence 2-10° and 15-20°. The inner structure of the thallus is compact and the filaments tightly joined and parallel. The inner diameter of filaments at base of branches varies between 20-50 microns, only rarely as much as 60 microns. Growth zones may or may not occur in variable amount depending on the size of the thallus. The small, hemispherical or subspherical thalli do not exhibit growth zones, but the fanlike or columnar-erect do". (Description by Dragastan (1985)).

Remarks

According to Dragastan (1985) this species is the senior synonym of the well known Early Cretaceous species *Cayeuxia moldavica* and *Pycnoporidium lobatum* Yabe and Toyama. It is also, according to him, the senior synonym of various records of *Cayeuxia kurdistanensis* Elliott, *Cayeuxia piae* Frollo, *Cayeuxia* sp., and many other cyanophyte or codiacean occurrences.

The species was originally described from the Late Triassic of Poland, and thus is considerably long ranging.

*Rivularia piae* (Frollo) also known from the Early Cretaceous is similar, but possesses coarser filaments (75-90 microns in diameter). *Rivularia kurdistanensis* (Elliott) can be distinguished by its small size, compact internal structure, filaments with a diameter of 15-30 microns and a low angle of divergence (3-5°).

For further discussion of this species and its distinction from other species of *Rivularia* see Dragastan (1985).

### Global Distribution and Stratigraphic Range

Anisian - Aptian

Pan Tethyan, possibly excluding the New World.

### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts given in Chapter 4 for precise sample distribution.

### Palaeoecology

Occurs in high energy, shallow water, bioclastic packstones - grainstones of the Habshan Formation. Also occurs in lower energy, oncoid rich wackestones.

Water depths are inferred to be very shallow, within the upper part of the photic zone, probably no more than a few meters at most.

*Rivularia fruticulosa* (Johnson and Kaska, 1965)

Plates 3.77 - 3.78

- T 1965 *Cayeuxia fruticulosa* n. sp. - Johnson and Kaska, pl. 12, figs. 1-2, pl. 13, figs. 1-3.  
1985 *Rivularia fruticulosa* (Johnson and Kaska) - Dragastan, pl. 10, figs. 3-7, pl. 11, figs. 1-5. Also complete synonymy until 1985.

### Diagnosis

Thallus hemispherical, nodular, subspherical or irregular ellipsoidal, sometimes quite flaring; height c. 3.0mm, width c. 9.0mm. Inner structure is lax with wide micritic zones between filaments. Filaments pseudobifurcate, fine with straight, curved or sinuous-irregular line. Diameter of filaments 10-45 microns and angle of divergence 5-10° (rarely 20°). False furcate filaments with marked angles. Some filaments show wide, coarsely recrystallized areas or "ampoules" on the exterior of the thallus and corresponding to the heterocysts (after Dragastan, 1985).

### Remarks

This species can be distinguished from other species of *Rivularia* by the very fine size of its filaments and their relatively broad angle of divergence.

For further discussion of this species and its distinction from other species of *Rivularia* see Dragastan (1985, 1988).

### Global Distribution and Stratigraphic Range

Tithonian - Early Aptian.

Pan Tethyan.

### Local Occurrence

Cylindroporella arabica Zone.

Hauterivian.

See range charts given in Chapter 4 for precise sample distribution.

### Palaeoecology

Occurs in high energy, shallow water, bioclastic packstones - grainstones of the Habshan Formation. Also occurs in lower energy, oncolite rich wackestones.

Water depths are inferred to be very shallow, within the upper part of the photic zone, probably no more than a few meters at most.

Indeterminate Cyanophyte (?) A

Plate 3.79

### Diagnosis

This taxa is recorded in only one sample; MS6, where it preserved a distinctive fragment, 1.15mm x 1.00mm. This is dome-shaped and consists of a internal calcitic area surround by a filamentous micritic area (up to 0.35mm in thickness). The filaments are quite numerous, are approximately 0.038mm in diameter and can be seen to bifurcate at a low angle (less than 10°).

### Remarks

The filamentous nature of this microfossil suggests that it is in some way related to the Cyanophyta, probably the Rivulariaceae. However no genus or species has been found in the published literature which matches the characteristics of this taxa.

It is possible that this microfossil is a poorly preserved codiacean, with the "filamentous" outer wall being the outer cortex, and the internal medulla having not been preserved.

### Global Distribution and Stratigraphic Range

Unknown.

### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts provided in Chapter 4 for precise sample distribution.

### Palaeoecology

Occurs in high energy grainstones and packstones of the Habshan Formation. Interpreted as a shallow water oolitic - bioclastic shoal fringing the carbonate platform.

Phylum RHODOPHYTA Wettstein 1901  
Class RHODOPHYCEAE Ruprecht 1851  
Order CRYPTONEMIALES Schmitz 1892  
Family GYMNOCODIACEAE Elliott, 1955  
Genus *Permocalculus* Elliott, 1955  
Type Species *Gymnocodium fragile* Pia, 1937

### Diagnosis

"Gymnodiaceae represented by segments and units of variable form; spherical ovoid or barrel-shaped segments, or elongate-irregular, finger-like or "waxing and waning" units. Calcification varying from very thin to massive or solid; pores small and cortical. Sporangia cortical or medullary. Segments or units usually larger, and the pores finer, than those of *Gymnocodium*". (Original diagnosis by Elliott (1955)).

### Remarks

Elliott (1955) erected the family Gymnocodiaceae, which contains only two genera, *Gymnocodium* and *Permocalculus*, for the remains of fossil plants similar to the living marine red alga *Galaxaura* (order Nemalionales: family Chaetangiaceae). These fossil forms are believed to have been erect, branched plants, but are known only from perforate, calcareous segments and fragments. The fossil Gymnocodiaceae are held to be distinct from their modern counterparts on the basis of greater calcification in the fossil forms and the discontinuous record of similar forms between the Permian, Cretaceous and Recent.

Simmons and Johnston (in press) have reported the occurrence of a species of *Permocalculus* (*Permocalculus iagifuensis*) in the Miocene Darai Limestone Formation of Papua New Guinea.

*Permocalculus* can be distinguished from *Gymnocodium* by the presence of smaller and more numerous pores.

*Permocalculus* has a peculiar discontinuous fossil record being known from Permian (from where it was originally recognised) and latest Jurassic, Cretaceous and Neogene sediments. It is often abundant in the Early to mid-Cretaceous platform carbonates of the Middle East.

### *Permocalculus inopinatus* Elliott, 1956

Plate 3.80 - 3.85

- T 1956 *Permocalculus inopinatus* n. sp. - Elliott, text-figs. 1-2.  
1958 *Permocalculus inopinatus* Elliott - Elliott, pl. 45, fig. 3, pl. 47, fig. 1, 3-4.  
1971 *Permocalculus inopinatus* Elliott - Basson and Edgell, pl. 6, figs. 5-6.  
1976 *Permocalculus* cf. *inopinatus* Elliott - Masse, pl. 2, fig. 3.

### Diagnosis

"Thallus fingerlike, somewhat irregular, circular in cross-section, up to 5mm long and 1.75mm in transverse diameter; calcification varying between different individuals from a thin irregular peripheral development to a nearly solid thallus; sporangia ill-defined, subcortical in position; pores with diameter of 0.020mm at the outer edge of calcification where they are clearly visible, only occasionally seen extending inwards, when they are fine and twisted, widening at the surface.

### Remarks

This species is very similar to the Permian species *Permocalculus solidus* (Pia) and *Permocalculus digitatus* Elliott and the Miocene species *Permocalculus iagifuensis* Simmons and Johnston, to which it can be considered an Cretaceous homeomorph.

Two other species of *Permocalculus* are common in the Early and mid-Cretaceous of the Middle East. *Permocalculus irenae* Elliott, typical of the Albian - Cenomanian interval, is smaller in diameter and length of thallus and possesses significantly smaller pores (0.015 - 0.007mm). *Permocalculus ampullacea* Elliott, originally described from the Hauterivian of Algeria and the Valanginian of Iraq (Elliott, 1959), possesses a distinctive "pinching and swelling" thallus of often greater diameter and length than *P. inopinatus*, with thin rather than solid calcification and smaller pores (typically 0.012mm). *P. ampullacea* is typically preserved as large or complete fragments, unlike *P. inopinatus* which is typically preserved as fine debris. The density of pores in *P. inopinatus* is also distinctive, there being about 35-50 pores per millimeter, a higher density than that seen in *P. ampullacea* or *P. irenae*.

#### Global Distribution and Stratigraphic Range

Iraq, Lebanon, Southern France, Oman Mountains.

Barremian - Aptian.

This species, although until now only illustrated from Barremian - Aptian sediments, is thought to have a Valanginian - Aptian age range in Southern France (Masse and Poignant, 1971; Masse, 1976). In this study it was clearly recorded from Valanginian/Hauterivian sediments, demonstrating the need to extend its global stratigraphic range.

#### Local Occurrence

Valanginian/Hauterivian - Early Aptian

Buccicrenata hedbergi Subzone - Choffatella decipiens Subzone.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

This microfossil occurs in a variety of carbonate platform facies, but is particularly common in bioclastic - peloidal wackestones and packstones with *Orbitolina*, *Choffatella* and codiaceans. These are suggestive of deposition in outer platform (circalittoral) environments.

Family SOLENOPORACEAE Pia 1927  
Genus *Marinella* Pfender, 1939  
Type Species *Marinella lugeoni* Pfender, 1939

Diagnosis

Thallus forms rounded nodular masses. The thalli are composed of closely packed fine cell threads that have constrictions and very thin cross partitions. In the upper portion of the plants, digitate lobes or branches develop. The filaments (cell threads) may change direction frequently. In longitudinal section they have a slightly radial to fan-shaped arrangement. After Johnson (1969).

Remarks

This genus has been recorded from across all parts of Tethys, in Late Jurassic to mid-Cretaceous sediments. However, it remains problematic being of uncertain taxonomic affinities. Pfender (1939), in his original description of the genus, considered it to be a cyanophyte. Johnson (1961, 1964, 1965), Imaizumi (1965), Ramahlo (1970) and Masse and Poignant (1979) considered it as a green alga (Codiaceae) on the basis of the presence of tubular filaments. In his 1969 review, Johnson had revised his opinion. He now considered *Marinella* to be a red alga of uncertain affinities because of its vague cellular structure. This view has been shared by numerous other workers including Xi-nan (1986).

Barattolo and del Re (1985) have reviewed this genus in some detail. They, like Dragastan (1980) considered it to belong to the Solenoporaceae, because of the general shape of the thallus, density of cell filaments, shape of the branches, and the absence of reproductive organs and hypothallus. Their view is followed here.

*Marinella* is similar to a number of algae doubtfully attributed to the genera *Lithophyllum* and *Lithothamnium* (*Lithophyllum* (?) *shebae* Elliott, *Lithophyllum* (?) *venezuelensis* Johnson and *Lithothamnium* (?) *primitiva* Johnson and Kaska). As first suggested by Poignant (1968) these taxa are probably referable to *Marinella*, although further research is required to prove this.

*Marinella lugeoni* Pfender, 1939

Plates 3.86 - 3.88

- T 1939 *Marinella lugeoni* n.sp. - Pfender, pl. 3, figs 1-2.
- ? 1959 *Lithophyllum* (?) *shebae* n. sp. - Elliott, pl. 1, fig. 7.
- 1961 *Marinella lugeoni* Pfender - Johnson, pl. 31, figs. 1-2.
- 1965 *Marinella lugeoni* Pfender - Johnson and Kaska, pl. 6, fig. 2.
- ? 1965 *Lithophyllum* (?) *venezuelensis* n. sp. - Johnson, pl. 89, figs. 1-2.

- 1969 *Marinella lugeoni* Pfender - Johnson, pl. 21, figs. 1-3.  
 1970 *Marinella lugeoni* Pfender - Saint-Marc, pl. 2, fig. 5.  
 ? 1971 *Lithophyllum (?) shebae* Elliott - Basson and Edgell, pl. 7, figs. 2-3.  
 1971 *Marinella lugeoni* Pfender - Ramalho, pl. 28, figs. 1-2.  
 1976 *Marinella lugeoni* Pfender - Masse, pl. 2, fig. 4.  
 1984 *Marinella lugeoni* Pfender - Cherchi *et al.*, pl. 1, fig. 2.  
 1985 *Marinella lugeoni* Pfender - Barattolo and del Re, pl. 1, figs 1-2, pl. 2, figs. 1-2.  
 1986 *Marinella lugeoni* Pfender - Xi-nan, pl. 2, figs. 1-2.

#### Diagnosis

The type material of this species is thoroughly reviewed by Barattolo and del Re (1985), to whom the reader is referred.

Species of *Marinella* with nodular thalli, typically 5-7mm wide and 2-3mm high. Digitation of the thalli occurs only in the upper part of the thallus. Only in fully grown specimens does true branching occur. The diameter of the filaments ranges from 6 microns to 10 microns, and is commonly about 9 microns.

#### Remarks

This species was originally recorded from the Liassic by Pfender (1939). However, this age assignment can now be revised to be probably Late Jurassic (Barattolo and del Re, 1985).

One other species of *Marinella* is known; *Marinella yugoslavica* Maslov. This species differs from *M. lugeoni* by virtue of a larger, less compact thallus, and by displaying more extensive branching throughout the entire thallus. Most Albian - Turonian records of *M. lugeoni* can probably be referred to *M. yugoslavica*.

*Lithophyllum (?) shebae* described by Elliott (1959) from Barremian - Aptian sediments of Iraq, is almost certainly a synonym of *M. lugeoni*. Comparison of type material is required to confirm this. This specimen illustrated by Elliott (p.1, fig. 7) is similar to the specimens illustrated herein (Plates 3.86 - 3.88).

#### Global Distribution and Stratigraphic Range

Tithonian - Aptian.

Pan-Tethyan

#### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

In this study, *M. lugeoni* has been recorded from shallow water, back-shoal, low energy, bioclastic - oncoidal wackestones. Conrad (1977) also recorded it from platform margin environments of the Urgonian Platform near Geneva. However, more specifically, he associated it with grainstones in a fore-shoal position.

Family SQUAMARIACEAE Zanardini, 1841

Genus *Ethelia* Weber van Bosse, 1913

Type Species *Ethelia biradiata* Weber van Bosse, 1913

#### Diagnosis

"Thallus may be thin ribbon-like, or crustose with rounded branches. The central area (medullary hypothallus) has a plumose structure of threads of cells. These are nearly parallel to the axis at the centre but curve outward to the edges which they meet almost perpendicularly. The cell walls are thin. The cell threads continue outward around the margins with well defined growth layers forming a thin marginal perithallus. Spherical or ovoid cavities, probably sporangia, develop within the central mass. They are oriented parallel to the cell threads, sometimes in rows, sometimes irregularly spaced in the tissue" (Johnson and Kaska, 1965).

#### Remarks

Massieux and Denizot (1962), and later in a highly detailed paper (1964), showed that the genus *Pseudolithothamnium* Pfender (including *P. alba* Pfender) is a synonym of the Recent squamariacean genus *Ethelia*. This is further discussed by Elliott (1963).

Dragastan (1967, 1969) reported a new Barremian - Aptian "gymnocodiacean" genus from Roumania: *Diversocallis*. As shown by Bakalova (1975) the type species, *Diversocallis undulatus* Dragastan is a synonym of *Ethelia alba*. Dragastan (1985) considers the genus *Diversocallis* (herein considered to be a junior synonym of *Ethelia*) to be a synonym of the cyanophyte genus *Rivularia*. This view cannot be supported because the wall structure of *Ethelia* (= *Diversocallis*) is clearly rhodophytic. The affinities of two other species of *Diversocallis*, *D. diana*e Dragastan and Bucur and *D. moesicus* Dragastan and Bucur, is less certain. Dragastan (1985) considers them to be separate species of *Rivularia*, however the type illustrations suggest they may well be within the range of variation of *E. alba*.

A number of new "codiacean" taxa described by Dragastan (1985), although poorly illustrated, appear to be combinations of several codiacean and non-codiacean taxa, including *Ethelia alba*. Examples include *Arabicodium hansii*, *Tethysicodium wrayi* and *Bacinellacodium calcareus*. Many of the taxa described by Dragastan need detailed study to establish their true affinities.

*Ethelia alba* (Pfender, 1936)

Plate 3.94

- T 1936 *Pseudolüthothamnium album* n. gen and n. sp. - Pfender, pl. 19, figs. 1-5.  
1962 *Pseudolüthothamnium kahetii* (Maslov) - Maslov, pl. 7, figs. a-d.  
1962 *Ethelia alba* (Pfender) - Massieux and Denizot, text-figs. 1-2.  
1963 *Ethelia alba* (Pfender) - Elliott, pl. 47, figs. 1-3.  
1964 *Ethelia alba* (Pfender) - Massieux and Denizot, pl. 1, figs. 1-10, pl. 2, figs. 1, 5. Also synonymy until 1964.  
1966 *Ethelia alba* (Pfender) - Praturlon, text-figs. 13-14.  
1967 *Diversocallis undulatus* n. gen and n. sp. - Dragastan, pl. 8, figs. 52-56.  
1972 *Ethelia alba* (Pfender) - Fourcade et al., pl. 4, fig. 5.  
1975 *Ethelia alba* (Pfender) - Bakalova, pl. 1, figs. 1-2, pl. 3, figs. 2-3.  
? 1978 *Diversocallis diana* n. sp. - Dragastan and Bucur, pl. 2, figs. 1-2, pl. 3, figs. 1-2.  
? 1978 *Diversocallis moesica* n. sp. - Dragastan and Bucur, pl. 1, figs. 1-4.  
1979 *Diversocallis undulatus* Dragastan - Masse and Poignant, pl. 2, figs. 5-6.  
? 1985 *Rivularia diana* (Dragastan and Bucur) - Dragastan, pl. 15, figs. 2-3.  
? 1985 *Rivularia moesica* (Dragastan and Bucur) - Dragastan, pl. 15, figs. 4-6.  
? 1985 *Arabicodium hansii* n. sp. (*pro parte*) - Dragastan, pl. 25, figs. 5-6.  
? 1985 *Tethysicodium wrayi* n. gen., n. sp. (*pro parte*) - Dragastan, pl. 26, figs. 1-4.  
? 1985 *Bacinellacodium calcareus* n. gen., n. sp. (*pro parte*) - Dragastan, pl. 27, figs. 1-3.  
1986 *Ethelia alba* (Pfender) - Xi-nan, pl. 1, figs. 4-5

Diagnosis

"Thallus bladed or ribbon-like, consisting of a central area of large elongated axial cells from which develop branching threads of rounded elongated cells. These threads curve outward toward the margins forming a loose perithallic tissue with the cells becoming gradually smaller. At the outer margin are layers of small, nearly rectangular cells, parallel to the outer surface. Spherical or ovoid cavities, possibly sporangia, have been reported from the perithallic tissue" (Johnson and Kaska, 1965).

### Remarks

Commonly well calcified, and has a distinctive yellowish brown tint and a somewhat glassy lustre.

### Global Distribution and Stratigraphic Range

Late Jurassic - Eocene.

Pan-Tethyan.

### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts provided in Chapter 4 for precise sample distribution.

### Palaeoecology

In all previous records, this species seems to be typically associated with high energy, platform margin environments, often being found associated with coralline algae in reefs or bioherms. In this study it was recorded from high energy, peri-shoal environments on the margin of the Thamama ramp.

Phylum CHLOROPHYTA Pascher, 1914

Class CHLOROPHYCEAE Kützing, 1843

Order SIPHONALES Wille, *in* Warming (1884)

orth. mut. Blackman and Tansley, 1902

Family CODIACEAE Zanardini, 1843

Genus *Arabicodium* Elliott, 1957

Type Species *Arabicodium aegagrapiloides* Elliott, 1957

### Diagnosis

Segmented codiacean algae, preserved as elongate, cylindrical segments, circular in cross-section and not flattened, rarely branching. Possesses a medullary zone of very fine, tangled, non-parallel tubular threads and a cortex of approximately radial fine branching threads.

### Remarks

Elliott (1965) considered *Arabicodium* (and also the Mesozoic codiacean alga *Boueina*) to be synonyms of the well known Cretaceous - Recent genus *Halimeda*. This view has been supported by Johnson (1968) and Badve

and Nayak (1983). The genera are very similar possessing longitudinal medullary threads and a zone of more or less radial cortical threads, but as noted by Elliott (1965), *Arabicodium* does not usually show the branching thallus of *Halimeda*, the thallus is not flattened, the medulla zone is much finer and the filaments are non-parallel, and the cortical threads are also finer than in *Halimeda*. On the basis of these differences *Arabicodium* is maintained as a separate genus from *Halimeda* herein. Clearly however, *Arabicodium* (and *Boueina*) are ancestral to *Halimeda*. Elliott (1965) suggested that *Halimeda sensu stricto* had arisen by hybridization from "*Boueina*" and "*Arabicodium*".

Elliott (1970, 1975, 1981, 1982) appears to have reversed his 1965 interpretation since he refers to *Arabicodium* and *Halimeda* as distinct genera.

Conrad and Rioult (1977) pointed out that the evidence available for defining codiacean genera in fossil occurrences was incomplete, and that different morphological patterns found in different species of *Halimeda* were recognisable in *Boueina* as well.

Bassoullet *et al.* (1983) considered *Halimeda* and *Arabicodium* to be distinct taxa because of the morphological differences outlined above, and because of differences in stratigraphical occurrence.

Flügel (1988) provides a review of the relationships between *Halimeda* and its fossil relatives.

*Arabicodium* can be distinguished from *Boueina* by the finer nature of its internal structure, in particular the presence of fine, slightly wavy, longitudinal threads in the medulla zone, and a cortex composed of very fine radial threads.

*Arabicodium aegagrapiloides* Elliott, 1957

Plates 3.89 - 3.93

- T 1957 *Arabicodium aegagrapiloides* n.sp. - Elliott, pl. 1, figs. 7-10.  
1965 *Arabicodium aegagrapiloides* Elliott - Elliott, pl. 23, figs. 3-4.  
non 1966 *Halimeda (Arabicodium) aegagrapiloides* Elliott - Praturlon, text-fig. 10.  
? 1971 *Arabicodium elongatus* n. sp. - Dragastan, pl. 7, figs. 1-9.  
1973 *Arabicodium aegagrapiloides* Elliott - Bakalova, pl. 3, figs. 3-4, 8.  
1984 *Arabicodium aegagrapiloides* Elliott - Cherchi *et al.*, pl. 1, figs. 3-4, 5.

### Diagnosis

As for generic description. Specimens are often preserved as cylindrical segments up to 3.0mm in length and with a diameter of 0.8mm. Segments are circular in cross-section; ends rounded and occasionally incipiently bifurcated at one end; internally showing a medullary zone of fine, irregularly twisted longitudinal threads and a cortical zone of irregular forward directed lateral threads widening sharply at their terminations at the outer surface; primary calcification of cortex dense, that of medulla patchy and irregular; diameter of medulla approximately half that of whole segment (after Elliott, 1957).

### Remarks

Other than *A. aegagrapiloides*, a number of species of *Arabicodium* have been described. These are: *A. cantabricus* Dragastan, *A. elongatus* Dragastan, *A. indica* Pal, *A. jurassicum* Dragastan, *A. orientalis* Dragastan, *A. texana* Johnson, *A. bicazensis* Dragastan, *A. hansii* Dragastan and *A. tibeticum* Yu Jing. However, most of these species are too poorly described to be sure they are *Arabicodium*, and others are probable synonyms of *A. aegagrapiloides*. *A. indica* described by Pal (1971) seems to be the most valid species. However, Badve and Nayak (1983) found only echinoid fragments in the type thin-sections. Bassoullet *et al.* (1983) provide a comparison of the described species of *Arabicodium*.

The distinguishing feature of *A. aegagrapiloides* from any of the above taxa are the small dimensions of its thallus.

The specimens described as *H. (A.) aegagrapiloides* by Praturlon (1966) from the Albian - Cenomanian of Abruzzi, Italy, appear to have medullary filaments which are too coarse and too parallel to be this taxon.

It should be noted that criteria used for distinguishing fossil halimediform species (and genera) are often those which are highly variable in extant species of *Halimeda* (Flügel, 1988).

### Global Distribution and Stratigraphic Range

India, Oman, Bulgaria, ?Roumania.

Early Cretaceous (?=Valanginian - Hauterivian/?Aptian).

Questionably described from Barremian (?) sediments of Roumania by Dragastan (1971) as *A. elongatus* n.sp., although this species has slightly larger dimensions than typical *A. aegagrapiloides*. Bakalova (1973) described more typical specimens from the Early Cretaceous of Bulgaria.

Cherchi *et al.* (1984) have described somewhat questionable specimens from Aptian sediments of Ladakh, India.

#### Local Occurrence

Hauterivian.

*Cylindroporella arabica* Zone.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

*Arabicodium* is thought to have inhabited similar environments to modern-day *Halimeda* (see Ghose (1977) for a summary of the environmental distribution of this genus). Typically this would include clear, shallow water (0-10m b.s.l.), low-moderate energy, platform, especially lagoonal, environments.

The specimens found in this study are from shallow water shoal and proximal back-shoal environments. Like the specimens of *Neomeris* and *Cylindroporella* associated with them, they have probably been transported offshore from a sheltered lagoonal environment. The large segmented nature of *Arabicodium* permits a moderate degree of transportation.

Bakalova and Khrishev (1973) recorded *A. aegagrapiloides* from similar environments in the Early Cretaceous of Bulgaria to those noted in this study. They recorded it from the high energy "peripheral littoral zone", an area with oolitic shoals, and from the "reef zone" fringing the platform.

Genus *Lithocodium* Elliott, 1956 emend. Banner *et al.*, in press

Type Species *Lithocodium aggregatum* Elliott, 1956

#### Diagnosis

"A codiacean genus of the subfamily Lithocodioidea...; initially encrusting, may in later growth become nodose; the subdermal tubular filaments of the medulla are irregularly arranged, and encrust each other in various directions which are dominantly subparallel to each other and are broadly oblique to, or nearly at right angles to, the long axis of the encrusting or nodular thallus; the subdermal filaments may bifurcate or trifurcate or variously ramify, and broaden before and during ramification, and are consequently of variable diameter; subdermal filaments are irregularly septate; in the area of terminal growth, the filaments narrow, become subparallel to the long-axis of growth of the previously formed encrustation or nodule (i.e., they become subperpendicular to the planes of the subdermal filaments) and become heavily encrusted with microgranules of

calcium carbonate to form a relatively heavily calcified cortex; in the cortex, the relatively narrow tubular filaments also bifurcate, trifurcate or variously ramify, but they diminish in diameter as they do so, so that the outmost cortical filaments (which have undergone the most ramifications) are the narrowest; the cortical filaments are terminated by a continuous thin sheet of calcium carbonate and are not open to the exterior, but this terminal sheet may be followed by resumed (originally lateral, then supraterminal) growth of subdermal filaments which are followed by another cortical development". (Emended diagnosis by Banner *et al.* (in press)).

### Remarks

Banner, Finch and Simmons (in press) have thoroughly reviewed the palaeobiological significance, taxonomy, palaeoecology, etc of this genus. Extensive use of this paper is made herein, and a copy of the paper is included within Appendix 2 of this thesis.

Banner *et al.* (in press) emended the diagnosis of *Lithocodium* (as reproduced above) to include the features seen within specimens previously described as *Bacinella* Radoičić, to emphasize the codiacean nature of this organism, and to highlight the differences between it and the closely related genus *Radoicicinellopsis* Banner, Finch and Simmons, and more questionably related "genus", *Bacinellacodium* Dragastan (see above section on *Ethelia*).

The biological affinities of *Lithocodium* and its relationship to *Bacinella* have been the subject of some debate since the genus was first described by Elliott (1956).

In his original description of *Lithocodium* from the Early Cretaceous of Iraq, Elliott (1956) firmly referred this genus to the codiacean algae. Quite independently of the proposal of *Lithocodium*, Radoičić (1959) described a new genus and species, *Bacinella irregularis*, from Barremian - Aptian limestones of the Yugoslav Dinarides. This was considered by Radoičić to be "algae *incertae sedis*".

Although some authors (eg. Poignant, 1968; Luperto Sinni, 1979; Alsharhan, 1985; Simmons and Hart, 1987) have concluded that *Lithocodium* and *Bacinella* are synonymous genera of the Codiaceae, others (eg. Barattolo and Pugliese, 1987; Bouroullec and Deloffre, 1968; Elliott, 1963; Jaffrezo, 1975; Ramalho, 1979) have considered them as separable, probably distinct genera of that same suprageneric group. Some (eg. Chrishev and Bakalova, 1974; Johnson, 1968, 1969) have been willing to refer *Lithocodium* to the Codiaceae, but have been unhappy to consider *Bacinella* as anything but "algae *incertae sedis*". Opposed to this view is that of those who believe *Lithocodium* and *Bacinella* to have had an organic origin, but do not belong to the Codiaceae (Segonzac and Marin, 1972). Masse (1976) has suggested that these microfossils were of botanical but multiple origin, comparable to the algal symbioses seen in terrestrial lichens. Maurin *et al.* (1985) and Maurin (pers.

comm., 1988) have claimed the origin of both genera was universally microbial. To support this claim they have described "bacinellid-textures" from the Precambrian to Recent, and demonstrated the presence of bacteria in SEM preparations of Early Cretaceous *Bacinella*. However, as pointed out by Banner *et al.* (in press), these could easily be contaminants, or have nothing to do with the construction of the organism. Similarly the highly structured nodular appearance of many "*Lithocodium - Bacinella*" specimens (eg. Ramalho, pl. 29, fig. 1) demonstrates that they have nothing in common with layered, unstructured stromatolites of gaseous, microbial origin.

Two key questions thus arise: are *Lithocodium* and *Bacinella* synonymous, and what are their origins? Banner *et al.* (in press) demonstrate that *Lithocodium* is the senior synonym of *Bacinella* and that this organism is a codiacean alga, as originally described by Elliott (1956). Their arguments are summarized below.

- (i) The global and stratigraphic ranges of *Lithocodium* and *Bacinella* are remarkably similar. Both are known with certainty from the Late Jurassic - mid-Cretaceous limestones of Tethys, in the Portugal to China area.
- (ii) The similarity of stratigraphic range and geographical distribution is paralleled by that of the morphology of the type specimens of the principal taxa concerned. Elliott (1956) illustrated microphotographs of three specimens of *L. aggregatum*, which represented the holotype and two paratypes derived from the same subsurface sample. Together, they show the character typical of *Lithocodium* - an encrusting or nodose growth-mode in a codiacean with a subdermal skeletal structure similar to that of regularly segmented genera (like *Halimeda*). One of the paratype specimens (Elliott, 1956, pl. 1, fig. 4) shows particularly well that the inner, irregularly orientated but coarse filaments could be surrounded by an outer layer of much finer, sub-radial filaments, and that, in both layers, the filaments could be separated by calcified tissues as thick, or even thicker than, the filaments themselves. This paratype is very similar indeed to the holotype of *Bacinella irregularis*.
- (iii) The holotype of *Bacinella irregularis* (Radoičić, 1959, pl. 3, fig. 1) is thus comparable to the type specimens of *Lithocodium aggregatum*, which thus places *Bacinella* into synonymy with *Lithocodium*. However, the illustrated paratype of *Bacinella irregularis* (Radoičić, 1959, pl. 3, fig. 2) has present only the inner layer of the thallus (no cortex is visible). The filaments are of the coarser kind and are very randomly arranged; their cells are divided only by thinly calcified walls. It is this "vacuolated" and apparently poorly organized structure, regardless of the precise morphology of the holotype, which has been taken by many authors to typify *Bacinella*, and led to its codiacean origin being questioned. However, as demonstrated by Banner *et al.* (in press), this

structure corresponds to the inner medulla zone of a codiacean, and is largely a result of variable calcification within the organism - a feature which should not be used for systematic distinction (Bassoullet *et al.*, 1977).

- (iv) Thus in simplistic terms *Lithocodium* represents the cortex and *Bacinella* the medulla of a codiacean algae. Banner *et al.* (in press) illustrate the interrelationship of the two forms, which can be found separately because of variable calcification within the organism. Often only the "bacinellid" medulla structure is preserved because *Lithocodium*, unlike most codiaceans, calcified first internally rather than externally. Segonzac and Marin (1972) also illustrated the interrelationship of *Bacinella* and *Lithocodium*, demonstrating that the two forms clearly were formed by the same organism.

The genus *Pseudolithocodium* Mišić is considered by Banner *et al.* (in press) to be a junior synonym of *Lithocodium*. This form illustrated by Mišić (1979) is clearly corticate, like *Lithocodium*, but in which "the tubes of (the) cortical layer are densely packed, not submerged in micrite" (Mišić, 1979, p. 709). This difference, a result of the degree of calcification, which can be extremely variable, seems an unsuitable means for taxonomic distinction.

*Bacinella? sterni* Radoičić (as figured by Radoičić (1972) from the Cenomanian of Yugoslavia), follows the same pattern of growth and calcification as in *Lithocodium*, but differs in the great reduction (almost to terminal absence) of a cortex. This species was described under a new generic name by Banner *et al.* (in press): *Radoicicinelopsis*. Banner *et al.* (in press) suggest that the opposite morphological trend is displayed by the Tithonian - Aptian taxon with a variably calcified medulla but a heavily calcified cortex, distinguished as *Bacinellacodium calcareus* by Dragastan (1985). In *Bacinellacodium* the cortical filaments are distinctly thinner, longer and more parallel, in comparison to *Lithocodium*. The medulla zone is essentially the same in both genera, but may be very weakly calcified in *Bacinellacodium*. In this later genus, the overall structure is distinctly codiacean, with strong medulla - cortex differentiation. However, as noted in the above section on *Ethelia*, the type figures of *Bacinellacodium* are poor, and it may be that is in fact a combination of taxa, possibly *E. alba* and *L. aggregatum*. Further studies are required of type material of this genus.

Banner *et al.* (in press) erected a new subfamily of the Codiaceae, the Lithocodioidea, to accommodate *Lithocodium*, *Radoicicinelopsis* and *Bacinellacodium*, which are clearly distinct from erect, regularly segmented Codiaceae, such as *Halimeda*, which display relatively regular calcification and were originally aragonitic, unlike *Lithocodium*, etc., which are thought to be originally calcitic. The erect, aragonitic forms were placed by Banner *et al.* (in press) into a separate new subfamily, the Halimedoidea.

The Lithocodioidea are typified by a thallus which is encrusting, lacks uniformity in the extent of calcification which began internally, possesses filaments divisible into an internal medulla and external cortex. The calcareous skeleton was probably primarily calcitic.

*Lithocodium aggregatum* Elliott, 1956 emend. Banner *et al.* (in press)

Plates 3.95 - 3.104

- T 1956 *Lithocodium aggregatum* n. sp. - Elliott, pl. 1, figs. 2, 4-5.  
1959 *Bacinella irregularis* n. sp. - Radoičić, pl. 3, figs. 1-2.  
1963 *Bacinella irregularis* Radoičić - Elliott, pl. 48, fig. 3.  
1964 *Lithocodium aggregatum* Elliott - Praturlon, text-figs. 28-29.  
1971 *Lithocodium aggregatum* Elliott - Ramahlo, pl. 9, fig. 1, pl. 28, figs. 3-5, pl. 29, fig. 1.  
1971 *Bacinella irregularis* Radoičić - Ramahlo, pl. 9, fig. 1, pl. 29, figs. 1-2.  
1971 *Lithocodium aggregatum* Elliott - Basson and Edgell, pl. fig. 1.  
1972 *Bacinella irregularis* Radoičić - Fourcade *et al.*, pl. 4, fig. 8.  
1972 *Lithocodium* sp. - Fourcade *et al.*, pl. 4, fig. 9.  
1972 *Lithocodium aggregatum* Elliott - *Bacinella irregularis* Radoičić - Segonzac and Marin, pl. 11.  
1976 *Bacinella irregularis* Radoičić - Masse, pl. 8, fig. 12.  
1979 *Lithocodium morikawai* Endo - Mišić, pl. 2, fig. 1.  
1979 *Pseudolithocodium carpaticum* n. sp. - Mišić, pl. 2, figs. 2-8.  
1987 *Bacinella irregularis* Radoičić - Barattolo and Pugliese, pl. 42, fig. 2.  
1987 *Lithocodium aggregatum* Elliott - Barattolo and Pugliese, pls. 51, 57.  
In press *Lithocodium aggregatum* Elliott - Banner *et al.*, pls. 1-5.

#### Diagnosis

"A species of the genus *Lithocodium* as defined above, in which the cortex is regularly formed and possesses two or more (usually three or more) phases of branching and diminution in size of the cortical filaments. The cortical filaments are circular or subcircular in cross-section, but those of the medulla are of irregular cross-section shape. The thalli are 1 to 5cm thick". (Emended diagnosis by Banner *et al.* (in press)).

#### Remarks

This species was reviewed and the diagnosis emended in the study by Banner *et al.* (in press). The emended diagnosis takes into account the fact that "*Bacinella irregularis*" represents the medulla structure of this codiacean algae.

As discussed above, *Bacinella irregularis* and *Pseudolithocodium carpaticum* Misik are considered to be junior synonyms of this species.

The genus *Lithocodium* is presently monotypic. *Lithocodium regularis* described by Johnson (1968) was a complete error. It is in fact a foraminifera - *Buccicrenata hedbergi*. *Lithocodium japonicum* Endo and *Lithocodium morikawai* Endo, do not seem to be separable at species level from the range of variation observed in *L. aggregatum*.

#### Global Distribution and Stratigraphic Range

Pan Tethyan, with the possible exception of the New World.

Oxfordian - Albian.

Johnson (1969) recorded, but did not illustrate, this species from Cuba, Texas and the Blake Escarpment.

#### Local Occurrence

Hauterivian - Aptian.

Cylindroporella arabica - Salpingoporella dinarica Zones.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

Most of the records of *Lithocodium aggregatum* (and synonymous references to *Bacinella irregularis*) which are cited above, and which give sufficient information for the palaeoenvironment under which the microfossils were deposited to be assessed, indicate that most occurrences of this alga are from marine, micritic limestones. If the limestones are sparitic, the *Lithocodium* specimens are usually found encased in micrite, and they are clearly allochthonous, having been transported and redeposited from micritic environments. These occurrences are rare; *in situ* specimens, in which no apparent abrasion or erosion has occurred, are found in abundance in calcareous, micritic limestone of mudstone or wackestone packing.

The micritic matrix in which *Lithocodium* usually occurs indicates low palaeocurrent velocities (broadly equivalent to those which would allow settlement of argillaceous mud, and therefore probably not exceeding about 10 cm/sec speeds), and, therefore, the occurrences are unlikely to be commonly in inner-shelf palaeoenvironments, but more likely to have been in water deeper than this. This agrees with the lack of association of *Lithocodium* with acknowledged shallow-water Codiacea (such as *Arabicodium*, *Boucina*, etc),

but with its occurrence with "deeper-water" dasyclads (*Acicularia*, *Salpingoporella*, etc), and the calcitic dasyclad "*Salpingoporella*" *dinarica* Radoičić). This is also in agreement with palaeodepth-estimations using associated foraminifera. Other palaeoenvironmental estimates (palaeosalinity, palaeotemperature) based on associated foraminifera and other microfossils are in line with the conclusions given below. Also, the palaeogeography is that which clearly associates the known occurrences of *Lithocodium* with Tethys.

As a result, it is estimated that the palaeoenvironment favoured by *Lithocodium* was that of a warm, fully marine, well oxygenated, calcium carbonate rich, mid-shelf sea (possible palaeodepths of abundant, *in situ* specimens ranging from *ca.* 15m to *ca.* 60m b.s.l.). This is quite different from that which would be concluded from the opinions published by Maurin *et al.* (1985).

Some workers, eg. Elliott (1968), Conrad (1977) and Bakalova and Khrishev (1973) associate *Lithocodium* with high energy, platform margin conditions, where the taxon is recorded in platform fringing reef settings or close to fringing shoals.

In this study, *Lithocodium* has been recorded in a variety of environments, but most notably in a high energy peri-shoal setting (Habshan Formation), or in a low energy, interior platform setting (Shuaiba Formation).

Order DASYCLADALES Pascher, 1931

Family DASYCLADACEAE Kützing, 1843 orth. mut. Hauck, 1884

Genus *Acicularia* d'Archiac, 1843

#### Diagnosis

Calcareous spicules, typically elongate appearing circular or ovoid in transverse section, set peripherally with small spherical cavities; in life part of the fertile whorl of the plant (after Elliott, 1968).

#### Remarks

*Acicularia* was proposed by d'Archiac (1843) for certain fossil spicules occurring in Eocene sediments of the Paris Basin. Their algal origin was recognised by Munier-Chalmas (1877) and the genus is extant. Closely related to *Acetabularia*, the living plant is a few centimetres high and possesses a slender stem bearing an inverted umbrella shaped disc at the apex. This is made up of radially arranged rays that contain spherical sporangial cavities. Fossils are usually individual rays or fragments resulting from the disaggregation of the apical disc. It is possible that *Acetabularia* and *Acicularia* are the same organism, at least in the Tertiary and Recent, with *Acetabularia* being the living plant and *Acicularia* its fossilized remains.

In thin section *Acicularia* can easily be confused with *Terquemella*, which are similar discoidal or spherical bodies, thought to be sporangial structures from the walls of fossil Bornetellae (Morellet and Morellet, 1913; 1922). In transverse sections they appear identical, but the elongate nature of *Acicularia* can be distinguished in longitudinal sections.

The questionable dasycladacean *Coptocampylodon* is also very similar when seen in thin section, but can be distinguished by the presence of longitudinal grooves rather than spherical sporangial cavities, which are seen in longitudinal section. In addition, some species of *Coptocampylodon* possess a central canal, a feature never seen in *Acicularia*.

Barattolo (1983) has described isolated reproductive organs of dasyclads from the Cretaceous of the Apennines, Italy, under the name *Russoella*. These are small, flattened, lenticular bodies with a small number of cavities, which are superficially similar to *Acicularia*, but can be distinguished by their flattened, non-spicular shape.

*Acicularia antiqua* Pia, 1936

Plates 3.105 - 3.106

T 1936 *Acicularia antiqua* n. sp. - Pia, pl. 3, figs. 1-14.

1968 *Acicularia antiqua* Pia - Elliott, pl. 1, figs. 1-3.

Diagnosis

"Rounded, cuneiform, calcareous bodies, circular or ovoid in cross-section, containing numerous submarginal spherical hollows (sporangial cavities). Length up to 0.78mm, with a maximum diameter of 0.364mm. The sporangial cavities are consistently about 0.04mm in diameter, and in thin section appear set apart by their own diameter or a little more along the margins of the spicules." (Description by Elliott (1968)).

Remarks

The distinction between this species and the superficially very similar *Coptocampylodon lineolatus* Elliott and species of *Terquemella* is covered in the above generic remarks.

*Acicularia elongata* Carozzi can be distinguished from *A. antiqua* by its more elongate outline, whilst *Acicularia endoi* Praturion is larger with larger sporangial cavities, which are regularly arranged and give a distinctive starred appearance in transverse thin section.

Global Distribution and Stratigraphic Range

North Africa, Middle East.

Valanginian - Cenomanian.

Originally described from the Cenomanian of Libya, this species is often very common in the Early Cretaceous of the Middle East. Elliott (198) also recorded but did not illustrate specimens from the Maastrichtian of Iraq.

#### Local Occurrence

Valanginian/Hauterivian - Hauterivian/Barremian.

Buccicrenata hedbergi Subzone - Permocalculus inopinatus Zone.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

Modern-day dasyclads, including *Acetabularia* (?= *Acicularia*), are typically found living in very shallow water depths (usually less than 5m b.s.l.) (Elliott, 1968; Wray, 1977). However, the small size of *Acicularia* spicules means that they can easily be transported to much greater depths offshore.

In this study *A. antiqua* was recorded from a number of facies, but particularly low energy, back-shoal and lagoonal micrites and bioclastic wackestones.

Genus *Acroporella* Pratulon, 1964, emend. Pratulon and Radoičić, 1974

Type Species *Acroporella radoicici* Pratulon, 1964

#### Diagnosis

Cylindrical, not segmented Dasycladaceae having whorls of long primary branches distally ramified in clusters of button-like secondary twigs (from the emended diagnosis of Pratulon and Radoičić, 1974).

#### Remarks

In the original diagnosis of Pratulon (1964) the branches were considered to be non-ramified and akrophorous. However, this was emended by Pratulon and Radoičić (1974), who illustrated that the type species, *A. radoicici*, possessed distally ramifying branches. This emendation may exclude *Acroporella assurbanipali* Elliott and *Acroporella nissovensis* Bakalova from the genus, since both species appear to have only one order of branches. However, both the above species and the genus are still poorly known, and further study is required before any taxonomic reassignment takes place.

Four other genera are similar to the emended concept of *Acroporella* in possessing two orders of branches; *Suppiluliumaella* Elliott, *Montenegrella* Sočák and Nikler, *Linoporella* Steinmann and *Triploporella* Steinmann. *Acroporella* can be distinguished from the first three genera by the characteristics of the primary branches (which widen regularly through their entire length) and secondary branches (which are distinct and short). *Triploporella* can be distinguished from *Acroporella* by the nature of the secondary branches. In *Triploporella* these are fine, elongate and perpendicular to the axis of the stem, in *Acroporella* they are oblique to this axis and short and button-like.

*Acroporella radoicici* Praturlon, 1964

Plates 3.113 - 3.117

T 1964 *Acroporella radoicici* n. gen and n. sp. - Praturlon, text-figs. 8-11.

1974 *Acroporella radoicici* Praturlon - Praturlon and Radoičić, text-figs. 1a-b, 2a-d, 3a-d.

Diagnosis

Species of *Acroporella* with cylindrical, unsegmented thallus. Primary branches arranged oblique to the long axis of the thallus (15-45), in euspondyl alternating whorls.

Remarks

Bassoullet *et al.* (1978) recorded the following dimensions for this species:

D: 0.36-0.7mm

d: 0.17-0.33mm

p: 0.05-0.07mm

w: 8-12

h: 0.085-0.11mm

L: 5.4mm

Distinguished from *A. assurbanipali* by its smaller size and the shape (and ramification?) of its branches.

See also generic remarks and section below on *A. assurbanipali*.

Global Distribution and Stratigraphic Range

Hauterivian - Aptian.

Italy, Yugoslavia, Oman.

The stratigraphic range of this poorly known taxon is not well documented. It has questionably been recorded from Israel (Johnson, 1968) and Portugal (Berthou, 1973).

#### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts provided with Chapter 4 for precise sample distribution.

#### Palaeoecology

Like most dasycladacean algae, this species is associated with very shallow, low energy platform conditions. In this study it was recorded from proximal back-shoal facies.

*Acroporella assurbanipali* Elliott, 1968

Plates 3.107 - 3.112

- 1965 *Acroporella assurbanipali* Elliott (in press) - Gollestaneh, pl. 75, figs. 1-3.  
T 1968 *Acroporella assurbanipali* n. sp. - Elliott, pl. 1, fig. 5.  
1978 *Acroporella?* *assurbanipali* Elliott - Bassoullet *et al.*, pl. 1, fig. 1.  
1987 *Acroporella assurbanipali* Elliott - Simmons and Hart, pl. 10.3, fig. 5, text-fig. 10.8d.

#### Diagnosis

"Cylindrical tubular calcified dasyclad, external diameter 1.36mm, internal diameter 0.55mm (40% of external); successive near-horizontal verticils, probably 3 or 4 per mm of tube-length, of perhaps twelve radial branches each. The single branches communicate with the stem-cavity by a pore of about 0.052mm diameter; they then swell out to a fig or flask shaped cavity of 0.182mm maximum diameter, narrow to a slightly curved tube of 0.078mm diameter, and at the outer surface flare out to a shallow terminal diameter of 0.156mm" (Elliott, 1968).

#### Remarks

As noted in the above generic remarks, it is uncertain if this alga belongs to the emended genus *Acroporella*. Further study of this poorly known species is required to clarify its taxonomic position. It is hoped to document more material from the prolific level in Oman were the specimens of this study were found, in order to clarify the taxonomy and morphology of this species.

Elliott (1968) distinguished this species from *A. radoicici* by its much larger dimensions and by the shape of its branches.

#### Global Distribution and Stratigraphic Range

Iraq, Iran, Oman Mountains, Arabian Gulf (BP internal reports).

Valanginian - Hauterivian.

This species forms a useful zonal marker for Valanginian - Hauterivian sediments in the Middle East. It appears to be endemic to the Middle East.

#### Local Occurrence

Hauterivian.

*Cylindroporella arabica* - *Acroporella assurbanipali* Zones.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

Like most dasycladacean algae, this species is associated with very shallow, low energy platform conditions. In this study it was recorded from lagoonal, back-shoal facies. Large accumulations of debris of this species, "dasycladacean packstones" are thought to have gathered in tidal(?) lagoonal channels.

Genus *Actinoporella* Gumbel in Alth, 1882  
emend. Conrad, Pratulon and Radoićić, 1974  
Type Species *Gyroporella podolica* Alth, 1878

#### Diagnosis

Cylindrical stalk bearing regularly spaced, disc-like whorls of branches. More or less marked outgrowths or excrescences, occur at the branches' proximal ends. These outgrowths develop upper and/or lower "coronas" surrounding the stalk. The term "corona" is used in the same sense as the characteristic structure present in the Recent genus *Acetabularia* (based on the emended diagnosis of Conrad *et al.*, 1974).

### Remarks

Conrad *et al.* (1974) presented a complete review of the genus *Actinoporella* and its constituent species, to which the reader is recommended for further details. They emended the generic diagnosis on the basis of the detailed study of topotypes.

According to Conrad *et al.* (1974), *Verticilloporella* Raviv and Lorch is a junior synonym of *Actinoporella*. They also considered "*Dasycladacea*" *dalmatica* Radoičić (nom. nud.) and *Radoičiella* Dragastan (*pro parte*) to be junior synonyms.

Two fossil genera may be confused with *Actinoporella*: *Clypeina* Michelin and *Pseudoactinoporella* Conrad. However, neither of the two later genera develop any special structures (i.e. coronas) at the proximal ends of their branches. Both these genera, like *Actinoporella*, have widely spaced whorls of branches, and may be confused with *Actinoporella* in tangential sections which do not cut the branches' proximal ends.

*Actinoporella podolica* (Alth, 1878)

emend. Conrad, Praturlon and Radoičić, 1974

Plates 3.118 - 3.123

- T 1878 *Gyroporella podolica* n. sp. - Alth, pl. 6, figs. 1-8.  
1882 *Actinoporella podolica* (Alth) - Alth, p. 322, not figured.  
1955 *Clypeina lucasi* n. sp. - Emberger, pl. 24, figs. 1, 2, 7.  
1958 *Actinoporella podolica* (Alth) - Elliott, pl. 45, fig. 1, ?pl. 47, fig. 5.  
1960 *Clypeina harrazaensis* n. sp. - Emberger, text-fig. 27.  
1968 *Actinoporella podolica* (Alth) - Elliott, pl. 1, fig. 2, ?4, 7.  
1968 *Clypeina lucasi* Emberger - Elliott, pl. 5, fig. 4.  
1968 "*Dasycladacea*" *dalmatica* n. sp. - Radoičić, pls. 12-16.  
1970 *Verticilloporella dalmatica* n. sp. (*pro parte*) - Raviv and Lorch, pls. 1-2.  
1971 *Radoičiella subtilis* n. sp. (*pro parte*) - Dragastan, pl. 4, figs. 5, 8.  
1974 *Actinoporella podolica* (Alth) - Conrad *et al.*, pls. 1-2, 4-6, 8-12. See also for a complete synonymy until 1974.

### Diagnosis

Species of *Actinoporella* possessing corona structures on both the upper and lower faces of the whorls. Following these proximal structures, the branches are more or less perpendicular to the stalk and widen out progressively, towards their rounded and slightly raised distal ends. The wall calcification is made up of a single layer of sparry calcite (based on the emended diagnosis of Conrad *et al.* (1974)).

Conrad *et al.* (1974) recorded the following dimensions for *A. podolica*:

Maximum height of thallus: 5.7mm

Greatest number of whorls in a thallus: 7

Outer diameter (D): 0.7 - 3.2mm

Diameter of stalk (d): 0.18 - 0.85 (1.85?)mm

Distance between whorls (h): 0.33 - 0.72mm

Number of branches in a whorl (w): 12 - 24

#### Remarks

As can be seen from the above figures, the dimensions of this species are quite variable. Conrad *et al.* (1974) further noted that the corona structures characteristic of this species are most strongly developed in Late Neocomian and Barremian specimens, and that Barremian specimens are much larger than those of Earliest Cretaceous - Latest Jurassic age.

Conrad *et al.* (1974) suggested that Pia's (1920) well known reconstruction of *A. podolica* in fact represented a combination of two different species and they presented their own reconstruction based on their emended diagnosis of the species.

A number of other Early Cretaceous dasyclad species may be confused with *A. podolica*. In particular *Clypeina? solkani* Conrad and Radoičić (often described as *Munieria baconica* Hauth), *Clypeina marteli* Emberger and *Pseudoactinoporella fragilis* Conrad are easily mistaken for *A. podolica* in random sections. However, as noted in the above generic remarks, neither *Clypeina* nor *Pseudoactinoporella* possess the corona structure of *Actinoporella*.

*Clypeina durandelgai* Jaffrezo and Fourcade, possess corona structures only on the lower part of each whorl. This serves to distinguish it from *A. podolica*, but furthermore, as a result of this structure, the species should be transferred to *Actinoporella*.

Five other species have been described under *Actinoporella*. *Actinoporella guembeli* Alth, is considered by all workers as a junior synonym of *A. podolica*, the original separation from *A. podolica* being based on a misconception of the number of branches.

*Actinoporella sulcata* Alth appears not to belong within the emended concept of *Actinoporella*, and indeed is very similar to *Clypeina jurassica* Favre and Richard. It may be the senior synonym of this well known taxon.

*Actinoporella cretatica* Raineri was shown by Pia (1936) to be an echinoid spine.

*Actinoporella? krymensis* Maslov, is poorly known, and according to Conrad *et al.* (1974) should be transferred to *Clypeina*, as should *Actinoporella maslovi* Praturlon. Therefore *Actinoporella* currently contains only two species, which are clearly distinctive: *A. podolica* and *A. durandelgai*.

*Clypeina lucasi* Emberger, *Clypeina harrazaensis* Emberger, "*Dasycladacea*" *dalmatica*, *Verticilloporella dalmatica* Raviv and Lorch and *Radoiciciella subtilis* Dragastan (*pro parte*) were all shown by Conrad *et al.* (1974) to be junior synonyms of *A. podolica*.

#### Global Distribution and Stratigraphic Range

Peri-Mediterranean, Southern Russia, Middle East.

Kimmeridgian - Barremian.

*A. podolica* is only known from Kimmeridgian strata at its type locality in the Nizniow area of Southern Russia. In southern Tethys the species has an effective Valanginian - Barremian range.

#### Local Occurrence

Hauerivian - Early Aptian.

*Acroporella assurbanipali* - *Palorbitolina lenticularis* Zones.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

Most records of this species are from low energy, protected, very shallow water platform environments. In this study, the species was recorded largely in very shallow, lagoonal facies.

Genus *Clypeina* Michelin, 1845

Type Species *Clypeina marginiporella* Michelin, 1845

#### Diagnosis

Form generally cylindrical, possessing first order branches. The genus is especially characterised by the presence of "fertile" branches, open or closed at their distal end, and variably inclined towards the axis of the

thallus, to which they are connected by a single pore. They show variable form, but are never trichophorous; the calcareous envelope of the branches is usually fused at their proximal end. The thallus is composed of simple whorls more or less regularly spaced along the axis, but never joined.

"Sterile" branches may be present below the whorls of fertile branches.

#### Remarks

This genus is one of the longer ranging fossil dasyclads, being known from Permian - Cenozoic strata.

This genus can be distinguished from the similar genus *Actinoporella* by the lack of "corona" structures at the proximal ends of the branches (see above section on *Actinoporella*).

#### *Clypeina? parvula* Carozzi, 1946

Plates 3.124 - 3.125

- T 1946 *Clypeina parvula* n. sp. - Carozzi, text-fig. 1.  
1955 *Clypeina parvula* Carozzi - Carozzi, text-figs. 13-14, pl. 6, fig. 2.  
1962 *Clypeina parvula* Carozzi - Sartoni and Crescenti, pl. 20, fig. 2, pl. 22, figs. 7-8.  
1968 *Clypeina parvula* Carozzi - Elliott, pl. 5, figs. 5-6.  
1971 *Clypeina parvula* Carozzi - Basson and Edgell, pl. 6, fig. 3.  
1972 *Clypeina parvula* Carozzi - Pecorini, pls. 1-2.  
1978 *Clypeina parvula* Carozzi - Bassoullet et al., pl. 4, figs. 8-9 and full synonymy.

#### Diagnosis

"Sterile whorls in the form of straight thick-walled calcareous tubes, widening in the upper portion and with the outer surface showing a number of shallow straight vertical flutings or concavities, usually about twelve, but from ten to twenty-five recorded. The fertile whorls are similar but widen much more, terminating in a kind of peripheral fringe or collar: internally, sporangial chambers correspond to the external flutings, the actual cavities being set in the thick calcareous wall. External diameter is said to be from 0.09-0.45mm and the diameter of the central canal 0.03-0.12mm (average 0.07mm)" (Elliott, 1968).

The fertile sporangial chambers are joined together along their whole length.

w: 10-25 (average 12)

D: 0.09-0.45mm

d: 0.03-0.12mm

### Remarks

This species may not necessarily belong to the genus *Clypeina*. Both Elliott (1968) and Bassoullet *et al.* (1978) questioned its taxonomic affinities, the latter going as far as to question its position as a dasyclad alga. It should be noted that it is often recorded as co-occurring with charophytes (as at its type locality in the Swiss Purbeckian). In the Middle East, Elliott (1968) described it as a freshwater fossil, and explained its co-occurrence with marine dasyclads as a result of offshore transport. This also explains why only the resistant parts of the whorls are found in the Middle East.

This species has usually been poorly illustrated with the exception of the figures given by Pecorini (1972). These figures, which are in close agreement with the original drawings of Carozzi (1946), clearly show the close affinity of this species to *Munieria baconica* which is now known to be a charophyte (Conrad and Radoičić, 1972).

It can easily be distinguished from other species of *Clypeina* by its peculiar whorl structure and small size.

### Global Distribution and Stratigraphic Range

Kimmeridgian - Valanginian (?Hauterivian)

The stratigraphic range of this species in the Middle East appears to be restricted to the Berriasian - Valanginian interval.

### Local Occurrence

Hauterivian - Hauterivian/Barremian.

Acroporella assurbanipali - Permocalculus inopinatus Zones.

See range charts provided in Chapter 4 for precise sample distribution.

\* Only questionable specimens of this species were recorded in the course of this study.

### Palaeoecology

In this study, this species has been recorded from low energy, shallow, protected lagoonal facies. However, as noted in the above remarks section, it may be transported offshore from more marginal marine conditions.

*Clypeina solkani?* Conrad and Radoičić, 1972

Plate 3.126

- ? 1948 *Munieria baconica* Hauth - Carozzi, text-fig. 48 (*pars.*).  
1958 *Munieria baconica* Hauth - Radoičić, pl. 1, figs. 1-3. text-figs. 2-3.  
1962 *Cylindroporella* sp. - Sartoni and Crescenti, pl. 35, figs. 4, 7.  
1968 *Munieria baconica* Hauth - Elliott, pl. 15, figs. 4-8.  
1968 *Munieria baconica* Hauth - Dragastan, pl. 1, figs. 6-7.  
? 1970 *Munieria baconica* Hauth - Saint-Marc, pl. 2, figs. 6-7.  
T 1972 *Clypeina? solkani* n. sp. - Conrad and Radoičić, pl. 1, fig. 4, pl. 2, figs. 1-4, text-figs. 1-3.  
1972 *Clypeina? solkani* Conrad and Radoičić - Fourcade *et al.*, pl. 1, fig. 2.  
1978 *Clypeina? solkani* Conrad and Radoičić - Bassoullet *et al.*, pl. 5, figs. 3-5 and further synonymy.

Diagnosis

"The stipe bears spaced-out whorls of fertile branches, normally not touching each other. Each whorl has the shape of a rather thick disk and bears 8 to 16, but commonly 10-14, fertile branches. Within a whorl, two contiguous branches touch each other along between one-half or two-thirds of their lengths. The shape of the branches varies according to their number in a whorl. For a low value of  $w$ , the branches are rather short, rounded and stocky...; when  $w$  is high, the branches are longer narrower, more slender and axially constricted in their proximal half-part...."

"In the living alga, the diameter  $d$  of the stipe probably reached one-fourth of the diameter of the whole plant at the most. In the fossil, the value of  $d$  is about one-third of  $D$ . The thallus of *C.? solkani*, n. sp., is commonly well calcified, especially around the stipe. However, there is seldom any true sheath. Similarly, the calcareous envelope also seldom extends beyond the point where two contiguous branches of a whorl are joined together..., so that the true shape of the distal part of the branches is unknown."

"When the distance  $h$  between two contiguous whorls was relatively high..., the stipe commonly broke between them, and isolated whorls were scattered throughout the sediment. In other cases, when the calcification is strong, the calcified tips of two contiguous branches sometimes touch each other. In all investigated sections, the calcareous envelope is made up of a single layer of hyaline calcite" (Conrad and Radoičić, 1972).

Dimensions:

D: 0.52 - 1.2mm

d: 0.15 - 0.31mm

h: 0.32? - 0.40mm, occasionally up to 0.56mm

w: 8 - 16, but commonly 10 - 14

#### Remarks

This species is very similar to, and has often been mistaken for, the charophyte *Munieria baconica*. It was not until the work of Conrad and Radoičić (1972) was published that *M. baconica* was in fact recognised as a charophyte, and that the dasyclad algae remains often described as *M. baconica*, belonged to a new species: *Clypeina? solkani*. The similarities between *C?. solkani* and *M. baconica*, were attributed by Conrad and Radoičić (1972) to homeomorphism within the green algae.

*M. baconica* can be distinguished from *C?. solkani* by the fact that its branches do not widen distally, and a thin crown, commonly striated, occurs around the outer part of the branches of the former species. In addition, the calcareous cover of *M. baconica* exhibits a yellowish colour.

Conrad and Radoičić (1972) in their original description of this species, questioned its generic assignment to *Clypeina*. Bassoullet *et al.* (1978) expanded on this by noting that the spacing of the whorls is sometimes so small that they touch. This phenomenon possibly excludes this species from *Clypeina*.

This species can be distinguished from other species of *Clypeina* by its dimensions, number of branches and closely spaced whorls. These features also serve to distinguish this species from the very similar alga; *Actinoporella podolica*, which is generally larger and may possess a greater number of branches per whorl (see separate section on this species). This later species can also be distinguished by the presence of corona structures on the upper and lower faces of each whorl. However, in random thin sections, fragments from the two species appear very similar and may easily be confused.

#### Global Distribution and Stratigraphic Range

Peri-Mediterranean, Near East and Middle East.

Berriasian - Aptian.

#### Local Occurrence

Hauterivian - Early Aptian.

Cylindroporella arabica Zone - Choffatella decipiens Subzone.

See range charts provided in Chapter 4 for precise sample distribution.

Only questionable specimens of this species were recorded in the course of this study.

#### Palaeoecology

According to Conrad and Radoičić (1972), the most favoured palaeoenvironment of this species was "the shelf-edge area, both in low-energy lagoons and washed areas". They also recorded it from "back-reef" environments in the Dinarides.

In this study it was largely recorded from low energy, lagoonal, back-shoal environments.

Genus *Coptocampylodon* Elliott, 1963

Type Species *Coptocampylodon lineolatus* Elliott, 1963

#### Diagnosis

Small solid cylindrical bodies, long axis gently curved or irregular, circular in cross-section but deeply incised by longitudinal grooves, thus giving a starred appearance in cross-section superficially similar to *Acicularia*; ends irregularly rounded. Some species possess a central canal similar to the axial stem cavity of most dasycladacean algae.

#### Remarks

In his original description of the genus, Elliott (1963) discounted the possibility that *Coptocampylodon* represents the remains of a calcareous alga. In particular he highlighted the differences between it and *Acicularia*. Instead he suggested that the genus might represent the skeletal remains of a small octocoral in which horny and calcareous joints alternated, similar to the Recent octocoral genus *Isis*.

Patrulius (1965) described a further species of *Coptocampylodon*, *Coptocampylodon fontis*, from the Early Cretaceous of Croatia. This species possesses a central cavity or axial canal, a feature not seen in the type specimens of *C. lineolatus*. Dragastan (1967) introduced a new genus of dasyclad algae, *Carpathoporella*, based on the species *Carpathoporella occidentalis* which he described from the Early Cretaceous of Roumania. As originally noted by Radoičić (1969) and later by Masse (1976), *Carpathoporella occidentalis* is clearly a junior synonym of *C. fontis*. The only difference between *C. fontis* and *C. lineolatus* is the presence of a central cavity. However, as alluded to by Basson and Edgell (1971), the presence or absence of a central cavity is probably controlled by variable recrystallization. Indeed in large sets of specimens of *C. lineolatus* from a single horizon in the Early Cretaceous of the Middle East, both specimens with and without a central cavity can be seen. I

therefore place *C. fontis* into synonymy with *C. lineolatus*, and suggest that the diagnosis of *Coptocampylodon* should include the possible presence of a central cavity.

Dragastan (1967) was thus the first to suggest that *Coptocampylodon* (= *Carpathoporella*) was a dasycladacean alga. He described *Carpathoporella occidentalis* (= *Coptocampylodon lineolatus*) as being a dasycladacean alga with a simple non-segmented, cylindrical thallus, widely spaced verticils, and pores of a special type, being flattened longitudinally to give the appearance of longitudinal grooves or canals. Many other workers have also agreed on the dasycladacean origin of *Coptocampylodon*. Radoičić (1969) suggested analogy with the sterile distal branches of *Triploporella neocomiensis*. Masse and Poignant (1971), Masse (1976) and Basson and Edgell (1971) also agreed that *Coptocampylodon* has a dasycladacean origin. The later authors maintained *Carpathoporella* and *Coptocampylodon* as separate genera but noted that the relationship between the two genera was unclear. More recently Deloffre (1988) in his review of Dasycladacean algae considered *Coptocampylodon* to be a genus of dasycladacean algae.

The presence of a central cavity (where present) and longitudinal grooves distinguishes *Coptocampylodon* from *Acicularia* and *Terquemella* which are superficially similar, particularly in transverse section. The later two genera possess only spherical sporangial cavities, rather than the grooves of *Coptocampylodon* which are clearly seen in longitudinal section.

*Coptocampylodon lineolatus* Elliott, 1963

Plates 3.127 - 3.129

- T 1963 *Coptocampylodon lineolatus* n. sp. - Elliott, pl. 46, figs. 4-6, 8, pl. 48, fig. 2.  
1965 *Coptocampylodon fontis* n. sp. - Patrušius, pl. 1-3.  
1967 *Carpathoporella occidentalis* n. sp. - Dragastan, pl. 1, figs. 7-9, pl. 2, figs. 10-16.  
1969 *Coptocampylodon fontis* Patrušius - Radoičić, pl. 1, fig. 2, pl. 2, figs. 1-3, pl. 3, figs. 1-5.  
1971 *Carpathoporella occidentalis* Dragastan - Masse and Poignant, pl. 1, fig. 7.  
1971 *Carpathoporella occidentalis* Dragastan - Basson and Edgell, pl. 4, figs. 6-8.  
1971 *Coptocampylodon lineolatus* Elliott - Basson and Edgell, pl. 4, figs. 9-11.  
1972 *Carpathoporella* sp. - Fourcade et al., pl. 4, fig. 1.  
1973 *Carpathoporella occidentalis* Dragastan - Bakalova, pl. 2, fig. 7, pl. 3, figs. 9-11.  
1976 *Coptocampylodon fontis* Patrušius - Masse, pl. 7, fig. 4.

Diagnosis

Short cylindrical calcareous bodies up to 3.0mm in length and varying from about 0.25 to 1.00mm in diameter. The long axis is gently curved or slightly irregular: the ends, when not obviously broken, are irregularly

rounded. The outer surface is deeply incised by parallel equidistant longitudinal grooves, from five to ten or possibly more in number. In transverse section these grooves are seen to widen inwards and may be near circular in cross-section, with an internal diameter of 0.04-0.05mm. The circular transverse section of the whole unit is notched by the grooves and has the appearance of a coarse sparsely spoked cog-wheel or of a stellate structure with truncated rays. Longitudinal sections show the parallel, matrix filled grooves, either curved or passing out of the plane of section owing to their irregularity. In some cross-sections a central cavity (?axial stem) is visible, the preservation of this feature being dependant on the degree of recrystallization. Where present it usually has a diameter of about 0.25mm, but may vary between 0.13mm and 0.70mm.

#### Remarks

As noted in the above generic remarks, this species is considered to be the senior synonym of *Coptocampylodon fontis* and *Carpathoporella occidentalis*, and to be derived from a dasycladacean alga.

It can easily be distinguished from species of *Acicularia* and *Terquemella* by the presence of longitudinal grooves and a central cavity (the latter not always present).

#### Global Distribution and Stratigraphic Range

Iraq, Lebanon, Southern France, Spain, Roumania, Bulgaria, Oman Mountains, Borneo?,

Hauterivian- Aptian

#### Local Occurrence

Hauterivian - Early Aptian.

Cylindroporella arabica Zone - Choffatella decipiens Subzone.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

Modern-day dasyclads, are typically found living in very shallow water depths (usually less than 5m b.s.l.) (Elliott, 1968; Wray, 1977). However, the small size of *Coptocampylodon* segments means that they can easily be transported to much greater depths offshore.

In this study, *C. lineolatus* was recorded from a number of facies, but particularly low energy, back-shoal and lagoonal micrites and bioclastic wackestones.

Genus *Cylindroporella* Johnson, 1954

Type Species *Cylindroporella barnesii* Johnson, 1954

Diagnosis

"Cylindrical calcareous bodies often tapered or restricted at the base and top. A few are broadly rounded at the top. They appear to have grown one above the other like a string of sausages. A few show budding or branching."

"The plant probably developed extended fronds, each composed of many segments somewhat similar to the modern *Cymopolia barbata* Harvey. The fossils represent the individual segments."

The central stem is relatively narrow (about 1/4 to 1/5 width of the entire fossils). Primary branches perpendicular to the axis of the stem, except at the ends where they are inclined. Primary branches in alternating annular rows. Secondary branches, small and steeply inclined to the primary branches bending so tips are approximately parallel to outer surface. Sporangia large, nearly spherical, attached to main stem. They occur in vertical rows separated by primary branches. These vertical rows alternate in position, so that in both vertical and annular rows, there is an alternation of primary branches and sporangia. The tapering ends of the thallus appear to contain only branches, no sporangia." From the original diagnosis of Johnson (1954).

Remarks

This particularly distinctive genus is commonly recorded in Late Jurassic - Early Cretaceous Tethyan platform carbonates.

The distinctive features of the genus are:

- A possibly tapered or restricted, cylindrical thallus.
- Alternation on each whorl of fertile and sterile branches.
- Vertical alternation of fertile and sterile branches.

Although the type species, *C. barnesii*, has a tapering cylindrical thallus like modern *Cymopolia barbata*, this feature is not present within every species assigned to the genus, and the absence of this feature should not be used to exclude a species from the genus.

A number of *Cylindroporella* species are poorly known, being only described from their type locality, and often only as random thin sections. For example *Cylindroporella adducta* (Maslov) Bassoulet, Bernier, Conrad, Deloffre and Jaffrezo, *Cylindroporella arsici* Radoicic, *Cylindroporella maslovi* Srivastava and *Cylindroporella*

*elliptica* Bakalova. A detailed review of the genus may well reveal that many of these are synonyms of well established taxa recorded in the Middle East such as *Cylindroporella arabica* Elliott and *Cylindroporella sugdeni* Elliott.

*Cylindroporella arabica* Elliott, 1957

Plate 3.130 - 3.134

- T 1957 *Cylindroporella arabica* n. sp. - Elliott, pl. 1, figs. 13-16.  
1967 *Cylindroporella arabica* Elliott - Bismuth *et al.*, pl. 8, figs. 1-3.  
1968 *Cylindroporella arabica* Elliott - Elliott, pl. 6, fig. 12.  
1969 *Cylindroporella arabica* Elliott - Barthel, pl. 2, fig. 2.  
1971 *Cylindroporella arabica* Elliott - Masse and Poignant, pl. 2, fig. 4.  
1971 *Cylindroporella arabica* Elliott - Ramalho, pl. 29, figs. 4-5.  
1973 *Cylindroporella arabica* Elliott - Jaffrezo, pl. 80, pl. 2.  
1975 *Cylindroporella arabica* Elliott - Dragastan, pl. 23, fig. 4.

Diagnosis

"Small cylindroporelliform segments, agreeing in internal structure with those of *Cylindroporella barnesii* and *Cylindroporella sugdeni*, but usually smaller in all dimensions". Original diagnosis of Elliott (1957).

Dimensions are:

L: 1.43mm

D: 0.31 - 0.57mm

d: 0.052 - 0.23mm

ds: 0.078 - 0.556mm

h: 0.13mm

w: 6

w': Uncertain, possibly 4.

Remarks

This species can be distinguished from other Early Cretaceous *Cylindroporella* species occurring in the Middle East by its smaller dimensions. The following table presents a summary of differences for *Cylindroporella* species commonly recorded in the Middle East:

	<i>C. arabica</i>	<i>C. barnesii</i>	<i>C. sugdeni</i>
Length of segment (L)	1.43	2.8-5.1	3.0+
Diameter of segment (D)	0.31-0.57	0.38-0.55	0.78-1.14
Diameter of central canal (d)	0.052-0.556	0.08-0.14	0.234-0.36
Diameter of sporangia (ds)	0.078-0.556	0.189-0.234	0.26-0.312
Number of sporangia per whorl	6	6	6
Number of primary branches per whorl (w)	6	6	6
Angle of branches to stem	90°	90°	90°
Number of secondary branches per tuft (w')	74	74	74
Vertical distance between whorls (h)	0.13	0.17-0.187	0.39

All dimensions are in millimeters. Table after Elliott (1968) and Johnson (1969).

*Cylindroporella texana* Johnson from the Late Jurassic of Texas, has smaller dimensions for internal structures but these occur in a very much longer slim segment.

The central canal of this species shows marked variation in diameter. This is perhaps a function of diagenetic recrystallization.

#### Global Distribution and Stratigraphic Range

Middle East, Tunisia, Bavaria, Carpathian Mountains, Southern and South-western France, Portugal.

Kimmeridgian - Valanginian.

The majority of the records of this species (including the type material from the Middle East) are from the Late Jurassic. The few Early Cretaceous records are from Southern France.

#### Local Occurrence

Hauterivian.

*Cylindroporella arabica* Zone.

See range charts provided in Chapter 4 for precise sample distribution.

This species forms a useful biozonal marker in the study area, where it is restricted to the Hauterivian stage (by association with *Choffatella decipiens* and other microfossils). This is the first record of this species from the Hauterivian. Previous occurrences suggest it is most common in the Late Jurassic. However, the dimensions and structure of the specimens found in this study are in keeping with the type description. It may be possible that previous records of this species should be reassessed with regard to their age.

#### Palaeoecology

This species was typically found in high or moderate energy, shallow water marginal shoal and peri-shoal facies of the Habshan Formation. However, as noted by Elliott (1968), these are not likely to be *in situ* occurrences. The stumpy, segmented nature of the thallus may allow transport from quieter back-shoal environments.

#### *Cylindroporella sugdeni* Elliott, 1957

Plates 3.135 - 3.137

- T 1957 *Cylindroporella sugdeni* n. sp. - Elliott, pl. 1, figs. 1-6.  
? 1976 *Cylindroporella* cf. *sugdeni* Elliott - Peybernes, pl. 24, figs. 5-6.

#### Diagnosis

"Large, thick cylindroporelliform segments, agreeing in internal structure with those of *Cylindroporella barnesii*, but with greater diameter of central canal and sporangia, and externally, and a greater distance between whorls; it is proportionally shorter and much thicker than the type species". Original diagnosis of Elliott (1957).

Dimensions are:

L: 3.0mm+

D: 0.78 - 1.14mm

d: 0.234 - 0.36mm

ds: 0.26 - 0.312mm

h: 0.39mm

w: 6

w': 4?

### Remarks

This species can be distinguished from other Early Cretaceous *Cylindroporella* species occurring in the Middle East by its larger dimensions. The table given in the above section on *C. arabica* summarizes the differences between this species and *C. barnesii* and *C. arabica*.

*Cylindroporella elitzae* Bakalova from the Early Cretaceous of Bulgaria is considered by Bassoullet *et al.* (1978) to be a probable junior synonym of *C. sugdeni*. However, according to the original description of *C. elitzae* (Bakalova, 1971), the thallus is not segmented, no secondary branches are present and eight rather than six branches per whorl are present. There are also differences in some of the internal and external dimensions. On the other hand, *C. elitzae* is poorly known and further study may show that the two species are in fact synonymous. Certainly, the two species could easily be confused in random thin-sections.

*C. maslovi* from the Early Barremian of the Balkhan Mountains, USSR is also similar to *C. sugdeni*, but is of somewhat smaller dimensions (see Bassoullet *et al.*, 1978).

The species was originally described from the Early Cretaceous of Oman (Elliott, 1957).

### Global Distribution and Stratigraphic Range

Oman, Iraq, ?Pyrenees.

Hauterivian? Barremian - Aptian.

The age range of this species is not well established. The main source of information is Elliott (1968) where the age assignments may be questionable following more recent regional data.

### Local Occurrence

Hauterivian - Late Barremian.

*Cylindroporella arabica* Zone - *Eopalorbitolina charollaisi* Subzone.

See range charts given in Chapter 4 for precise sample distribution.

### Palaeoecology

In this study, this species was found low energy, shallow back-shoal facies, or in lagoonal facies. Occasionally it appears to have been reworked into higher energy, relatively deeper water environments.

Genus *Neomeris* Lamouroux, 1816

Type Species *Neomeris dumetosa* Lamouroux, 1816

Diagnosis

Unsegmented, cylindrical thallus with regular successive verticils of branches in which each primary branch divides into a stalked sporangium and two secondary sterile branches set in the same plane. Calcification surrounds the sporangia and secondary branches, but the thallus is essentially uncalcified around the central stem and primary branches.

Remarks

This extant genus which has a range of Early Cretaceous to Recent was originally described based on Recent species. Some Recent species possess sporangia and secondary branches which are sited on slightly different levels. Deloffre (1970) emended the diagnosis of *Neomeris* to include these forms within the genus, but it is considered here more suitable to retain them in a separate genus: *Larvaria* Defrance.

In the fossil record the genus is very distinctive because of the position of the sporangia and secondary branches.

*Neomeris cretacea* Steinmann, 1899

Plate 3.138

- T 1899 *Neomeris (Herouvalina) cretacea* n. sp. - Steinmann, text-figs. 14-21.  
1922 *Neomeris cretacea* Steinmann - Raineri, text-figs. 5-6.  
1955 *Neomeris cretacea* Steinmann - Elliott, pl. 1, fig. 7.  
1962 *Neomeris cretacea* Steinmann - Delmas and Deloffre, pls. 1-3.  
1968 *Neomeris cretacea* Steinmann - Elliott, pl. 15, figs. 1-2.  
1968 *Neomeris cretacea* Steinmann - Johnson, pl. 2, fig. 1, pl. 3, fig. 1.  
1971 *Neomeris cretacea* Steinmann - Basson and Edgell, pl. 5, fig. 4-5.  
1973 *Neomeris cretacea* Steinmann - Berthou, pl. 13, fig. 2.  
1973 *Neomeris cretacea* Steinmann - Bakalova, pl. 3, figs. 1-2, 6-7, 10.

Diagnosis

Cylindrical thallus, typically found in fragments a few millimeters in length (up to 10mm). External diameter (D) may vary between 1.1 and 2.0mm. Diameter of the internal cavity (d) is usually about 50-75% of that of the external diameter, typical values being 1.2 - 1.5mm. Close-set verticils of neomerid groupings of sterile branches of about 0.05mm diameter and ovoid sporangia of about 0.1mm diameter and 0.2mm length.

### Remarks

This species was originally described from the Cenomanian of Mexico and has since been described from much of the Tethyan region. It is thought to be long ranging being known from Early Cretaceous to Maastrichtian sediments.

*Neomeris budaense* Johnson described from the Cenomanian of Texas and Portugal (Johnson, 1968; Berthou, 1973), is similar but is of overall smaller dimensions with slender branches, small sporangia and thicker calcification.

*Neomeris pfenderae* Konishi and Epis is a very similar species to *N. cretacea* originally described from the Albian of Texas (Konishi and Epis, 1962). It can be distinguished from *N. cretacea* by the presence of finer secondary branches and a stronger degree of calcification. Otherwise the two forms are virtually identical and further research may show that they are synonymous.

### Global Distribution and Stratigraphic Range

Mexico, Texas, Portugal, Southern France, Bulgaria, Libya, Lebanon, Middle East.

Barremian - Maastrichtian.

This species, which is typically Cenomanian, is thought to have an Hauterivian - Danian range by Conrad (pers. comm, 1986), although illustrated records of this species extend only as old as Barremian (Bakalova, 1973). If *N. pfenderae* is included in the synonymy of *N. cretacea* this extends its range into the Hauterivian because of the record of the former species by Srivastava (1973).

### Local Occurrence

Hauterivian.

*Cylindroporella arabica* - *Acroporella assurbanipali* Zones.

See range charts provided in Chapter 4 for precise sample distribution.

### Palaeoecology

Konishi and Epis (1962) described the typical environment of *Neomeris* as being within water depths of 0 - 10m, with water temperatures of between 15 and 20 C.

In this study the species was recorded from high energy, shallow water (probably less than 10m b.s.l.) peri-shoal facies of the Habshan Formation, and quieter micritic back-shoal and lagoonal facies of the Lekhwair Formation. Like the specimens of *Cylindroporella* and *Arabicodium* associated with this species in the Habshan Formation, transportation seems to be likely from back-shoal environments by offshore currents.

Genus *Salpingoporella* Pia in Trauth, 1918 emend. Conrad, 1969

Type Species *Diplopora muehlbergii* Lorenz, 1902

#### Diagnosis

Cylindrical thallus, neither ramified nor segmented. Branches are arranged in more or less spaced out, euspondyl and alternating whorls. They are simple, phloioporous, perpendicular to the axis of the thallus, or slightly oblique. They communicate with the axial cell by means of a proximal narrowing. The living plant, made the distal enlargement of the branches to touch at their distal ends, beyond the calcification, thus resulting in a peripheral cortex. There are no secondary branches, or at least they were not calcified. The genus is cladoporous. Many species however, do not show this characteristic. The calcification is complete and reaches the axial cell. (Translation of the emended diagnosis for *Pianella* (= *Salpingoporella*) by Conrad (1969)).

#### Remarks

This genus is often abundant in Early Cretaceous platform carbonates, and includes a relatively high diversity of species. Although highest diversities are recorded from the circum - Mediterranean region, moderately diverse faunas are now known from the Middle East. Some of species described below are recorded from the Middle East for the first time herein. Species diversities are low in Tethyan carbonates from the New World.

The genus is very distinctive and can be characterised by the following features: simple cylindrical non segmented thallus, bearing whorls of phloioporous branches of only one order. The genus shows considerable variation however, particularly in thallus size and number, size and shape of branches.

Some species now included in *Salpingoporella* were originally described under the generic names *Pianella* (a junior synonym of *Salpingoporella*; Conrad *et al.*, 1973), or *Macroporella*. *Macroporella* is similar to *Salpingoporella* in many respects, particularly in having a simple, non segmented thallus, and only a single order of branches. However *Macroporella* has an aspondyle or mesospondyle thallus, whilst that of *Salpingoporella* is euspondyle.

*Salpingoporella muehlbergii* (Lorenz, 1902) emend. Conrad, 1970

Plates 3.139 - 3.142

- T 1902 *Diplopora muehlbergii* n. sp. - Lorenz, text figs. 3-6, ?7.  
1918 *Salpingoporella muehlbergii* (Lorenz) - Pia in Trauth, text fig. 4a.
- non 1938 *Salpingoporella muehlbergii* (Lorenz) - Andrusov, pl. 3, fig. 2.  
1958 *Salpingoporella muehlbergii* (Lorenz) - Dufaure, pl. 2, fig. 18.  
1962 *Salpingoporella muehlbergii* (Lorenz) - Sartoni and Crescenti, pl. 26, fig. 1, pl. 45, fig. 5, ?6.  
1966 *Salpingoporella* sp. - Dragastan, pl. 1, figs. 5-6.  
1967 *Pianella muehlbergii* (Lorenz) - Praturlon and Radoičić, text fig. 1.  
1967 *Salpingoporella muehlbergii* (Lorenz) - Ziegler, text figs. 6-7.
- non 1968 *Salpingoporella* cf. *muehlbergii* (Lorenz) - Lefeld, pl. 6, fig. 3.  
1968 *Pianella dinarica* (Radoičić) - Bouroullec and Deloffre, pl. 7, fig. 15.  
1969 *Salpingoporella carpathica* n. sp. - Dragastan, pl. 1, figs. 1-6.  
1970 *Pianella muehlbergii* (Lorenz) - Conrad, text fig. 6, pls. 6-7.  
1971 *Pianella muehlbergii* (Lorenz) - Masse and Poignant, pl. 1, fig. 3.  
1971 *Salpingoporella carpathica* Dragastan - Basson and Edgell, pl. 4, fig. 1.  
1971 *Salpingoporella muehlbergii* (Lorenz) - Bakalova, pl. 2, figs. 1-2, 6.  
1971 *Salpingoporella annulata* Carozzi - Bakalova, pl. 1, fig. 4.  
1972 *Pianella muehlbergii* (Lorenz) - Fourcade *et al.*, pl. 1, fig. 8.  
1976 *Salpingoporella muehlbergii* (Lorenz) - Peybernes, pl. 24, figs. 10-11.

Diagnosis

"The thallus is cylindrical, unbranched but frequently curved. Only primary branches are perpendicular to the stipe, arranged in regularly spaced euspondyl alternating whorls. Branches are phloiophorous, consisting of a tubular proximal part and a funnel-like distal part transversally slightly flattened out. The relative lengths of these two portions of the branches vary considerably. Practically no trace of spores in the branches. The fossil envelope consists of a simple layer of sparry calcite.

Dimensions are:

L: 2.5mm or more

D: 0.2 - 0.85mm

d: 0.1 - 0.3mm

d/D: 0.28 - 1.63

h: 0.07 - 0.18mm

w: 5-11

### Remarks

This species was reviewed and a neotype introduced by Conrad (1970). The dimensions and transversally flattened branches distinguish this species from other members of the genus.

*Salpingoporella arabica* Elliott, was suggested by Bassoullet *et al.* (1978) to be a junior synonym of *S. muehlbergii*. However as pointed out by Elliott (1968), *S. arabica* has finer walls and the branches lack an inner narrow portion. The two species, although clearly closely related, are distinct in the study material from Oman. The records of *S. muehlbergii* from Oman refute the suggestion of Elliott (1968) that *S. arabica* is the "Middle Eastern form" of *S. muehlbergii*. Both species are present in the Middle East.

### Global Distribution and Stratigraphic Range

Switzerland, Southern France, Southern Italy, Roumania, Bulgaria, Spain, Algeria, Oman Mountains.

Barremian - Aptian, typically Barremian.

### Local Occurrence

Hauterivian - Hauterivian/Barremian.

Acroporella assurbanipali - Permocalculus inopinatus Zones.

See range charts given in Chapter 4 for precise sample distribution.

### Palaeoecology

Modern-day dasyclads are typically found living in very shallow water depths (usually less than 5m b.s.l.) (Elliott, 1968; Wray, 1977). The fragile nature of *Salpingoporella* means that it is unlikely to be transported far.

In this study *S. muehlbergii* was recorded from a number of facies, but particularly low energy, back-shoal and lagoonal micrites and bioclastic wackestones.

*Salpingoporella* sp. A

Plate 3.143

### Diagnosis

Very small, delicate species of *Salpingoporella*. Preserved as small segments of thallus showing typical salpingoporellid branching. Dimensions are as follows:

Length of preserved thallus: 0.38mm

Outer diameter (D): 0.15 - 0.16mm

Inner diameter (d): 0.08 - 0.11mm

Ratio d:D: (average) 0.55

Length between verticils: 0.08mm

Straight side thallus preserved as drusy calcite.

#### Remarks

The extremely small dimensions of this species serve to distinguish it from any comparable species of *Salpingoporella*. Superficially similar to *S. arabica*, *S. muehlbergii* and "*S.* *dinarica*", these species are all somewhat larger (eg. *S. arabica* D = 0.31-0.73mm, *S. muehlbergii* D = 0.2-0.85mm, "*S.* *dinarica* D = 0.24-0.56). Additionally "*S.* *dinarica* can be distinguished by its distinctive radial calcite preservation.

*Salpingoporella johnsoni* is the most comparable species, but even this, the smallest species of *Salpingoporella* previously reported, is larger than typical specimens of *Salpingoporella* sp. A (eg D = 0.20-0.31mm).

This species was only rarely encountered in the study material precluding a more detailed description.

#### Global Distribution and Stratigraphic Range

Unknown.

#### Local Occurrence

Hauterivian.

Acroporella assurbanipali Zone.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

Modern-day dasyclads are typically found living in very shallow water depths (usually less than 5m b.s.l.) (Elliott, 1968; Wray, 1977). The delicate nature of this species of *Salpingoporella* means that it is unlikely to have been transported far. It was recorded in lagoonal micrites of the Lekhwair Formation.

*Salpingoporella arabica* Elliott, 1968

Plate 3.144

T 1968 *Salpingoporella arabica* n. sp. - Elliott, pl. 21, figs. 1-3.

Diagnosis

"Thin-walled tubular calcified dasyclad, straight sided with very gentle increase in diameter; observed lengths (incomplete) up to 2.73mm, external diameter 0.31-0.73mm, internal diameter 0.21-0.47mm; ratio of internal to external diameters 55-66%; horizontal verticils set regularly 0.104mm apart, each verticil with 8-10 branches which open rapidly and widely to external pore depressions of 0.065-0.078mm or more diameter. The wall calcification is thin and rather ragged: the pores have a somewhat irregular appearance, partly due to slight irregular deviations from the horizontal in their orientation." (Original diagnosis from Elliott (1968)).

Remarks

As noted above, this species was considered by Bassoullet *et al.* (1978) to be a likely synonym of *S. muehlbergii*. However, as pointed out by Elliott (1968), *S. arabica* has finer walls and the branches lack an inner narrow portion. The two species, although clearly closely related, are distinct in the study material from Oman. The records of *S. muehlbergii* from Oman refute the suggestion of Elliott (1968) that *S. arabica* is the "Middle Eastern form" of *S. muehlbergii*. Both species are present in the Middle East.

Global Distribution and Stratigraphic Range

Iraq, Oman Mountains.

Aptian - Albian.

Unillustrated records by Elliott (1968) indicate that this species may have a Valanginian - Albian range in the Middle East. There are several records from Early Cretaceous, Thamama Group equivalents.

Local Occurrence

Hauterivian.

Acroporella assurbanipali Zone.

See range charts given in Chapter 4 for precise sample distribution.

### Palaeoecology

Modern-day dasyclads are typically found living in very shallow water depths (usually less than 5m b.s.l.) (Elliott, 1968; Wray, 1977). The delicate nature of this species of *Salpingoporella* means that it is unlikely to have been transported far. It was recorded in lagoonal micrites of the Lekhwair Formation.

### *"Salpingoporella" dinarica* Radoičić, 1959

Plates 3.145 - 3.153

- T 1959 *Salpingoporella dinarica* n. sp. - Radoičić, pls. 3-5.  
1960 *Hensonella cylindrica* n. gen, n. sp. - Elliott, pl. 8, fig. 1.  
1961 *Hensonella cylindrica* Elliott - Reiss, text-figs. 93-107.  
1962 *Salpingoporella dinarica* Radoičić - Sartoni and Crescenti, pl. 17, pl. 35, figs. 1-3.  
1967 *Pianella dinarica* (Radoičić) - Praturlon and Radoičić, text-fig. 2.  
1968 *Salpingoporella dinarica* Radoičić - Elliott, pl. 21, fig. 4, pl. 22.  
1969 *Hensonella cylindrica* Elliott - Sampo, pls. 32, 37.  
non 1973 *Pianella dinarica* (Radoičić) - Berthou, pl. 15, figs. 1-2, pl. 20, fig. 1, pl. 31, fig. 4.  
1978 *Salpingoporella dinarica* Radoičić - Bassoullet *et al.*, pl. 28, figs. 6-10. See also for a complete synonymy until 1978.

### Diagnosis

Elongated, cylindrical tubes, with more or less conical ends. Rather wide axial hollow. Only primary pores exist; they are few in number, funnel-like and sometimes give the impression of being slightly flattened. Primary pores are perpendicular to the axial hollow and arranged in a quincunx. The height between two whorls is half the distance separating two pores within a whorl. The axis of the plant appears, within thin sections, to be made up of a thin dark layer, located on the inner side of the calcareous tube. Preservation of the axis depends on the type of sediment containing the algae. Preservation of the calcareous tube also varies according to different types of limestones. Recrystallisation of calcium carbonate is much stronger in pure limestones than in marly or bituminous limestones. (Partial translation of the original diagnosis of Radoičić (1959)).

Dimensions are:

L: circa. 3mm

D: (0.112) 0.24 - 0.56mm

d: (0.035) 0.128 - 0.4mm

h: 0.048mm

w: 8-10 (?)

Values in parentheses are for rare, exceptionally small specimens.

### Remarks

This species is often common in Tethyan platform carbonates and has been frequently illustrated. However, there are a number of still unresolved problems concerning the origin and taxonomy of this fossil. Most workers (including Elliott (1968)) accept that *Hensonella cylindrica* Elliott is a junior synonym, although there are those (eg. Johnson, 1968) who maintain that they are distinct. Nor are all workers convinced that *S. dinarica* (including *H. cylindrica* as a synonym), is a dasycladacean algae. *H. cylindrica* was originally described as a problematicum, possibly a scaphopod (Elliott, 1960). Elliott (1968) whilst accepting that *S. dinarica* is the senior synonym of *H. cylindrica*, still expressed doubt concerning its algal origin: "In conclusion, I consider this organism is best classified as a problematicum" (p. 77). In direct opposition to this Bassoullet *et al.* (1978) and also Conrad (pers. comm., 1988) and Radoičić (pers. comm., 1988) are in no doubt that *S. dinarica* and *H. cylindrica* are synonyms and refer to a dasycladacean alga.

The reason for the uncertainty discussed above centres around the crystalline structure of the calcified thallus wall. This is alluded to in the original diagnosis of Radoičić (1959) and more clearly illustrated and discussed for *H. cylindrica* by Elliott (1960). Three features are noticeable: (i) the wall appears to be made up of radial, fibrous calcite, (ii) this has a yellowish or honey coloured tint, (iii) a dark, inner micritic layer is typically present. These features are clearly unusual for a dasycladacean algae and have been used by Elliott (1960; 1968) and others to argue for a non-algal origin for this fossil. Typical *Salpingoporella*, and other dasyclads have a wall composed of drusy, unstructured calcite, neomorphosed from original aragonite. The fibrous, radial calcite seen in *S. dinarica/H. cylindrica* is thought to originate from an original organic calcite structure (Elliott, 1968). Bassoullet *et al.* (1978) and Radoičić (1959) place little significance on this, arguing that the radial structure originates from diagenetic alteration (presumably of aragonite), which can, according to them, be extremely variable. Initial SEM and isotopic studies of specimens of "*H. cylindrica*" from the Middle East (Emery and Simmons, in prep.) strongly suggest that the thallus of *S. dinarica/H. cylindrica* was originally composed of organic calcite rather than aragonite. This research is currently ongoing.

To investigate the above problems further, topotype specimens of *S. dinarica* and the holotype material of *H. cylindrica* were examined in addition to the material from the Oman Mountains collected in the course of this study.

Examination of the type figures of *H. cylindrica* and *S. dinarica* strongly suggest that the two species are synonymous. This is confirmed by comparison of topotypes of *S. dinarica* (kindly supplied by Dr. M.A. Conrad) and the syntypes of *H. cylindrica* held in the British Museum (Natural History). As stated by Elliott

(1968): "Slight differences in the two author's descriptions can be reconciled by examination of large sets of specimens" (p. 76).

Having established that the two species are synonymous and that *Salpingoporella dinarica* is the senior synonym, it needs to be determined if this fossil is truly a dasycladacean alga, and if so, if it belongs in the genus *Salpingoporella*.

Both specimens described as *S. dinarica* and those described as *H. cylindrica* show considerable variability particularly in the calcareous nature of the wall, but also in terms of morphology. Within the topotype specimens of *S. dinarica*, some clearly show a fibrous, radial wall whilst in others it is poorly developed. These specimens do not show a particularly strong yellowish tint, as do the syntype specimens of *H. cylindrica*. More importantly, the topotype specimens of *S. dinarica* (and indeed the holotype illustrations) clearly show morphological affinities with dasycladacean algae, especially the genus *Salpingoporella*. These features were not clear in the syntypes of *H. cylindrica*, but as noted and illustrated by Elliott (1968), they do occur "not uncommonly" in Middle Eastern specimens referred to *Hensonella*. This is confirmed by examination of the specimens from the Oman Mountains recovered during the course of this study. Much of the morphological variation associated with this species can be associated with attributed to preservation problems (erosion, etc) and variability with depth and orientation of thin section.

Of particular note is the presence of "pores" which are regularly spaced, alternating in position from level to level. These can be interpreted as verticils of lateral branches. Overall the morphology is closely comparable with that of *S. muehlbergii*, the type species of *Salpingoporella*. The thallus is unsegmented with a wide axial hollow, and only primary branches are present. These are clearly visible in both transverse and longitudinal sections of the topotypes of *S. dinarica*.

Thus it would appear that the morphology of this species is in agreement with it being a dasycladacean alga of the genus *Salpingoporella*. However as discussed above, the crystalline nature of the wall is remarkable and certainly very unusual for a dasycladacean alga. The dark inner micritic wall can be interpreted as being the preserved organic membrane lining the main axis of the thallus. Elliott (1968) noted that crushed specimens are still held together by this layer suggesting that it had an original organic nature with some flexibility.

More problematic is the yellowish, radial wall, typical of this species and thought to be derived from original calcite, rather than aragonite which is typical for dasyclads (Wray, 1977). However, there are other records of algae which otherwise show all the features of the dasycladaceans, yet are considered to be originally calcitic. Of note is the Visean alga *Koninckopora* which has been described by Wright (1981) as being originally calcitic. This fossil is preserved in very fine grained, sometimes acicular calcite, rather than coarse, blocky

calcite typical of dasyclads. Also like *S. dinarica*, *Koninckopora* often displays a micritic lining to the walls. Besides *Koninckopora*, there may be other dasyclads with a calcitic origin, for example *Salpingoporella sellii* (Crescenti) (Wright, 1981). Elliott (1963) considered that *Pseudovermiporella* Elliott, a questionable Permian dasyclad, was of calcitic origin. It is worth noting that other mineral phases besides aragonite are known within dasyclads, eg. calcium oxalate in the reproductive discs of *Acetabularia* (Elliott, 1979). It can be suggested therefore, that although most dasyclads were originally aragonitic, there may be small groups within the dasyclads which were originally calcitic. *S. dinarica* can be included in such a group. It could of course be argued that such groups should be assigned to a new order separate from the Dasycladales, but it is considered that too little is yet known about such forms to warrant such a change.

Some specimens of the dasyclad genus *Macroporella*, particularly those of the species *Macroporella embergeri* display fibro-radial walls with a yellowish tint, as in *S. dinarica*, and also a micritic inner wall layer. However, no research has been undertaken to establish how well developed this feature is in the genus and its constituent species and whether it is derived from original organic calcite. The thallus of *S. dinarica* is euspondyle, otherwise it could be considered to fit well within *Macroporella*.

In conclusion I consider *S. dinarica* to be the senior synonym of *H. cylindrica*. The species is a dasycladacean alga which was originally calcitic. It is provisionally retained in the genus *Salpingoporella* (generic name quoted in parentheses) since it shows all the morphological features of that genus. Further research into originally calcitic dasycladaceans may require them to be separated taxonomically from their originally aragonitic counterparts. For example a new order for originally calcitic forms may be required which would include *dinarica* within the genus *Hensonella*, this genus being the originally calcitic homeomorph of *Salpingoporella*.

"*S. dinarica*" can easily be distinguished from other Early Cretaceous species of *Salpingoporella* by its wall structure and pronounced flattened branches as seen in transverse section.

#### Global Distribution and Stratigraphic Range

Yugoslavia, Southern Italy, Algeria, Lebanon, Israel, Iraq, Iran, Oman Mountains.

Valanginian (?) - Latest Aptian.

This species is typical of the Barremian - Aptian period in Southern Tethys. Records from the pre-Barremian are rare and include the "Valanginian - Hauterivian" record of Sampo (1969) from Iran. My research suggests that this may in fact refer only to the Hauterivian.

### Local Occurrence

Valanginian/Hauterivian - Early Aptian.

Buccicrenata hedbergi Subzone - Salpingoporella dinarica Zone.

See range charts provided in Chapter 4 for precise sample distribution.

### Palaeoecology

As noted above, most dasyclads are typical of very shallow water, low energy, protected platform conditions. However, this species (perhaps also suggesting taxonomic separation from the dasycladaceae) is found in a variety of facies across the Thamama ramp from fore-shoal and slope environments, to very shallow water lagoonal conditions.

However, it should be noted that the species is most common in shallow, lagoonal conditions where it occurs together with other dasyclads. Records from deeper water environments may be a function of transportation offshore.

*Salpingoporella johnsoni* (Dragastan, 1971)

Plate 3.154

- T 1971 *Pianella johnsoni* n. sp. - Dragastan, pl. 3, figs. 1-11.  
1974 *Pianella johnsoni* Dragastan - Canerot, pl. 4, figs. 5-6.  
1978 *Salpingoporella johnsoni* (Dragastan) - Bassoullet *et al.*, pl. 29, figs. 14-15.

### Diagnosis

"A very small alga with a cylindrical thallus and a conspicuous central canal. Branches are phloiophorous and show an euspondylic arrangement in very narrow verticils. Branches are tilted. Their angle on the thallus varies from 5 to 10 degrees. Sporangia are probably of the cladosporous type." (Original diagnosis from Dragastan (1971)).

Dimensions (cited in Bassoullet *et al.*, 1978) are:

D: 0.20 - 0.31mm

d: 0.10 - 0.15mm

e: 0.020 - 0.030mm

l: 0.05 - 0.07mm

p: 0.02 - 0.04mm  
h: 0.033 - 0.045mm  
w: 14 -20

#### Remarks

This species is very similar to *Salpingoporella pygmaea* (Gumbel) in morphology. However it can be distinguished from this species and all other Late Jurassic - Early Cretaceous members of *Salpingoporella*, with the exception of *Salpingoporella* sp. A defined herein, by its very small dimensions.

#### Global Distribution and Stratigraphic Range

Roumania, Northern Spain.

Kimmeridgian - Tithonian.

#### Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

This species was rare in the study material. It was only recorded from peloidal - bioclastic packstone facies, thought to represent proximal back-shoal environments in the Habshan Formation.

*Salpingoporella pygmaea* (Gumbel) emend. Pia, 1925

Plates 3.155 - 3.159

- T 1891 *Gyroporella pygmaea* n. sp. - Gumbel, text-figs. 6-7.  
1925 *Macroporella pygmaea* (Gumbel) - Pia, pl. 1, figs. 4-7.  
1955 *Macroporella pygmaea* (Gumbel) - Carozzi, pl. 6, fig. 3.  
1962 *Pianella pygmaea* (Gumbel) - Radoičić, p. 202.  
1968 *Pianella pygmaea* (Gumbel) - Elliott, pl. 17, figs. 6-8.  
? 1971 *Macroporella pygmaea* (Gumbel) - Basson and Edgell, pl. 5, figs. 1-3.  
1978 *Salpingoporella pygmaea* (Gumbel) - Bassoulet *et al.*, pl. 30, figs. 6-9. See also for complete synonymy until 1978.

### Diagnosis

"Calcified cylindrical dasyclad tube, external diameter 0.33 - 0.78mm, internal diameter, 0.10 - 0.34mm (d/D 27-43%, usually about 30%), showing consecutive horizontal verticils of branches, about 18-20 verticils per millimeter of length, each verticil of 15-20 branches. The branches are straight, unbranched, near-circular in cross-section, and widen radially with straight sides to the exterior, from a very narrow insertion on the stem-cell cavity to the exterior where they have a diameter of about 0.052mm, sometimes with a terminal widening to give a diameter of 0.090mm." (Description given in Elliott (1968)).

### Remarks

This species was originally described within the genus *Gyroporella* by Gumbel (1891). It was later assigned to *Macroporella* by Pia (1925), and has usually been described under this generic name. However, the species is clearly euspondyle and therefore belongs to the genus *Salpingoporella* as pointed out by Bassoullet *et al.* (1978). This may have been earlier realized by Radoićić (1962) and Elliott (1968) who assigned it to *Pianella*, now known to be a junior synonym of *Salpingoporella*.

This species is very similar to *S. johnsoni*, but possesses larger dimensions. The perpendicular to slightly oblique branches, which are wider in the outer part than in the inner part, and the general dimensions of this species, serve to distinguish it from other Early Cretaceous and Late Jurassic members of *Salpingoporella*, in particular *Salpingoporella grudii* (Radoićić).

### Global Distribution and Stratigraphic Range

Switzerland, Bavaria, Yugoslavia, Roumania, Southern Italy, Southern France, Lebanon, Iraq, Oman Mountains.

Late Oxfordian - Valanginian (?Aptian).

The majority of records of this species are from Kimmeridgian or Tithonian sediments (see Bassoullet *et al.*, 1978). However there are a few significant records from the earliest Cretaceous, notably Elliott (1968) who recorded the species from the Valanginian (but no younger) of Iraq. The extinction of this species may therefore be a useful marker for the recognition of sediments no younger than Valanginian. However, Basson and Edgell (1971) recorded this species from the Late Aptian of Lebanon. The dimensions they give of this species and the morphology of their illustrations are in close agreement with that of *S. pygmaea*. However measurement of their illustrations suggest their specimens have a D value of more than 1mm and a d value of about 0.4mm. These are greater than those for true *S. pygmaea*, and thus question their identification. It is possible that the Late Aptian

material represents a separate species, but part of the *S. johnsoni* - *S. pygmaea* lineage with corresponding increase in dimensions. Further research on the Late Aptian specimens from Lebanon is required.

In this study the species has confidently been recorded from Hauterivian sediments (association with *Choffatella decipiens* and other foraminiferal taxa).

#### Local Occurrence

Hauterivian.

*Cylindroporella arabica* - *Acroporella assurbanipali* Zones.

See range charts provided in Chapter 4 for precise sample distribution.

#### Palaeoecology

Modern-day dasyclads are typically found living in very shallow water depths (usually less than 5m b.s.l.) (Elliott, 1968; Wray, 1977). The delicate nature of this species of *Salpingoporella* means that it is unlikely to have been transported far. It was recorded in protected back-shoal sediments of the Habshan and Lekhwa Formations.

### Genus *Terquemella* Munier-Chalmas, 1877

#### Diagnosis

"Small, disc-like, lenticular or spherical calcareous bodies, with numerous tiny subdermal spherical sporangial cavities, the bodies themselves considered dissociated sporangial structures from Dactyloporae (Dasycladaceae)". (Description by Elliott, 1968).

#### Remarks

This genus has been used in a somewhat artificial sense to group together various sporangial structures thought to originate from fossil Dactyloporae (= Bornetelleae). They are thus unrelated to the morphologically very similar *Acicularia* spicules.

In transverse sections *Acicularia* and *Terquemella* may be indistinguishable. However, in longitudinal sections the elongate, spicular nature of *Acicularia* is evident.

*Coptocampylodon* can be distinguished from *Terquemella* by the presence of longitudinal grooves rather than sporangial pits, plus a more elongate long axis and the occasional presence of a central cavity.

*Terquemella* sp. A  
Plates 3.160 - 3.161

1976 *Terquemella* (?) cf. *triangularis* Ramahlo - Masse, pl. 5, figs. 13-15.

Diagnosis

Small, spherical - lenticular calcareous bodies, circular in transverse section, distinctly lenticular in longitudinal section. Diameter about 0.1-0.15mm, thickness about 0.1mm. Hollow circular cavities of about 0.05mm diameter occur around the outer edge of the body. In transverse sections, between 5 and 8 cavities are present, in longitudinal sections only 2 are visible, a distinctive feature of this species.

Remarks

This species corresponds very well with that described by Masse (1976) as *Terquemella* (?) cf. *triangularis* Ramahlo. The form is clearly distinct from *T. triangularis* which has a characteristic triangular outline in transverse sections, with three sporangial cavities being present.

This species, with its distinctive longitudinal cross-section, is unlike any other Early Cretaceous species of *Terquemella* yet recorded. However, it is very rare in the study material and is hence still poorly known.

Global Distribution and Stratigraphic Range

Southern France, Oman Mountains

Late Barremian

Local Occurrence

Hauterivian.

Cylindroporella arabica Zone.

See range charts provided in Chapter 4 for precise sample distribution.

Palaeoecology

This species was recorded from proximal back-shoal facies of the Habshan Formation. However, its size and shape permit this fossil to be transported considerable distances, so this record may not be *in situ*.

### **3.5: Introduction - Calpionellids**

The taxonomic classification of calpionellids used in this study follows that of Remane (1971, 1978, 1985). Remane (*op. cit.*) has shown, contrary to popular belief (eg. Colom, 1948; Tappan and Loeblich, 1968), that calpionellids, which are only known from Tethyan Tithonian to Valanginian pelagic sediments, are unrelated to modern tintinnids, hence their systematic position is uncertain. Calpionellids have a primary hyaline calcite wall, whilst that of tintinnids is organic. Calpionellids are also unrelated to the Aptian - Albian Colomiellidae which have a microgranular calcite wall.

Calpionellids are thus grouped at the family level (the Calpionellidae), with higher taxonomic classification presently remaining unknown.

In the following section a description, discussion and comparison of genera is provided. This is followed by the systematic description of species within a genus arranged in alphabetical order, unless the type species of a genus is present, which is always placed first.

For each species a synonymy is provided. This detail of this varies for different species. For those species which are stratigraphically useful, or have been taxonomically revised an attempt has been made to provide as full a synonymy as possible. This has often been necessary to establish the true stratigraphic and geographic range of a species. For certain less important species a more basic synonymy is given which outlines the type description, generic shifts and at least one recent well illustrated reference, if available.

Following the synonymy a description of the species is given, followed by remarks concerning identification of the species, comparison with similar taxa, evolutionary relationships, etc. This is followed by a statement of the species global distribution and stratigraphic range. The local occurrence of a species within the study area is noted. Finally a statement of the palaeoecology of a species is given.

The letter "T" before a record of a species in the following synonymy lists indicates the type description of that species.

### 3.6: Systematic Micropalaeontology - Calpionellids

Family CALPIONELLIDAE Bonet, 1956

Genus *Calpionella* Lorenz, 1902

Type Species *Calpionella alpina* Lorenz, 1902

#### Diagnosis

The genus is characterized by a short cylindrical collar, narrower than the often subspherical or elongate oval lorica. The base of the collar is well defined and a very typical "shoulder" appears below the collar in all sections.

#### Remarks

The morphology of the collar and lorica in this genus makes it extremely distinctive. The only possible confusion at generic level is between small, atypical specimens of Early Berriasian *Calpionella alpina* with a less pronounced shoulder and oblique sections of *Crassicollaria parvula* Remane, but the separation of these forms is not important for stratigraphy.

Only two species are present within the genus: *Calpionella alpina* and *Calpionella elliptica* Cadisch. The genus attains its maximum frequency around the Tithonian - Berriasian boundary. At this level faunas may consist almost exclusively of *C. alpina*.

*Calpionella alpina* Lorenz, 1902

Plates 3.162 - 3.163

- T 1902 *Calpionella alpina* n. sp. - Lorenz, text-figs. 1-2.  
1985 *Calpionella alpina* Lorenz - Remane, text-figs. 6, 18.1-3.

#### Diagnosis

Lorica somewhat variable in shape, but subspherical or elongate-ovoid with a rounded aboral pole. Distinctive projecting short collar, approximately two-thirds the width of the lorica. Shoulder is present between the lorica and collar. Typical length: 45-105 microns, typical width: 35-75 microns.

### Remarks

As noted in the above generic remarks *Calpionella* is clearly distinctive from other calpionellid genera. *Calpionella alpina* can be distinguished from *Calpionella elliptica*, which has a relatively longer, elongate lorica, and less distinctive shoulder between lorica and collar. Certain oblique sections of *Calpionella elliptica* look exactly like small *Calpionella alpina*. The distinction of the two species is important for stratigraphy, and can be achieved by comparison of the length (without collar) to width ratio. All sections with a ratio  $>1.35 = C. elliptica$ , those  $<1.25 = C. alpina$  (Remane, 1985).

*C. alpina* has a relatively long range of early Late Tithonian (Calpionellid Zone A2 of Remane (1985)) to Late Berriasian (Zone D3). Within this range however the species shows significant morphological changes in the course of evolution. Large, elongate forms pass into small, subspherical forms, which are replaced by a small, elongate forms. Recognition of these forms is thus useful in biostratigraphic studies and is explained in detail by Remane (1985). The specimens obtained by from the Oman Mountains in this study are small subspherical forms typical of the earliest Berriasian (Zone B2 of Remane (1985)).

### Global Distribution and Stratigraphic Range

Pan-Tethyan.

Late Tithonian - Late Berriasian (but see also notes on morphogroups above).

### Local Occurrence

Early Berriasian.

*Calpionella alpina* Zone.

See range charts provided in Chapter 4 for precise sample distribution.

### Palaeoecology

Open marine, pelagic sedimentation. Water depths probably at least bathyal, possibly deeper. Possible anaerobic bottom water conditions, considering lack of benthos associated with calpionellid faunas.

Genus *Calpionellopsis* Colom, 1948  
Type Species *Calpionella thalmanni* Colom, 1939

Diagnosis

Elongate parallel or sub-parallel sided lorica, with length markedly greater than width, with pointed or rounded aboral end. The inner rim of the opening of the lorica is formed by a separate ring, showing extinction between crossed nicols at 45 degrees. The genus thus possesses a small internal collar, which is optically distinct from the lorica wall.

Remarks

The presence of an internal optically distinct internal collar distinguishes this genus from other calpionellid genera. However, this feature is not always conspicuous and may be lost by disaggregation after death. *Calpionellites* Colom also possesses an internal collar, but in this genus the lorica wall and collar are deflected inward by 45° at the lorica opening, and there is a partial space between the lorica and collar giving the appearance the lorica wall has bifurcated.

Two species are present within the genus *Calpionellopsis*: *Calpionellopsis simplex* (Colom) and *Calpionellopsis oblonga* (Cadisch). The later species is considered to be the senior synonym of *Calpionella thalmanni* Colom, the type species of the genus (Remane, 1965).

*Calpionellopsis oblonga* (Cadisch, 1932)

Plates 3.164 - 3.167

- T 1932 *Calpionella oblonga* n. sp. - Cadisch, pl. 3, figs. 20-21.  
1939 *Calpionella thalmanni* n. sp. - Colom, pl. 2, fig. 17.  
1965 *Calpionellopsis oblonga* (Cadisch) - Remane, pl. 5, pl. 6, fig. 16. Also full synonymy until 1965.  
1985 *Calpionellopsis oblonga* (Cadisch) - Remane, text-figs, 10, 18.7-8.

Diagnosis

Elongate species of *Calpionellopsis*, with straight sided lorica in which the walls converge slightly towards the opening over two-thirds of the length. Axial sections show a pointed aboral end to the lorica. Typical length: 100-120 microns, typical width: 40-60 microns.

### Remarks

As noted in the above generic remarks, *Calpionellopsis* cannot easily be confused with any other genus of calpionellid. *Calpionellopsis oblonga* can be distinguished from *Calpionellopsis simplex*, by its slightly convergent lorica walls and pointed aboral end. *C. simplex* is also broader than *C. oblonga*.

As noted above, Remane (1965) considers *C. oblonga* to be the senior synonym of *Calpionella thalmani*, the type species of *Calpionellopsis*.

### Global Distribution and Stratigraphic Range

Probably Pan-Tethyan.

Berriasian - Earliest Valanginian (Calpionellid Zones D1-D3, ?E of Remane (1985)).

### Local Occurrence

Early Berriasian.

*Calpionella alpina* Zone.

See range charts given in Chapter 4 for precise sample distribution.

### Palaeoecology

Open marine, pelagic sedimentation. Water depths probably at least bathyal, possibly deeper. Possible anaerobic bottom water conditions, considering lack of benthos associated with calpionellid faunas.

Genus *Crassicollaria* Remane, 1962

Type Species *Crassicollaria brevis* Remane, 1962

### Diagnosis

Elongate, elliptical lorica with length markedly greater than width, and with pointed or sub-rounded aboral end. Possesses a wide opening with a marked collar. Below the collar there is a more or less pronounced swelling, but never a well defined shoulder as in *Calpionella*.

### Remarks

This genus can be distinguished from the similar genus *Calpionella* by its wider opening, smooth transition from lorica to collar and lack of well defined shoulder.

The collar is variable. In some species (*C. intermedia* Remane, *C. brevis*), the distal part shows a sharp outward deflection. According to Remane (1985) this character is inherited from the genus *Tintinnopsella*, since a transition from *Tintinnopsella carpathica* (Murgeanu and Filipescu) through *Tintinnopsella remanei* Borza to *C. intermedia* can be observed in the Late Tithonian - Early Berriasian.

Within the genus there is a progression from elongate (*C. intermedia*) to shorter, conical forms (*C. brevis*, *C. parvula* Remane).

*Crassicollaria parvula* Remane, 1962

Plates 3.168 - 3.169

- T 1962 *Crassicollaria parvula* n. sp. - Remane, text-figs. 36-45.  
1985 *Crassicollaria parvula* Remane - Remane, text-fig. 18.13.

Diagnosis

Short conical species of *Crassicollaria*, with an elliptical lorica and a collar which does not show any outward deflection. Axial sections show a pointed aboral end to the lorica. Typical length: 63 microns, typical width: 36 microns.

Remarks

This species can be distinguished from other species of *Crassicollaria* by the presence of a collar which shows no outward deflection. This species is also shorter and less elongate than *C. brevis* and *C. intermedia*.

In random sections it may be confused with *Calpionella alpina*, but can be distinguished by the lack of shoulder between collar and lorica, and by the presence in axial sections of a pointed aboral end.

Global Distribution and Stratigraphic Range

Probably Pan-Tethyan.

Late Tithonian - Early Berriasian (Calpionellid Zones A2?/3 - B?/C of Remane (1985)).

Local Occurrence

Early Berriasian.

*Calpionella alpina* Zone.

See range charts provided in Chapter 4 for precise sample distribution.

Palaeoecology

Open marine, pelagic sedimentation. Water depths probably at least bathyal, possibly deeper. Possible anaerobic bottom water conditions, considering lack of benthos associated with calpionellid faunas.

## **CHAPTER 4: BIOSTRATIGRAPHY**

### **4.1: Microfossil Distribution**

Figures 4.1 - 4.9 show the distribution of microfossils in the Thamama Group sections of Wadi Mi'aidin, Jebel Madar and Wadi Bani Kharus. For each section, the occurrence of microfossils in individual samples is plotted in terms of qualitative abundance (i.e rare, present, common, abundant or questionable). The distribution of foraminifera, algae, calpionellids, and other microfossil groups (eg. molluscan debris, calcified radiolaria, spicules) is shown in separate columns.

The microfossil distribution charts also show the microfacies character for each of the samples in the studied sections. Broad microfacies type is indicated by reference to the classification of Dunham (1962). The types of allochems present and any general sedimentary features (eg. burrows, dolomitization, micritization) are shown in separate columns.

The significance of the microfossil distribution in terms of its application to chronostratigraphy and biozonation is shown on the right-hand side of each diagram (see Section 4.3 for discussion of the biozonation scheme employed).

Figures 4.1 - 4.9 form the raw biostratigraphic data of this study. This data has been interpreted, partly using Graphic Correlation techniques (see Section 4.2), to develop a biozonation scheme, via a total stratigraphic range chart, for the Thamama Group in the Oman Mountains area (see Section 4.3), and serves as the basis for biostratigraphic correlations between sections (see Section 4.4), which in turn reveals details of the time transgressive nature of sedimentary facies belts within the Thamama Group. The palaeoenvironmental interpretations possible from the raw biostratigraphic and sedimentological data shown in Figures 4.1 - 4.9 have been used in the development of a model for the geological history of the Thamama Group in the study area (see Chapter 5).

# DISTRIBUTION OF MICROFOSSILS AND MICROFACIES RAYDA AND SALIL (PARS) FORMATIONS, WADI MI' AIDIN

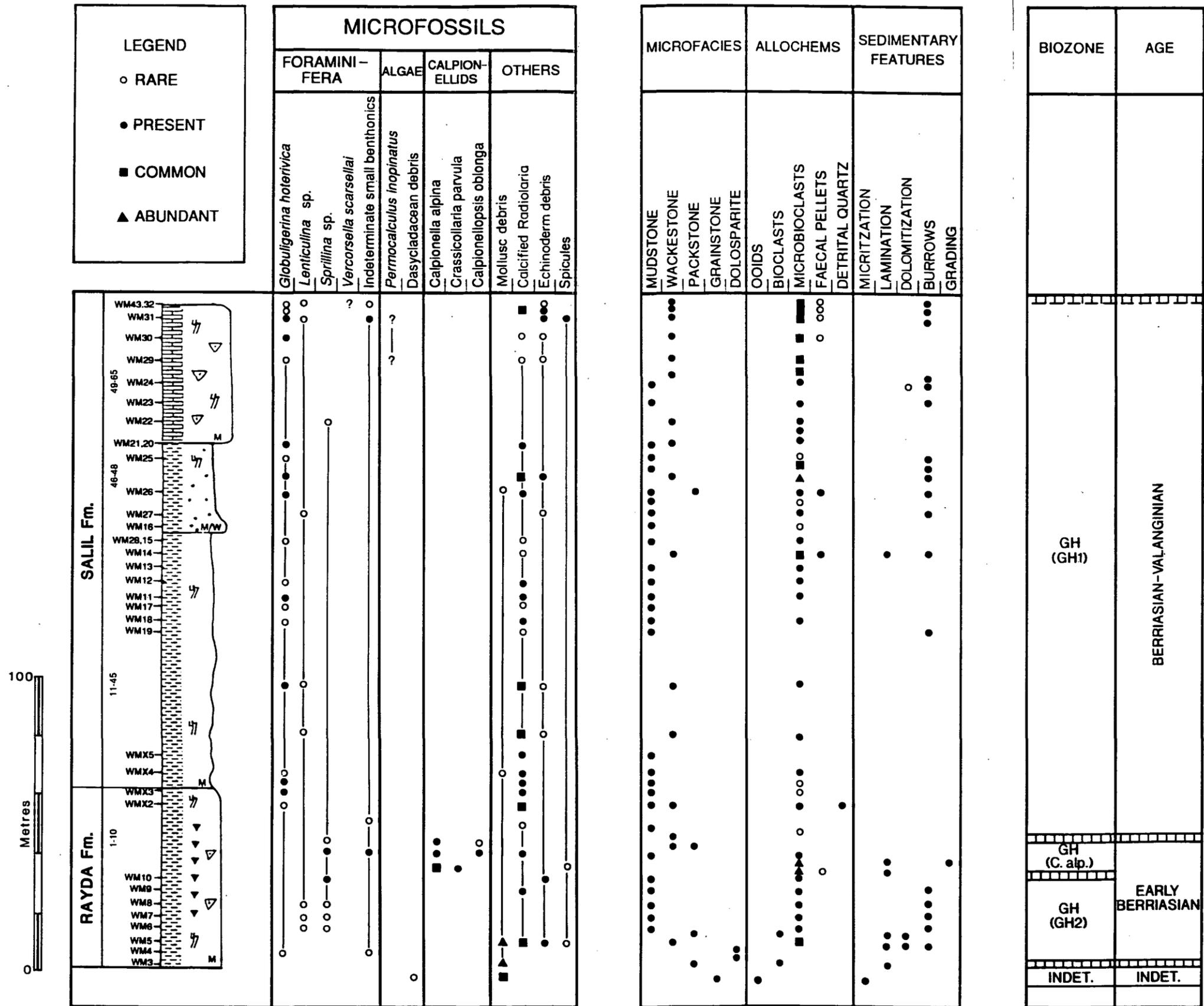
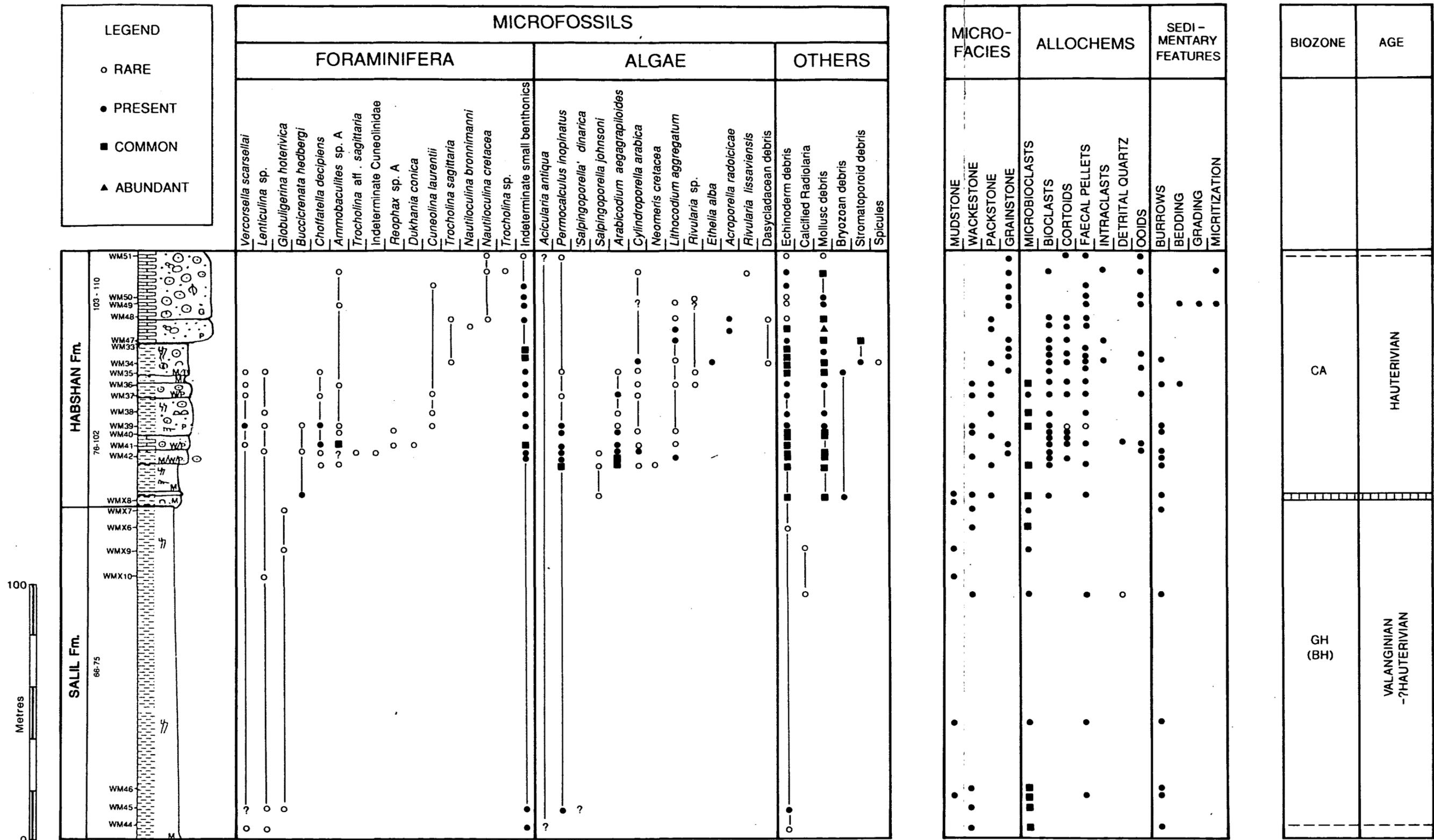


Figure 4.1

# DISTRIBUTION OF MICROFOSSILS AND MICROFACIES SALIL (PARS) AND HABSHAN FORMATIONS, WADI MI' AIDIN



Metres

FORMATION	ELEVATION (m)	SAMPLES	MICROFOSSIL DISTRIBUTION
HABSHAN Fm.	103-110	WM51, WM50, WM49, WM48	Foraminifera: ●, ○ Algae: ●, ○ Others: ●, ○
	76-102	WM47, WM33, WM34, WM35, WM36, WM37, WM38, WM39, WM40, WM41, WM42	Foraminifera: ●, ○ Algae: ●, ○ Others: ●, ○
	66-75	WMX8, WMX7, WMX6, WMX9, WMX10	Foraminifera: ○ Algae: ○ Others: ○
	66-75	WM46, WM45, WM44	Foraminifera: ○ Algae: ○ Others: ○

Figure 4.2

# DISTRIBUTION OF MICROFOSSILS AND MICROFACIES LEKHWAIR AND KHARAIB FORMATIONS, WADI MI' AIDIN

LEGEND	
○	RARE
●	PRESENT
■	COMMON
▲	ABUNDANT

	MICROFOSSILS		
	FORAMINIFERA	ALGAE	OTHERS
	<i>Cuneolina laurentii</i> <i>Trocholina</i> sp. <i>Trocholina</i> aff. <i>sagittaria</i> <i>Chofatella decipiens</i> <i>Vercorsella arenata</i> <i>Nautiloculina bronnimanni</i> <i>Trocholina sagittaria</i> <i>Ammobaculites</i> sp. A <i>Cuneolina hensoni</i> <i>Cuneolina camposaurii</i> Indeterminate <i>Cuneolinidae</i> <i>Praechrysalidina infractetacea</i> <i>Trocholina molesta</i> <i>Vercorsella scarsella</i> <i>Epairolitina lentiginosa</i> <i>Epairolitina chatollaisi</i> <i>Ammobaculites</i> sp. <i>Buccerinata hedbergi</i> <i>Dukhania cecilia</i> Indeterminate small benthonics <i>Perminoculus inopinatus</i> <i>Salingoporella pygmaea</i> <i>Actinoporella assuraniipali</i> <i>Lithocodium aggregatum</i> <i>Arableodinium aegagropiloides</i> <i>Cylindroporella sugdeni</i> <i>Coplocampyloeden lineolatus</i> <i>Actinoporella pedolica</i> <i>Salingoporella dinarica</i> <i>Actularia antiqua</i> <i>Salingoporella muhlbergii</i> Dasycladacean debris Mollusc debris Echinoderm debris Bryozoan debris Stromatopora debris Spicules Coral debris		
WM69-192			
WM68			
WM67-192			
WM66			
WM65			
WMX13			
WMX12			
WMX11			
WM64			
WM63			
WM62			
WM61			
WM60			
WM59			
WM58			
WM57			
WM107			
WM106			
WM105			
WM104			
WM103			
WM102			
WM56			
WM55			
WM54			
WM53			
WM52			

	MICROFACIES	ALLOCHEMS	SEDIMENTARY FEATURES
	MUDSTONE WACKSTONE PACKSTONE GRAINSTONE DOLOSPARITE BIOCLASTS CORTOIDS FAECAL PELLETS INTRACLASTS BURROWS DOLOMITIZATION ALGAL VUGS/FENESTRAE LAMINATION MICRITIZATION		
WM69-192			
WM68			
WM67-192			
WM66			
WM65			
WMX13			
WMX12			
WMX11			
WM64			
WM63			
WM62			
WM61			
WM60			
WM59			
WM58			
WM57			
WM107			
WM106			
WM105			
WM104			
WM103			
WM102			
WM56			
WM55			
WM54			
WM53			
WM52			

BIOZONE	AGE
PL (PA-CD)	LATE BARREMIAN - EARLY APTIAN
PI	HAUTERIVIAN - BARREMIAN
AA	HAUTERIVIAN
CA	

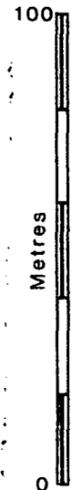


Figure 4.3

# DISTRIBUTION OF MICROFOSSILS AND MICROFACIES, SHUAIBA FORMATION, WADI MI' AIDIN

LEGEND	
○	RARE
●	PRESENT
■	COMMON
▲	ABUNDANT

MICROFOSSILS			
FORAMINIFERA	ALGAE	OTHERS	
<i>Palorbitolina lenticularis</i>			
<i>Dukhanina conica</i>			
<i>Cuneolina laurentii</i>			
<i>Orbitolinopsis simplex</i>			
<i>Nautiloculina bronnimanni</i>			
<i>Ammobaculites</i> sp. A			
Indeterminate small benthonics			
<i>Lithocodium aggregatum</i>			
<i>Saproporella dinarica</i>			
Dasycladacean debris			
Echinoderm debris			
Mollusc debris			
Coral debris			

MICROFACIES	ALLO-CHEMS	SEDIMENTARY FEATURES
BOUNDSTONE		
MUDSTONE		
WACKESTONE		
PACKSTONE		
GRAINSTONE		
BIOLASTS		
FAECAL PELLETS		
CORTOIDS		
BURROWS		

BIOZONE	AGE
SD	APTIAN
PL (PL)	EARLY APTIAN

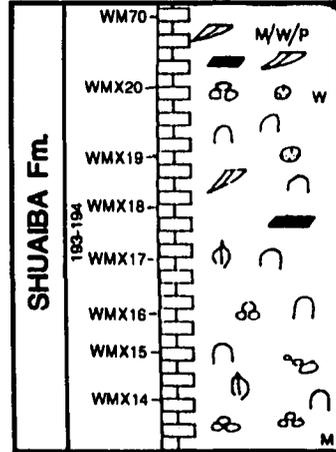


Figure 4.4

# DISTRIBUTION OF MICROFOSSILS AND MICROFACIES, LOCALITY 1, JEBEL MADAR

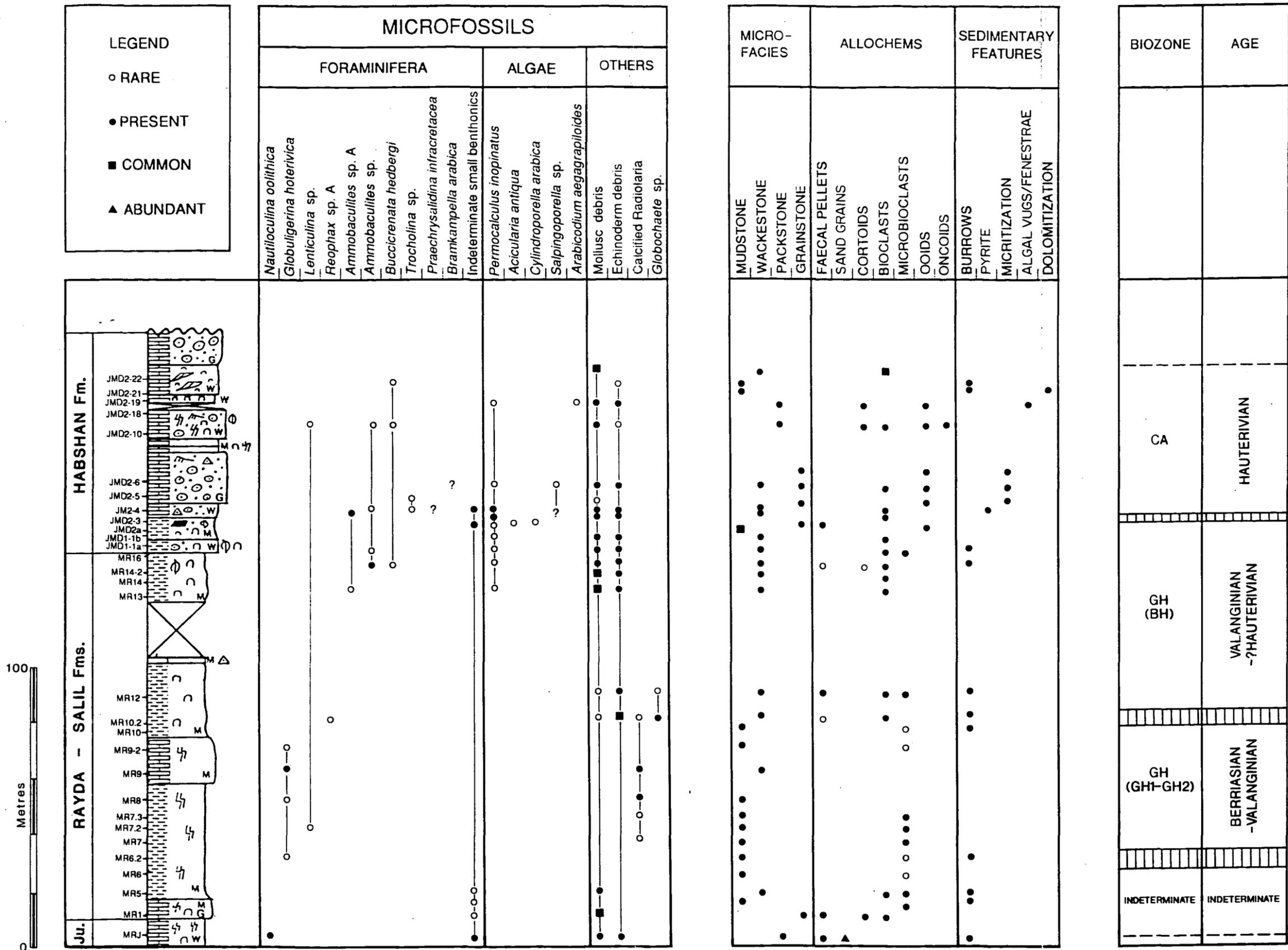


Figure 4.5

# DISTRIBUTION OF MICROFOSSILS AND MICROFACIES SALLIL - LEKWHAIR FORMATIONS, LOCALITY 2, JEBEL MADAR

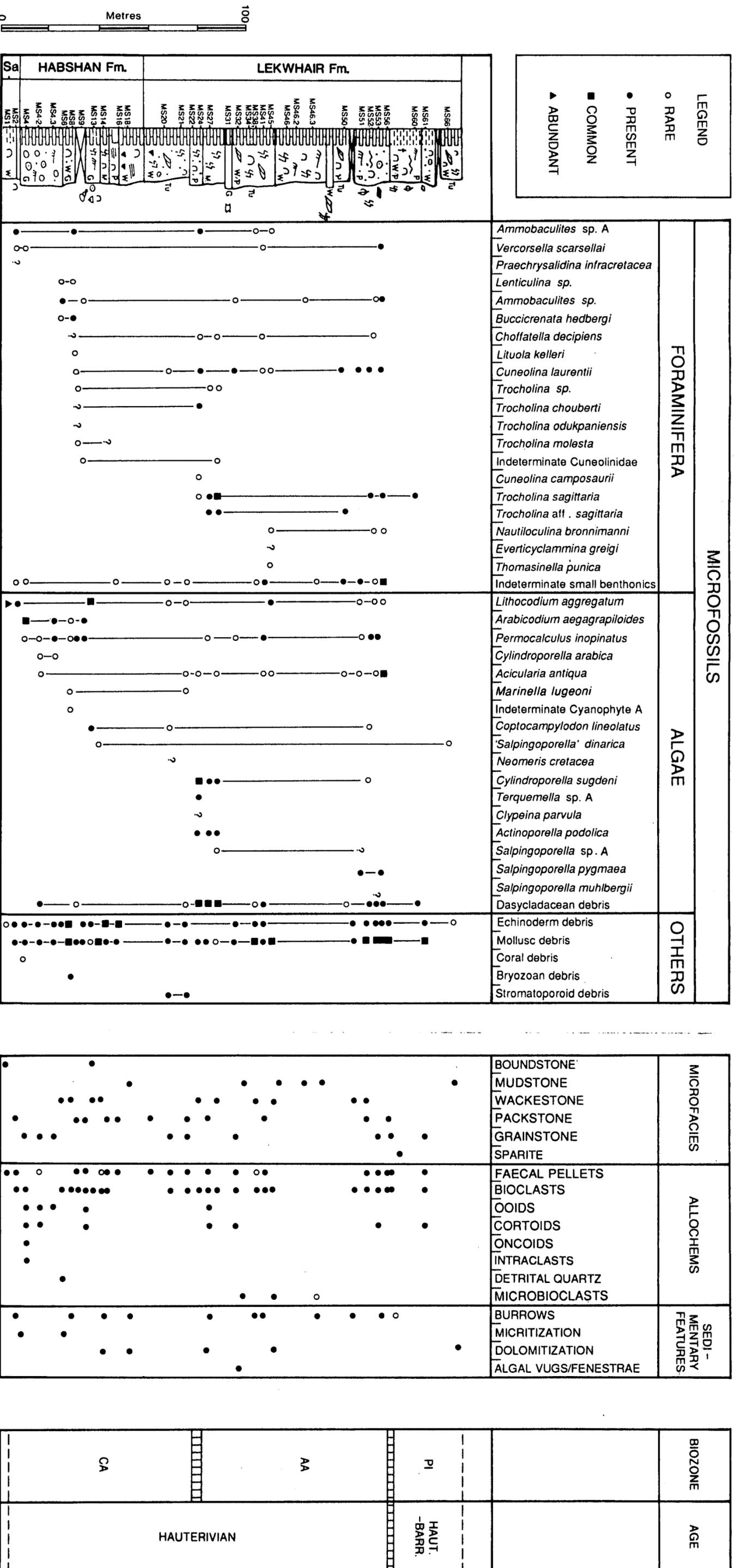


Figure 4.6

# DISTRIBUTION OF MICROFOSSILS AND MICROFACIES KHARAIB AND SHUAIBA FORMATIONS, LOCALITY 2, JEBEL MADAR

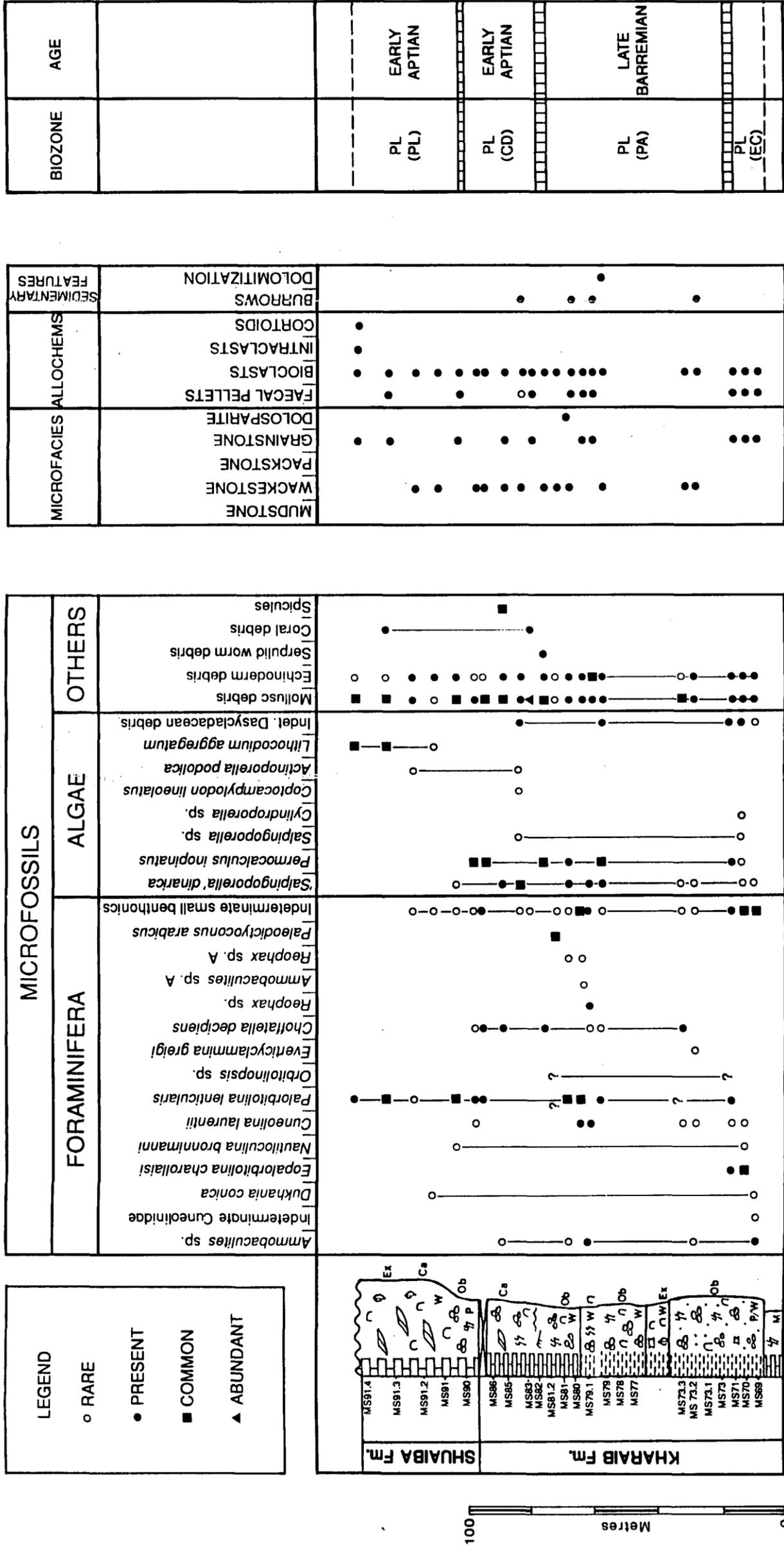


Figure 4.7

# DISTRIBUTION OF MICROFOSSILS AND MICROFACIES RAYDA AND SALIL FORMATIONS, WADI BANI KHARUS

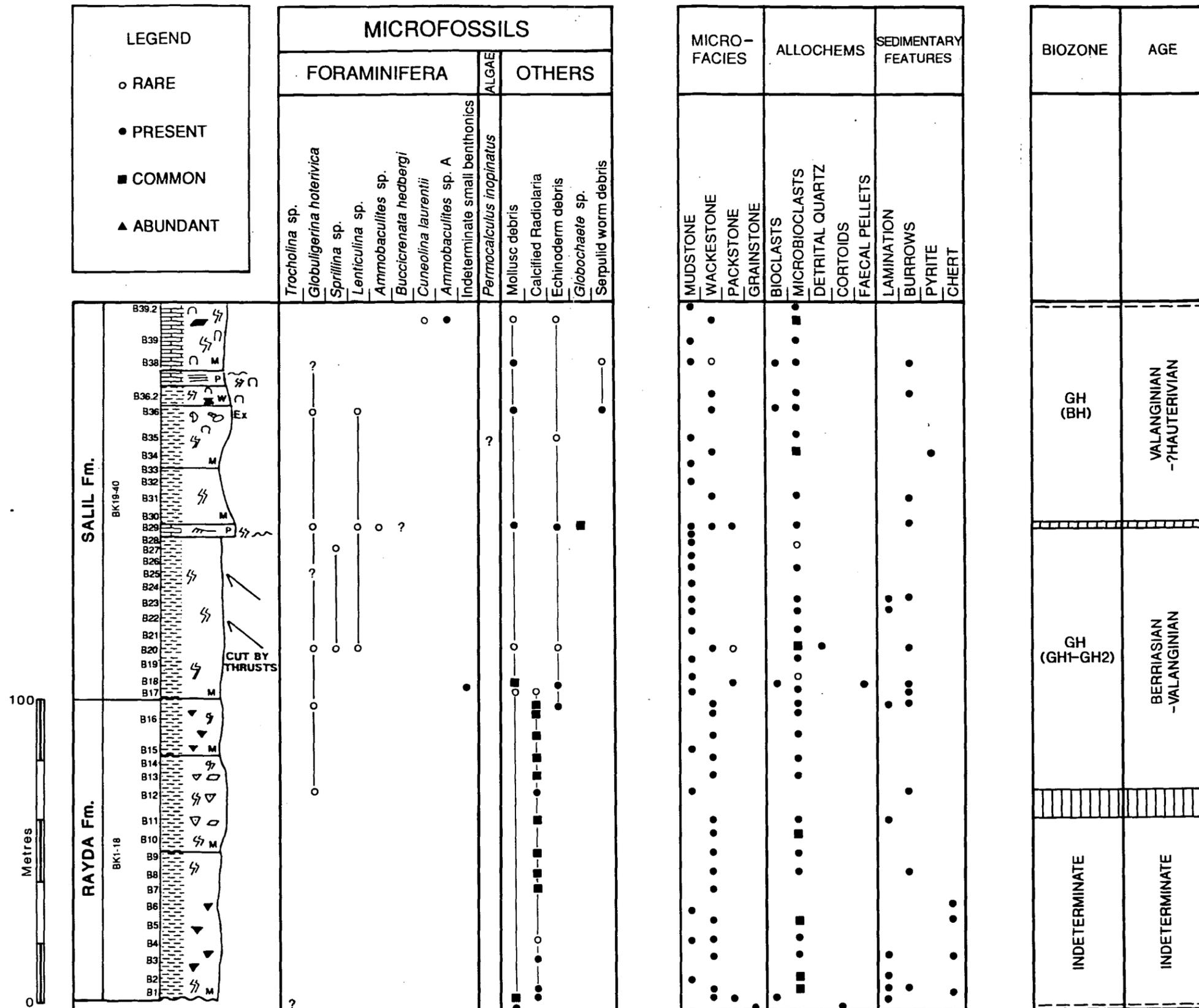


Figure 4.8

# DISTRIBUTION OF MICROFOSSILS AND MICROFACIES HABSHAN - SHUAIBA FORMATIONS, WADI BANI KHARUS

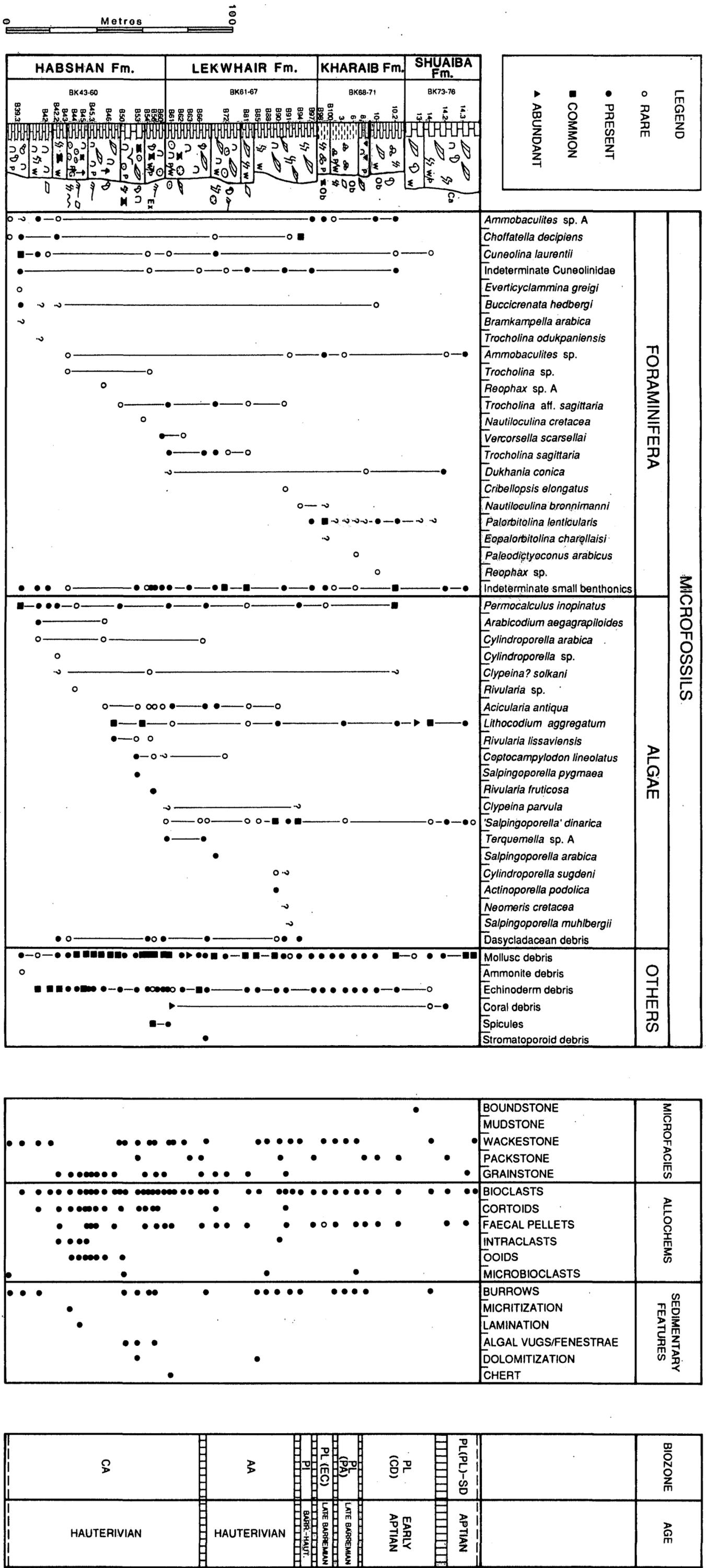


Figure 4.9

## **4.2: Graphic Correlation**

In order to fully employ all the biostratigraphic data presented on the microfossil distribution charts (Figures 4.1 - 4.9) the semi-quantitative Graphic Correlation technique devised by Shaw (1964) was used in this study. Using this technique has five distinct advantages:

- (i) All the biostratigraphic data is considered when undertaking correlations between sections, not just selected fossil occurrences.
  
- (ii) It provides a means of developing a composite standard reference section in which the maximum range of each taxa is shown. This can be used as the basis for developing a regional biozonation scheme.
  
- (iii) It provides an alternative means of making chronostratigraphically significant correlations between sections, and hence provides a means of testing correlations made by more standard biostratigraphic correlation methods (eg. on the extinction levels of significant taxa) which may in turn be facies controlled.
  
- (iv) It highlights spurious fossil occurrences which may be the result of reworking or misidentification. These can then be rechecked.
  
- (v) It provides information on the rate of rock accumulation (not strictly sedimentation rate), changes in this rate, and highlights sedimentary hiatus.

The Graphic Correlation technique was first described by Shaw (1964). Later, Miller (1977) provided an excellent account of how to apply the technique, whilst Edwards (1984) has provided a discussion on the

reasons why the technique works using a hypothetical dataset. Sweet (1979) provided an example of the use of the technique.

Graphic Correlation involves graphing two outcrop (or well) sections against each other on a normal X/Y plot where X equals section 1 (often chosen as a standard reference section - see below) and Y section 2. The oldest rocks in both sections are plotted nearest to the origin of the graph. The tops (extinction points) and bases (inceptions) of individual fossil taxa are plotted as points on this graph, and a Line of Correlation (LOC) drawn through them, with most tops to the right of the line and most bases to the left, or better still, lying on the LOC (see Figure 4.10). This could be calculated as a regression line, but it is best if the palaeontologist draws a "line of best fit" taking into account his/her interpretation of the validity and significance of each of the data points. Points that lie far off the LOC are often reworked, facies controlled or misidentified taxa. Time significant sedimentological features can also be used in the construction of the LOC (eg. hardground surfaces). The LOC must pass through points which relate to known isochronous events (eg. a layer of volcanic ash). Once the LOC has been constructed, correlation of the two sections is then possible via this line.

Edwards (1984) noted that the Graphic Correlation method makes seven assumptions: (1) the law of superposition holds; (2) the taxa are consistently identified; (3) the first and last stratigraphic occurrences of a taxon are non-recurring events; (4) the first and last stratigraphic occurrences of a taxon (globally) are excellent indicators of geological time; (5) at the level of precision at which most stratigraphic work is done, the relative rates of rock accumulation in the studied sections vary in a manner that can be approximated by a line or a series of line segments; (6) occurrences of fossil taxa used in the method indicate the presence of living taxa at the time of sediment accumulation (ie. reworking and contamination do not exist, or, if they do, the species involved can be recognized and disregarded); (7) the best line of correlation is that which causes the minimum net disruption of the best established ranges, subject to the best judgement of the compositor.

As stated above, this method has the advantage that it considers all the palaeontological data available, and thus diminishes the effects of facies control on fossil ranges and correlation. However, because the

Simplified example of graphic correlation  
to extend fossil ranges in the composite  
Standard Reference Section.

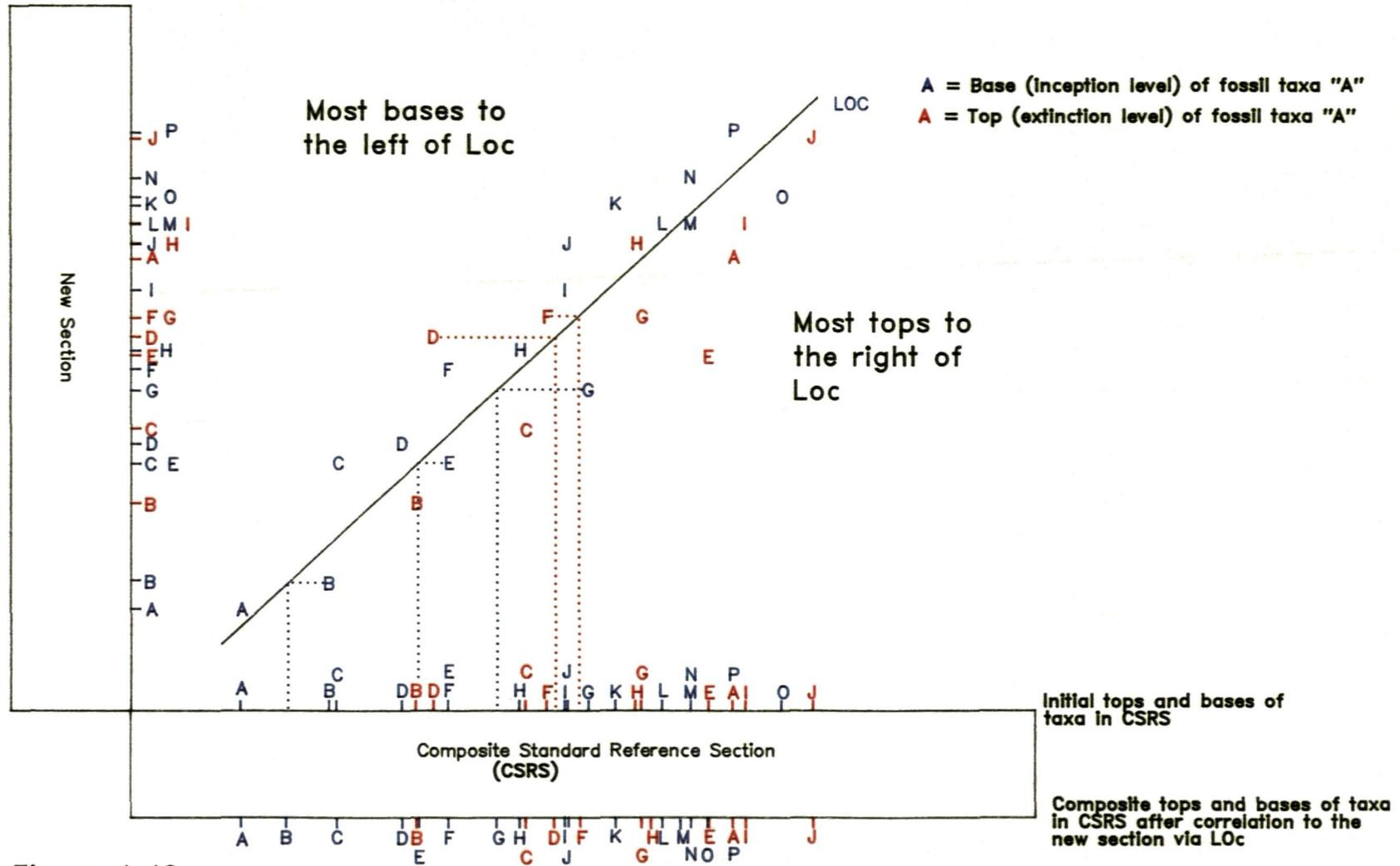


Figure 4.10

correlation in effect becomes a function of the rate of rock accumulation (not simply sedimentation rate, but also including compaction, etc), in sequences in which this is highly variable there may be drawbacks to using the method. This problem of the need to assume a linear rate of rock accumulation is highlighted by Harper and Crowley (1984) and is also discussed by Miller (1977) and Edwards (1984, 1985). Note that in carbonate platform and basinal settings such as those in which the Thamama Group of the Oman Mountains was deposited, rock accumulation rates can be considered to be relatively uniform.

The angle of the LOC reflects the rate of rock accumulation. Changes in the angle of the LOC imply changes in this rate, and therefore possible changing sedimentary regimes. A horizontal terrace within a LOC indicates that a hiatus is present in a section being compared to a standard reference section (see below for discussion of this concept).

The Graphic Correlation method can be used to develop a Composite Standard Reference Section (CSRS) by plotting all other sections against one original section. This original section should be as complete as possible with no stratigraphic breaks. It should also have a large and varied fossil content, be the thickest section possible and have been extensively sampled.

Fossil ranges in the CSRS are progressively maximised by incorporating data from other sections. This is achieved as follows:

In a graphic correlation of a given section to the CSRS, some tops will plot to the left of the LOC and some bases will plot to the right of it. This indicates that the range of these taxa is currently incomplete in the CSRS. In order to place their correct position on the CSRS tops are moved to the right and bases to the left until the LOC is reached. The points in the CSRS directly below these points in the LOC are the corrected bases and tops for each species. Figure 4.10 illustrates a simple example of how this works. This method can also be used to plot on the CSRS taxa which do not occur in the original CSRS, but do occur in new sections graphed against it.

Equal divisions of the CSRS can be considered as chronostratigraphically significant units and used for correlation between sections via a graphically defined LOC. These are termed Composite Standard Time Units (CSTU's). They are chronostratigraphically significant because they relate to the rate of rock accumulation which is thought to be effectively constant. Furthermore, the Graphic Correlation method allows a range chart of taxa to be derived from the CSRS which can be expressed in terms of CSTU's.

As noted in Section 4.1, Graphic Correlation has been used in this study as a means of correlation and as a means of developing a biozonation scheme via construction of a total stratigraphic range chart. Figures 4.11 and 4.12 present the graphing stages of the method when applied to the Thamama Group sections studied at Wadi Mi'aidin, Jebel Madar and Wadi Bani Kharus.

Figure 4.11 is a graphic correlation for Jebel Madar and Wadi Mi'aidin. Wadi Mi'aidin is adopted as the Composite Standard Reference Section because it honours the criteria listed above for selecting a CSRS: it is the thickest section, there are no major stratigraphic breaks present, it has been sampled extensively and it has a varied fossil content. The data points on the right-hand edge of the Jebel Madar column, and on the upper edge of the Wadi Mi'aidin column are the original tops and bases as recorded in Figures 4.1 - 4.7. Those on the lower edge of the Wadi Mi'aidin section represent the tops and bases after the sections have been composited via the LOC. The LOC shows a change in angle because of a change in rock accumulation rates between the Rayda - Salil sections and the Habshan - Shuaiba sections. This reflects the change from basinal - slope facies to platformal facies. The CSTU's are shown for Wadi Mi'aidin (the CSRS) and are correlated to Jebel Madar.

Figure 4.12 shows the graphic correlation for Wadi Bani Kharus and the CSRS (derived from Wadi Mi'aidin). The positioning of datasets is as for Figure 4.11. The LOC is effected by faulting in the Wadi Bani Kharus section and is therefore less reliable for correlation of the Rayda and Salil sections. The lower edge of the CSRS section displays the final tops and bases of taxa as a result of compositing Wadi Bani Kharus to the CSRS. This is used as the basis for the total range chart shown in Figure 4.13, which is in turn used in the

GRAPHIC CORRELATION PLOT FOR JEBEL MADAR - WADI MI' AIDIN  
 WADI MI' AIDIN IS ADOPTED AS THE  
 COMPOSITE STANDARD REFERENCE SECTION (CSRS)

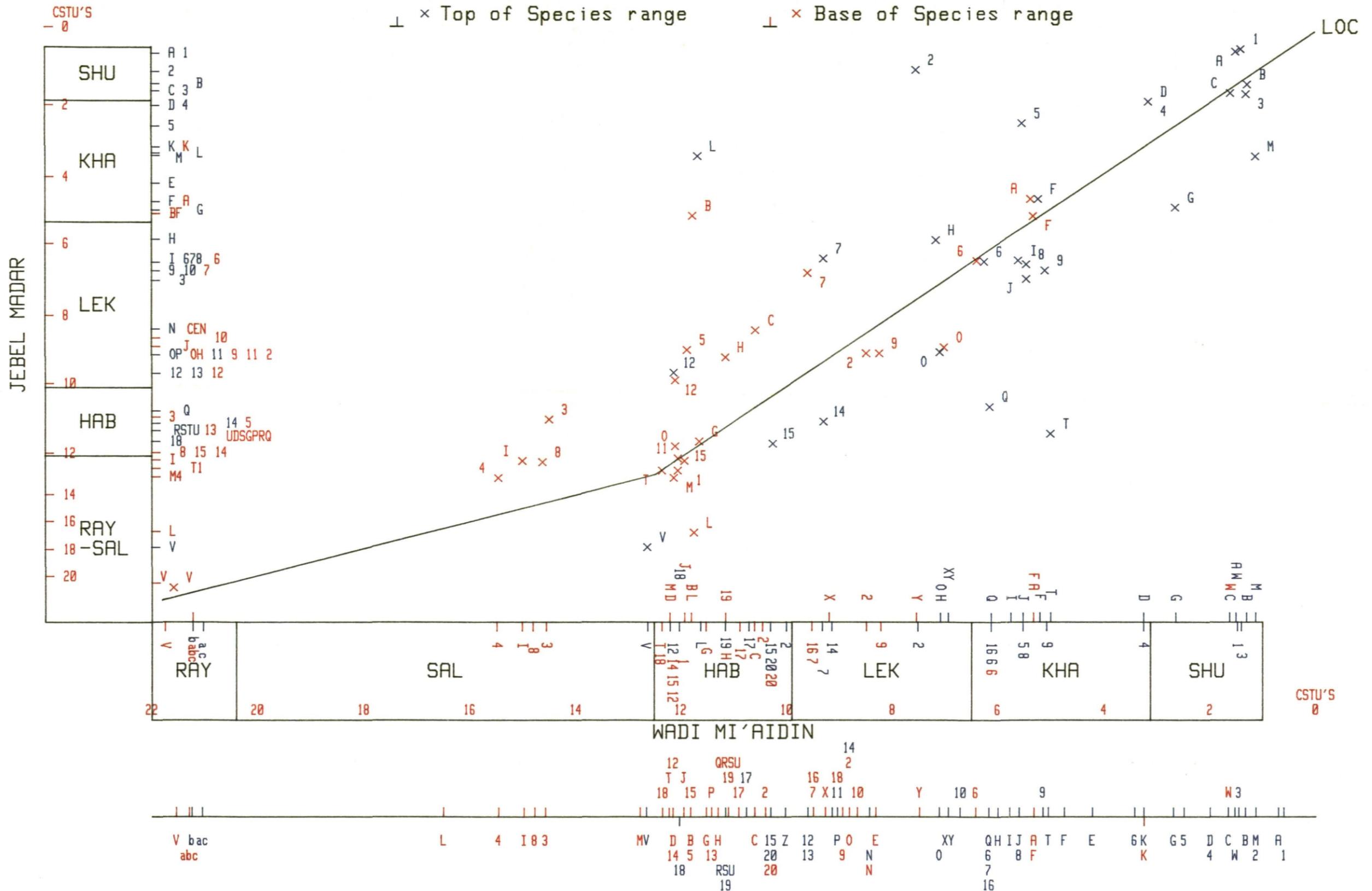


Figure 4.11

KEY FOR FIGURES 4.11 AND FIGURE 4.12

Foraminifera

A = *P. lenticularis*  
B = *D. conica*  
C = *N. bronnimanni*  
D = *C. decipiens*  
E = *E. greigi*  
F = *E. charollaisi*  
G = *C. laurentii*  
H = *T. sagittaria*  
I = *V. scarsellai*  
J = *T. aff. sagittaria*  
K = *P. arabicus*  
L = *Reophax* sp. A  
M = *Ammobaculites* sp. A  
N = *T. punica*  
O = *C. camposaurii*  
P = *T. chouberti*  
Q = *T. molesta*  
R = *T. odukpaniensis*  
S = *L.?* *kelleri*  
T = *B. hedbergi*  
U = *B. arabica*  
V = *G. hoterivica*  
W = *O. simplex*  
X = *V. arenata*  
Y = *C. hensoni*  
Z = *N. cretacea*  
AA = *C. elongatus*

Calcareous algae

1 = *L. aggregatum*  
2 = *A. podolica*  
3 = "*S.*" *dinarica*  
4 = *P. inopinatus*  
5 = *C. lineolatus*  
6 = *S. muehlbergii*  
7 = *S. pygmaea*  
8 = *A. antiqua*  
9 = *C. sugdeni*  
10 = *Salpingoporella* sp. A  
11 = *Terquemella* sp. A  
12 = *N. cretacea*  
13 = *M. lugeoni*  
14 = *A. aegagrapiloides*  
15 = *C. arabica*  
16 = *A. assurbanipali*  
17 = *A. radoicici*  
18 = *S. johnsoni*  
19 = *E. alba*  
20 = *R. lissaviensis*  
21 = *C.?* *solkani*  
22 = *C. parvula*  
23 = *R. fruticosa*  
24 = *S. arabica*

Calpionellids

a = *C. alpina*  
b = *C. parvula*  
c = *C. oblonga*

GRAPHIC CORRELATION PLOT FOR WADI BANI KHARUS  
 - COMPOSITE STANDARD REFERENCE SECTION (CSRS)  
 CSRS Based on original Wadi Mi'aidin section (see text)  
 ⊥ × Top of Species range      ⊥ × Base of Species range

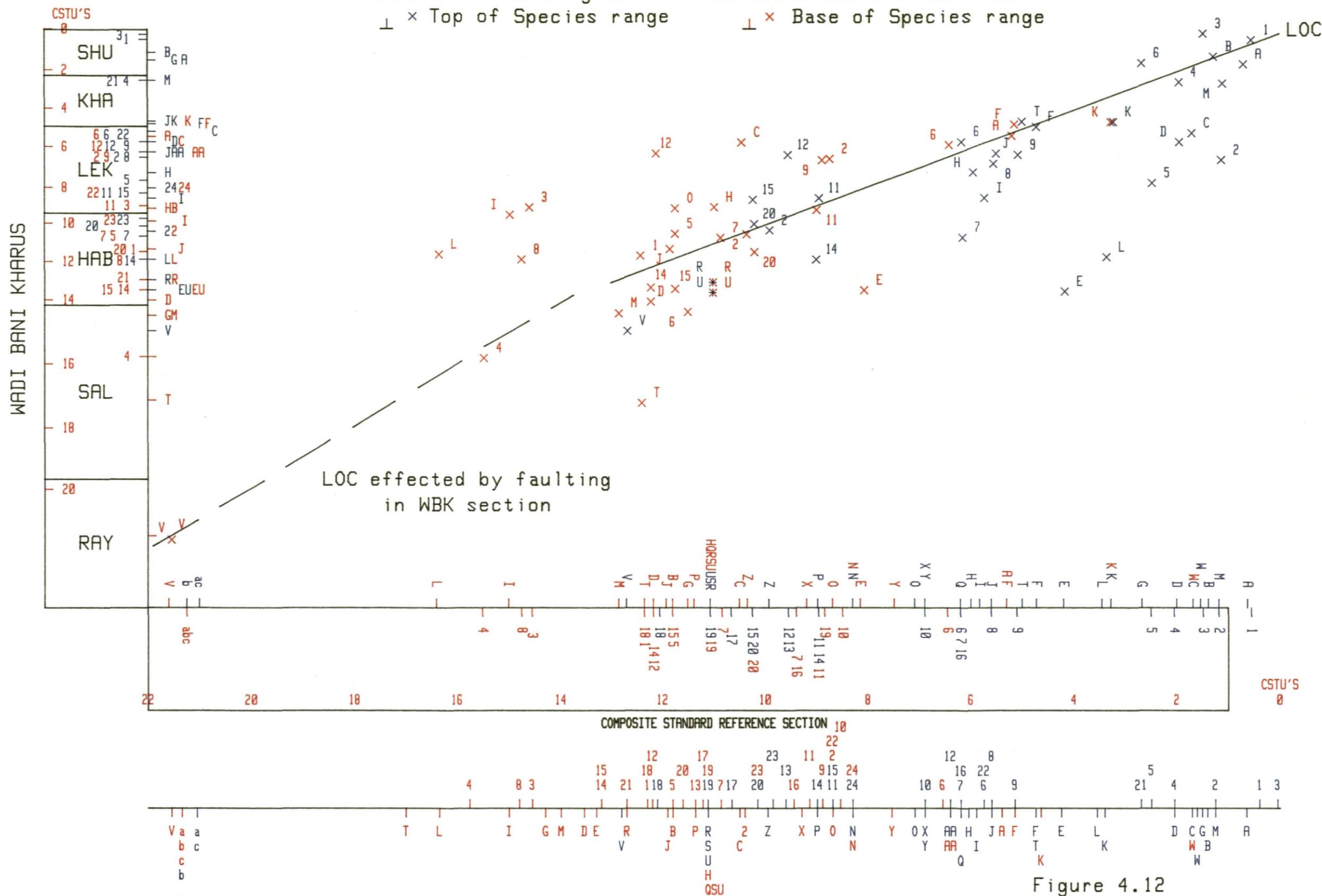


Figure 4.12

SUMMARY BIOSTRATIGRAPHY DIAGRAM FOR THE EARLY CRETACEOUS OF THE OMAN MOUNTAINS.

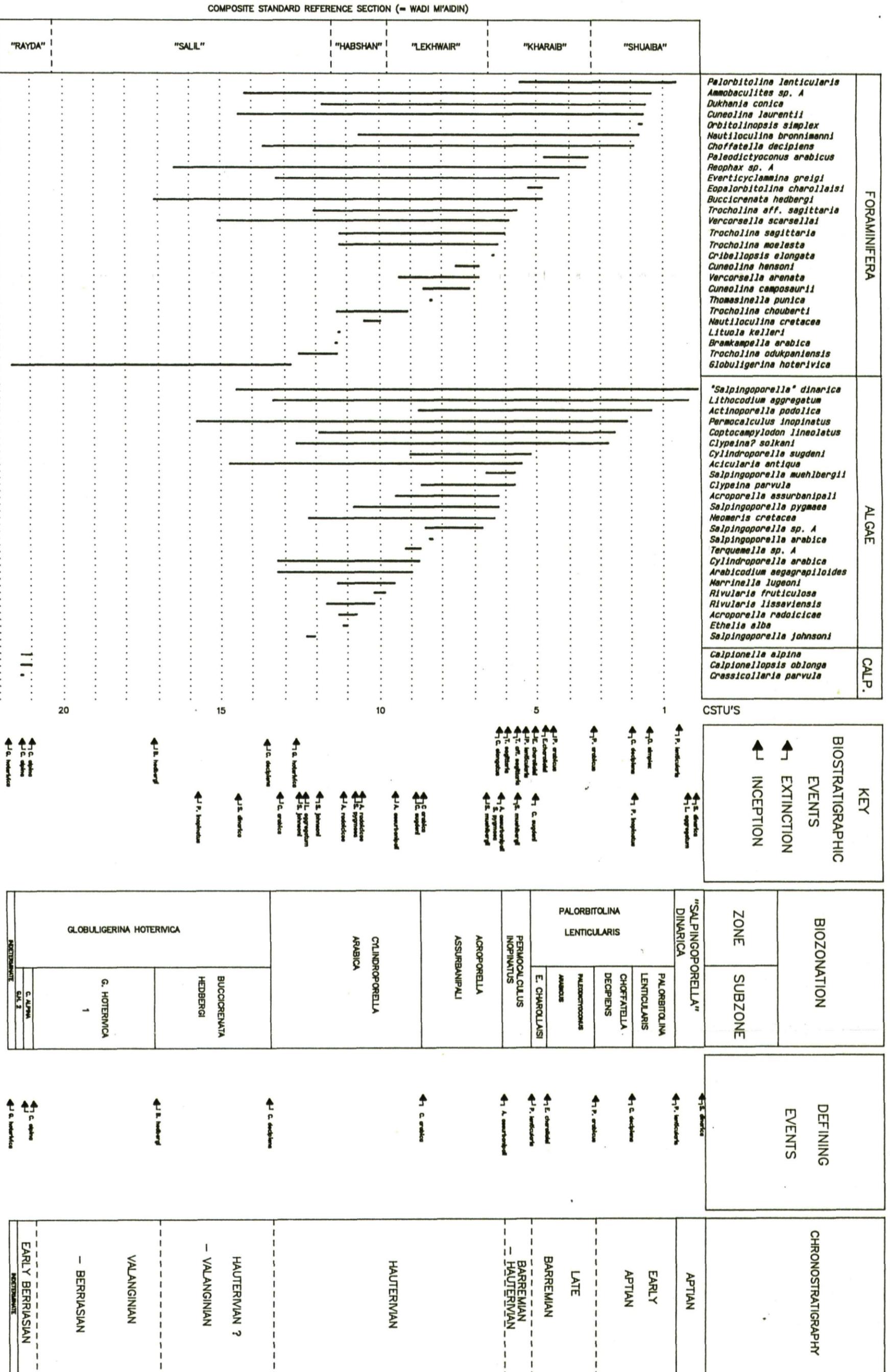
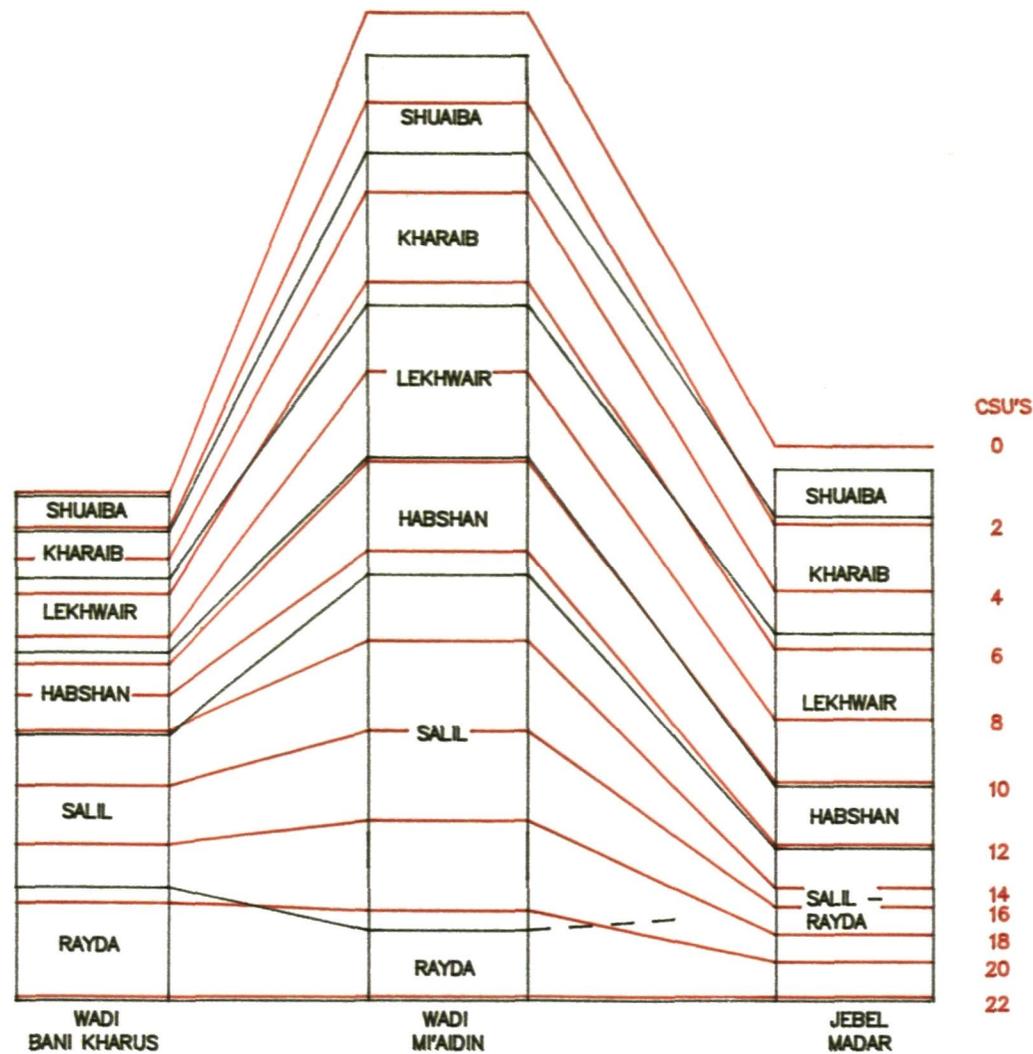


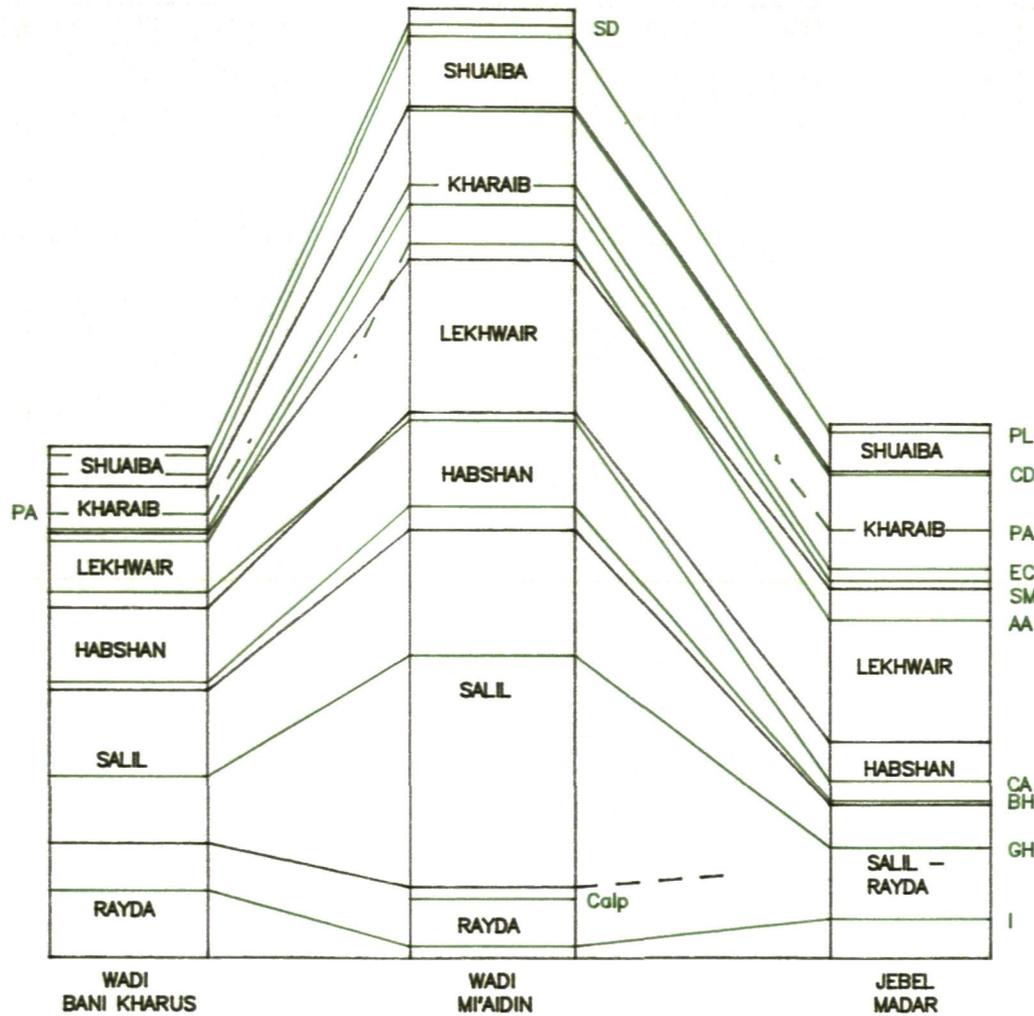
Figure 4.13



CORRELATION OF EARLY CRETACEOUS OMAN MOUNTAINS SECTIONS BY GRAPHIC CORRELATION TECHNIQUE

— = Lithostratigraphic correlation lines  
 — = Correlation lines derived from graphic correlation

Figure 4.14



Key:

- SD = *Salpingoporella dinarica* Zone
- PL = *Palarbitolina lenticularis* Zone
- CD = *Choffatella decipiens* Subzone
- PA = *Paleodictyoconus arabicus* Subzone
- EC = *Eopalorbitolina charollaisi* Subzone
- SM = *Salpingoporella muehlbergii* Zone
- AA = *Acroporella assurbanipali* Zone
- CA = *Cylindroporella arabica* Zone
- GH = *Globuligerina hoterivica* Zone
- BH = *Buccirenata hedbergi* Subzone
- Calp = *Calpinella alpina* Subzone
- I = Indeterminate Interval

CORRELATION OF EARLY CRETACEOUS OMAN MOUNTAINS SECTIONS BY BIOZONAL/ABSOLUTE AGE CORRELATION TECHNIQUE

- = Line of lithostratigraphic correlation
- - - = Line of biozonal correlation

Figure 4.15

definition of the regional biozonation scheme further discussed in Section 4.3. It is important to note that the total range chart shown in Figure 4.13 honours the raw data shown in Figures 4.1 - 4.9.

Figure 4.14 presents the results of a correlation of the three studied sections using Graphic Correlation (correlation of CSTU's). This is further discussed in Section 4.4, where it is compared to a correlation based on biozones (Figure 4.15).

### **4.3: Biozonation**

Figure 4.13 illustrates the total range of key microfossils recorded in the Thamama Group sediments of the Oman Mountains. This range chart was derived primarily by use of the Graphic Correlation technique (see Section 4.2), although it also incorporates observations made in outcrop sections across the Oman Mountains area. The ranges of the taxa are initially expressed in terms of CSTU's (far left-hand column), but via the biozonation scheme that this range chart permits, standard chronostratigraphic values can also be applied (far right-hand column).

The ranges of the key microfossil taxa and thus the key biostratigraphic events (extinctions and inceptions) recorded in the Thamama Group sediments of the Oman Mountains form the basis for developing the biozonation scheme which is shown in Figure 4.13.

It should be noted that this biozonation scheme is of value only in *local* correlation studies. It should be considered as the starting point for developing a more regionally applicable scheme. The stratigraphic ranges of microfossils given in Figure 4.13 are not always consistent with their ranges as documented elsewhere in the Tethyan region (Saint-Marc, 1977; Arnaud-Vanneau, 1980; Moullade *et al.*, 1985). The stratigraphic ranges shown in Figure 4.13 are the local ranges on which the local biozonation scheme is built. Because the stratigraphic ranges of benthonic microfossils are different across the Tethyan region, it is suggested that alternative means of correlation should be sought. Graphic Correlation is one suitable method.

The defining event for each of the biozones is shown in Figure 4.13. Further discussion of this biozonation scheme is given below. For each of the biozones (and subzones), a definition is given together with comments on regional synonymy, distribution in the studied sections, assemblage characteristics, palaeoenvironmental significance and chronostratigraphic significance. The biozonation scheme is described in descending stratigraphic order.

### **"Salpingoporella" dinarica Zone**

**Definition:** Top defined by the local extinction level of the nominate taxon, base by the top of the underlying zone.

**Synonymy:** Choffatella decipiens - Orbitolina lenticularis Zone (*pars.*) (Harris *et al.* (1984), Choffatella decipiens zone (*pars.*) (Sampo, 1969), Orbitolina - Choffatella - Salpingoporella dinarica Zone (*pars.*) (Gollesstaneh, 1965).

**Distribution:** Wadi Mi'aidin, Shuaiba Formation; ?Wadi Bani Kharus, Shuaiba Formation.

**Assemblage Characteristics:** Characterized by sparse assemblages which include only the algae "*Salpingoporella*" *dinarica* and *Lithocodium aggregatum*.

**Palaeoenvironmental Significance:** The above assemblage suggests deposition in low energy middle neritic conditions with water depths in the range of 15m to c. 60m b.s.l.

**Chronostratigraphic Significance:** The presence of "*Salpingoporella*" *dinarica* suggests an age no younger than Late Aptian, but as old as Hauterivian. The age is restricted to Aptian (probably Early Aptian on regional grounds and associated macrofauna) by the age of the underlying zone.

**Comments:** This zone coincides with the uppermost part of the Shuaiba Formation.

The nominate taxon, "*Salpingoporella*" *dinarica*, is herein regarded as the senior synonym of *Hensonella cylindrica*, the more commonly used name to describe this fossil in the Early Cretaceous sediments of the Middle East. It is regarded as being a dasycladacean alga (see Section 3.4).

### **Palorbitolina lenticularis Zone**

**Definition:** Top defined by the local extinction level of the nominate taxon, base by the local inception level of the nominate taxon. Divisible into four subzones.

**Synonymy:** Choffatella decipiens - Orbitolina lenticularis Zone (*pars.*) (Harris *et al.* (1984), Choffatella decipiens zone (*pars.*) and Dictyoconus arabicus Zone (*pars.*) (Sampo, 1969), Orbitolina - Choffatella - Salpingoporella dinarica Zone (*pars.*) (Gollesstaneh, 1965).

**Distribution:** Wadi Mi'aidin, Shuaiba - KharaiB Formations; Jebel Madar, Shuaiba - KharaiB Formations; Wadi Bani Kharus, Shuaiba - Lekhwair Formations.

**Assemblage Characteristics:** See separate subzone sections for details.

**Palaeoenvironmental Significance:** See separate subzone sections for details.

**Chronostratigraphic Significance:** The presence of *Palorbitolina lenticularis* indicates an Early Aptian - Late Barremian age. See separate subzone sections for further details.

**Comments:** This zone coincides with the lower Shuaiba Formation and the upper part of the KharaiB Formation.

This zone can be recognized across much of the Middle East and indeed across across the entire central and eastern Tethyan region. The nominate taxon has an Early Aptian - Late Barremian age range, but further stratigraphic subdivision is possible by the recognition of various evolutionary stages within *P. lenticularis* (but see Section 3.2 for note of caution), and/or by the recognition of subzones. Four subzones are recognized in this study and are described below. Note that because of facies variations these subzones are not always recognizable in any given outcrop (or well) section. It is for this reason that they are given subzonal status.

#### **Palorbitolina lenticularis Subzone**

**Definition:** Top defined by the local extinction level of the nominate taxon, base by the top of the underlying subzone.

**Synonymy:** Pseudocyclammina hedbergi Subzone (*pars.*) (Harris *et al.*, 1984).

**Distribution:** Wadi Mi'aidin, Shuaiba Formation; Jebel Madar, Shuaiba Formation; ?Wadi Bani Kharus, Shuaiba Formation.

**Assemblage Characteristics:** Significant microfossils recorded from this subzone include *Palorbitolina lenticularis* (advanced forms), *Ammobaculites* sp. A, *Dukhanian conica*, *Cuneolina laurentii*, *Orbitolinopsis simplex*, *Nautiloculina bronnimanni*, "*Salpingoporella*" *dinarica*, *Lithocodium aggregatum* and *Actinoporella podolica*.

**Palaeoenvironmental Significance:** The above assemblage suggests deposition in platformal, most likely middle - outer neritic, conditions.

**Chronostratigraphic Significance:** The dominance of advanced forms of *Palorbitolina lenticularis* suggests an Early Aptian age for this subzone. This is supported by the occurrence of *Orbitolinopsis simplex*.

**Comments:** This subzone coincides with the lower part of the Shuaiba Formation.

### **Choffatella decipiens Subzone**

**Definition:** Top defined by the local extinction level of the nominate taxon, base by the top of the underlying subzone. Top can also be recognized by the local extinction level of *Permocalculus inopinatus*.

**Synonymy:** *Pseudocyclammina hedbergi* Subzone (*pars.*) (Harris *et al.*, 1984).

**Distribution:** ?Wadi Mi'aidin, Kharab Formation; Jebel Madar, Kharab Formation; Wadi Bani Kharus, Shuaiba - Kharab Formations.

**Assemblage Characteristics:** Significant microfossils recorded from this subzone include *Choffatella decipiens*, *Palorbitolina lenticularis* (moderately advanced forms), *Ammobaculites* sp. A, *Dukhanian conica*, *Cuneolina laurentii*, *Nautiloculina bronnimanni*, "*Salpingoporella*" *dinarica*, *Lithocodium aggregatum*, *Actinoporella podolica*, *Permocalculus inopinatus*, *Coptocampylodon lineolatus* and *Clypeina? solkani*.

**Palaeoenvironmental Significance:** The above assemblage suggests deposition in platformal, most likely middle - outer neritic, conditions.

**Chronostratigraphic Significance:** The dominance of moderately advanced forms of *Palorbitolina lenticularis* suggests an Early Aptian age for this subzone. The lower part of this subzone is particularly poorly age constrained, often containing only relatively long ranging taxa. It is considered to be Early Aptian because of the age of the overlying and underlying intervals, but extension of this subzone into the Late Barremian is possible.

**Comments:** This subzone usually coincides with the lower part of the Shuaiba Formation and the uppermost Kharab Formation.

### **Paleodictyoconus arabicus Subzone**

**Definition:** Top defined by the local extinction level of the nominate taxon, base by the top of the underlying subzone. Base can also be recognized by the local inception level of the nominate taxon.

**Synonymy:** None known.

**Distribution:** ?Wadi Mi'aidin, Kharaib Formation; Jebel Madar, Kharaib Formation; Wadi Bani Kharus, Kharaib Formation.

**Assemblage Characteristics:** Significant microfossils recorded from this subzone include *Paleodictyoconus arabicus*, *Choffatella decipiens*, *Palorbitolina lenticularis* (primitive forms), *Ammobaculites* sp. A, *Dukhanian conica*, *Cuneolina laurentii*, *Nautiloculina bronnimanni*, *Reophax* sp. A, *Everticyclammina greigi*, "*Salpingoporella*" *dinarica*, *Lithocodium aggregatum*, *Actinoporella podolica*, *Permocalculus inopinatus*, *Coptocampylodon lineolatus* and *Clypeina? solkani*.

**Palaeoenvironmental Significance:** The above assemblage of microfossils indicates deposition in carbonate platform environments. The majority of the subzone appears to equate to a period of inner neritic - shallow platform lagoon deposition, as demonstrated by the presence of dasycladacean algae. However, episodes of middle - outer neritic deposition are indicated by levels with abundant orbitolinids and *Choffatella*.

**Chronostratigraphic Significance:** The presence of *Paleodictyoconus arabicus* indicates that this subzone is of Late Barremian age. This age assignment is supported by the dominance of primitive forms of *Palorbitolina lenticularis*, and the age of the underlying subzone.

**Comments:** This subzone usually coincides with levels within the upper part of the Kharaib Formation.

### **Eopalorbitolina charollaisi Subzone**

**Definition:** Top defined by the local extinction level of the nominate taxon, base by local inception level of *Palorbitolina lenticularis*.

**Synonymy:** None known.

**Distribution:** Wadi Mi'aidin, Kharab Formation; Jebel Madar, Kharab Formation; Wadi Bani Kharus, Kharab - Lekhwair Formations.

**Assemblage Characteristics:** Significant microfossils recorded from this subzone include *Eopalorbitolina charollaisi*, *Buccicrenata hedbergi*, *Choffatella decipiens*, *Palorbitolina lenticularis* (primitive forms), *Ammobaculites* sp. A, *Dukhanian conica*, *Cuneolina laurentii*, *Nautiloculina bronnimanni*, *Reophax* sp. A, *Everticyclammina greigi*, "*Salpingoporella*" *dinarica*, *Lithocodium aggregatum*, *Actinoporella podolica*, *Permocalculus inopinatus*, *Coptocampylodon lineolatus*, *Cylindroporella sugdeni* and *Clypeina? solkani*.

**Palaeoenvironmental Significance:** The above assemblage of microfossils indicates deposition in carbonate platform environments. The majority of the subzone appears to equate to a period of inner neritic - shallow platform lagoon deposition, as demonstrated by the presence of dasycladacean algae. However, episodes of middle - outer neritic deposition are indicated by levels with abundant orbitolinids and *Choffatella*.

**Chronostratigraphic Significance:** The presence of *Eopalorbitolina charollaisi* indicates that this subzone is of Late Barremian age. This age assignment is supported by the dominance of primitive forms of *Palorbitolina lenticularis*, and the age of the overlying subzone.

**Comments:** This subzone usually coincides with levels within the upper and middle parts of the Kharab Formation.

Within this subzone the local extinction levels of the key taxa *Buccicrenata hedbergi* and *Cylindroporella sugdeni* occur. The nominate taxon has an inception level near the base of this subzone.

### **Permocalculus inopinatus Zone**

**Definition:** Interval zone defined between the base of the *Palorbitolina lenticularis* Zone (local inception level of *Palorbitolina lenticularis*) and top of the *Acroporella assurbanipali* Zone (local extinction level of *Acroporella assurbanipali*).

**Synonymy:** *Choffatella decipiens* - *Orbitolina lenticularis* Zone (*pars.*) (Harris *et al.*, 1984), *Dictyoconus arabicus* zone (*pars.*) (Sampo, 1969), *Orbitolina* - *Choffatella* - *Salpingoporella dinarica* Zone (*pars.*) (Gollesstaneh, 1965).

**Distribution:** Wadi Mi'aidin, Kharab Formation; Jebel Madar, Lekhwair Formation; Wadi Bani Kharus, Lekhwair Formation.

**Assemblage Characteristics:** Significant microfossils recorded from this zone include *Buccicrenata hedbergi*, *Ammobaculites* sp. A, *Dukhanian conica*, *Cuneolina laurentii*, *Nautiloculina bronnimanni*, *Reophax* sp. A, *Everticyclammina greigi*, *Vercorsella scarsellai*, *Trocholina* aff. *sagittaria*, *Trocholina sagittaria*, "*Salpingoporella*" *dinarica*, *Lithocodium aggregatum*, *Actinoporella podolica*, *Permocalculus inopinatus*, *Coptocampylodon lineolatus*, *Cylindroporella sugdeni*, *Clypeina?* *solkani*, *Acicularia antiqua*, *Salpingoporella muehlbergii* and *Clypeina parvula*.

**Palaeoenvironmental Significance:** The above assemblage, which is often dominated by dasycladacean algae and *Trocholina* spp., indicates that deposition of this zone took place in very shallow water inner neritic environments.

**Chronostratigraphic Significance:** This zone is poorly age constrained. The local extinction level of *Salpingoporella muehlbergii*, which lies within this zone, indicates that it cannot be younger than Early Barremian. A Barremian - Hauterivian age is indicated by the age of the underlying and overlying zones. This age assignment is supported by the overall assemblage.

**Comments:** This zone usually coincides with levels within the lower part of the Kharab Formation.

Within this subzone the local extinction levels of the key taxa *Salpingoporella muehlbergii* and *Trocholina* spp. occur. These events can also be used to recognize the zone.

#### **Acroporella assurbanipali Zone**

**Definition:** Top defined by the local extinction level of the nominate taxon, base by the top of the underlying zone.

**Synonymy:** Unzoned interval (*pars.*) (Harris *et al.*, 1984), *Pseudocyclammina lituus* Zone (*pars.*) (Sampo, 1969), *Pseudocyclammina lituus* - *Pseudochrysalidina arabica* - algae zone (*pars.*) (Gollesstaneh, 1965).

**Distribution:** Wadi Mi'aidin, Kharab - Lekhwair Formations; Jebel Madar, Lekhwair Formation; Wadi Bani Kharus, Lekhwair Formation.

**Assemblage Characteristics:** Significant microfossils recorded from this zone include *Buccicrenata hedbergi*, *Ammobaculites* sp. A, *Dukhania conica*, *Cuneolina laurentii*, *Nautiloculina bronnimanni*, *Reophax* sp. A, *Everticyclammina greigi*, *Vercorsella scarsellai*, *Trocholina* aff. *sagittaria*, *Trocholina sagittaria*, *Trocholina molesta*, *Cribellopsis elongatus*, *Cuneolina hensoni*, *Vercorsella arenata*, *Cuneolina camposaurii*, *Thomasinella punica*, *Acroporella assurbanipali*, *Salpingoporella pygmaea*, *Neomeris cretacea*, *Salpingoporella* sp. A, *Salpingoporella arabica*, "*Salpingoporella*" *dinarica*, *Lithocodium aggregatum*,

*Actinoporella podolica*, *Permocalculus inopinatus*, *Coptocampylodon lineolatus*, *Cylindroporella sugdeni*, *Clypeina? solkani*, *Acicularia antiqua*, *Salpingoporella muehlbergii* and *Clypeina parvula*.

**Palaeoenvironmental Significance:** The above assemblage, which is dominated by dasycladacean algae, cuneolinids, and *Trocholina* spp., indicates that deposition of this zone took place in very shallow water, low energy inner neritic - shallow platform lagoon environments.

**Chronostratigraphic Significance:** The presence of *Acroporella assurbanipali* suggests that this zone is no younger than Hauterivian in age. The association with *Dukhania conica*, *Nautiloculina bronnimanni*, *Cribellopsis elongatus*, *Vercorsella arenata*, *Neomeris cretacea* and *Cylindroporella sugdeni* suggests that it cannot be older than Hauterivian. An Hauterivian age assignment is supported by the age of the underlying zone.

**Comments:** This zone usually coincides with levels within the Lekhwair Formation.

The top of this zone also coincides with the local extinction level for *Salpingoporella pygmaea*.

#### **Cylindroporella arabica Zone**

**Definition:** Top defined by the local extinction level of the nominate taxon, base by the local inception level of *Choffatella decipiens*.

**Synonymy:** Unzoned interval (*pars.*) (Harris *et al.*, 1984), *Pseudocyclammina lituus* Zone (*pars.*) (Sampo, 1969), *Pseudocyclammina lituus* - *Pseudochrysalidina arabica* - algae zone (*pars.*) (Gollesstaneh, 1965).

**Distribution:** Wadi Mi'aidin, Lekhwair - Habshan Formations; Jebel Madar, Lekhwair - Habshan Formations; Wadi Bani Kharus, Lekhwair - Habshan Formations.

**Assemblage Characteristics:** Significant microfossils recorded from this zone include *Choffatella decipiens*, *Buccicrenata hedbergi*, *Ammobaculites* sp. A, *Dukhania conica*, *Cuneolina laurentii*, *Nautiloculina cretacea*, *Nautiloculina bronnimanni*, *Reophax* sp. A, *Everticyclammina greigi*, *Vercorsella scarsellai*, *Trocholina odukpaniensis*, *Trocholina* aff. *sagittaria*, *Trocholina chouberti*, *Trocholina sagittaria*, *Trocholina molesta*, *Vercorsella arenata*, *Cylindroporella arabica*, *Arabicodium aegagrapiloides*, *Marinella lugeoni*, *Rivularia fruticosa*, *Rivularia lissaviensis*, *Acroporella radoicici*, *Acroporella assurbanipali* (uppermost part of the zone only), *Ethelia alba*, *Salpingoporella johnsoni*, *Salpingoporella pygmaea*, *Neomeris cretacea*, *Terquemella* sp. A, "*Salpingoporella*" *dinarica*, *Lithocodium aggregatum*, *Permocalculus inopinatus*, *Coptocampylodon lineolatus*, *Cylindroporella sugdeni* (uppermost part of the zone only), *Clypeina?* *solkani*, and *Acicularia antiqua*.

Calcareous algae are particularly common and diverse in assemblages from this zone.

**Palaeoenvironmental Significance:** Assemblages from this zone, which are often dominated by dasycladacean, codiacean and cyanophytic algae, lituolids, and *Trocholina* spp., indicate that deposition of this zone took place in shallow water, platform environments probably with open marine influence. A middle - outer ramp position is envisaged although with relatively shallow water depths.

**Chronostratigraphic Significance:** The presence of *Choffatella decipiens* indicates that this zone can be no older than Hauterivian. An Hauterivian age for this zone is confirmed by the age of the overlying zone, and the general aspect of the microfauna and microflora. In particular, the presence of *Acroporella radoicici* and *Cylindroporella arabica* indicates that this zone cannot be younger than Hauterivian.

**Comments:** This zone usually coincides with levels within the Lekhwair and Habshan Formations.

### **Globuligerina hoterivica Zone**

**Definition:** Top defined by the base of the overlying zone (local inception level of *Choffatella decipiens*), base by the local inception level of the nominate taxon.

This zone is divided into four subzones.

**Synonymy:** *Caucasella hoterivica* Zone and calpionellid zones (*pars.*) (Harris *et al.*, 1984), *Pseudocyclammina lituus* Zone (*pars.*) (Sampo, 1969), *Pseudocyclammina lituus* - *Pseudochrysalidina arabica* - algae Zone (*pars.*) and *Tintinnids* Zone (*pars.*) (Gollesstaneh, 1965).

**Distribution:** Wadi Mi'aidin, Salil - Rayda Formation; Jebel Madar, Habshan - Rayda Formations; Wadi Bani Kharus, Salil - Rayda Formations.

**Assemblage Characteristics:** See separate subzone sections for details.

**Palaeoenvironmental Significance:** See separate subzone sections for details.

**Chronostratigraphic Significance:** This zone is poorly age constrained. The age of the overlying zone implies it cannot be younger than Hauterivian. Calpionellids near its base suggest it cannot be older than Early Berriasian. For further details see separate subzone sections.

**Comments:** This zone usually coincides with levels within the Salil and Rayda Formations.

Graphic Correlation suggests that the nominate taxon ranges above the top of this zone. However, it is facies restricted and effectively constrained to this zone. This reflects the diachronous nature of biozonal boundaries based on facies controlled microfossils (ie. base *Cylindroporella arabica* zone - top *Globuligerina hoterivica* zone).

### **Buccicrenata hedbergi Subzone**

**Definition:** Top defined by the base of the overlying zone (local inception level of *Choffatella decipiens*), base by the local inception level of the nominate taxon.

**Synonymy:** None known.

**Distribution:** Wadi Mi'aidin, Salil Formation; Jebel Madar, Habshan - Salil/Rayda Formations; Wadi Bani Kharus, Salil Formation.

**Assemblage Characteristics:** Significant taxa recorded from this subzone include *Buccicrenata hedbergi*, *Ammobaculites* sp. A, *Cuneolina laurentii*, *Reophax* sp. A, *Globuligerina hoterivica*, *Salpingoporella dinarica*, *Permocalculus inopinatus* and *Acicularia antiqua*.

**Palaeoenvironmental Significance:** Many of the benthonic microfossils recorded from this subzone are clearly reworked downslope. The presence of common *Globuligerina* points to open marine conditions and moderate (outer neritic - upper bathyal?) water depths. The reworked benthos suggests a distal ramp or slope environment of deposition.

**Chronostratigraphic Significance:** This subzone is poorly age constrained. The age of the overlying zone implies it cannot be younger than Hauterivian. The presence of *Salpingoporella dinarica* in the upper part of the zone is suggestive of a age no older than Hauterivian (although this species has been questionably recorded from Valanginian sediments), whilst the presence of *Buccicrenata hedbergi* indicates that the subzone cannot be older than Valanginian. On balance, an Hauterivian? - Valanginian age is suggested.

**Comments:** This subzone usually coincides with levels within the Salil Formation.

### **Globuligerina hoterivica Subzone I**

**Definition:** Interval zone defined between the base of the overlying subzone (local inception level of *Buccicrenata hedbergi*) and top of underlying zone (local extinction level of *Calpionella alpina*).

**Synonymy:** None known.

**Distribution:** Wadi Mi'aidin, Salil - Rayda Formations; ?Jebel Madar, Salil/Rayda Formations; ?Wadi Bani Kharus, Salil - Rayda Formations.

**Assemblage Characteristics:** The sparse microfauna recorded from this subzone consists of *Globuligerina hoterivica* and calcified radiolaria.

**Palaeoenvironmental Significance:** The presence of common *Globuligerina* and radiolaria points to open marine conditions and moderate (outer neritic - upper bathyal?) water depths. A basinal - slope environment of deposition is suggested.

**Chronostratigraphic Significance:** This subzone is age constrained by the age of the overlying and underlying intervals. It is thus Valanginian - Berriasian in age.

**Comments:** This subzone usually coincides with levels within the Salil and Rayda Formations.

### **Calpionella alpina Subzone**

**Definition:** Total range zone with top defined by the local extinction level of the nominate taxon, and base defined by the local inception level of the nominate taxon.

**Synonymy:** None known.

**Distribution:** Wadi Mi'aidin, Rayda Formation; ?Jebel Madar, Salil/Rayda Formation; ?Wadi Bani Kharus, Salil - Rayda Formations.

**Assemblage Characteristics:** The microfauna recorded from this subzone consists of *Calpionella alpina*, *Calpionellopsis oblonga*, *Crassicollaria parvula*, *Globuligerina hoterivica* and calcified radiolaria.

**Palaeoenvironmental Significance:** The presence of common calpionellids, *Globuligerina* and radiolaria points to open marine conditions and upper bathyal water depths. A basinal environment of deposition is suggested.

**Chronostratigraphic Significance:** The presence of Early Berriasian forms of *Calpionella alpina* (see Remane, 1985) indicates that this subzone is of Early Berriasian age.

**Comments:** This subzone usually coincides with levels within the Rayda Formation.

#### **Globuligerina hoterivica Subzone II**

**Definition:** Top defined by the base of the overlying subzone (local inception level of *Calpionella alpina*), base by the local inception of the nominate taxon.

**Synonymy:** None known.

**Distribution:** Wadi Mi'aidin, Rayda Formation; ?Jebel Madar, Salil/Rayda Formations; ?Wadi Bani Kharus, Salil - Rayda Formations.

**Assemblage Characteristics:** The only significant microfossils recorded from this subzone are *Globuligerina hoterivica* and calcified radiolaria.

**Palaeoenvironmental Significance:** The presence of *Globuligerina* and calcified radiolaria points to open marine conditions and upper bathyal water depths. A basinal environment of deposition is suggested.

**Chronostratigraphic Significance:** This subzone lacks age significant taxa, but its limited thickness and the age of the overlying subzone suggests that it is Early Berriasian.

**Comments:** This subzone usually coincides with levels within the Rayda Formation.

### **Indeterminate Interval**

**Definition:** An interval lacking significant microfossils at the base of the Thamama Group. Top defined by base of overlying zone (local inception level of *Globuligerina hoterivica*), base by the base of the Thamama Group.

**Synonymy:** None known.

**Distribution:** Wadi Mi'aidin, Rayda Formation; Jebel Madar, Rayda Formation; Wadi Bani Kharus, Rayda Formation.

**Assemblage Characteristics:** No significant taxa present.

**Palaeoenvironmental Significance:** The absence of significant microfossils precludes any interpretation.

**Chronostratigraphic Significance:** The absence of significant microfossils precludes any interpretation.

**Comments:** This interval corresponds with the basal sediments of the Thamama Group.

#### 4.4: Correlation of Studied Sections

Figures 4.14 and 4.15 illustrate two alternative biostratigraphic methods of correlating the Thamama Group sediments of the studied sections at Wadi Mi'aidin, Jebel Madar and Wadi Bani Kharus. Figure 4.14 is a correlation using Composite Standard Time Units (CSTU's) derived by the use of the Graphic Correlation method explained in Section 4.2. Figure 4.15 is a more traditional type of correlation using the local biozonation scheme defined in Section 4.3 (see also Figure 4.13). Figures 4.1 - 4.9 also show the occurrence of biozone tops and bases in the studied sections.

The objective of these correlations is to investigate if the lithostratigraphic units (= sedimentary facies belts) are time transgressive. The recognition of diachronous (and isochronous) facies belts is important when elucidating a palaeoenvironmental model and geological history for the Thamama Group of the Oman Mountains. Although not discussed here further, the identification of diachronous facies belts, particularly of reservoir facies (eg. an oolitic shoal), is highly significant for locating hydrocarbon reserves in the region. Diachronous facies belts often form stratigraphic traps, for example by means of updip pinch-outs.

In order to recognize diachronous facies, the methods of correlation need to be chronostratigraphically significant. The majority of biozonal marker species used herein are considered to be chronostratigraphically significant, at least on a local scale. Even so, foraminiferal and algal taxa occurring in platform carbonate environments, such as that represented by the Thamama Group, must be somewhat facies controlled. As such, they are limited in their ability to demonstrate the time transgressive nature of the sedimentary facies they relate to. However, all the taxa do have absolute inception and extinction points, and these may be isochronous across a basin, especially if they relate to evolutionary events within a phylogenetic series, in turn relating to more basin-wide or global events (eg. eustatic sea-level change). Some of the marker taxa used in this study are obviously of this type (eg. *Eopalorbitolina charollaisi* - evolution to *Palorbitolina lenticularis*).

The problems of facies control on fossil ranges with the Thamama Group of the Oman Mountains prompted the investigation of quantitative and semi-quantitative biostratigraphic methods of correlation. Graphic Correlation was chosen as a suitable alternative method of biostratigraphic correlation to biozonal correlation because of its advantages outlined in Section 4.2. Because it uses all the biostratigraphic data available it is less susceptible to facies control. Furthermore, it allows for the construction of an independent time scale, and for the correlation of sections by this timescale (Composite Standard Time Units - CSTU's).

It is interesting to note that the two correlation methods show results (Figures 4.14 and 4.15) which in some cases are similar, but in others quite dissimilar. The results are discussed further below with primary reference to the correlation by CSTU's which is considered to be more reliable.

It can be seen from Figure 4.14 that the lower part of the Thamama Group is demonstrably younger at Wadi Bani Kharus than at Wadi Mi'aidin. At Wadi Mi'aidin the top of the Rayda Formation is older than CSTU 20, whilst at Wadi Bani Kharus, the top of the formation lies above CSTU 20 and is therefore younger than it. At Jebel Madar the Rayda and Salil Formations are condensed, as is clear from the close stacking of CSTU's within these formations.

The Habshan Formation shows clear diachroneity. At Jebel Madar the base of the formation is almost equivalent to CSTU 12. At Wadi Mi'aidin and Wadi Bani Kharus, the onset of Habshan deposition is progressively older. At Wadi Bani Kharus it is almost equivalent to CSTU 14. However, the top of the formation shows a reverse diachroneity. At Wadi Bani Kharus the top of the formation is younger than CSTU 10, whilst at Jebel Madar it is slightly older. The biozonal correlation suggests that the base of the formation is virtually isochronous (top of the *Buccicrenata hedbergi* Subzone). This is likely to be a function of facies control on the top of the biozone. Biozonal correlation suggests that the top of the formation is older at Wadi Bani Kharus than at Wadi Mi'aidin or Jebel Madar. This is the reverse of the situation suggested by Graphic Correlation. It is thought that the biozonal correlation, based on the top of the *Cylindroporella arabica* Zone is unreliable, relating to facies control and the scarcity of zonal indices in the studied samples. The diachronous

nature of the Habshan Formation is in agreement with the concept that it represents a prograding oolitic shoal (see Chapter 5). Regional evidence supports this model. In Abu Dhabi the formation is Berriasian in age (Hassan *et al.*, 1975); in Oman it is as young as Hauterivian.

The Lekhwair Formation also shows a time transgressive nature. The base of the formation is equivalent to CSTU 10 at Jebel Madar and Wadi Mi'aidin, whilst at Wadi Bani Kharus it is younger being closer to CSTU 8. The top of the formation is younger than CSTU 6 at Wadi Bani Kharus and Jebel Madar, but is slightly older than CSTU 6 at Wadi Mi'aidin. However this is probably in the range of error of the correlation method and the top of the formation may be isochronous. The biozonal correlation of the Lekhwair Formation is limited by the few zones recognized in this formation. However, the top of the formation would appear to be older at Wadi Mi'aidin than at Wadi Bani Kharus or Jebel Madar, as suggested by the Graphic Correlation method.

Both Graphic Correlation and biozonal correlation suggest that base of the Kharuib Formation is slightly older at Wadi Mi'aidin than at Wadi Bani Kharus or Jebel Madar. Furthermore, the top of the formation is older than CSTU 2 at Wadi Mi'aidin, whilst at Wadi Bani Kharus and Jebel Madar it is younger than this correlation line (Figure 4.14).

The Shuaiba Formation is condensed at Wadi Bani Kharus, but also includes younger sediments than at Wadi Mi'aidin or Jebel Madar. Figure 4.14 shows that at Wadi Bani Kharus the top of the Formation is almost equivalent with CSTU 0. At Jebel Madar and Wadi Mi'aidin the top of the formation lies intermediate between CSTU's 0 and 2. Some support for this comes from the biozonal correlation (Figure 4.15), where at Jebel Madar the top of the formation closely corresponds to the top of the *Palorbitolina lenticularis* Zone, whilst at Wadi Bani Kharus and Wadi Mi'aidin, it is younger, above the top of the *Salpingoporella dinarica* Zone. The variable age of the top of the Shuaiba Formation is thought to relate to differential erosion prior to the the deposition of the Albian, Nahr Umr Formation. Regional evidence supports this: in Musandam and Abu Dhabi the formation extends into the Late Aptian (Hassan *et al.*, 1975, BP internal reports).

Both correlation methods show that the formations of the Thamama Group are often time transgressive or condensed at some localities. However, both methods suffer from a number of introduced uncertainties. These are:

- (i) Inconsistent identification of taxa.
- (ii) Sample spacing.
- (iii) Picking of formation boundaries.

As such the correlations presented here and any conclusions drawn from them must be considered provisional pending further more detailed regional studies.

#### **4.5: Regional Considerations**

It is interesting to compare the biostratigraphic data and interpretations presented in Sections 4.1 - 4.4 with previous biostratigraphic studies of the Early Cretaceous of the Middle East region.

Figure 4.16 presents a comparison of the local biozonation scheme for the Oman Mountains developed herein (Section 4.3) with those previously developed for other parts of the Middle East region. In platformal facies, no previous scheme is of equal resolution. Including subzones, thirteen biozones are recognized in the current study. These have an average resolution of 2.15 million years (using the timescale of Harland *et al.*, 1982). However, it must be stressed that the scheme defined herein is of limited value outside the study area. The lower resolution schemes shown in Figure 4.16 are probably simpler to apply in regional correlation studies.

A COMPARISON OF MICROFOSSIL BIOZONATION SCHEMES FOR THE EARLY CRETACEOUS OF THE MIDDLE EAST

AGE	THIS STUDY	HARRIS et al (1985) (ARABIAN PENINSULA) *	SAMPO (1969) (IRAN)	GOLLESSTANEH (1965) (IRAN)		
APTIAN		O. TELAMA O. SUBOCCAVATA (PASS.)	H. TROCHOIDEA G. ALGERIANUS G. BLOWI	ORBITOLINA LENTICULARIS PSEUDOCYCLAMMINA HEDBERGI (PARS.)	CHOFFATELLA DECIPIENS G. BLOWI	ORBITOLINA LENTICULARIS PSEUDOCYCLAMMINA HEDBERGI (PARS.)
	*SALPINGOPORELLA* DINARICA PALORBITOLINA LENTICULARIS					
BARREMIAN	PALORBITOLINA LENTICULARIS CHOFFATELLA DECIPIENS PALEODICTYOCONUS ARABICUS EPALORBITOLINA DHAROLLABI	CHOFFATELLA DECIPIENS ORBITOLINA LENTICULARIS	HEDBERGELLA SIGALI	DICTYOCONUS ARABICUS	SALPINGOPORELLA DINARICA	SALPINGOPORELLA DINARICA
	PERMOCALCULUS INOPINATUS					
HAUTERIVIAN	ACROPORELLA ASSURBANIPALI CYLINDROPORELLA ARABICA	UNZONED INTERVAL	CAUCASELLA HOTERIVICA	PSEUDOCYCLAMMINA LITUUS	PSEUDOCYCLAMMINA LITUUS PSEUDOCHRYSLIDINA ARABICA	PSEUDOCYCLAMMINA LITUUS PSEUDOCHRYSLIDINA ARABICA
	CYLINDROPORELLA ARABICA		CALPIONELLID ZONES			
VALANGINIAN	BUCCICRENATA HEDBERGI GLOBULIGERINA HOTERIVICA	UNZONED INTERVAL	CALPIONELLITES DARDERI CALPIONELLA LONGA	PSEUDOCYCLAMMINA LITUUS	PSEUDOCHRYSLIDINA ARABICA ALGAE	PSEUDOCHRYSLIDINA ARABICA ALGAE
	GLOBULIGERINA HOTERIVICA		CALPIONELLA LONGA			
BERRIASIAN	CALPIONELLA ALPINA GLOBULIGERINA HOTERIVICA II INDETERMINATE	KURNUBIA PALASTINIENSIS PFENDERINA NEOCOMIENSIS	CALPIONELLA ALPINA CALPIONELLOPSIS Spp.	MUNIERIA SALPINGOPORELLA	TINTINNIDS (PARS.)	TINTINNIDS (PARS.)

\* Planktonic scheme not entirely applicable to Oman

Figure 4.16

The biozonation scheme of Harris *et al.* (1984) for the Arabian Peninsula is of low resolution. In the same time interval as for this study they recognize three biozones for platformal facies, including one "unzoned interval". Their *Kurnubia palastiniensis* - *Pfenderina neocomiensis* Zone cannot be recognized in the Oman Mountains area because the nominate taxa are absent. Their planktonic microfossil zones are only applicable to the Salil and Rayda Formations in Oman. Their *Caucasella hoterivica* Zone does not equal the *Globuligerina hoterivica* Zone herein. Their zone is Late Hauterivian in age, whilst the zone herein is of Berriasian - ?Hauterivian age. Of their calpionellid zones only the *Calpionella alpina* - *Calpionellopsis* spp. Zone is recognizable in the Oman Mountains, where it is partially equivalent to the *Calpionella alpina* Subzone defined herein.

Sampo (1969) recognized four biozones in the Berriasian - Aptian sediments of south-western Iran. The Early Aptian *Salpingoporella dinarica* and *Choffatella decipiens* and *Palorbitolina lenticularis* Subzones recognized in this study are partially equivalent to the *Choffatella decipiens* Zone recognized by Sampo (1969). The *Dictyoconus arabicus* Zone of Sampo (1969) corresponds not only with the *Paleodictyoconus arabicus* Subzone defined herein, but also with the *Eopalorbitolina charollaisi* Subzone and the *Permocalculus inopinatus* Zone. The *Pseudocyclammina lituus* Zone of Sampo (1969) equates to the *Acroporella assurbanipali* and *Cylindroporella arabica* Zones and *Buccicrenata hedbergi* Subzone defined herein. Somewhat surprisingly, the nominate taxon for Sampo's zone, *Pseudocyclammina lituus*, was absent from the Oman Mountains study material. The *Munieria* - *Salpingoporella* Zone of Sampo (1969) cannot be recognized in the Oman Mountains region because of unsuitable facies.

Gollesstaneh (1965) recognized three broad assemblage zones in the Berriasian - Aptian of southern Iran, which are somewhat loosely dated. The *Orbitolina* - *Choffatella* - *Salpingoporella dinarica* Zone is partially equivalent to the *Salpingoporella dinarica*, *Palorbitolina lenticularis* and *Permocalculus inopinatus* Zones defined herein. The *Pseudocyclammina lituus* - *Pseudochrysalidina arabica* - algae Zone equates to the *Acroporella assurbanipali* and *Cylindroporella arabica* Zones and *Buccicrenata hedbergi* Subzone defined herein. Neither *Pseudocyclammina lituus* nor *Pseudochrysalidina arabica* has been recorded from the Oman

Mountains study material. The Berriasian - Valanginian Tintinnids Zone of Gollesstaneh (1965) is more limited in occurrence in the Oman Mountains because of the scarcity of calpionellids (= "tintinnids"). The *Calpionella alpina* Subzone defined herein represents this zone, whilst the remainder equates to the *Globuligerina hoterivica* Zone.

The biostratigraphic data presented above allows for the Thamama Group formations of the Oman Mountains to be dated accurately for the first time. This is summarized in Figure 4.17. Note that because most the formations are diachronous (see Section 4.4) these age assignments are inevitably somewhat generalized. The Rayda Formation is of Early Berriasian age. It possibly extends into the earliest Valanginian at some localities (eg. Wadi Bani Kharus). The Salil Formation is of Berriasian - Valanginian age, possibly Hauterivian in age in its upper part at some localities. The Habshan Formation is of Hauterivian age everywhere, with possible extension into the Late Valanginian in its lower part. The Lekhwair Formation is essentially of Hauterivian - Barremian age (often largely Hauterivian). The Kharaiib Formation is typically of Late Barremian - Early Aptian age, whilst the Shuaiba Formation in the Central Oman Mountains is of Early Aptian age.

These age assignments substantiate the regional lithostratigraphic correlations made in Chapter 2 and in Figure 2.2, but also serve to demonstrate that on a regional scale formations within the lower part of the Thamama Group can be seen to be diachronous (eg. the Habshan Formation is as old as Berriasian in Abu Dhabi, whilst in the Oman Mountains it is largely Hauterivian).

CENTRAL OMAN MOUNTAINS THAMANA GROUP BIOZONATION AND AGE OF FORMATIONS

AGE		BIOZONE	SUBZONE	DEFINING EVENT	FORMATION *
APTIAN	E	"SALPINGOPORELLA" DINARICA		T <sup>1</sup> S <sup>1</sup> : dinarica	SHU'IBA
		PALORBITOLINA LENTICULARIS	PALORBITOLINA LENTICULARIS	T <sup>1</sup> P. lenticularis	KHARAIB
CHOFFATELLA DECIPIENS	PALEODICTYOCONUS ARABICUS		T <sup>1</sup> C. decipiens		
BARREMIAN		PERMOCALCULUS INOPINATUS	EOPALORBITOLINA CHAROLLAISI	T <sup>1</sup> P. arabicus	LEKHWAIR
HAUTERIVIAN		ACROPORELLA ASSURBANIPALI		J <sup>1</sup> P. lenticularis	HABSHAN
		CYLINDROPORELLA ARABICA		T <sup>1</sup> A. assurbanipali	
				T <sup>1</sup> C. arabica	
VALANGINIAN		GLOBULIGERINA HOTERIVICA	BUCCICRENATA HEDBERGI	J <sup>1</sup> C. decipiens	SALIL
BERRIASIAN		GLOBULIGERINA HOTERIVICA	GLOBULIGERINA HOTERIVICA I	J <sup>1</sup> B. hedbergi	RAYDA
			CALPIONELLA ALPINA	T <sup>1</sup> C. alpina	
			GLOBULIGERINA HOTERIVICA II	J <sup>1</sup> C. alpina	
				J <sup>1</sup> G. hoterivica	

\* N.B. Position approximate because formations are diachronous

Figure 4.17

## **CHAPTER 5: DEPOSITIONAL ENVIRONMENTS AND GEOLOGICAL HISTORY**

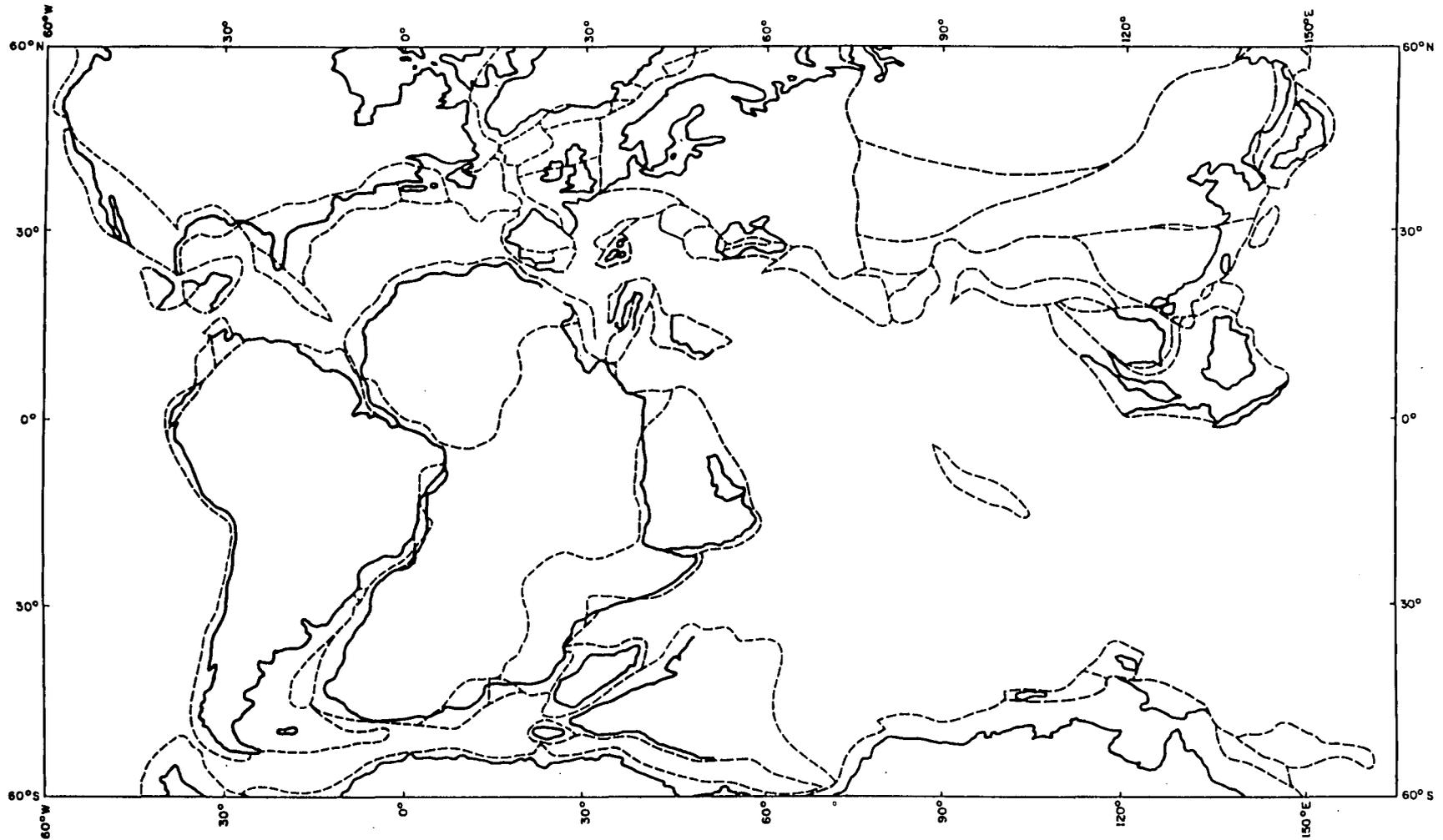
Before considering the depositional environments and geological history of the Thamama Group of the Central Oman Mountains in detail, it is necessary to introduce an overall depositional model for the succession.

The broader setting of the Early Cretaceous carbonate platform in Oman has been discussed by Saint-Marc (1978) and Murriss (1980, 1981), and is illustrated further in Figures 5.1 and 5.2 (adapted from originals produced from the BP Research Centre GLOBE database). A broad carbonate platform, trending approximately north-south, lay to the east of the exposed Arabian Shield and faced out into the open Tethyan Ocean. In the Early Cretaceous, Eastern Arabia was essentially in a passive margin setting, with carbonate shelves/ramps building out into the Tethyan Ocean. Oman occupied a sub-equatorial position at a palaeolatitude of 15 - 20° South. The edge of the continental shelf is thought to have been close to the current shoreline of Oman and ran north through Iran and Iraq (Figure 5.2).

Palaeowind directions were dominantly offshore (Figure 5.2) (although note that seasonal variations are likely). Wind regimes of this type prevent the development of bioherms (Sellwood, 1986), thus the Thamama platform was not rimmed by reefs. Instead, an open ramp developed, although in Hauterivian times, oolitic shoals may have occurred in the outer part of the ramp ("Habshan shoal"). In the context of the above, it is interesting to note that within the Early Cretaceous sediments of Somalia, where the palaeowind direction was predominantly onshore (see Figure 5.2), a reef belt developed parallel to the palaeo- continental margin.

The sedimentary facies discussed in Section 2.3 and the microfacies and biofacies illustrated in Section 4.1, together with their diachronous nature as demonstrated in Section 4.4, suggests that deposition of the Thamama Group of the Central Oman Mountains took place in carbonate ramp environments. The carbonate ramp was prograding, allowing for the development of a vertical succession of originally laterally adjacent facies. The fact that these facies belts are relatively thick, indicates that they were originally broad, a feature typical of carbonate ramps (Ahr, 1973; Read, 1985).

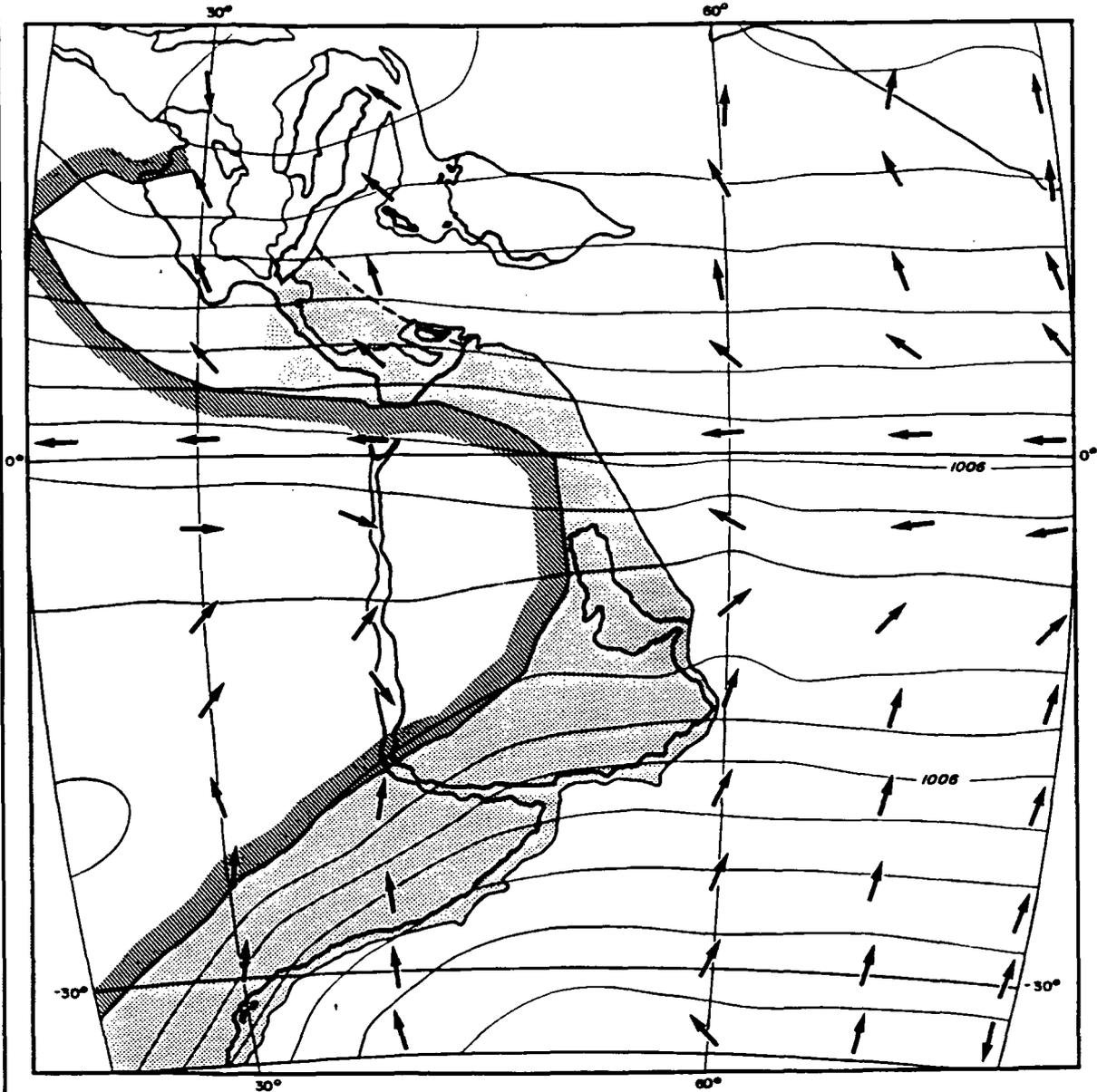
**PALAEORECONSTRUCTION SHOWING SETTING OF THE ARABIAN PENINSULA REGION  
IN EARLY CRETACEOUS TIMES (125ma.)**



**PLATE BOUNDARIES**

**Figure 5.1**

**PALAEOGEOGRAPHIC AND PALAEOCLIMATIC  
RECONSTRUCTION OF THE ARABIAN PENINSULA REGION  
FOR EARLY CRETACEOUS TIMES (125ma.)**



**WIND DIRECTION**



**SHORELINE**



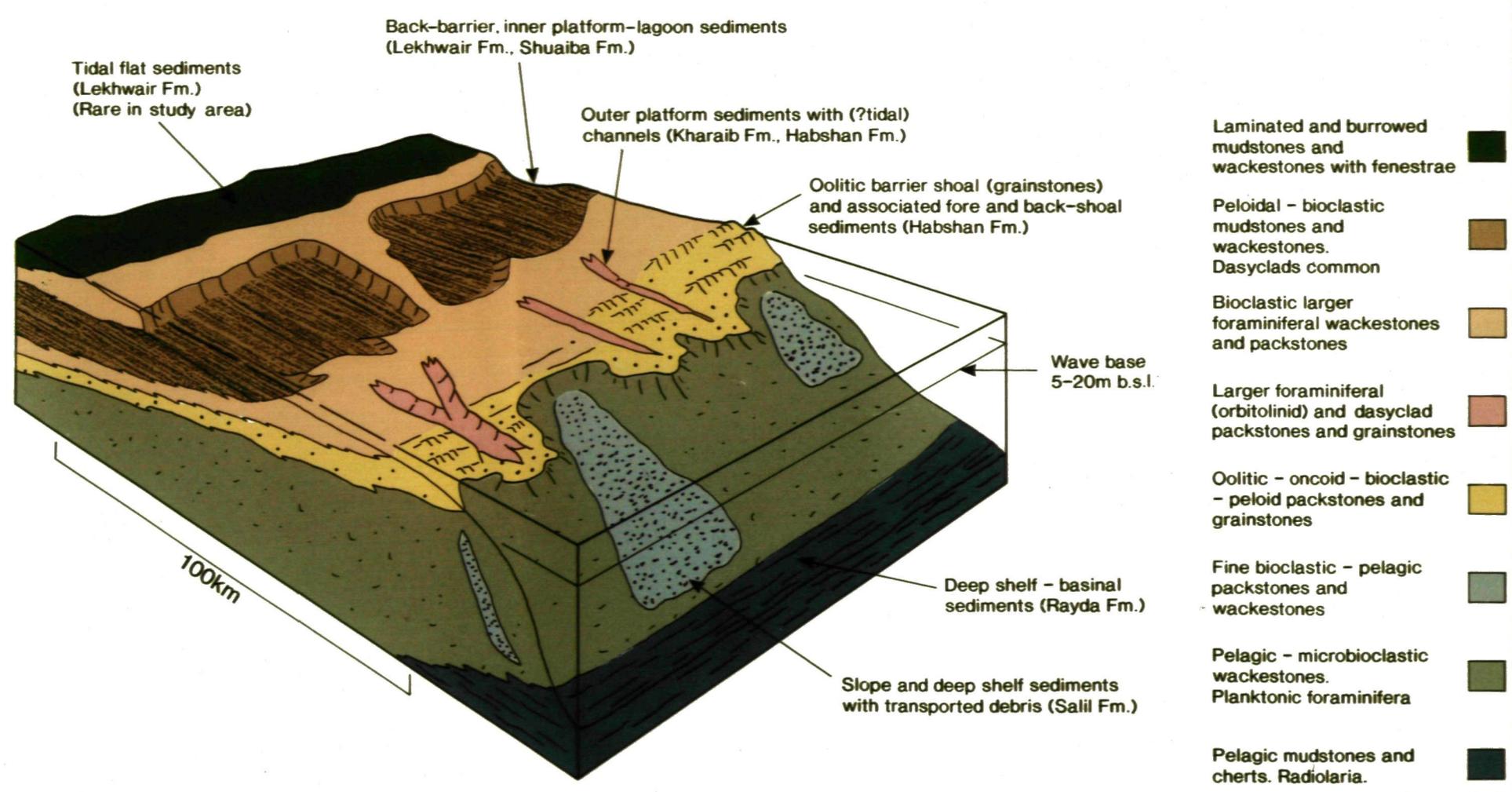
**CARBONATE SHELF**



**ISOBAR SPACING IS 2 MILLIBARS.**

**Figure 5.2**

## SIMPLIFIED MODEL FOR THAMAMA GROUP DEPOSITION



**Figure 5.3**

The type of ramp envisaged is similar to the "ramps with barrier ooid shoal complex" (type "E") described by Read (1985), although the actual width of the carbonate ramp must have been extremely wide (coeval carbonate facies are known from Oman through to central Saudi Arabia (Saint-Marc, 1978) - see also Figure 5.2). Holocene examples of this type of ramp include the Arabian Gulf (Purser and Evans, 1973). Ancient examples include the Jurassic Smackover Formation, Gulf Coast, United States (Baria *et al.*, 1982). The distal slope of the ramp was downwarped in the earliest Cretaceous and drowned by a eustatic sea-level rise (Haq *et al.*, 1987), to produce the somewhat deeper water sediments of the Rayda and Salil Formations. These pass into slope sediments and eventually the oolitic barrier shoal sediments of the Habshan Formation. Behind this barrier, bioclastic - peloidal wackestones and packstones were deposited in relatively very shallow lagoonal environments, now represented by the Lekhwair, Kharab and Shuaiba Formations. The shallow, back-shoal nature of these formations is confirmed by the associations of larger foraminifera and dasycladacean algae found within them, and by the presence of biostromes of toudasid and monopleurid rudists. Figure 5.3 presents a somewhat schematic three-dimensional view of the "Thamama ramp" based on the sedimentological and palaeontological data presented herein.

The geological history and development of the Thamama Group is now considered formation by formation, with particular reference to microfacies and biofacies, beginning with the oldest sediments:

**Rayda Formation (Berriasian - ?Valanginian):** This formation consists of pelagic mudstones and wackestones, equivalent to Standard Microfacies 3 of Wilson (1975) and Flügel (1982). There are a variety of subfacies. The lower beds of the formation are micrites with common calcified radiolaria and some small benthonic and planktonic foraminifera. Sponge spicules and echinoderm fragments are also present. There is often evidence for secondary partial dolomitization. Some units are burrowed and these contain less fauna. Overlying these units may be a micrite with abundant calpionellids, echinoderm debris and microbioclasts (seen only at Wadi Mi'aidin in this study, but known to occur regionally). Belemnites and cherts (a result of silica derived from the often abundant radiolaria found in this formation) are a feature of the Rayda Formation in the field.

Deposition of this formation is thought to have taken place at the deep shelf margin of the Thamama ramp. The abundance of radiolaria and calpionellids and the presence of cherts suggests water depths were relatively deep (upper bathyal?) and oxygen deficient. An abundance of siliceous planktonic organisms points to upwelling (Kennett, 1982) along the Oman continental margin. However, it is also worth noting that drowning of the Arabian Platform in the earliest Cretaceous by subsidence and a eustatic sea-level rise would cause a rise in the C.C.D. by reducing the supply of platform derived carbonate.

**Salil Formation (Berriasian - ?Hauterivian):** The greater part of this formation consists of pelagic mudstones and wackestones, with microbioclasts, calcified radiolaria and rare planktonic foraminifera. These suggest outer neritic - upper bathyal deep shelf - slope deposition. Burrowing is common and burrow infills include faecal pellet grainstones and dolosparites. Some horizons contain quite abundant microbioclasts or are peloidal packstones and show small-scale unidirectional cross bedding. These units probably represent derived sediment from the higher regions of the carbonate ramp slope by means of bottom currents. This suggestion is supported by the presence of reworked shallow water benthos (eg. algae, cuneolinid foraminifera, rudist bivalve debris).

**Habshan Formation (?Valanginian - Hauterivian):** The lowest units of this formation are usually bioclastic wackestones with microbioclasts, litiolids and large echinoderm and mollusc fragment. These represent the transition from slope to shoal environments.

The overlying units of this formation consist of high energy deposits which indicate deposition on the flanks of, or within, the oolitic shoal which rimmed the margin of the Thamama ramp. A wide range of microfacies are represented. These include highly burrowed peloidal packstones with abundant micritized mollusc debris and *Lithocodium* together with codiacean, gymnocodiacean and dasycladacean algae; oolitic - peloidal packstones with micritized ooids, cortoids and large echinoderm and mollusc fragments. Micritization is very common in this formation, with micritized ooids and macrofossil fragments surrounded by micritic envelopes being abundant. This suggests a shallow-water environment of deposition. Elliott (1968) suggests that the algal

assemblage described above with common *Lithocodium* represents reef or shoal debris, the result of wave action and subsequent transportation by bottom currents. The dasyclad algae remains which include *Cylindroporella*, owe their preservation to the relatively large, stumpy, well calcified segments surviving transport - the plants themselves would have grown on the lee side of the shoals.

Locally (tidal?) channel-fills and low-angle cross bedding is developed. Palaeocurrent directions indicate that the general direction of progradation was to the north-west.

Faecal peloid grainstones are present, these often also contain cortoids, litiolid foraminifera, and echinoderm and mollusc fragments. Intraclasts and lithoclasts are also moderately common allochems in this formation indicating high-energy, shallow water conditions of deposition, perhaps a function of local storm events.

The uppermost units of the Habshan Formation are often well sorted oolitic grainstones, ooid - peloid packstones/grainstones and faecal peloid grainstones (eg. Wadi Mi'aidin). Intraclasts, mollusc debris and benthonic foraminifera are rarer allochems. These units usually have a sparite cement indicating that the original matrix has been winnowed out. The oolitic units are equivalent to Standard Microfacies 15 of Wilson (1975) and Flügel (1982). Standard Microfacies type 11 (grainstones with coated bioclasts in sparry cement) also occurs in the upper part of this formation. These microfacies suggest deposition in facies zone 6 of Wilson (1975) - winnowed platform edge sands and oolitic shoals - all areas with constant wave action, at or above wave base (probably no more than 10m b.s.l. water depth).

**Lekhwaier Formation (Hauterivian - Barremian):** The microfacies present in this formation represent relatively quiet-water deposition in a back-shoal environment:

Bioclastic wackestones and packstones (Standard Microfacies 9 and 10 of Wilson (1975)) are dominant. These include burrowed micrites with mollusc debris and/or dasycladacean algae. In outcrop, caprinid and requienid

rudists are common and may form biostromes. Micritization of allochems is common. Burrows often have a dolosparite infilling.

Dasycladacean grainstones (Standard Microfacies 18 of Wilson (1975)) are a feature of this formation. They indicate very shallow environments of deposition, possibly in lagoonal channels.

Another typical microfacies of this formation is that of micritic wackestones with highly fragmented gymnocodiacean and dasycladacean algal remains and some benthonic foraminifera. This is the "Algal Debris Facies" of the Middle East, first described by Elliott (1958). Only moderate energies are required to rework and disaggregate these algal remains. No major transportation is indicated. Reworking probably took place where the plants were originally growing. However, Elliott (1968) suggests that transportation may have been more extensive, particularly in an offshore direction.

**Kharaib Formation (Barremian - Early Aptian):** Peloidal grainstones, algal - foraminiferal packstones and orbitolinid packstones characterize the microfacies present in this formation. Algae are less common than in the underlying Lekhwair Formation. Orbitolinid packstones often also contain lituolids and *Salpingoporella dinarica*, and may be partially dolomitized. Burrowing is a common feature. Within the orbitolinid packstones the orbitolinids are often micritized. Mollusc debris (notably oyster) is quite a common allochem.

The above facies suggest shallow back-shoal conditions of deposition, with the orbitolinid packstones perhaps having been deposited in broad lagoonal channels (broad channel structures can be seen in the field - see Section 2.3). Although still shallow water, the reduced abundance of dasycladacean algae and abundance of orbitolinids suggests water depths in the middle neritic range are likely, with an open circulation. There may be a correspondence between eustatic sea-level changes and levels with abundant orbitolinids and *Choffatella*.

**Shuaiba Formation (Early Aptian):** The lowest beds in this formation are usually *Lithocodium* boundstones, overlain by packstones with *Lithocodium* fragments, foraminifera (including orbitolinids) and peloids. The

upper part of the formation largely consists of faecal peloid packstones and grainstones with some foraminifera (Standard Microfacies 16 of Wilson (1975)). There are also thin interbedded *Lithocodium* boundstones. The highest beds of the formation often contain rudist bivalve fragments and orbitolinids in peloidal packstones. The large mollusc fragments are often encrusted by algae. Caprinid and toucasid rudist biostromes are a feature of this formation in outcrop (see Section 2.3). Deposition in low energy, relatively shallow water, protected inner neritic conditions are suggested by these facies.

It is suggested that the Thamama Group represents a major unconformity bounded sequence, that internally displays shoaling-up. Since the Arabian Plate is known to be relatively stable in the Early Cretaceous (Murriss, 1980, 1981), the unconformities bounding the Thamama Group formed in response to changes in relative sea-level (Harris *et al.*, 1984). Sedimentation during Thamama Group times was also controlled by eustatic sea-level change.

The initiation of Thamama Group deposition relates to subsidence of the Arabian carbonate platform and drowning by the Early Berriasian eustatic sea-level rise documented by Haq *et al.* (1987). Scott (pers. comm., 1988) suggests that the Oman Mountains area was submerged to a depth of 200m during deposition of the Rayda Formation. The rate of relative sea-level rise was 4cm per 1000 years if all drowning occurred within the Berriasian. Following this drowning event, the Habshan shoal and associated platform sediments prograded eastward across the Rayda and Salil sediment wedge that covered the drowned platform.

Deposition of the Lekhwair, Kharaib and Shuaiba Formations was influenced by eustatic sea level change. The cyclicity identified in these formations, and pulses of deepening (eg. beds with abundant *Lithocodium* in the Shuaiba and Lekhwair Formations, beds with abundant orbitolinids and *Choffatella* in the Kharaib Formation) often, allowing for the relatively poor chronostratigraphic resolution, relate to peaks in the Haq *et al.* (1987) eustatic sea-level curve.

The unconformity at the Shuaiba Formation - Nahr Umr Formation boundary could relate to the rapid Early Aptian sea level rise documented by Haq *et al.* (1987). This would account for the erosive hardground surface often seen at this boundary. However, the fact that the top of the Shuaiba Formation is markedly younger at some localities (eg. Wadi Bani Kharus) than at other implies differential erosion, perhaps relating to subaerial exposure. Perhaps uplift and erosion in the Early Aptian was followed by drowning relating to the Early Aptian (or later Early Albian - Haq *et al.*, 1987) sea-level rise, with subsequent hardground formation.

## **CHAPTER 6: CONCLUSIONS**

The following key conclusions can be drawn from this study:

### **General**

- (1) Up to 1500m of Early - Mid-Cretaceous carbonate sediment is exposed in the outcrop sections of the Central Oman Mountains. It can be lithostratigraphically subdivided into two groups: the Thamama Group and Wasia Group. Each group is bounded by regional unconformities. The Thamama Group is divisible into six formations: the Rayda, Salil, Habshan, Lekhwair, Kharab and Shuaiba Formations. The Wasia Group is divisible into two formations: the Nahr Umr and Natih Formations.
- (2) Microfossils (particularly benthonic foraminifera, planktonic foraminifera, calcareous algae and calpionellids) are present in all lithostratigraphic units. They can be used to biostratigraphically subdivide and correlate these units and to elucidate their depositional setting. A detailed study of the micropalaeontology and biostratigraphy of the Thamama Group has been carried out.

### **Lithostratigraphy**

- (3) A complete revision of Cretaceous Middle Eastern lithostratigraphic nomenclature is required. Many lithostratigraphic names are superfluous, whilst others have been applied to sections that bear little sedimentological relation to the original type section.
- (4) The term "Thamama Group" as used in the Arabian Gulf, is preferred to "Kahmah Group" as introduced by Glennie *et al.* (1974). The two units have overall similar lithologies and virtual

chronostratigraphic equivalence. The fact that in Oman the Thamama Group is not underlain by the Hihi Anhydrite does not preclude use of the name.

- (5) The terms "Musandam Limestone" and "Musandam Group" are superfluous. The subdivisions of the Thamama Group and Wasia Group used here should be applied across all northern Oman.
- (6) The local term "Natih Formation" is preferred to division into "Mauddud Formation", "Khatiyah Formation" and "Mishrif Formation" as used in the Arabian Gulf region, because of lithological differences between Abu Dhabi and the Oman Mountains.
- (7) The term "Wasia Group" has a confused origin and does not wholly comply with the rules of lithostratigraphic nomenclature. However, it now has a well established meaning and is therefore impractical to revise.
- (8) The sediments of the Thamama Group and the Wasia Group of the Oman Mountains outcrop sections are fully described herein for the first time.

### **Taxonomy**

- (9) 29 species of foraminifera (20 genera), 25 species of calcareous algae (16 genera) and 3 species of calpionellids (2 genera) are described in detail. Many are recorded from the Middle East for the first time.
- (10) The foraminiferal subfamilies Choffatellinae and Hemicyclammininae are herein raised to family level to indicate they are phylogenetically distinct from the Cenozoic and Recent Cyclamminidae.

- (11) *Choffatella decipiens* is shown to have a Hauterivian - Aptian stratigraphic range and thus forms a useful biostratigraphic marker for this interval.
- (12) The Chrysalidinidae are considered to be a group in which iterative evolution has taken place giving rise to the gross homeomorphs *Praechrysalidina*, *Dukhania*, *Chrysalidina*, etc.
- (13) The type species of *Orbitolina* is shown to be *Orbitolina gigantea* d'Orbigny, a species of coral. As a result of this study, it has been recommended to the ICZN that this designation be suppressed and that *Orbulites concava* Lamarck be introduced as a replacement type species. The genus *Palorbitolina*, type species *Madreporites lenticularis* Blumenbach, is entirely valid. It does not share the same type species as *Orbitolina*.
- (14) Increases in the size and complexity of the embryonic apparatus of *Palorbitolina lenticularis* should only be used with caution when attempting to distinguish Late Barremian strata from Early Aptian strata. Dominance of "advanced" (= Early Aptian) and "primitive" (= Late Barremian) forms can only be reliably determined from large populations.
- (15) Levels with abundant orbitolinids and *Choffatella* are thought to correspond to transgressive events where the taxa move into vacant ecological niches.
- (16) *Lithocodium*, previously considered as a Problematicum, algae *incertae sedis*, foraminifera, codiacean, sponge or to be of bacterial origin, etc, is herein considered to be the senior synonym of *Bacinella* and to be a codiacean alga, as originally described by Elliott (1956).
- (17) "*Salpingoporella*" *dinarica* is shown to be the senior synonym of *Hensonella cylindrica*. It is a dasycladacean alga which was originally calcitic.

## **Biostratigraphy**

- (18) The distribution of microfossils and microfacies in Thamama Group sediments is detailed for three localities (Wadi Mi'aidin, Wadi Bani Kharus and Jebel Madar), together with subsequent biozonal and chronostratigraphic interpretations.
- (19) The Graphic Correlation technique of Shaw (1964) has been applied to the Thamama Group biostratigraphic data. A Composite Standard Reference Section has been developed, which in turn has allowed for a local total stratigraphic range chart and biozonation scheme to be constructed. The method also provides an alternative means of correlating between sections.
- (20) A local biozonation scheme has been devised and described using tops and bases of biostratigraphically significant taxa. 13 zones/subzones are recognized with an average resolution of 2.15 million years (using the timescale of Harland *et al.*, 1982). Application of this zonation permits chronostratigraphic interpretation and correlation of Thamama Group sections in the Oman Mountains area. This scheme is of a greater resolution than any previously published biozonation scheme in the Middle East region.
- (21) Both Graphic Correlation and correlation by biozones demonstrates that most Thamama Group formations are diachronous and may be condensed at some localities.
- (22) Biostratigraphic studies demonstrate that in the Central Oman Mountains region the Thamama Group formations are of the following ages: The Rayda Formation is of Early Berriasian age. It possibly extends into the earliest Valanginian at some localities (eg. Wadi Bani Kharus). The Salil Formation is of Berriasian - Valanginian age, possibly Hauterivian in age in its upper part at some localities. The Habshan Formation is of Hauterivian age everywhere, with possible extension into the Late Valanginian in its lower part. The Lekhwair Formation is essentially of Hauterivian -

Barremian age (often largely Hauterivian). The Kharaib Formation is of typically Late Barremian - Early Aptian age, whilst the Shuaiba Formation is of Early Aptian age.

- (23) Although not discussed in detail in this study, the age of the Nahr Umr Formation in the Oman Mountains is thought to be Early - Late Albian, whilst the Natih Formation is Late Albian/Early Cenomanian - earliest Turonian. However, pre-Aruma Group erosion at some localities results in the absence of Latest Cenomanian and earliest Turonian strata.

### **Depositional Environments and Geological History**

- (24) Thamama Group deposition took place on an initially downwarped carbonate ramp, prograding towards the Tethyan Ocean (towards the north and east). Offshore palaeowinds precluded the development of reefs, but an oolitic shoal was located at the margin of the ramp at least during Hauterivian times.
- (25) The Rayda Formation is thought to have been deposited at the deep shelf margin of the Thamama ramp. Water depths were relatively deep (upper bathyal?) and oxygen deficient. Upwelling may account for the abundance of siliceous microfossils. Alternatively, the C.C.D. may have been raised by the initial drowning of the Arabian Platform.
- (26) The Salil Formation was deposited in outer neritic - upper bathyal, deep shelf - slope environments. Downslope transport of sediment by bottom currents is thought to have occurred.
- (27) The Habshan Formation was largely deposited in high energy shoal, and fore-shoal or proximal back-shoal environments, at, or above, wave base.

- (28) The microfacies and microfossils present in the Lekhwair Formation suggest relatively quiet-water deposition in a back-shoal lagoon environment.
- (29) Facies within the Kharai Formation suggest shallow back-shoal conditions of deposition, with orbitolinid packstones perhaps having been deposited in broad lagoonal channels. Although still shallow water, the reduced abundance of dasycladacean algae and abundance of orbitolinids suggests water depths in the middle neritic range are likely, with an open circulation.
- (30) The Shuaiba Formation was deposited in low energy, relatively shallow water, protected inner neritic conditions.
- (31) Eustatic sea-level changes, such as those documented by Haq *et al.* (1987) played an important role in the depositional history of the Thamama Group of the Oman Mountains. Subsidence of the Arabian Platform and the Early Berriasian eustatic sea-level rise initiated Thamama Group deposition. Subsequently, eustatic overprinting can be seen in the Thamama Group formations, especially the Lekhwair Formation and Kharai Formation. Uplift (?) and the Early Aptian or Early Albian eustatic sea-level rise led to the development of the Shuaiba - Nahr Umr disconformity surface.

This study can only be considered a preliminary review of the Cretaceous stratigraphy of the Oman Mountains and of the taxonomy of the microfossils found in the Early Cretaceous sediments. Much more research is required in a number of areas.

Of particular importance are examination of more outcrop sections to supplement the data presented in this study. Stratigraphic correlation both locally (for example to Abu Dhabi) and to other areas of Tethys (for example to the Mediterranean) will provide valuable information on geological events across Tethys such as sea-level fluctuations. Graphic correlation of Cretaceous sections across the Tethyan region should be attempted

in order to develop a innovative mechanism for correlation and to better understand the stratigraphic range of the taxa involved.

The taxonomy of many Early Cretaceous microfossil genera and species recorded from the Middle East (but often not in this study) needs to be revised, particularly in the light of the numerous recent studies of similar faunas and floras from the Peri-Mediterranean region. Much of the Middle East microfauna and microflora needs to be further redescrbed in line with recent advances in taxonomy. This will also provide information on the palaeobiogeography of the various taxa involved.

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## APPENDIX 1 - RECENT LITERATURE

After this thesis went into the final stages of completion, a number of publications came to hand which were pertinent to the subject matter of this study. It was decided not to incorporate the ideas and data they presented into this thesis because it would have been too time consuming and necessitated rewriting large sections of the thesis. However, these references are listed below, with brief notes on their implications for this study.

Alsharhan, A.S. & Nairn, A.E.M. 1986. A review of the Cretaceous formations in the Arabian Peninsula and Gulf: Part I, Lower Cretaceous (Thamama Group) stratigraphy and paleogeography. *J. Petrol. Geol.*, **9**, 365-392.

This paper reviews the Early Cretaceous lithostratigraphy of the Arabian Peninsula and Gulf region, and reaches similar conclusions to those presented in Chapter 2 of this thesis. In particular, the paper focuses on the stratigraphy of the Abu Dhabi region, and the Thamama Group type sections in Saudi Arabia. The lithostratigraphy of the Oman Mountains is not considered in detail. A historical review provides an explanation for the profusion of lithostratigraphic terms. This problem is related to the fact that the Thamama Group type section exposed in Saudi Arabia cannot be applied to the subsurface sections of the Arabian Gulf region.

The lithostratigraphy of the Arabian Peninsula and Gulf region is discussed in terms of a standard series of formations (Habshan Formation, Lekhwair Formation, Kharaiib Formation, Shuaiba Formation and Bab Member). For each formation the following information is listed: author, synonymy, type locality, thickness, lithology, fossils and age. Whilst this is a useful exercise, the papers value is limited by: (i) the authors failure to recognize that each lithostratigraphic unit is likely to be diachronous (although they do accept that the section represents a progradational carbonate platform). (ii) The standard section is only applicable in terms of lithology (and usually age) to central offshore Abu Dhabi. (iii) The microfossils they record from each formation are applicable largely only to Abu Dhabi, are sometimes incorrect, and not always compatible with their subsequent

age determinations. (iv) No new data is presented. Only old and sometimes conflicting descriptions of formations, or their fossil content and age are given. However, this paper is commendable because the formal description of type and/or reference sections of the Thamama Group formations of Abu Dhabi has been needed for some time.

The description of the age of the Thamama Group formations as seen in the Oman Mountains is in general agreement with the conclusions reached in this study. An exception to this is the age of the Rayda Formation which Alsharhan and Nairn (1986) consider to be Tithonian in age and separated from the Salil Formation by an unconformity. This differs from the view presented in this study which states that the Rayda Formation is Berriasian in age and passes up into the Salil Formation conformably. Alsharhan and Nairn (1986) provide no biostratigraphic data to support their argument, whilst the Berriasian calpionellids found at the base of the formation in this study have also been recorded by Scott *et al.* (1988) (see below).

Alsharhan and Nairn (1986) recognize two carbonate cycles within the Lower Cretaceous sequence. The first ends at the top of the Habshan Formation (or equivalents) in Hauterivian times. The second continues to the top of the Shuiba Formation. Whilst this seems likely in Abu Dhabi, where the top of the Habshan Formation and the top of the Shuaiba Formation could be considered the top of major shallowing-up cycles, in Oman the situation is less clear. There is no biostratigraphic evidence for an unconformity at the top of the Habshan Formation in the Oman Mountains.

In the latter part of their paper, Alsharhan and Nairn present a useful discussion of depositional environments and paleogeography within the Early Cretaceous of the Arabian Peninsula and Gulf. In general, their model is in agreement with that presented in this study (i.e. a progradational carbonate ramp). However, there is a tendency to correlate similar facies too far across the study region (for example the Salil Formation of Oman, considered to be a slope facies, as in this study, is thought to be similar to the Sulaiy Formation of Saudi Arabia, which in fact probably represents much shallower water, inner platform deposition (from

considerations of the description of that unit by Powers *et al.* (1966) and Powers (1968), and the general palaeogeographic setting).

Alsharhan, A.S. & Nairn, A.E.M. 1988. A review of the Cretaceous formations in the Arabian Peninsula and Gulf: Part II, Mid-Cretaceous (Wasia Group) stratigraphy and paleogeography. *J. Petrol. Geol.*, **11**, 89-112.

In a similar manner to the above paper by the same authors, the stratigraphic sequence of the mid-Cretaceous of the Arabian Peninsula and Gulf (Wasia Group) is reviewed. Type section and synonymy are established for the succession in Abu Dhabi. As with the Thamama Group, the authors recognize that the problems of lithostratigraphic nomenclature in the Wasia Group relate to the fact the type section of the Wasia Group in Saudi Arabia does not easily correlate with the subsurface sections of the Arabian Gulf. Refinement of lithostratigraphic correlation await the publication of detailed biostratigraphic studies for the whole region.

In the outcrop sections of the Oman Mountains Alsharhan and Nairn (1988) follow Harris and Frost (1984) and prefer the Arabian Gulf terms Mauddud Formation and Mishrif Formation for platform facies, and Khatiyah Formation for basinal facies, to Natih Formation. Natih Formation Members E-G are equated to the Mauddud Formation, Members A-D to the Mishrif Formation.

As with their earlier paper on the Thamama Group, Alsharhan and Nairn (1988) provide a useful standard section of formations (Nahr Umr Formation, Mauddud Formation, Shilaif Formation and Mishrif Formation) for which they describe a type section and/or a reference section in Abu Dhabi. They also cite original author, synonymy, age, and fossil content (the later only in Abu Dhabi). Unfortunately, also as in their earlier paper, the authors do not emphasize the possibility of diachroneity in the formations described and the fossil data they present is old and sometimes of questionable validity.

The authors recognize two cycles of deposition within the Wasia Group. A Nahr Umr - Mauddud cycle overlain by a Mishrif cycle. In Oman, the hardground seen within the Natih Formation (probably at the top of the "E" member) corresponds to the boundary between these two cycles. The paleogeography of these two cycles is discussed. In Oman, the Nahr Umr Formation is considered to represent deposition on an open shelf, which further westwards is clastic dominated. The Mauddud Formation in Oman (=lower Natih Formation) is interpreted as a open carbonate shelf which followed on from the Nahr Umr Formation when clastic input from the west abruptly ceased. Shilaif/Khatiyah type carbonates within the Natih Formation (=Natih Member "E") are interpreted as an intra-shelf basin. No comment is made on the basinal sediments seen in the Natih Member "B" which cannot correlate to the Shilaif/Khatiyah of Abu Dhabi because of age differences. The Mishrif facies in Oman (=Natih members A-D) is interpreted as a offshore shoal prograding eastward into mud-rich carbonates deposited below wave base.

See the paper by Smith, Simmons and Racey (in prep.) presented in Appendix 2 for further discussion of the depositional setting of the Natih Formation and its correlation to the formations seen in the Arabian Gulf.

Banner, F.T. & Desai, D. 1988. A review and revision of the Jurassic - Early Cretaceous Globigerinina, with especial reference to the Aptian assemblages of Speeton (North Yorkshire, England). *J. Micropalaeont.*, 7, 143-185.

This paper presents a phyletic and taxonomic revision of the Jurassic - Albian globigerinids. The genus *Globuligerina* is placed within the superfamily Favusellacea, and together with *Conoglobigerina* is considered ancestral to *Favusella*. This lineage is thought to be separate from the Globigerinacea, which includes the forms ancestral to *Hedbergella*.

The genus *Globuligerina* is very precisely defined. It is considered as a trochospiral, muricate form with two or more whorls and four or more (commonly five) chambers per whorl. Spire may be variable and the umbilical side is almost completely involute with a narrow, but distinct, umbilicus. The aperture is a narrow,

high, asymmetrical, loop-shaped, "bulimine-like" opening. The genus has a restricted range of Bajocian - Kimmeridgian. *Globuligerina hoterivica* is transferred to the genus *Favusella*, because it possess a more distinctive reticulum and an intra-umbilical aperture. This species is considered to be restricted to the Hauterivian.

This highly precise (taxonomic "splitters") view of Early Cretaceous planktonic foraminifera differs from the broader (taxonomic "lumpers") view presented in this thesis. However, whilst perhaps biologically incorrect, a broad concept of the genus *Globuligerina* and the species *G. hoterivica* is applicable to this study, because the specimens have only been observed in thin-section. Indeed, it is not possible to be certain if the specimens in this study are reticulate/muricate or not. Given their age and general form, according to Banner and Desai (1988) they would be referable to *Conoglobigerina gulekhensis* (Gorbachik and Poroshina) if muricate, or *Gorbachikella parva* (Kuznetsova) if smooth walled.

Beydoun, Z.R. 1988. *The Middle East: Regional Geology and Petroleum Resources*. Scientific Press Ltd., 292pp.

This book presents a complete review of the geology and hydrocarbon and mineral resources of the Middle East region. Because of this book covers a great geographic area and the entire stratigraphic column, the Early - mid Cretaceous of the Oman Mountains is not discussed in any detail.

Of particular relevance to this thesis are the Cretaceous lithostratigraphic correlation charts and summary of Omani petroleum resources.

Connally, T.C. & Scott, R.W. 1985. Carbonate sediment-fill of an oceanic shelf, Lower Cretaceous, Arabian Peninsula. *SEPM Core Workshop*, 6, 266-302.

This paper presents a review of the depositional setting of the lower part of the Thamama Group (Rayda - Lekhwair Formations) in the Oman Mountains and Sajaa Field, U.A.E. Some of the biostratigraphic and sedimentological data incorporated in this study was supplied by the author.

These authors suggest that the initial Cretaceous relative sea-level rise drowned the Jurassic shelf on the eastern margin of the Arabian Plate forming a marginal shelf basin. Sediments in the deepest part of the basin were silica-rich, radiolarian-calpionellid lime mudstones of the Rayda Formation. These are overlain by the mudstones of the Salil formation which are influenced by density currents. The grainstone dominated Habshan Formation represents shoals and bars forming at the margin of this marginal shelf basin. The mudstones of the overlying Lekhwair Formation were deposited in the protected shelf lagoon.

The above model of deposition of these units is in agreement with that presented in this thesis. Similarly, Connally and Scott (1985) also note that these units were prograding eastwards as verified by the time-transgressive character of the Habshan Formation.

The sedimentology and diagenesis of the lower Thamama Group in the Oman Mountains and Sajaa Field is described and illustrated in detail. Certain key biostratigraphic events and the age of the formations are documented (in agreement with those recorded in this study).

Hughes-Clarke, M.W. 1988. Stratigraphy and rock-unit nomenclature in the oil-producing area of interior Oman. *J. Petrol. Geol.*, **11**, 5-60.

This paper presents a description of all the major rock units in the sedimentary sequence seen in the oil producing area of interior Oman. The lithostratigraphic nomenclature of the region is comprehensively reviewed. The occurrence of hydrocarbons within this sedimentary sequence is also discussed. Most importantly with regard to this thesis, type and/or reference sections of all the Early - mid-Cretaceous formations occurring

in the Oman Mountains are described. However, the description of the formations is not as detailed as that undertaken in this thesis.

The Early Cretaceous (Berriasian - Aptian) carbonates are referred to the Kahmah Group. This term is preferred to Thamama Group (as used in this study) because of the presence of pelagic facies at the base of the sequence. The Kahmah Group is described as unconformably overlying Jurassic carbonates of the Sahtan Group. It is described as being unconformably overlain by mid-Cretaceous carbonates of the Wasia Group. Like Alsharhan and Nairn (1986; 1988), two cycles of deposition are recognized within the Kahmah Group and within the Wasia Group.

The type section of the Rayda Formation is given as SE Jebel Akhdar with a reference section being noted in the well Dhulaima-4. Description and interpretation of environment of deposition are essentially similar to those given in this study. Also, (unlike Alsharhan and Nairn, 1986) the age of this formation is considered to be Berriasian - Valanginian. Contact with the overlying Salil Formation is described as gradational.

The type section of the Salil Formation is also given as SE Jebel Akhdar, with a reference section also being described from the well Dhulaima-4. Description and interpretation of environment of deposition are essentially similar to those given in this study. Age of this formation is given as Valanginian - Hauterivian (as in this study).

Reference sections for the Habshan formation are given as SE Jebel Akhdar and Dhulaima-4. Description and interpretation of environment of deposition are essentially similar to those given in this study, although more emphasis is placed on a tidally influenced depositional setting. Age of this formation is given as Hauterivian (as in this study).

The type section for the Lekhwair Formation is described from the well Lekhwair-7. This type section differs from the outcrop sections seen in the Oman Mountains. It is more argillaceous and bears closer

similarities to the formation as seen in Abu Dhabi. No discussion of the formation in outcrop is given. However, the interpretation of age and depositional environment for this formation are similar to those given in this study (age: Hauterivian - Barremian).

A reference section of the Kharab Formation is described from the well Lekhwair-7. Description and interpretation of environment of deposition are essentially similar to those given in this study. As in this study, the age of this formation is suggested to be Barremian - Aptian.

Reference sections for the Shuaiba Formation are given from the wells Lekhwair-7 and Al Huwaisah-2. Description and interpretation of environment of deposition are essentially similar to those given in this study. As in this study, the age of this formation is suggested to be Aptian, although unlike this study, a possible earliest Albian age is also suggested (but without any biostratigraphic support).

A reference section for the Nahr Umr Formation is described from the well Maqhoul-1. Description and interpretation of environment of deposition are essentially similar to those given in this study. As in this study, the age of the formation is considered to be broadly Albian.

The use of the term Natih Formation is upheld (instead of Mishrif Formation and Mauddud Formation, etc.). The type section from the well Fahud North-3 is briefly described and a reference section at Wadi Mi'aidin is proposed. Description and interpretation of environment of deposition are essentially similar to those given in this study. A surface reference section at Wadi Mi'aidin seems to be unsuitable because the Natih Formation there is incomplete (see Simmons and Hart, 1987; Smith, Simmons and Racey, in press - presented in Appendix 2). A better section would be at Jebel Salak. The age of the formation is given as Albian - Cenomanian, although biostratigraphic evidence gathered during the course of this study suggests extension into the earliest Turonian (see Chapter 2 and Appendix 2).

Kalantari, A. 1986. Microfacies of carbonate rocks of Iran. *National Iranian Oil Company Geological Laboratories Publication*, 11, 287pp.

This book presents an atlas of the microfacies and microfossils found within the Phanerozoic sedimentary sequence of Iran. 55 plates of the microfacies of Early - Mid-Cretaceous carbonates are given, whilst a separate series of plates illustrate the various microfossil species found. This book is however limited by the use of outdated taxonomy and by occasional questionable determinations.

Scott, R.W., Frost, S.H. & Shaffer, B.L. 1988. Early Cretaceous sea-level curves, Gulf Coast and Southeastern Arabia. *SEPM Spec. Pub.*, 42, 275-284.

In this paper, three sections of Early - mid-Cretaceous strata from the Gulf Coast of the U.S.A. are biostratigraphically correlated with three sections in Oman (Wadi Tanuf, Wadi Bani Kharus and Wadi Mi'aidin), using graphic correlation. Some of the original biostratigraphic data for the sections in Oman was supplied by the author.

This correlation reveals two synchronous relative sea-level rise events. An intra-Aptian rise began about 115.8Ma, whilst an intra-Cenomanian rise began about 94.6Ma. In Oman, this later rise is represented by hardground surfaces which formed following the drowning of the carbonate shelf.

The paper lists the ranges of a few key microfossil taxa which occur in the Early - mid-Cretaceous Oman Mountains sections. These ranges are in agreement with those presented in this study, and confirm the ages of the various Thamama and Wasia Group formations as given in this study. Interestingly, these authors record rather more calpionellid taxa from the Rayda Formation than I did (i.e. 6). However, they also conclude that this formation is of Berriasian age.

Scott *et al.* (1988) also note that the top of the Shuaiba Formation may be younger in western Oman and Abu Dhabi than in the Oman Mountains. They suggest that in these areas, deposition may have been continuous from the Shuaiba Formation to the Nahr Umr Formation. However this needs further biostratigraphic documentation.

Watts, K.F. & Garrison, R.E. 1986. Sumeini Group, Oman - Evolution of a Mesozoic carbonate slope on a south Tethyan continental margin. *Sed. Geol.*, **48**, 107-168.

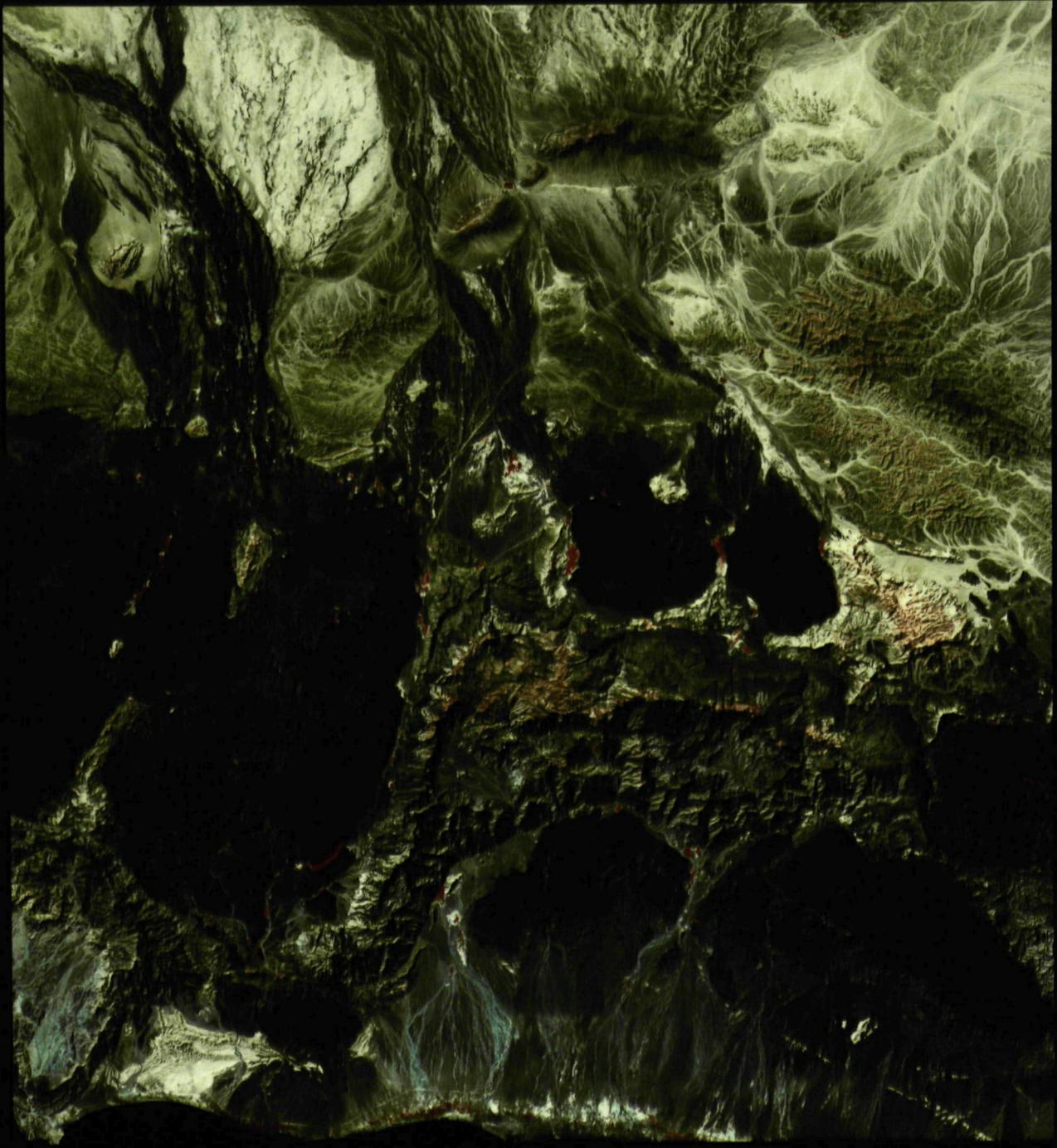
This paper reviews the sedimentology and deposition of the Permian - Cretaceous Sumeini Group outcropping in and around the Oman Mountains.

Deposition of the Sumeini Group occurred on the slope between the shallow marine Arabian carbonate platform (i.e. the Hajar Super-group) and the deep oceanic Hawasina Basin or southern Tethys Ocean, the later now obducted over the more proximal facies. It therefore contains sedimentary units which are the lateral equivalents of the Thamama and Wasia Groups discussed in this thesis.

The Mayhah Formation represents the lateral equivalents of the Thamama and Wasia Groups. In the Early Cretaceous it is formed of radiolarian cherts deposited on the slope (probably below C.C.D.) between the basinal limestones of the Rayda and Salil Formations and the true abyssal Tethyan ocean floor. In mid-Cretaceous times this margin became much more pronounced, and megabreccias were deposited at the base of an extremely steep shelf edge - oceanic margin.

## PLATE 1.1

Plate 1.1: LANDSAT photograph of the Central Oman Mountains. Width of photograph area is approximately 125km. Mountainous area in the upper central part of the photograph is the Jebel Akhdar Dome, a tectonic window exposing autochthonous carbonates of the Hajar Super-group, including the Thamama and Wasia Groups. Dark green mountainous areas surrounding this are outcrops the Oman Mountains Ophiolite. Distinctively folded light green area to bottom left of photograph is the outcrop of the Hawasina Series in the Hamrat Duru region. The three isolated jebels towards the bottom of the photograph are from left to right: Jebel Salak, Jebel Madamar and Jebel Madar. These expose Thamama and Wasia Group sediments. Figures 1.1 and 1.3 give further location and geological details.



## PLATES 2.1 - 2.2

**Plate 2.1:** Exposure of the Hajar Super-group on the eastern side of Wadi Bani Kharus. Well exposed strata consist largely of Thamama Group and Wasia Group sediments.

**Plate 2.2:** Lower Thamama Group sediments exposed (and logged) on the western side of Wadi Bani Kharus. Shaley, poorly exposed sediments are Rayda Formation and Salil Formation. Bedded grey limestones are of the Habshan Formation.

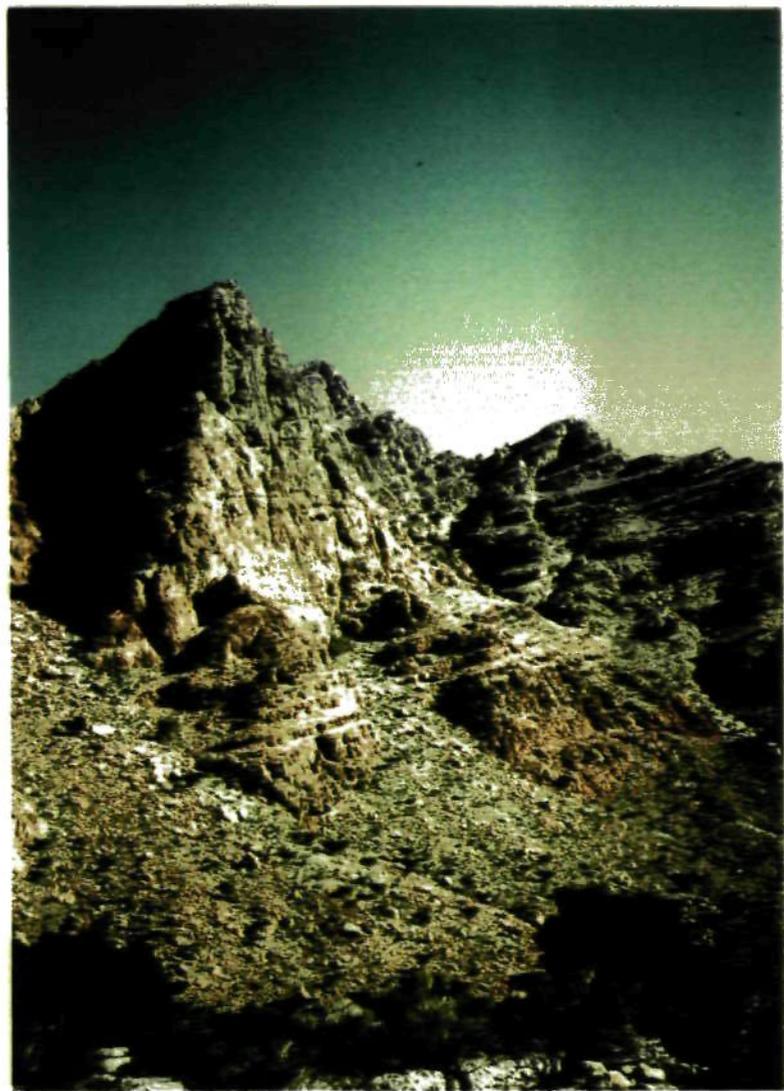


Plate 2.1

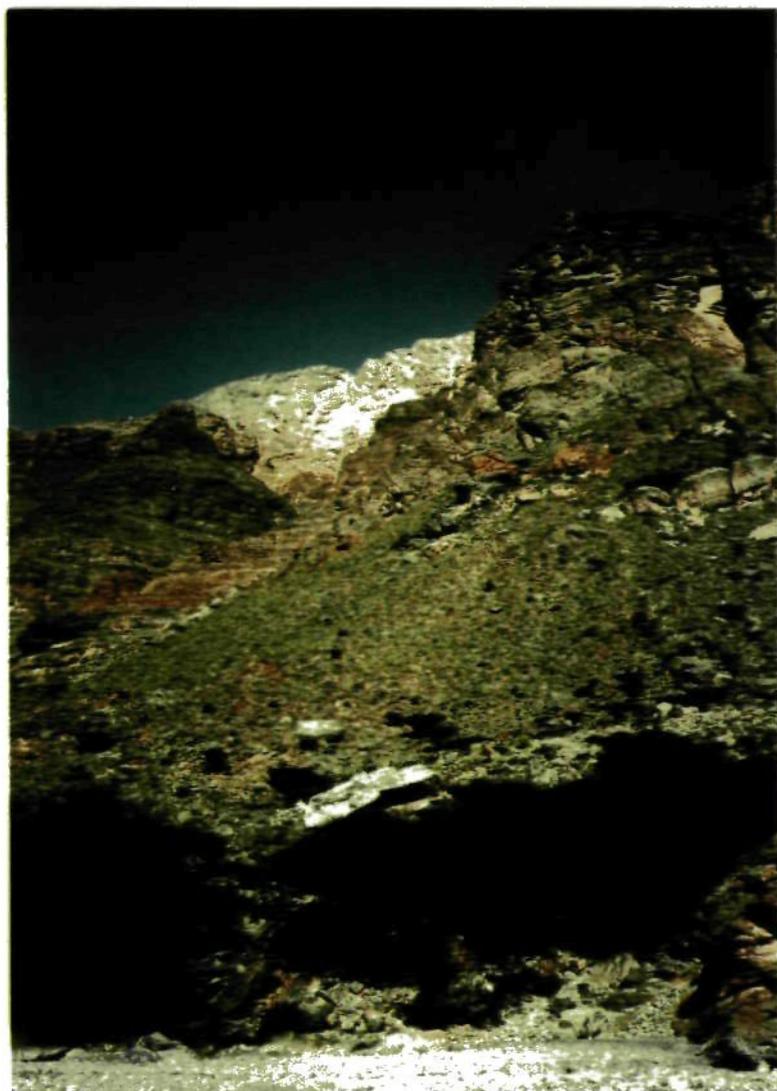


Plate 2.2

PLATES 2.3 - 2.4

Plate 2.3: Thinly bedded lime mudstones of the Salil Formation, West valley side, Wadi Bani Kharus.

Plate 2.4: Bioclastic - oncoidal wackestone with *Exogyra* and toucasid rudists present. Habshan Formation, West valley side, Wadi Bani Kharus.



Plate 2.3



Plate 2.4

PLATES 2.5 - 2.7

Plate 2.5:            Oncoidal - oolitic packstone with oyster debris. Habshan Formation, West valley side,  
Wadi Bani Kharus.

Plate 2.6:            Oncoidal - oolitic packstone with oyster debris. Habshan Formation, West valley side,  
Wadi Bani Kharus.

Plate 2.7:            Low angle trough cross bedding in bioclastic packstones. Basal Lekhwair Formation,  
West valley side, Wadi Bani Kharus. Palaeocurrent direction is towards north.

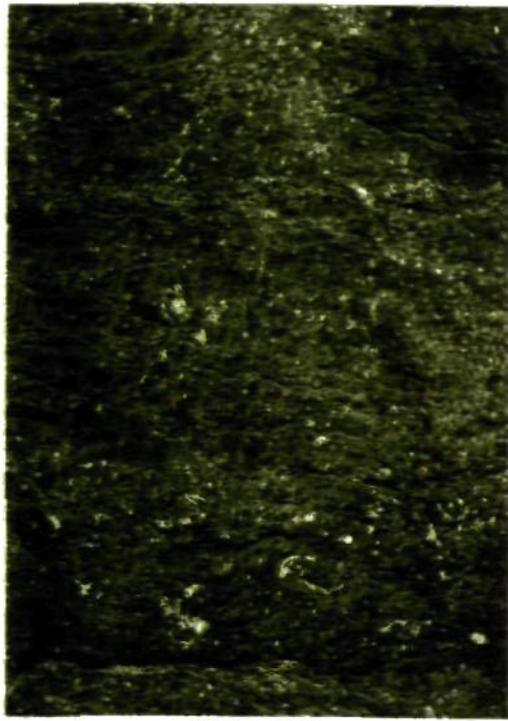


Plate 2.5

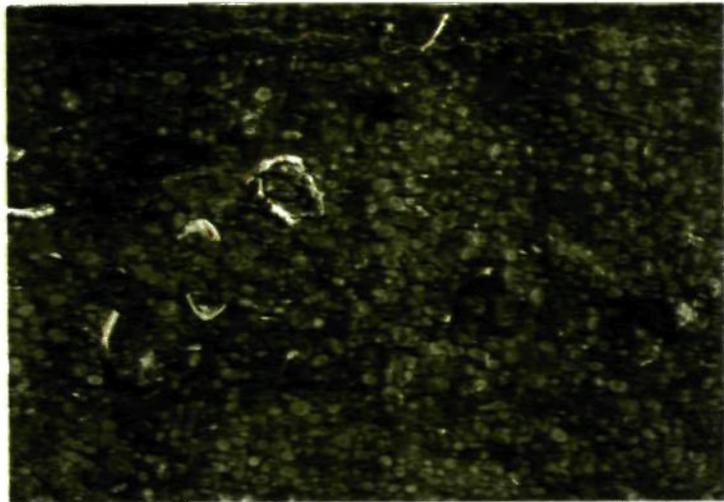


Plate 2.6

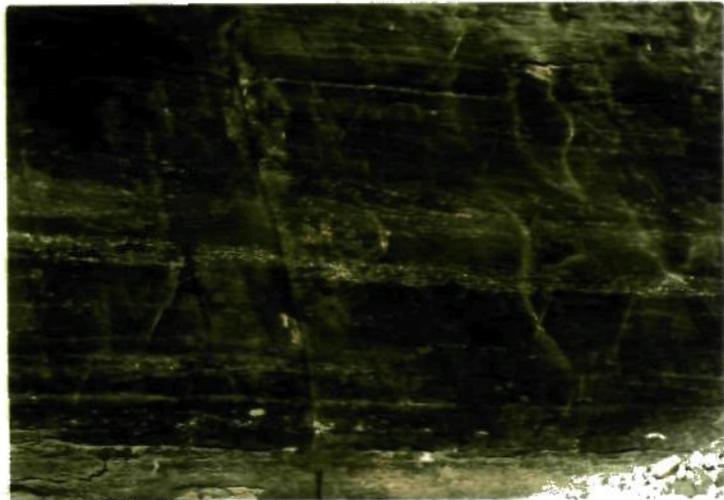


Plate 2.7

PLATES 2.8 - 2.10

Plate 2.8: Caprinid rudist biostromes, Lekhwair Formation, West valley side, Wadi Bani Kharus.

Plate 2.9: Detail of caprinid rudist biostrome, Lekhwair Formation, West valley side, Wadi Bani Kharus.

Plate 2.10: Nodular and rhythmic bedding, lower Kharab Formation, West valley side, Wadi Bani Kharus.

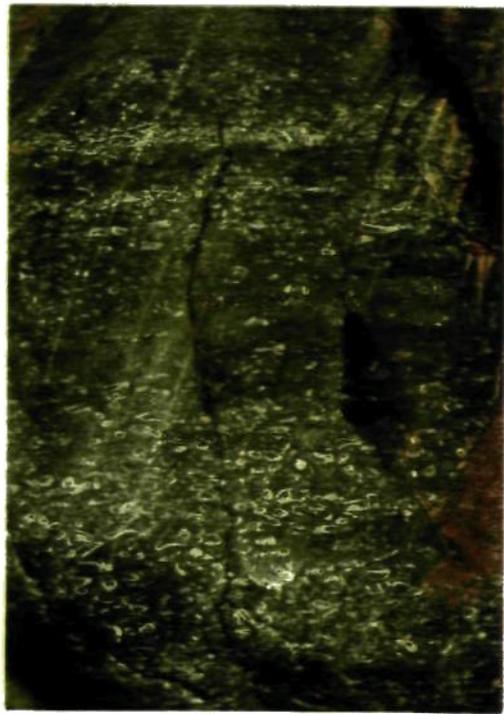


Plate 2.8



Plate 2.9

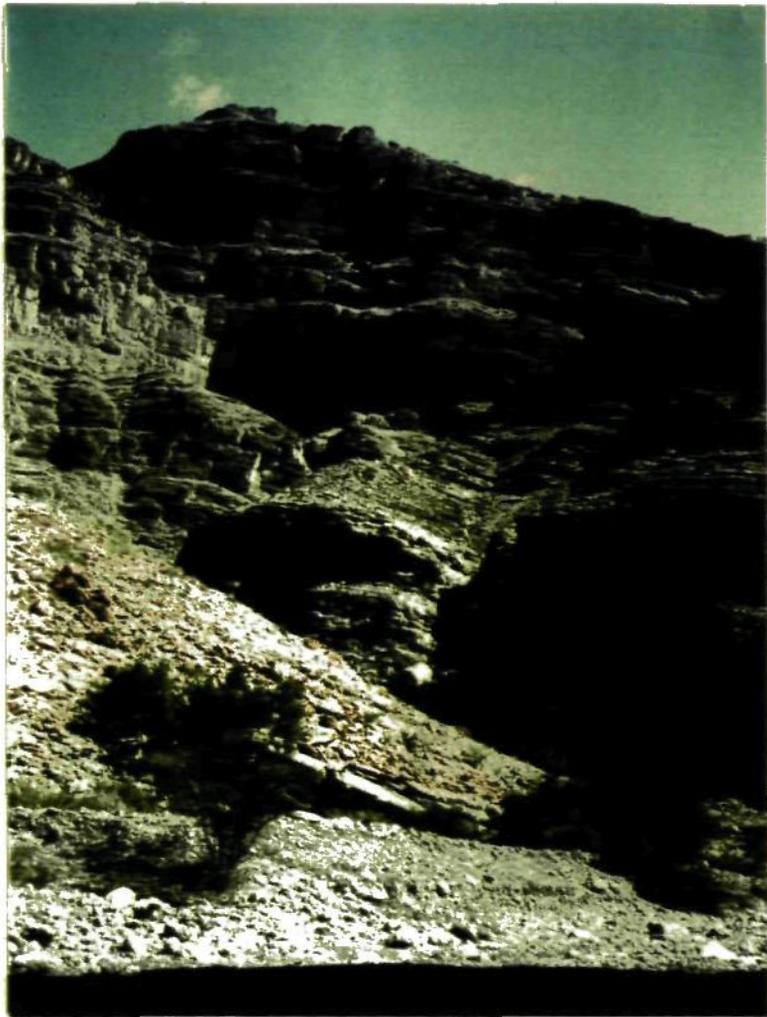


Plate 2.10

PLATES 2.11 - 2.12

Plate 2.11: General view of the Thamama Group, east valley side, Wadi Mi'aidin. Rayda and Salil Formations are in foreground. Higher cliffs are of Lekhwair Formation and Kharab Formation sediments.

Plate 2.12: Upper Sahtan Group surface with abundant *Thalassinoides* burrows, Wadi Mi'aidin.



**Plate 2.11**



**Plate 2.12**

PLATES 2.13 - 2.15

Plate 2.13: Rayda Formation, Wadi Mi'aidin. Porcellanous limestone with chert bands typical of the formation.

Plate 2.14: Abundant belemnites visible on bedding surface, Rayda Formation, Wadi Mi'aidin.

Plate 2.15: Lower Salil Formation, Wadi Mi'aidin. Thinly bedded lime mudstones.



Plate 2.13

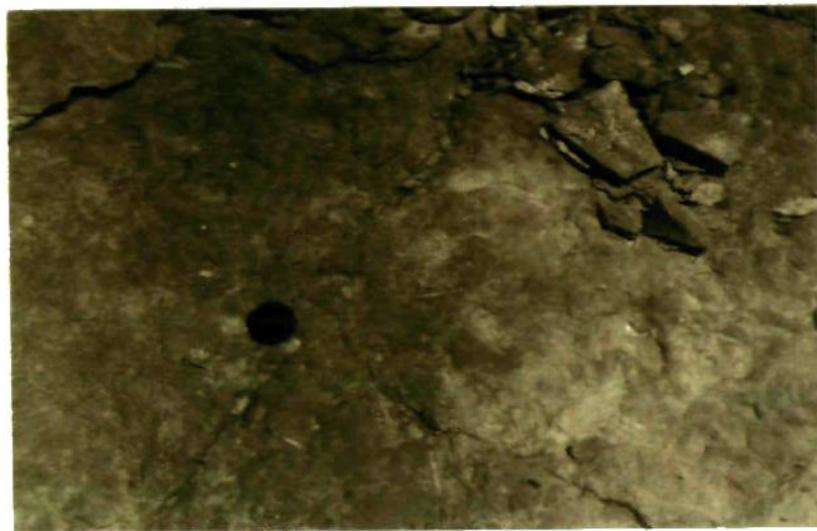


Plate 2.14



Plate 2.15

PLATES 2.16 - 2.18

- Plate 2.16: Highly burrowed and dolomitized bioclastic wackestones and packstones of the Kharai Formation, Wadi Mi'adin. Note how the dolomitization preferentially exposes the burrow networks.
- Plate 2.17: Thinly bedded, cyclic sediments of the Kharai Formation abruptly overlain by the massively bedded limestones of the Shuaiba Formation, Wadi Mi'adin.
- Plate 2.18: Massive limestones of the Shuaiba Formation (Thamama Group) overlain by the shaley lime packstones and marls of the Nahr Umr Formation (Wasia Group).

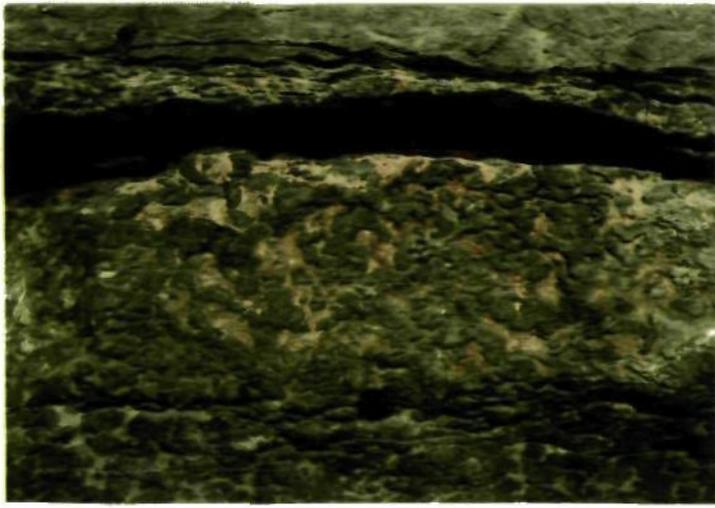


Plate 2.16

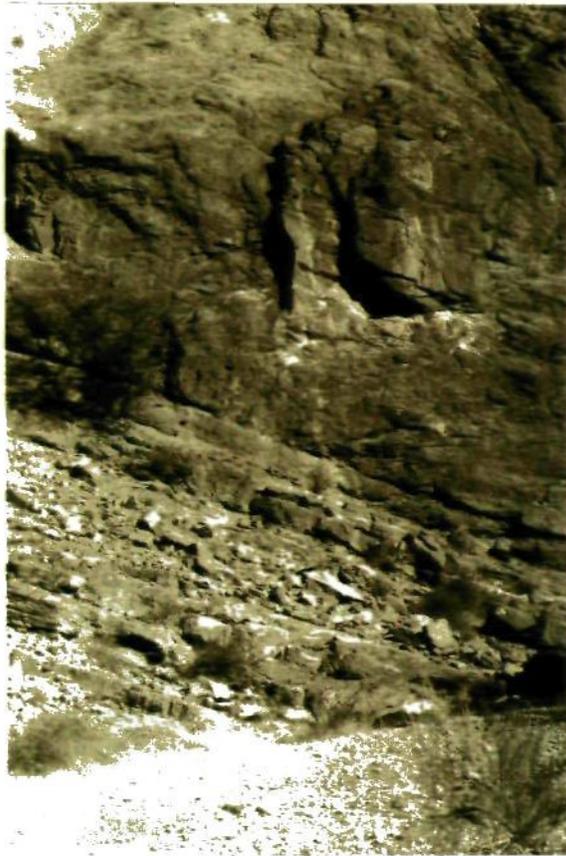


Plate 2.17



Plate 2.18

PLATE 2.19

Plate 2.19: Limestones of the Natih Formation forming a prominent cliff overlying more thinly bedded limestones of the Nahr Umr Formation, west valley side, Wadi Mi'aidin.

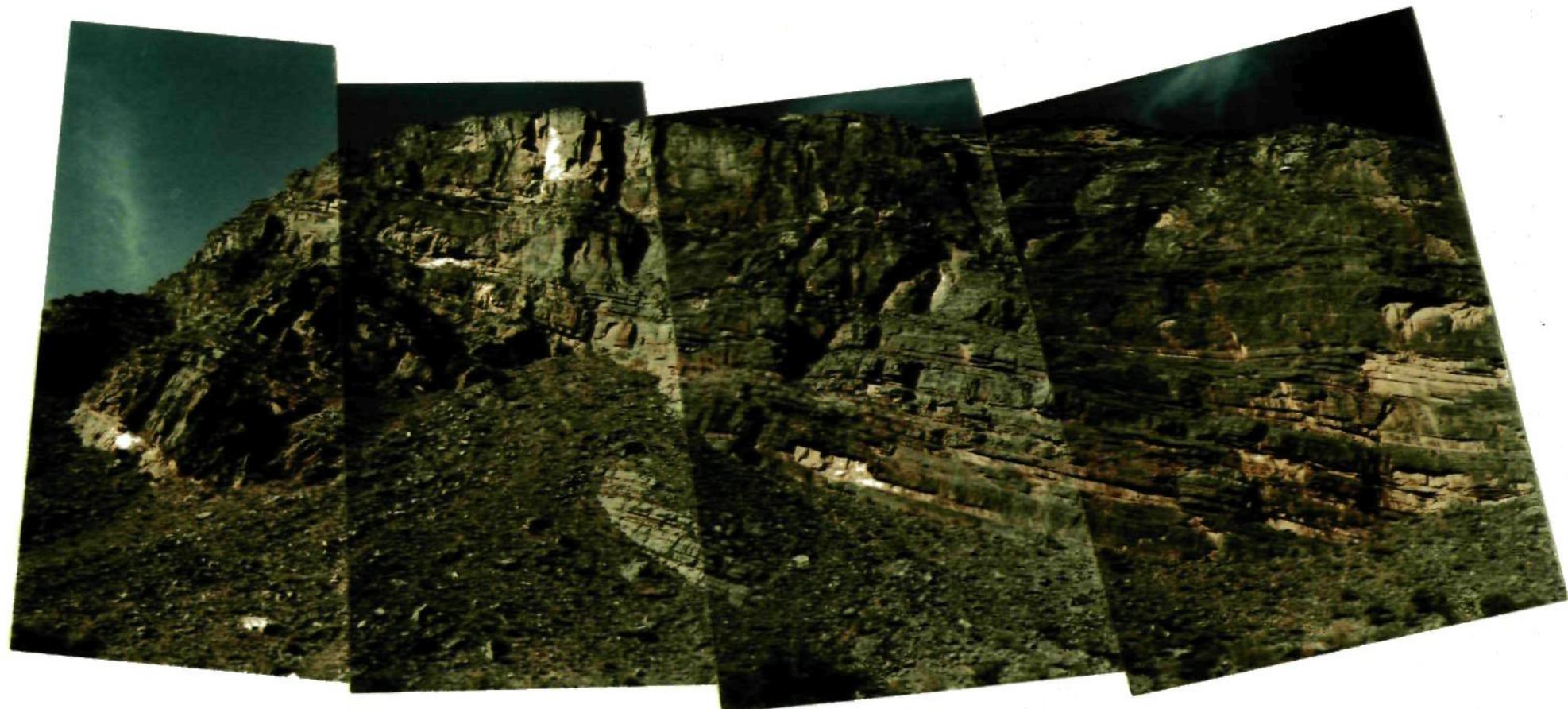


Plate 2.19

PLATES 2.20 - 2.21

Plate 2.20: Limestones of the Shuaiba Formation overlain by recessive, thinly bedded limestones and marls of the Nahr UMr Formation, in turn overlain by a distinctive cliff of Natih Formation limestone, east valley side, Wadi Mi'aidin.

Plate 2.21: Intraformational hardground surface, upper Natih Formation, Wadi Mi'aidin.



Plate 2.20

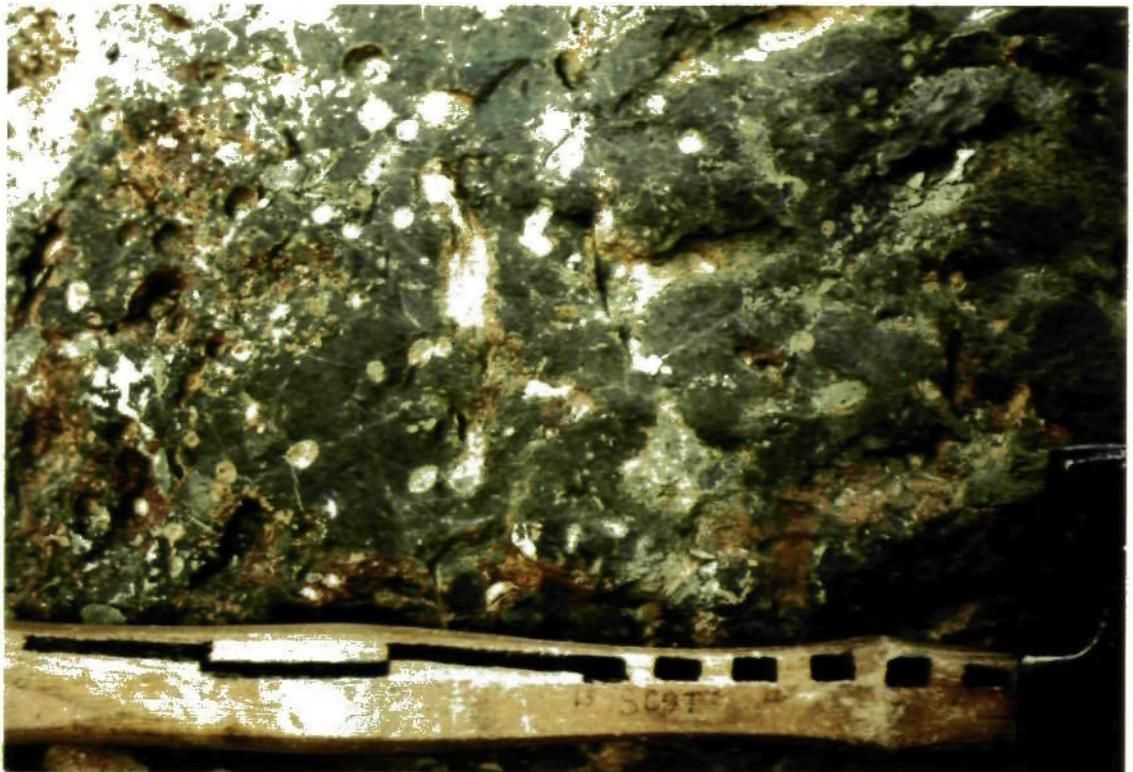


Plate 2.21

PLATE 2.22

Plate 2.22: General view of Jebel Madar approaching from the west.



**Plate 2.22**

PLATES 2.23 - 2.24

Plate 2.23: Exposures of the Thamama Group, Jebel Madar. The exposed section is measured section 2 at this locality (see Figure 2.5 and Figure 2.9).

Plate 2.24: Exposures of the Thamama Group and Wasia Group at Jebel Madar. the prominent cliff in the upper part of the photograph is the Natih Formation. This view corresponds to part of measured section 4 at this locality (see Figures 2.5 and 2.9).

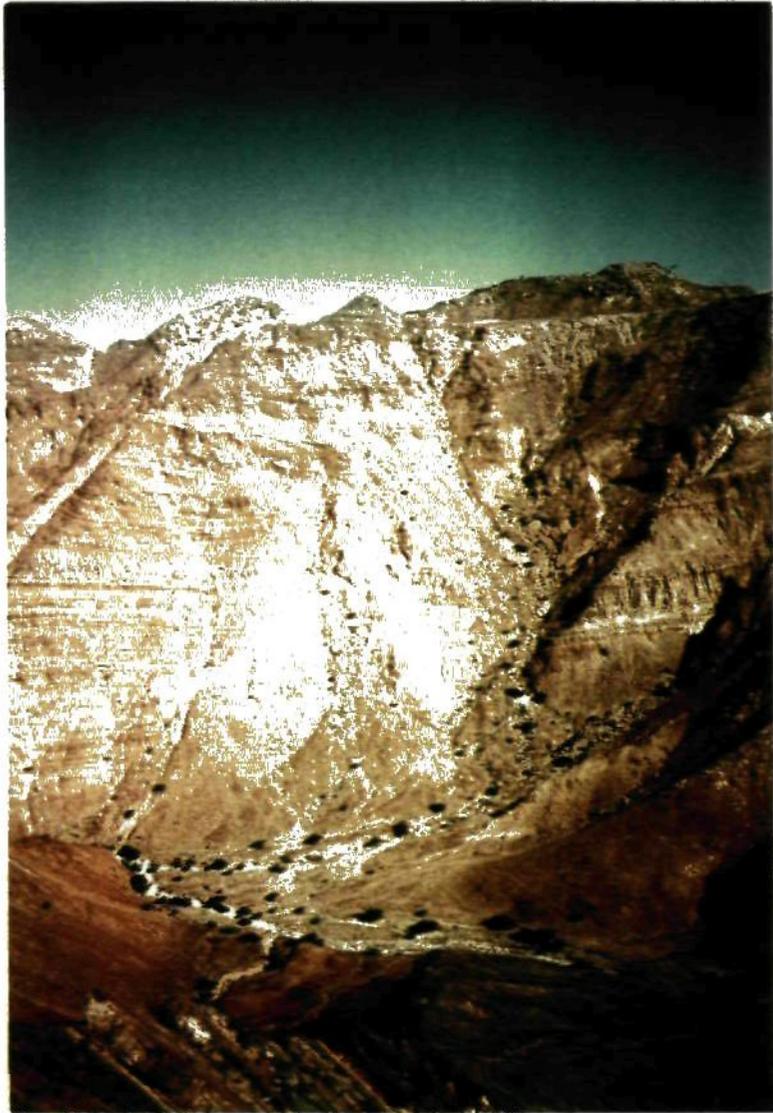


Plate 2.23



Plate 2.24

PLATES 2.25 - 2.27

Plate 2.25: Limestones of the Lekhwair, Kharaib and Shuaiba Formations (Thamama Group) are overlain by recessive thinly bedded limestones and marls of the Nahr Umr Formation (Wasia Group). The limestones of the Natih Formation can be seen in the upper left hand corner of the photograph. Measured section 4, Jebel Madar (see Figure 2.9).

Plate 2.26: Rhythmically bedded limestones of the Lekhwair and Kharaib Formations. Measured section 2, Jebel Madar.

Plate 2.27: Thamama Group sediments in the foreground are overlain by the recessive Nahr Umr Formation. The prominent limestone cliff at the top of the exposure is the Natih Formation. Measured section 3, Jebel Madar (see Figures 2.5 and 2.9).

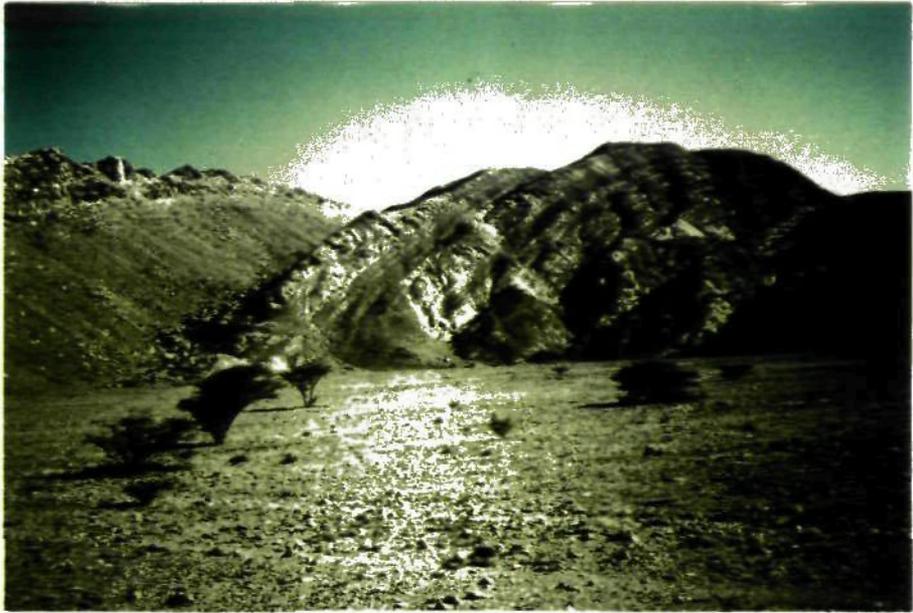


Plate 2.25

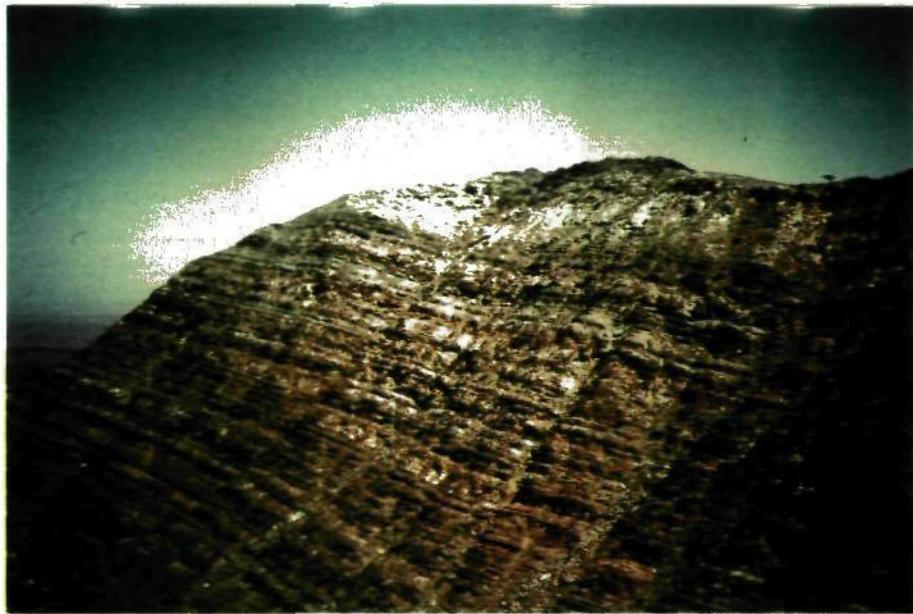


Plate 2.26

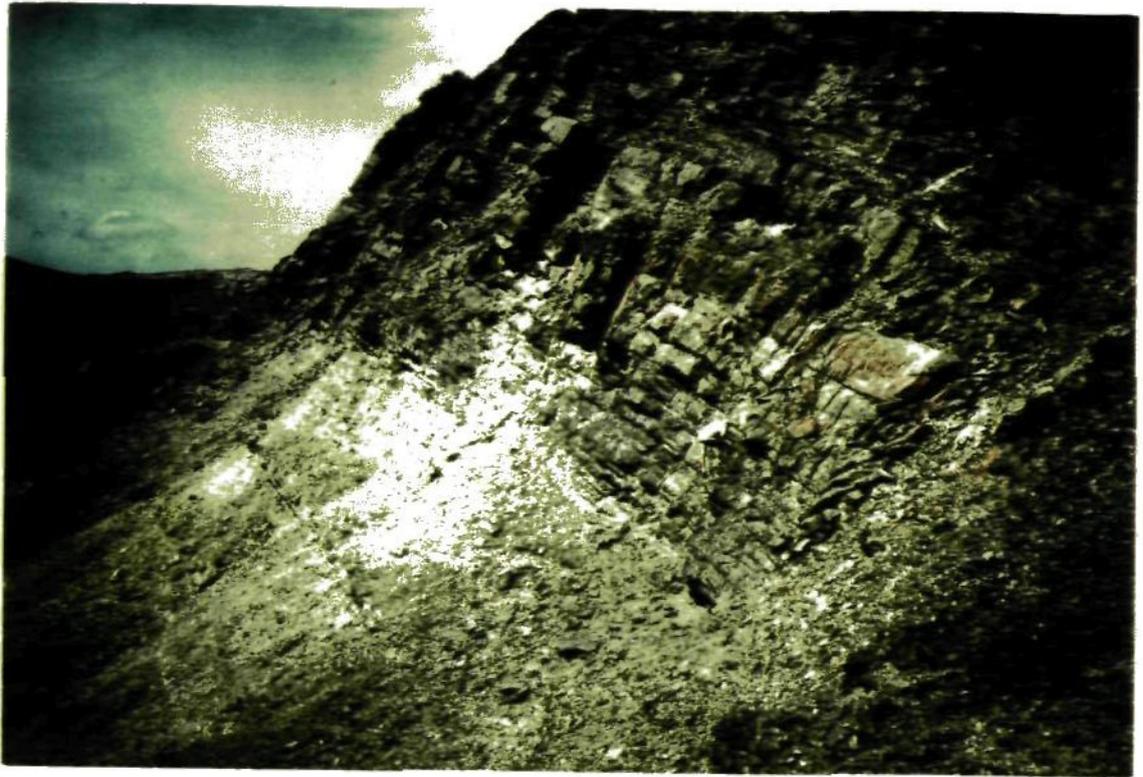


Plate 2.27

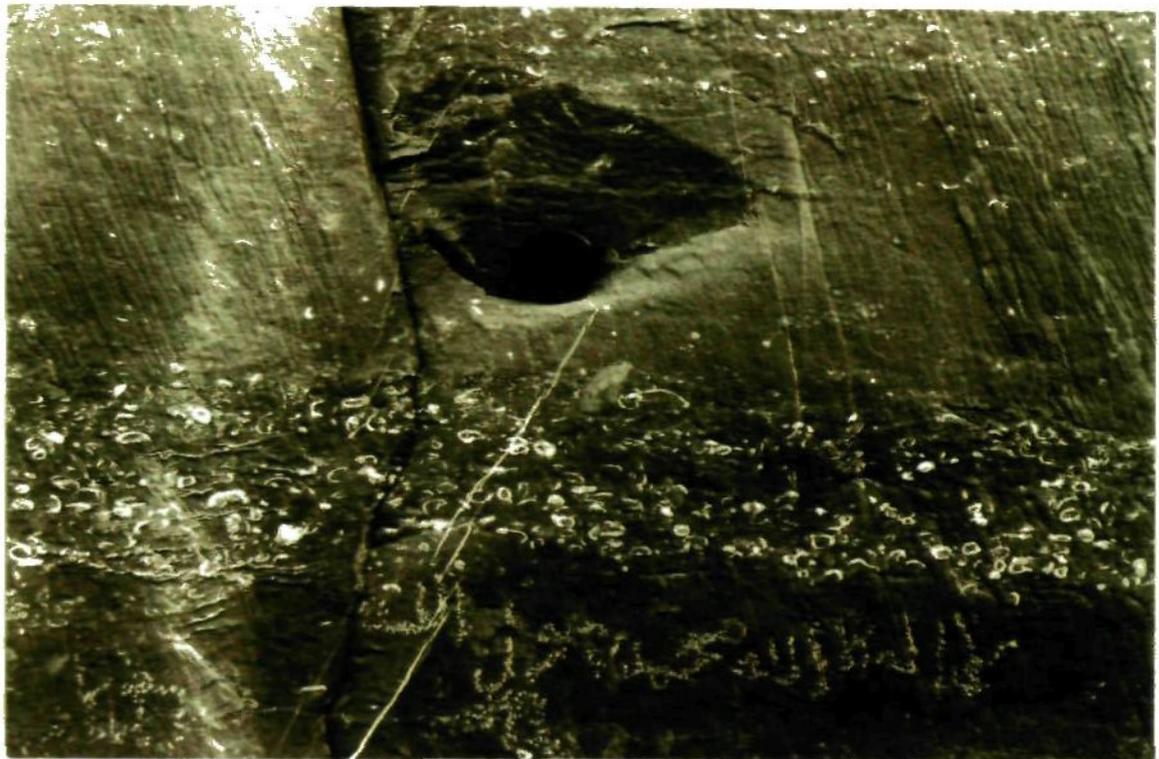
PLATES 2.28 - 2.29

**Plate 2.28:** Well bedded oolitic grainstones of the Habshan Formation overlie shaley limestones of the Salil Formation. Measured section 1, Jebel Madar (see Figures 2.5 and 2.9). Prof. Malcolm Hart provides scale.

**Plate 2.29:** Coquina of oysters and small toucasid rudists, Habshan Formation, Jebel Madar.



**Plate 2.28**



**Plate 2.29**

PLATES 2.30 - 2.32

- Plate 2.30: Bioclastic packstone of toucasid rudist and other bivalve debris, together with *in situ* stromatoporoid, Habshan Formation, Jebel Madar.
- Plate 2.31: Hardground surface, or minor karstified exposure surface within the Lekhwair Formation, Jebel Madar.
- Plate 2.32: Algal lamination within the Lekhwair Formation, Jebel Madar. Mudcracks are visible cutting down into the lamination, indicating periods of exposure. Fenestral limestones are visible in the upper part of the photograph.



Plate 2.30

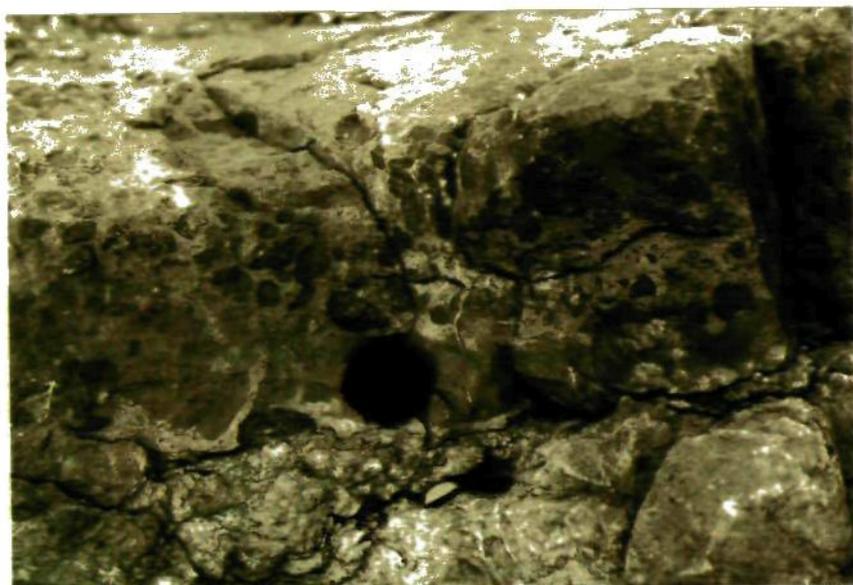


Plate 2.31



Plate 2.32

PLATES 2.33 - 2.34

Plate 2.33: Poorly exposed Nahr Umr Formation to right of photograph overlain by better exposed limestones of the Natih Formation. Measured section 4, Jebel Madar.

Plate 2.34: Limestones of the lower part of the Natih Formation, measured section 4, Jebel Madar.

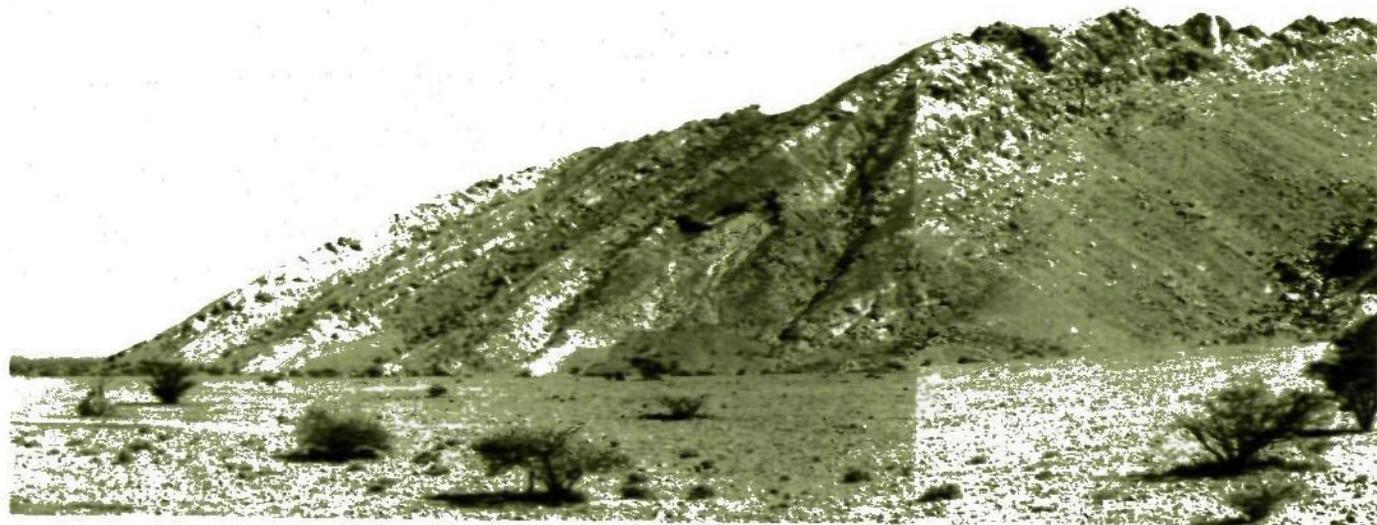


Plate 2.33



Plate 2.34

PLATES 2.35 - 2.37

- Plate 2.35: Well preserved radiolitid rudist, Natih Formation, Jebel Madar.
- Plate 2.36: Distinctive mottled (burrowed) unit within the Natih Formation, Jebel Madar. This is the "Echinoid Marker Bed" a useful horizon for correlation of the Natih Formation between localities. The larger foraminifera *Praealveolina*, and the echinoid *Coenholectypus cenomanensis* are abundant at this level.
- Plate 2.37: Medium bedded wackestones in the upper part of the Natih Formation, Jebel Madar.

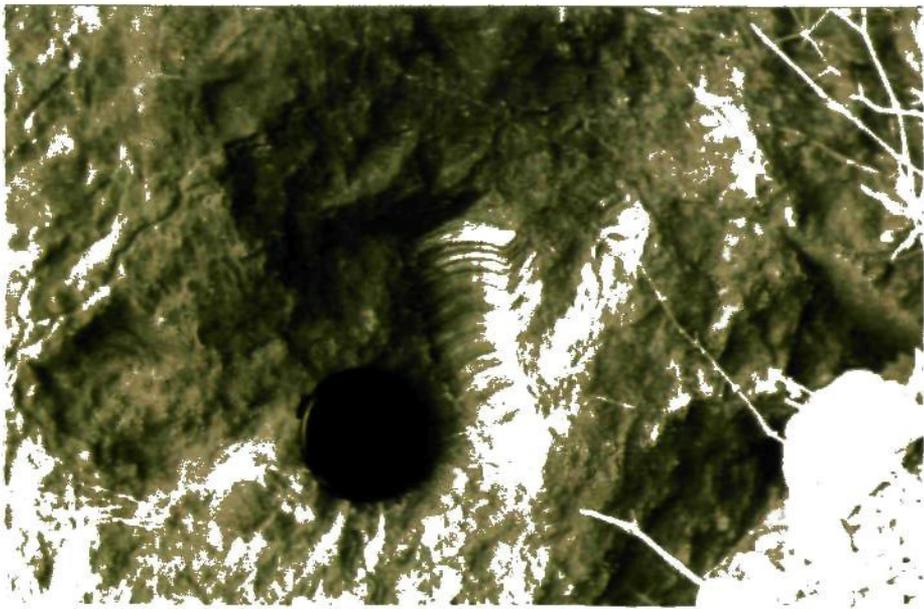


Plate 2.35



Plate 2.36



Plate 2.37

PLATE 2.38

Plate 2.38: General view of exposures of the Natih Formation at Jebel Madamar.



Plate 2.38

PLATE 2.39

Plate 2.39: Middle part of the Natih Formation exposed at Jebel Madamar. The "Echinoid Marker Bed" forms the ledge in the foreground on the left of the photograph.

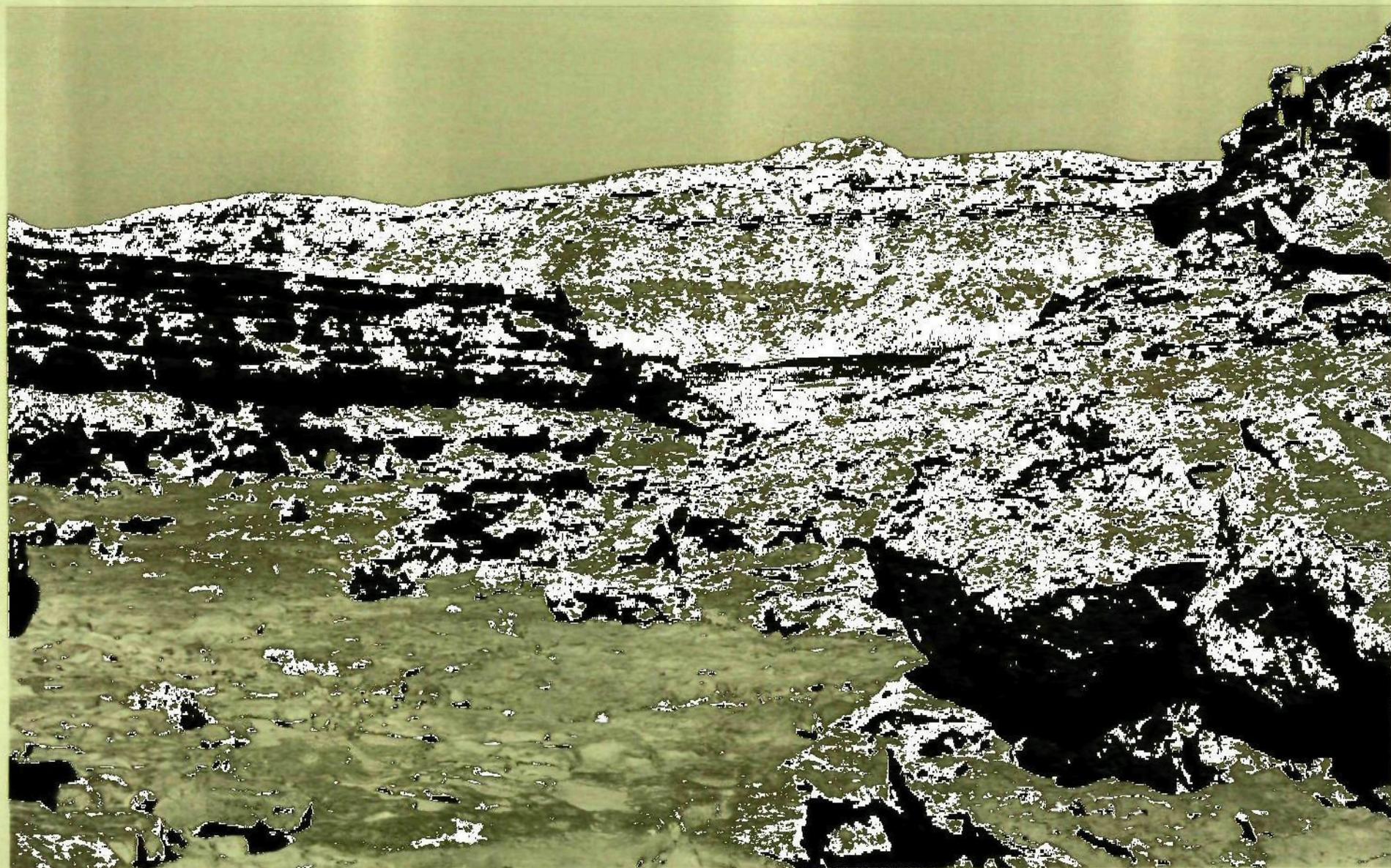


Plate 2.39

PLATES 2.40 - 2.41

Plate 2.40: Radiolitid rudist within the Natih Formation, Jebel Salak.

Plate 2.41: Upper part of the Natih Formation, Jebel Salak.

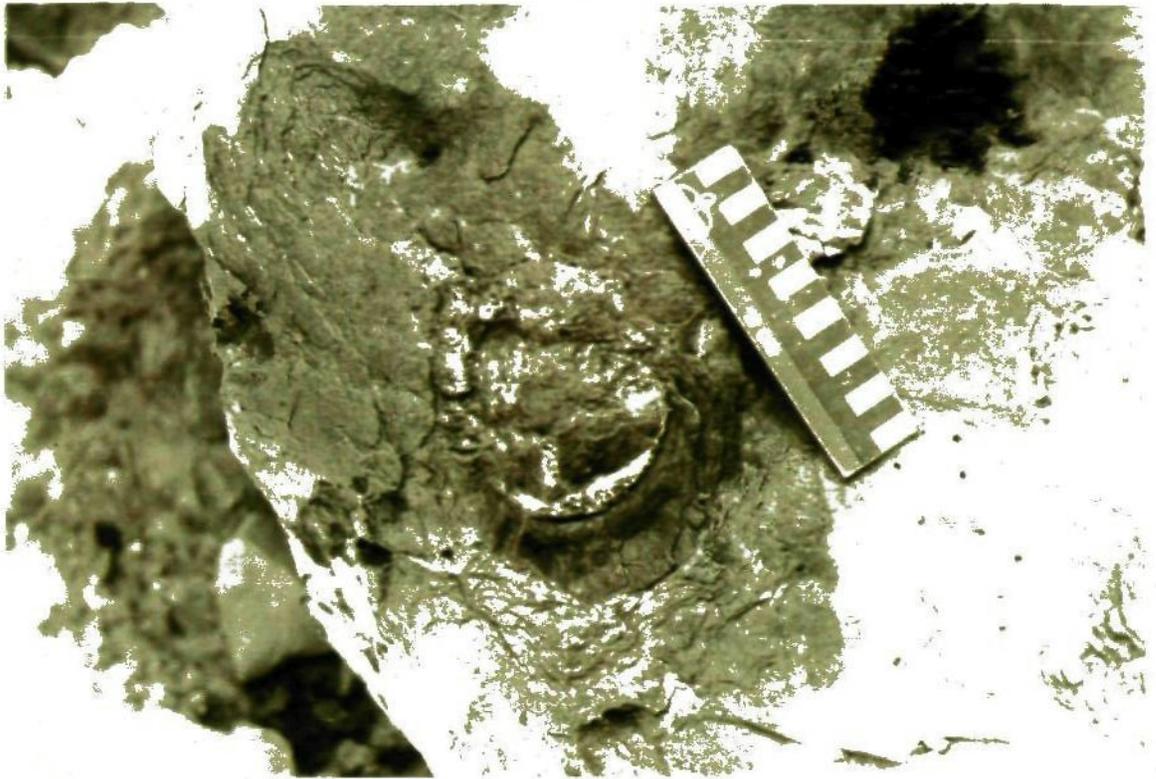


Plate 2.40



Plate 2.41

PLATES 2.42 - 2.44

Plate 2.42: Rhythmic bedding of bioclastic wackestones and mudstones within the upper part of the Natih Formation, Jebel Salak. Dr. Chris Dodd provides scale.

Plate 2.43: *Exogyra* rich limestones, upper Natih Formation, Jebel Salak.

Plate 2.44: Uppermost Natih Formation, Jebel Salak. The bedding surface is rich in ammonites.



Plate 2.42

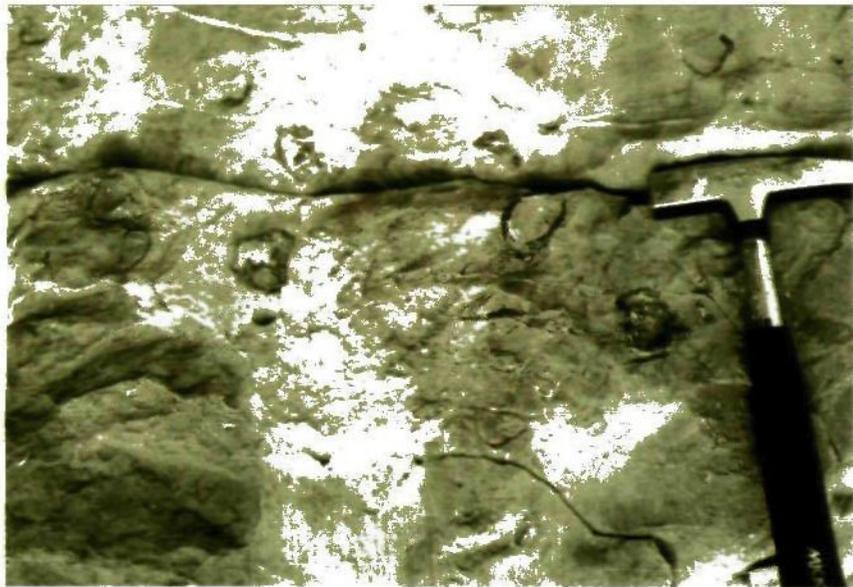


Plate 2.43



Plate 2.44

PLATES 3.1 - 3.6

Plate 3.1: *Reophax* sp. A., x100. MR10.2

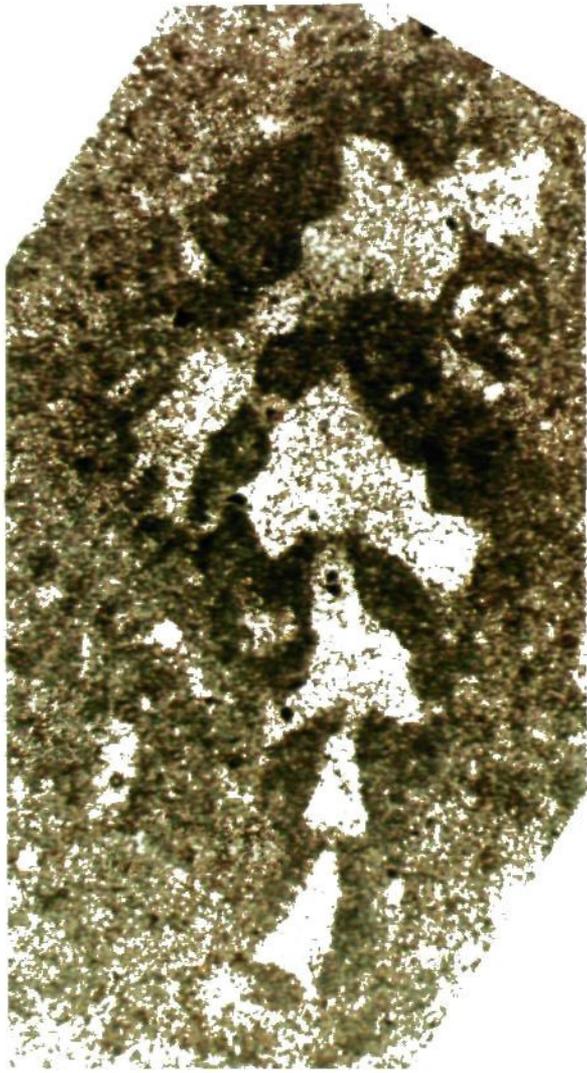
Plate 3.2: *Thomasinella punica*, x40. MS41

Plate 3.3: *Nautiloculina bronnimanni*, x100. MS41

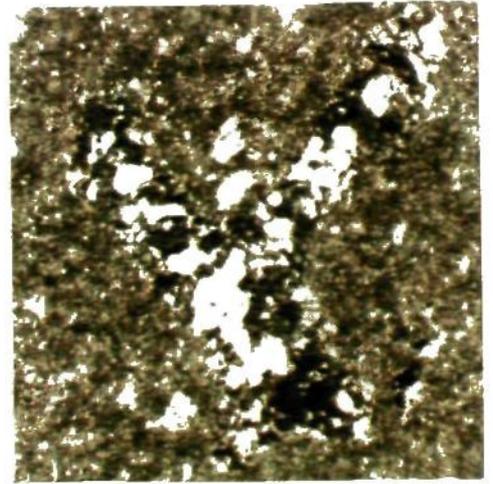
Plate 3.4: *Nautiloculina bronnimanni*, x100. MS52

Plate 3.5: *Nautiloculina cretacea*, x40. JDS109

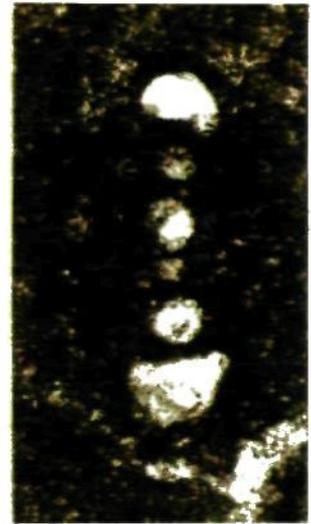
Plate 3.6: *Nautiloculina cretacea*, x40. WM48



3.1



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3.6

PLATES 3.7 - 3.12

Plate 3.7: *Nautiloculina cretacea*, x40. WM48

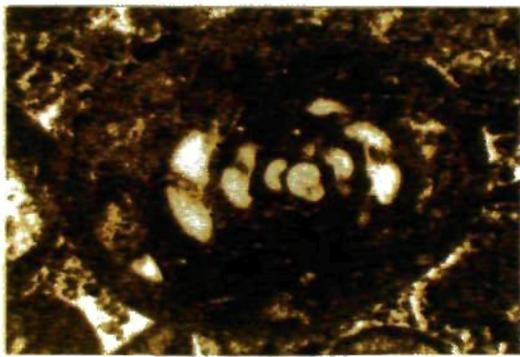
Plate 3.8: *Lituola? kelleri*, x40. MS6

Plate 3.9: *Ammobaculites* sp. A, x25. MS22

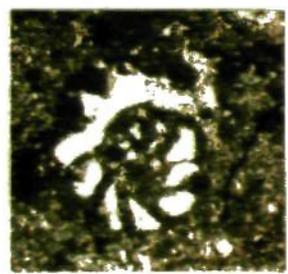
Plate 3.10: *Ammobaculites* sp. A, x25. WM102

Plate 3.11: *Ammobaculites* sp. A, x40. MS79/2

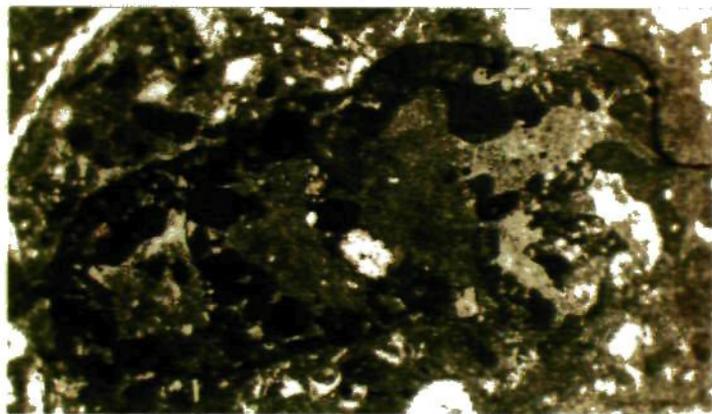
Plate 3.12: *Ammobaculites* sp. A, x40. B42.2



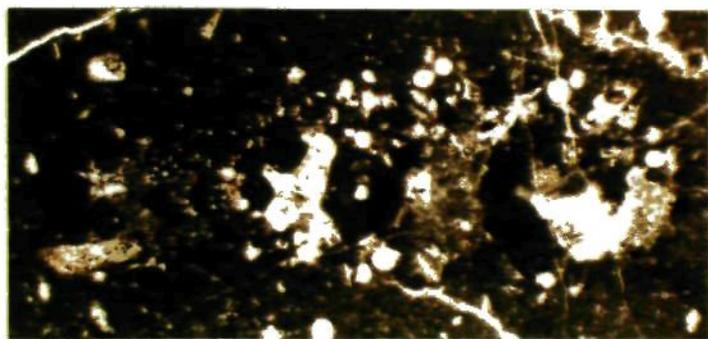
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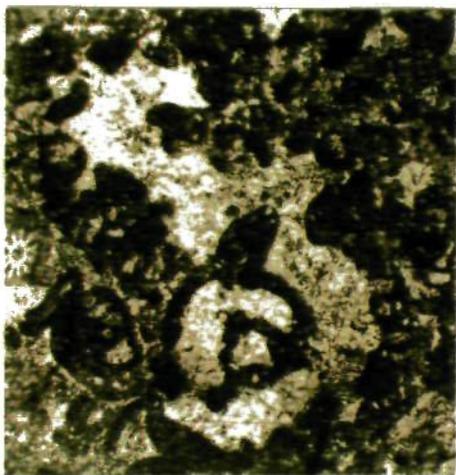
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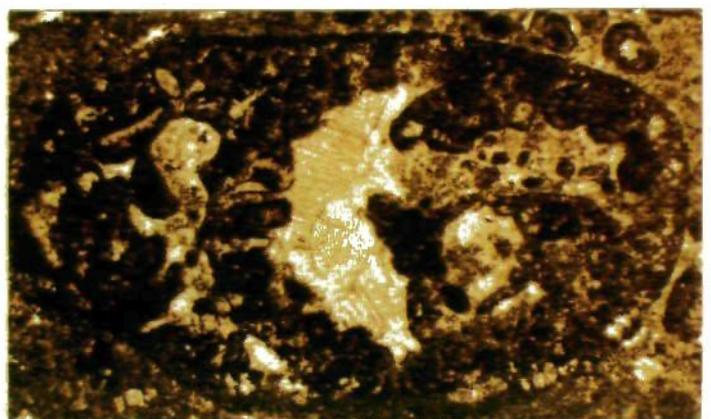
3.9



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3.12

PLATES 3.13 - 3.18

Plate 3.13: *Ammobaculites* sp. A, x40. WM41

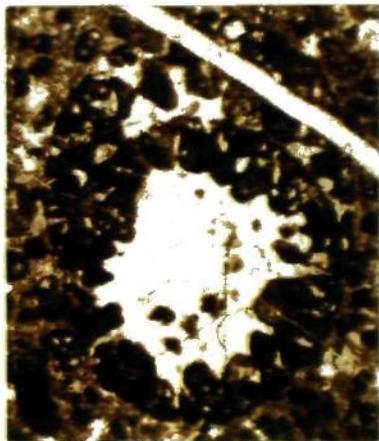
Plate 3.14: *Choffatella decipiens*, x40. WM67

Plate 3.15: *Choffatella decipiens*, x40. B94

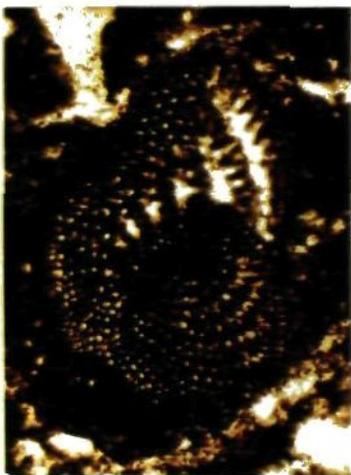
Plate 3.16: *Choffatella decipiens*, x40. MS85

Plate 3.17: *Choffatella decipiens*, x40. B94

Plate 3.18: *Choffatella decipiens*, x100. B94



3.13



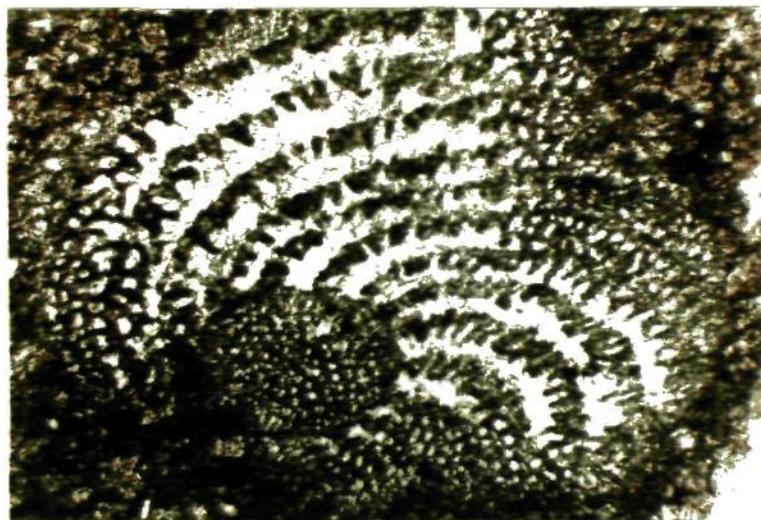
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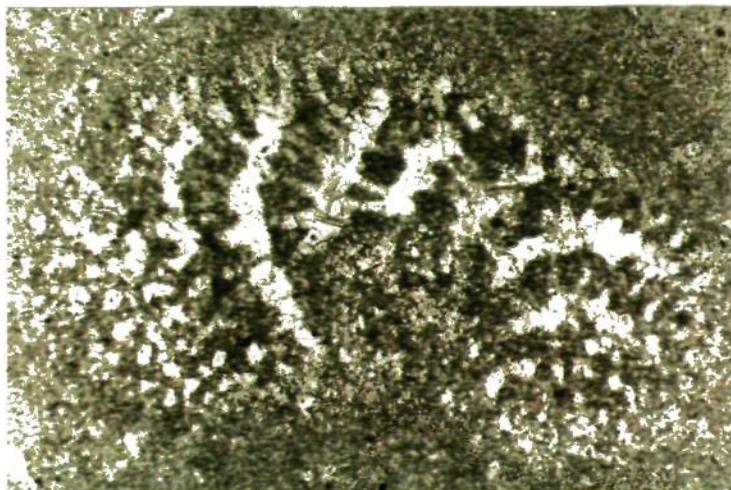
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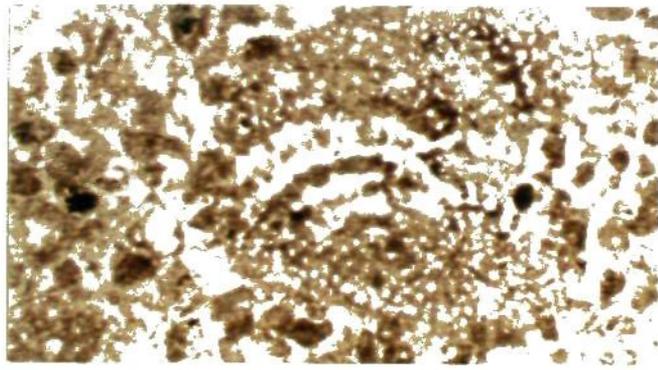
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3.18

PLATES 3.19 - 3.24

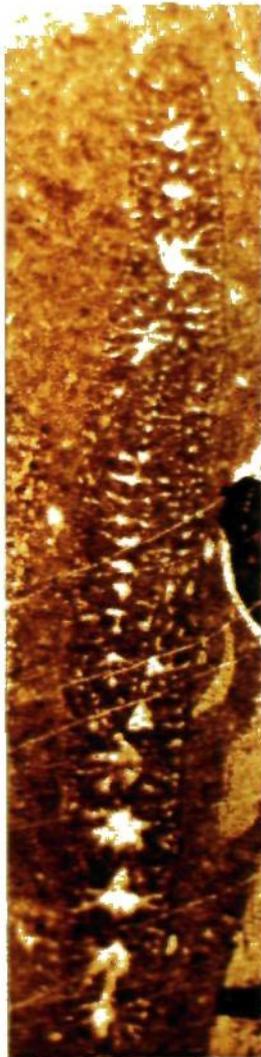
- Plate 3.19: *Choffatella decipiens*, x40. WM41.
- Plate 3.20: *Choffatella decipiens*, x40. MS81.2
- Plate 3.21: *Choffatella decipiens*, x30. WM(JDS)86.
- Plate 3.22: *Bramkampella arabica?*, x100. B39.3.
- Plate 3.23: *Everticyclammina greigi*, x100. MS73/2.
- Plate 3.24: *Everticyclammina greigi*, x100. B39.3.



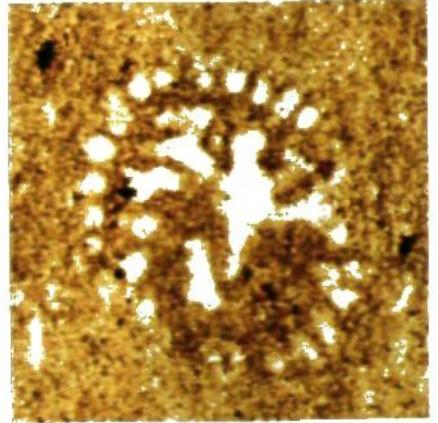
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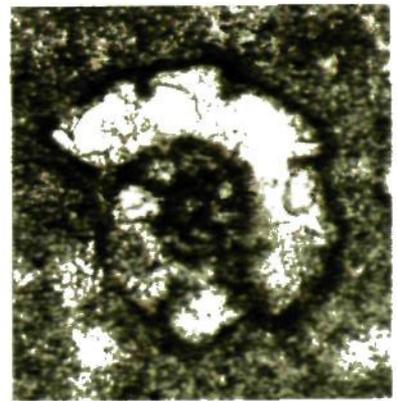
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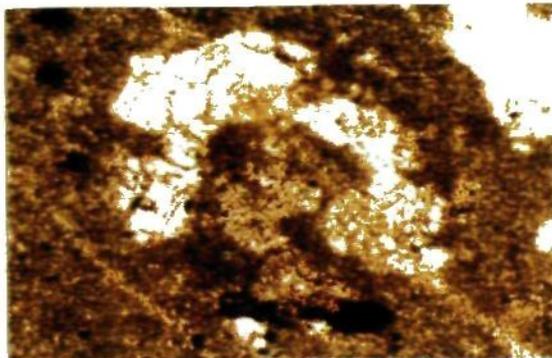
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PLATES 3.25 - 3.32

Plate 3.25: *Buccicrenata hedbergi*, x40. WM39.

Plate 3.26: *Buccicrenata hedbergi*, x40. WM(JDS)76.

Plate 3.27: *Buccicrenata hedbergi*, x40. MS6.

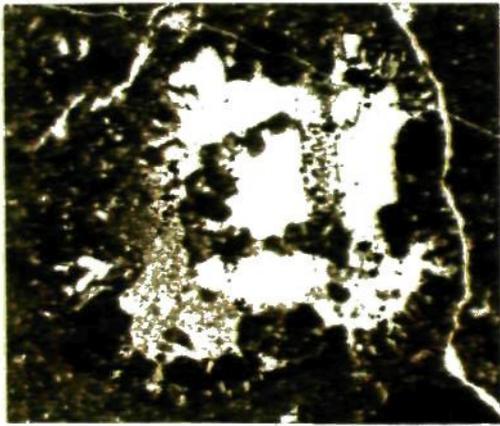
Plate 3.28: *Buccicrenata hedbergi*, x40. MR14.2.

Plate 3.29: *Praechrysalidina infracretacea*, x40. WM57.

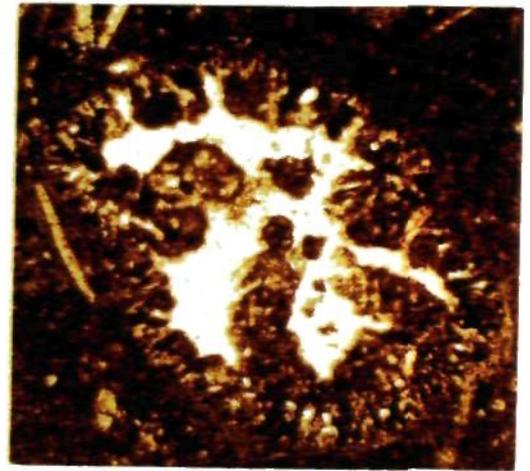
Plate 3.30: *Dukhania conica*, x40. WM41.

Plate 3.31: *Dukhania conica*, x40. MS91.

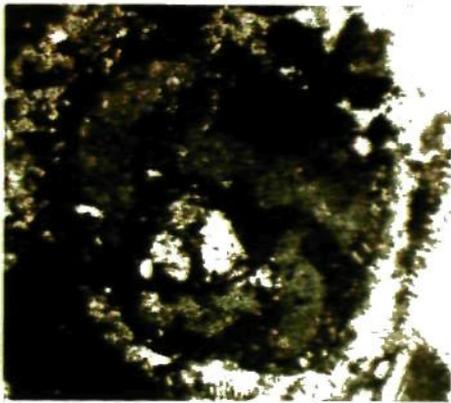
Plate 3.32: *Dukhania conica*, x40. WM(JDS)181.



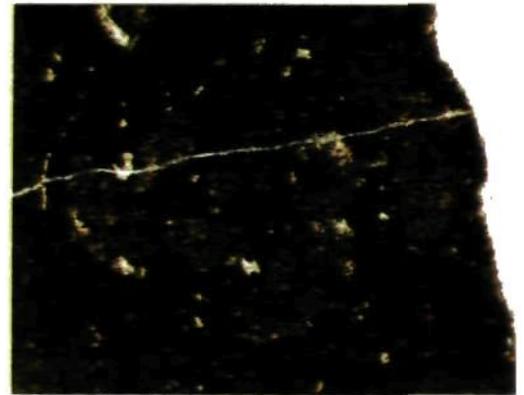
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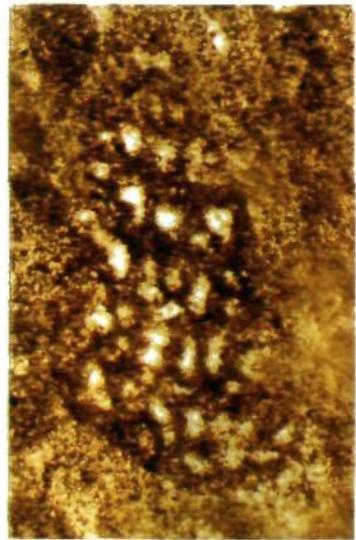
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PLATES 3.33 - 3.38

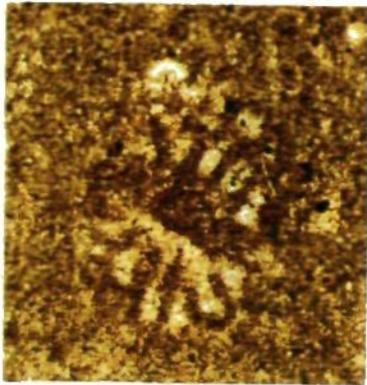
- Plate 3.33: *Cuneolina laurentii*, x100. WM56.
- Plate 3.34: *Cuneolina laurentii*, x100. B39.3.
- Plate 3.35: *Cuneolina laurentii*, x100. B39.3.
- Plate 3.36: *Cuneolina laurentii*, x100. MS22.
- Plate 3.37: *Cuneolina laurentii*, x100. WM39.
- Plate 3.38: *Cuneolina camposaurii*, x100. MS22.



3.33



3.34



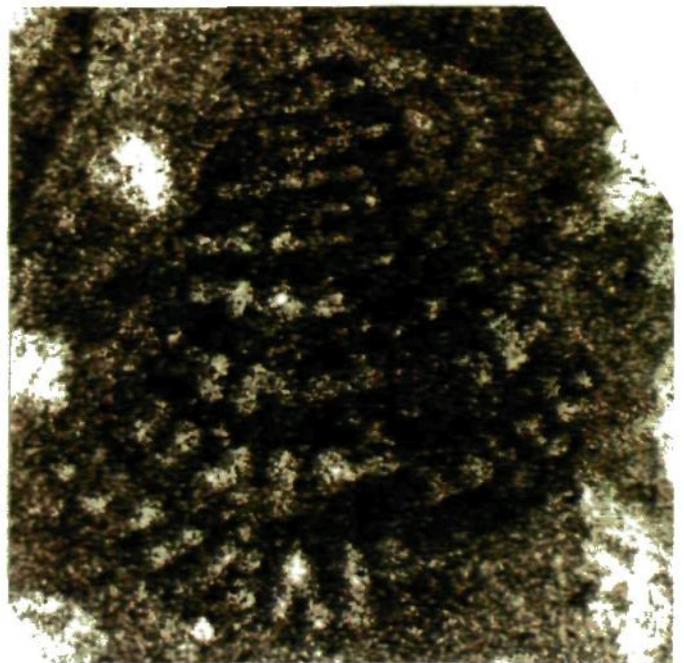
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PLATES 3.39 - 3.44

Plate 3.39: *Cuneolina camposaurii*, x100. MS22.

Plate 3.40: *Vercorsella arenata*, x100. WM104.

Plate 3.41: *Vercorsella scarsellai*, x100. WM41.

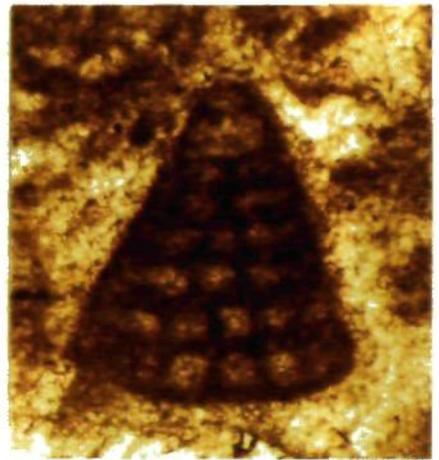
Plate 3.42: *Vercorsella scarsellai*, x100. PLR1370 (Wadi Daiga).

Plate 3.43: *Vercorsella scarsellai*, x100. WM39.

Plate 3.44: *Palorbitolina lenticularis*, x40. WM(JDS)177.



3.39



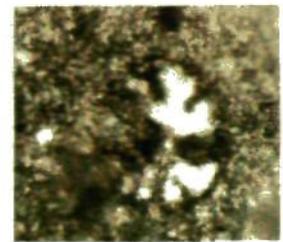
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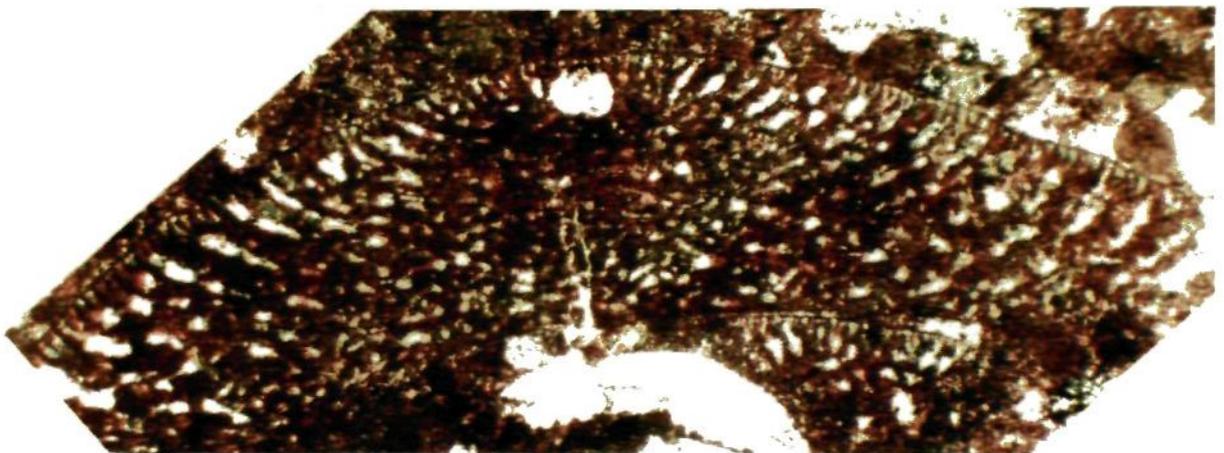
3.41



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PLATES 3.45 - 3.50

Plate 3.45: *Palorbitolina lenticularis*, x100. WM59.

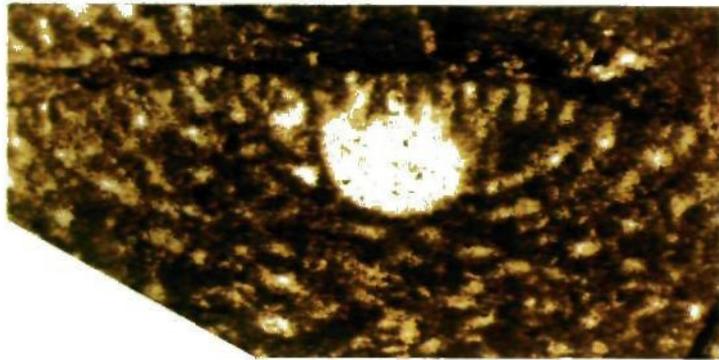
Plate 3.46: *Palorbitolina lenticularis*, x40. K10.2.

Plate 3.47: *Palorbitolina lenticularis*, x100. BK69.

Plate 3.48: *Palorbitolina lenticularis*, x40. MS88.

Plate 3.49: *Palorbitolina lenticularis*, x63. K10.2.

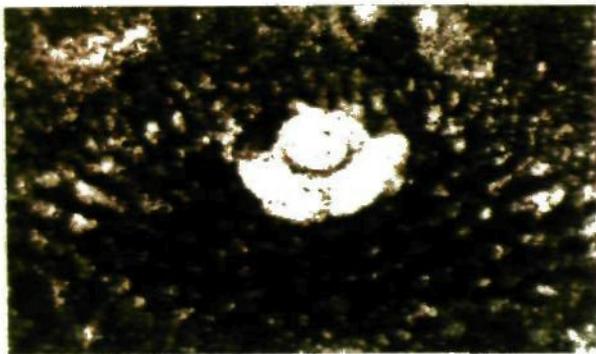
Plate 3.50: *Palorbitolina lenticularis*, x63. MS71.



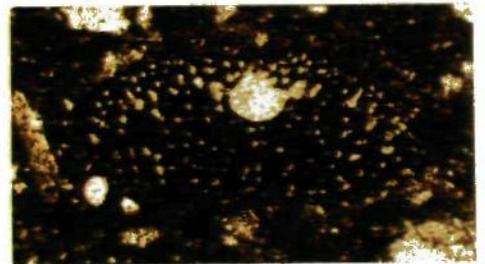
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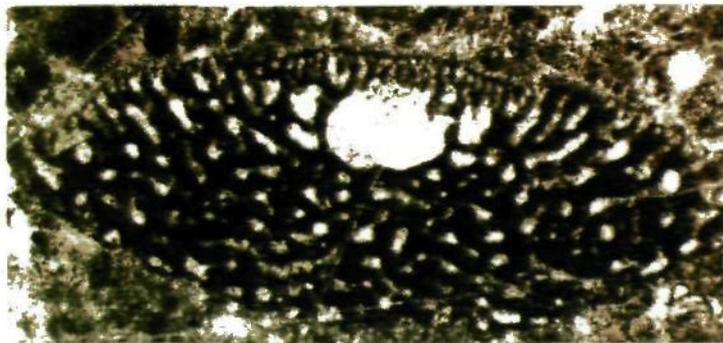
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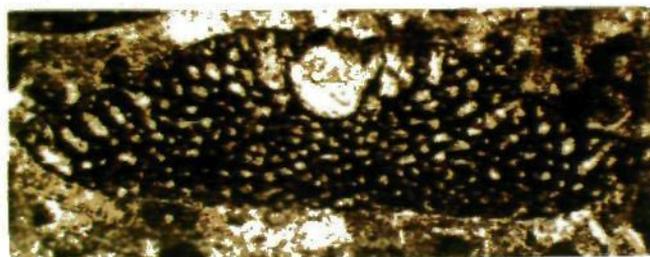
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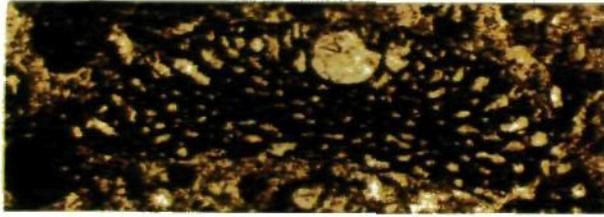
PLATES 3.51 - 3.54

Plate 3.51: *Palorbitolina lenticularis*, x40. MS90.

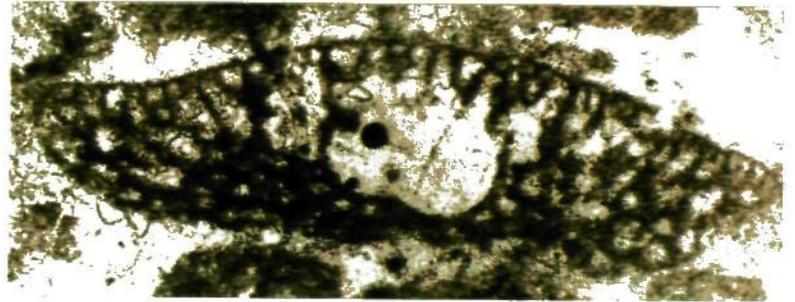
Plate 3.52: *Palorbitolina lenticularis*, x100. MS71.

Plate 3.53: *Palorbitolina lenticularis*, x100. MS90.

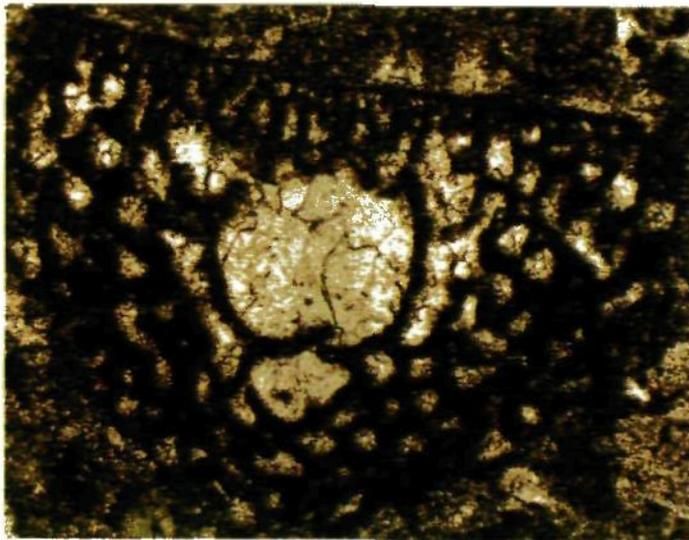
Plate 3.54: *Palorbitolina lenticularis* (left) and *Eopalorbitolina charollaisi* (right), x40. MS71.



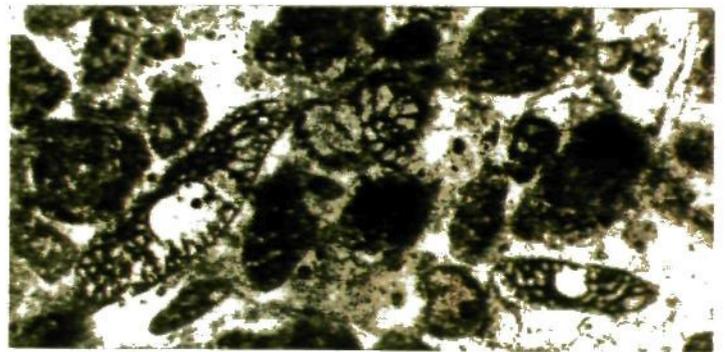
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PLATES 3.55 - 3.59

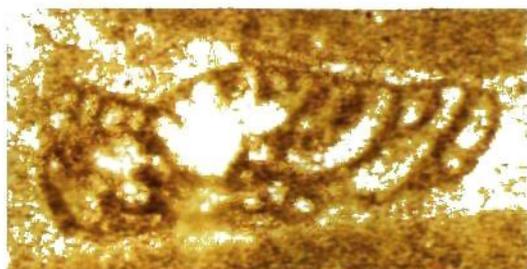
Plate 3.55: *Eopalorbitolina charollaisi*, x100. WM58.

Plate 3.56: *Eopalorbitolina charollaisi*, x100. WM59.

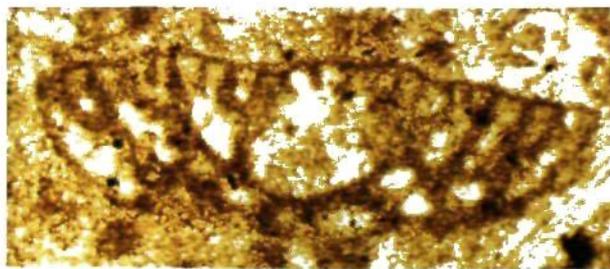
Plate 3.57: *Cribellopsis elongatus*, x40. B91.

Plate 3.58: *Cribellopsis elongatus*, x40. B91.

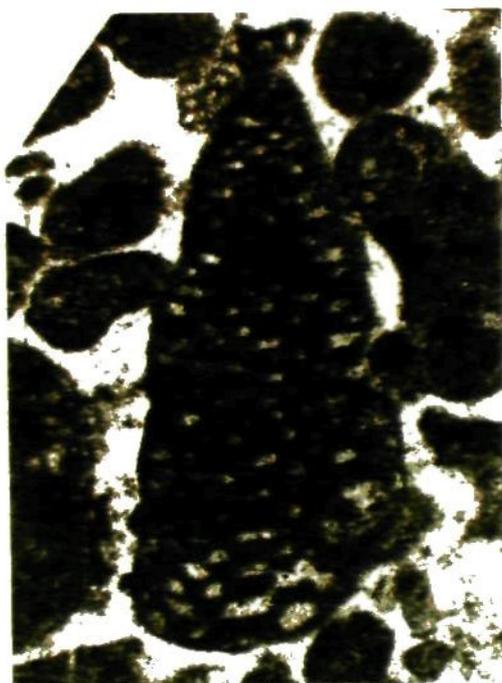
Plate 3.59: *Paleodictyoconus arabicus*, x40. MS81.



3.55



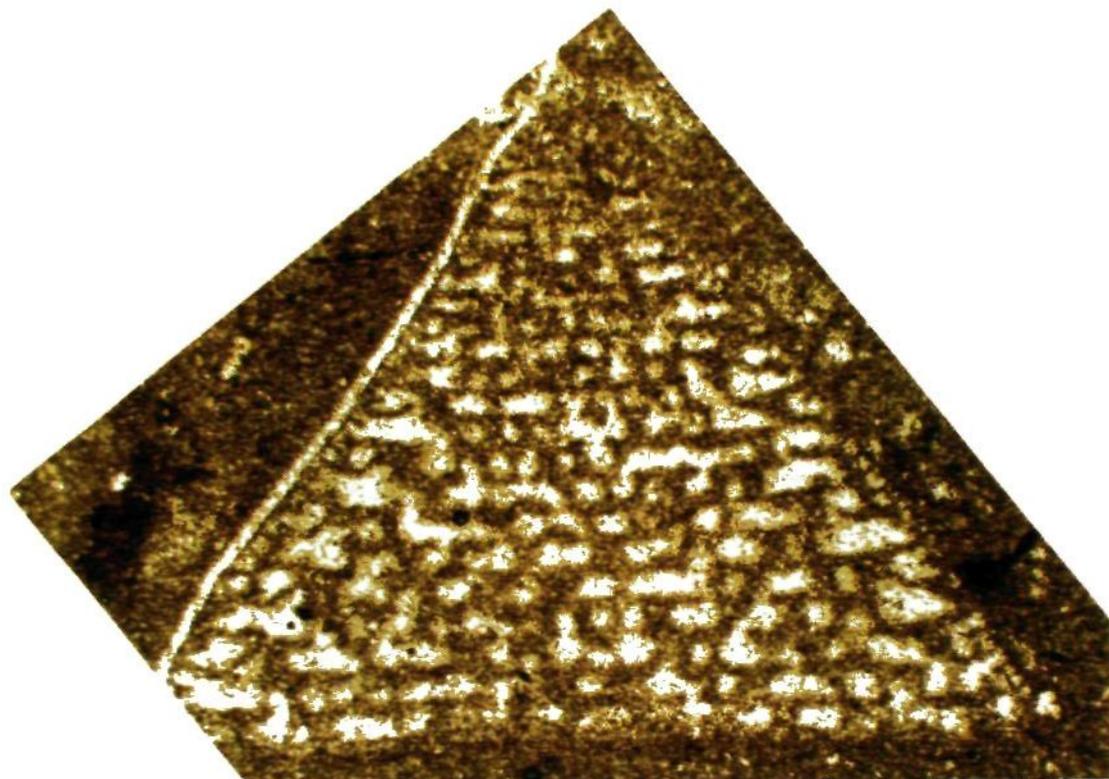
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3.58



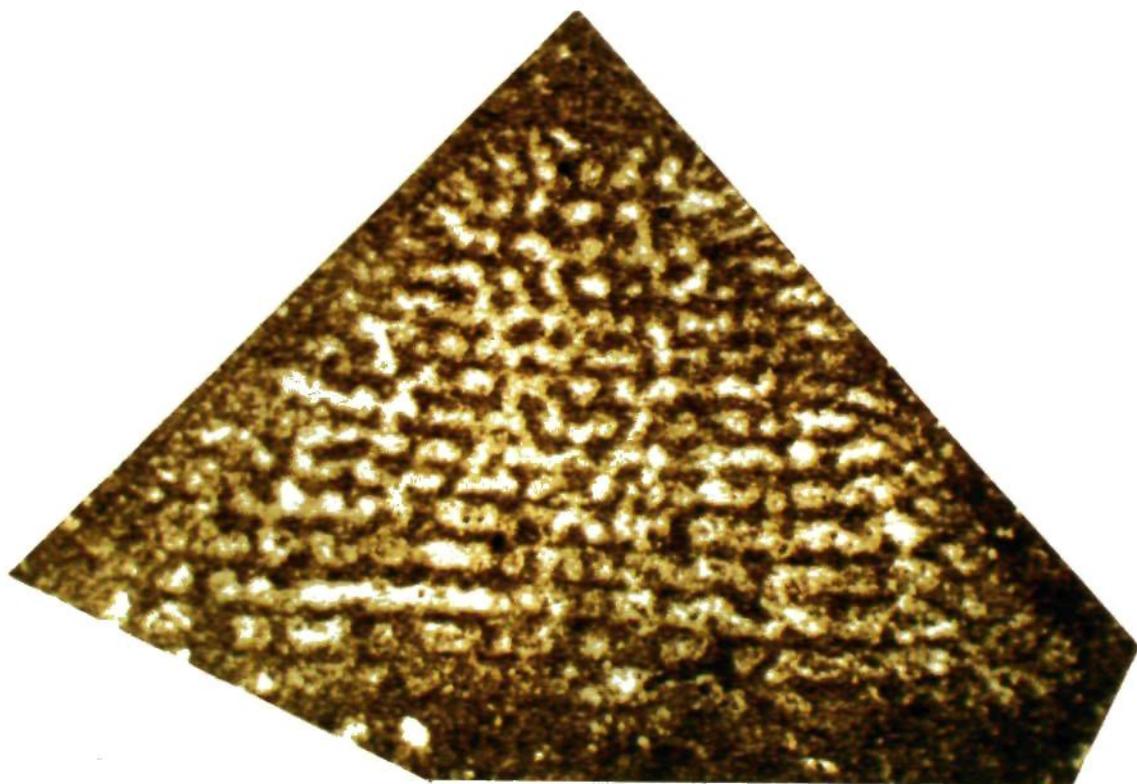
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PLATES 3.60 - 3.62

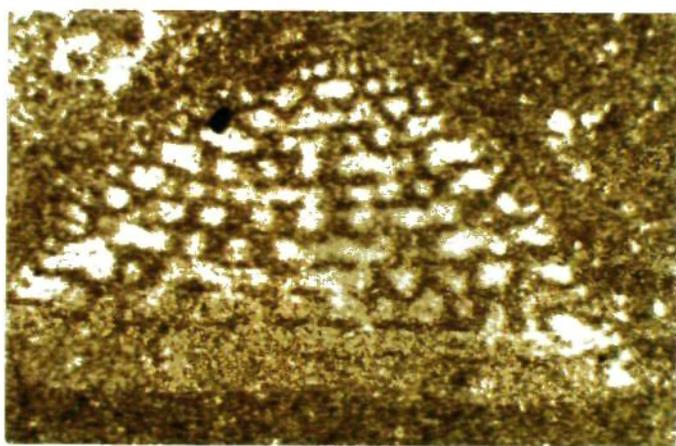
Plate 3.60: *Paleodictyoconus arabicus*, x40. MS81.

Plate 3.61: *Paleodictyoconus arabicus*, x40. MS81.

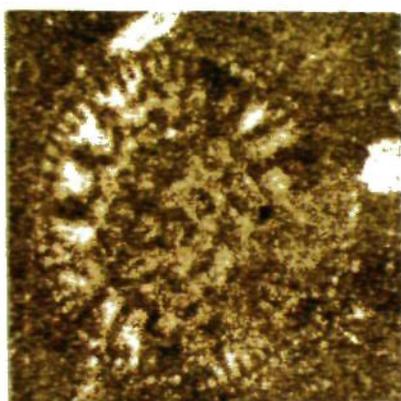
Plate 3.62: *Paleodictyoconus arabicus*, x40. MS81.



3.60



3.61



3.62

PLATES 3.63 - 3.70

Plate 3.63: *Trocholina sagittaria*, x100. MS51.2.

Plate 3.64: *Trocholina sagittaria*, x100. MS60.

Plate 3.65: *Trocholina sagittaria*, x100. MS60.

Plate 3.66: *Trocholina* sp. aff. *T. sagittaria*, x100. WM103.

Plate 3.67: *Trocholina* sp. aff. *T. sagittaria*, x100. WM103.

Plate 3.68: *Trocholina molesta*, x100. WM105.

Plate 3.69: *Trocholina odukpaniensis*, x100. K67.

Plate 3.70: *Trocholina chouberti*, x100. MS22.



3.63



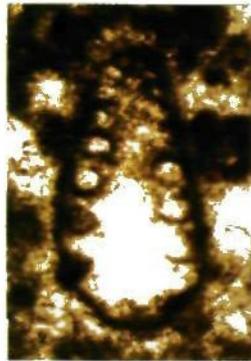
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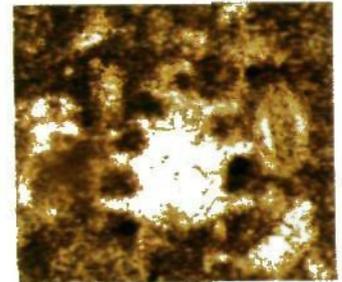
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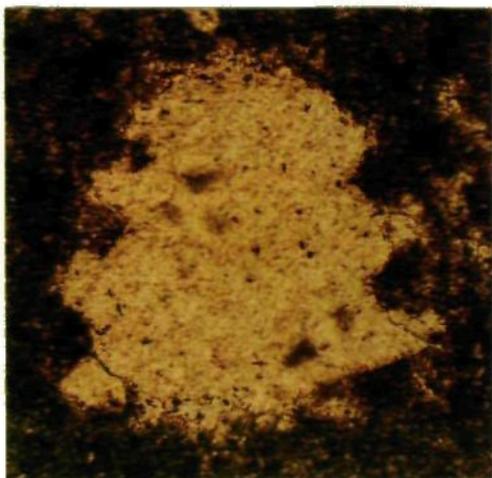
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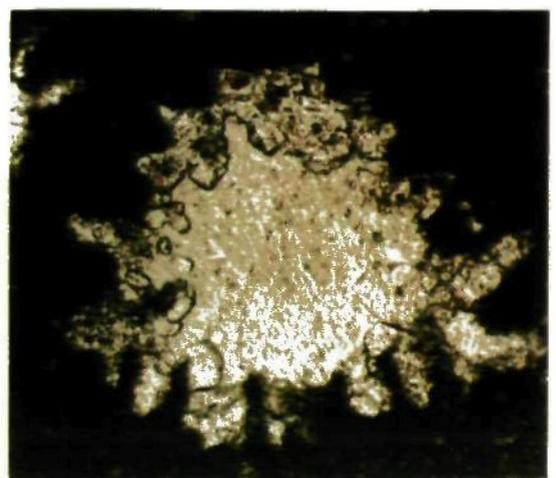
3.67



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PLATES 3.71 - 3.76

Plate 3.71: *Globuligerina hoterivica*, x100. WM(JDS)11.

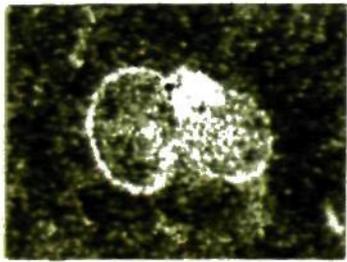
Plate 3.72: *Globuligerina hoterivica*, x100. WM(JDS)49.

Plate 3.73: *Globuligerina hoterivica*, x100. WM11.

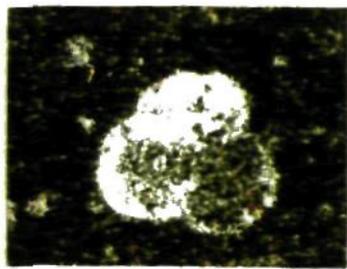
Plate 3.74: *Globuligerina hoterivica*, x100. WM(JDS)11.

Plate 3.75: *Rivularia lissaviensis*, x40. B53.

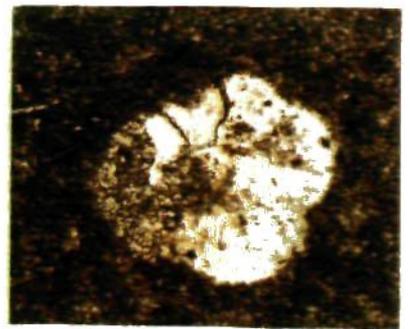
Plate 3.76: *Rivularia lissaviensis*, x40. B54.



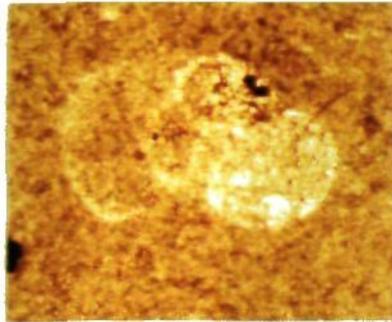
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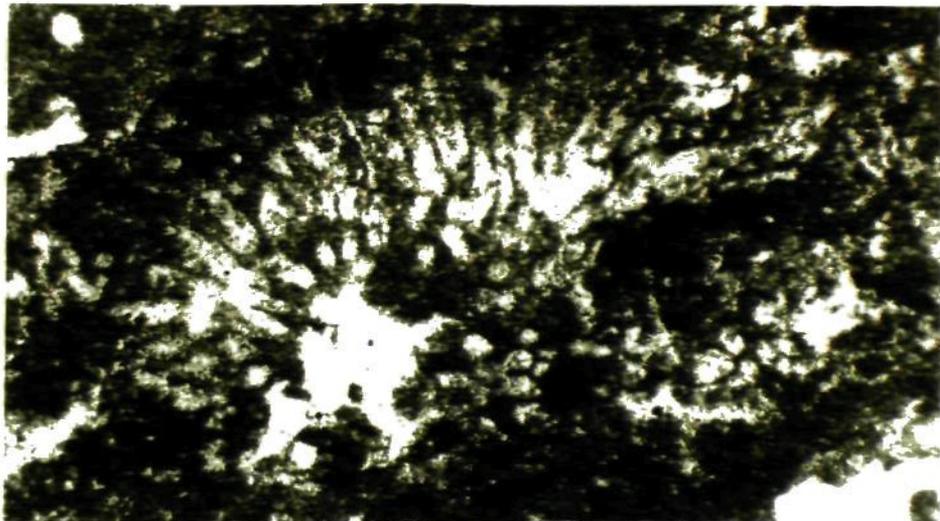
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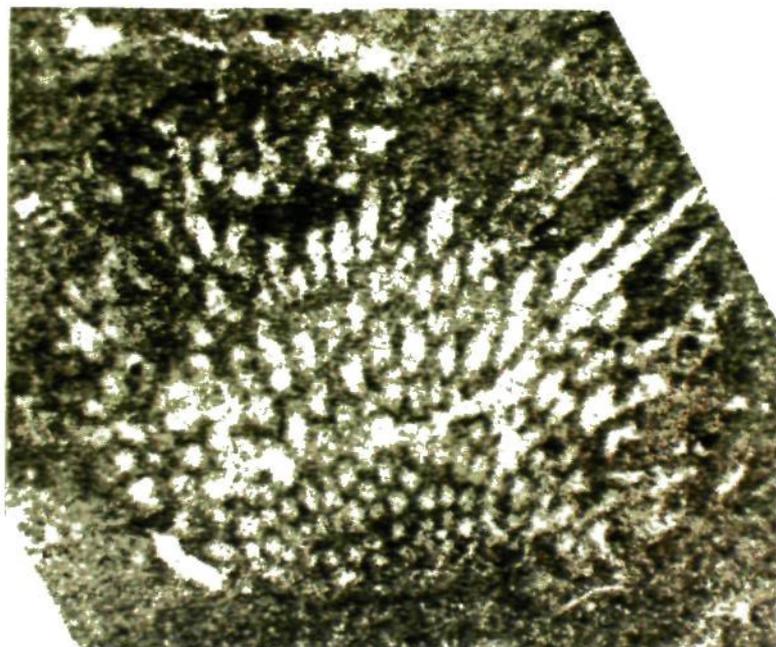
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3.74



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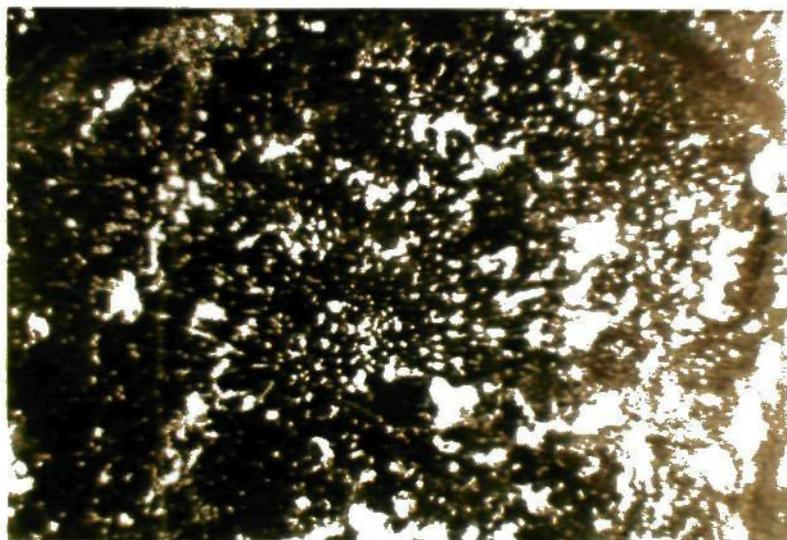
PLATES 3.77 - 3.80

Plate 3.77: *Rivularia fruticosa*, x16. BK58.

Plate 3.78: *Rivularia fruticosa*, x40. BK58.

Plate 3.79: Indeterminate Cyanophyte A, x40. M56.

Plate 3.80: *Permocalculus inopinatus*, x40. WM(JDS)83.



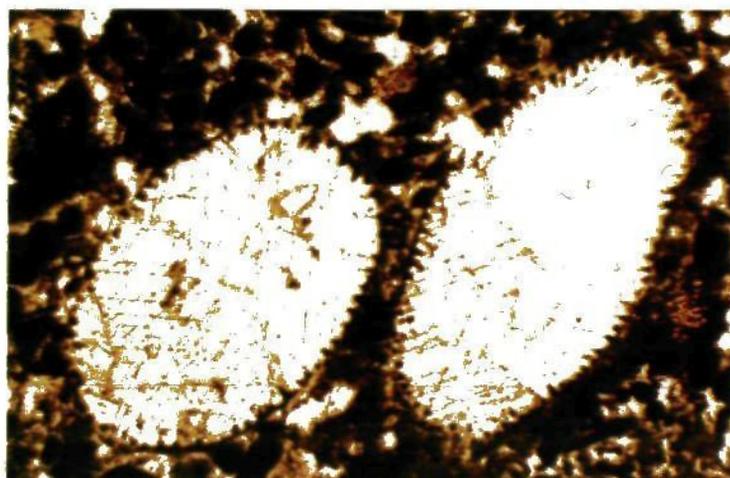
3.77



3.78



3.79



3.80

PLATES 3.81 - 3.85

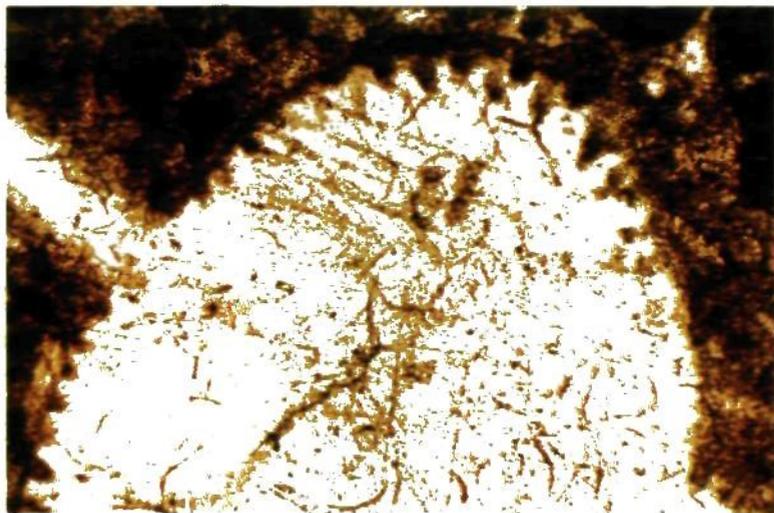
Plate 3.81: *Permocalculus inopinatus*, x100. WM(JDS)83.

Plate 3.82: *Permocalculus inopinatus*, x40. WM(JDS)83.

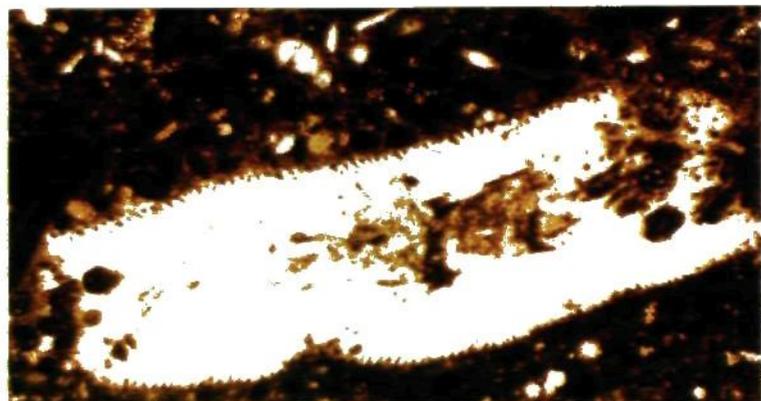
Plate 3.83: *Permocalculus inopinatus*, x100. WMX11.

Plate 3.84: *Permocalculus inopinatus*, x100. B39.3.

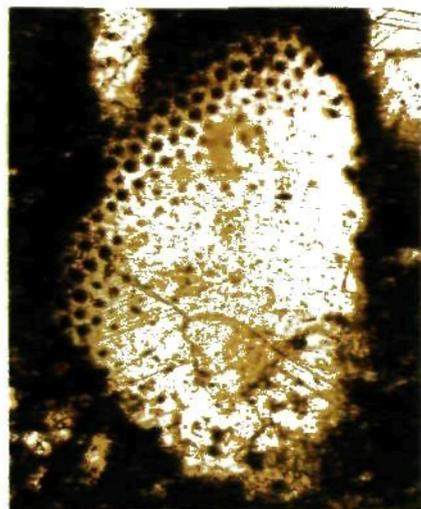
Plate 3.85: *Permocalculus inopinatus*, x100. MS51.2.



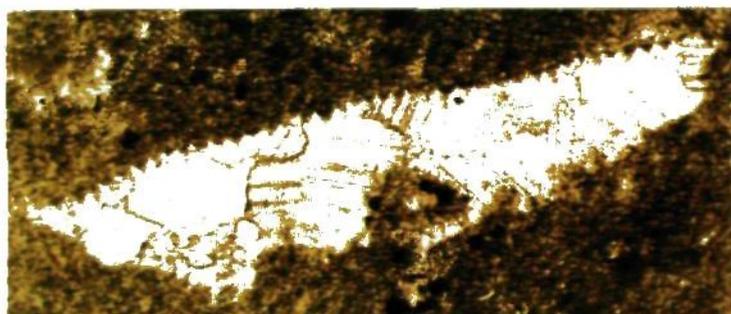
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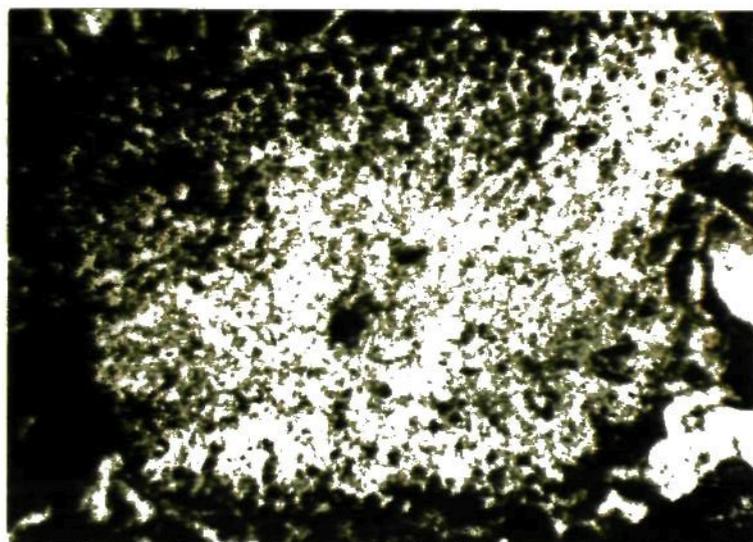
3.82



3.83



3.84



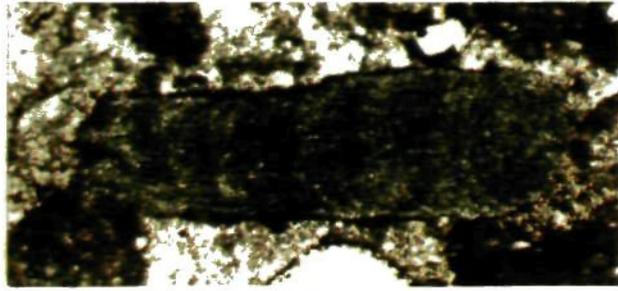
3.85

PLATES 3.86 - 3.88

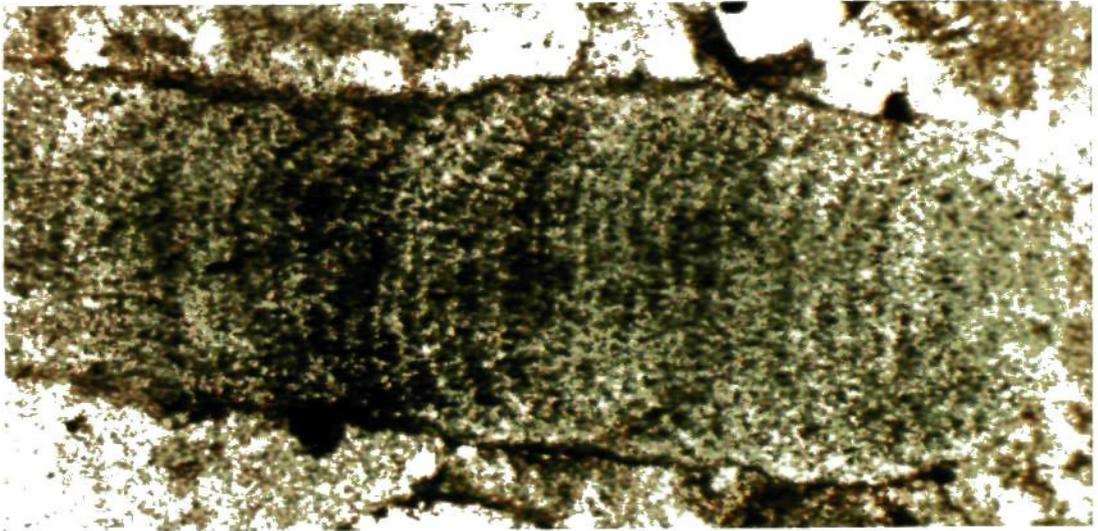
Plate 3.86: *Marinella lugeoni*, x40. MS6.

Plate 3.87: *Marinella lugeoni*, x100. MS6.

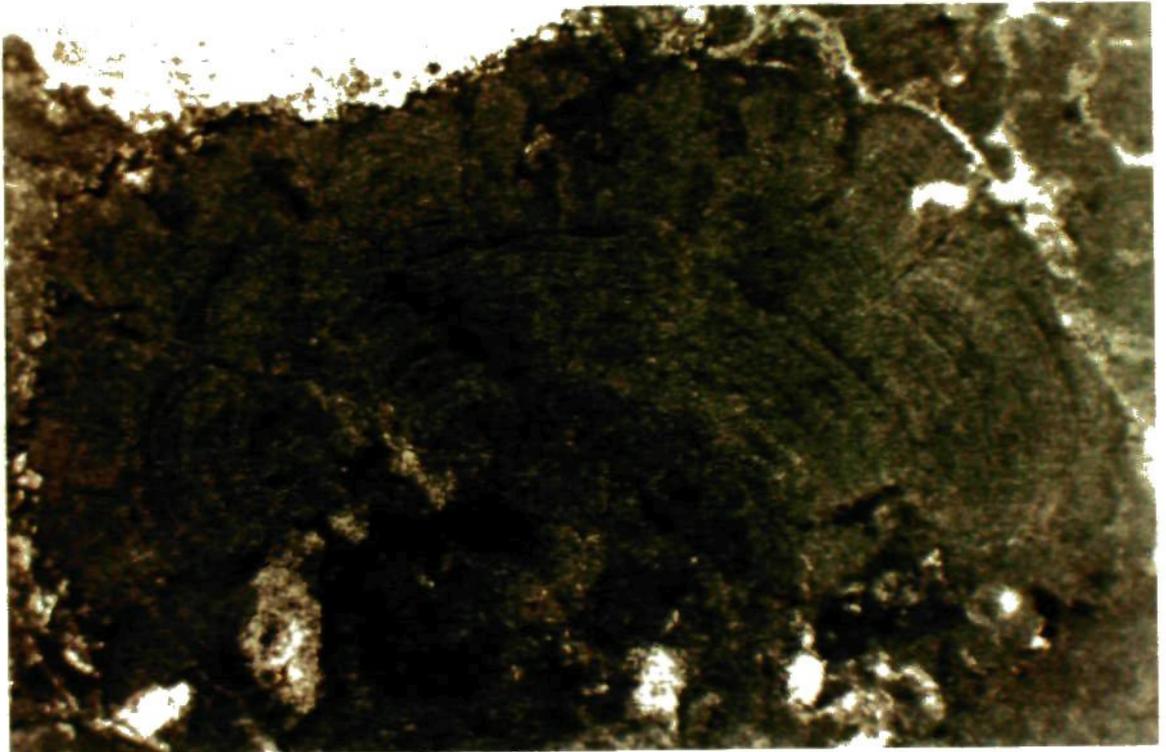
Plate 3.88: *Marinella lugeoni*, x40. MS21.



3.86



3.87



3.88

PLATES 3.89 - 3.93

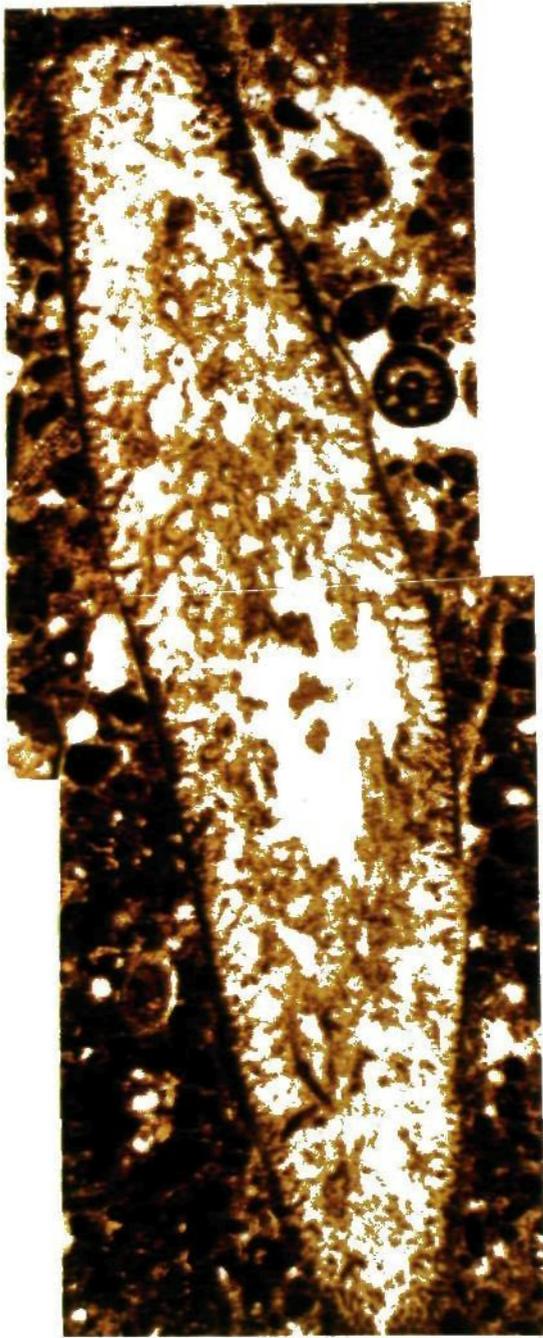
Plate 3.89: *Arabicodium aegagrapiloides*, x40. WM(JDS)83.

Plate 3.90: *Arabicodium aegagrapiloides*, x16. WM(JDS)83.

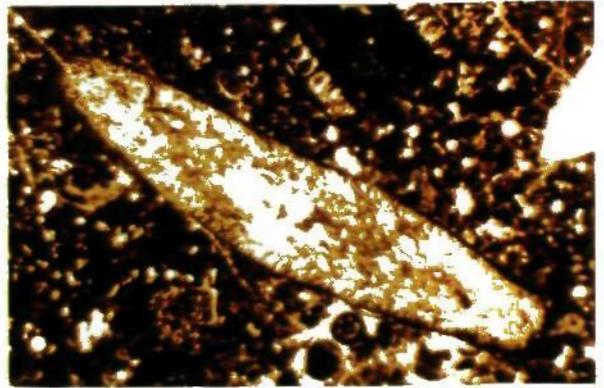
Plate 3.91: *Arabicodium aegagrapiloides*, x40. WM(JDS)83.

Plate 3.92: *Arabicodium aegagrapiloides*, x40. WM(JDS)83.

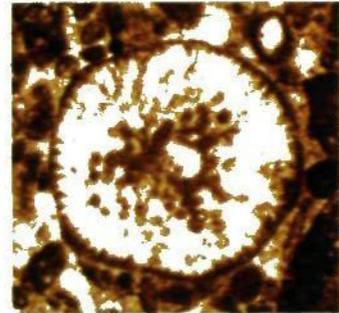
Plate 3.93: *Arabicodium aegagrapiloides*, x40. WM(JDS)83.



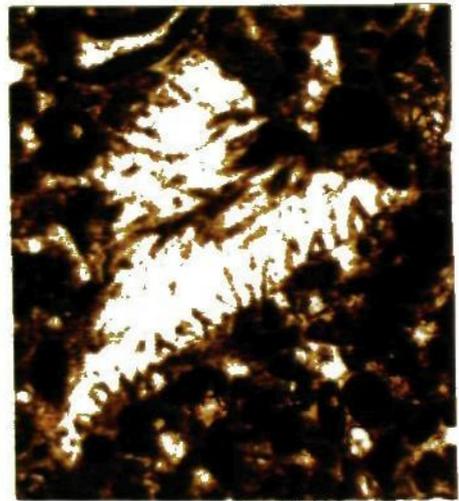
3.89



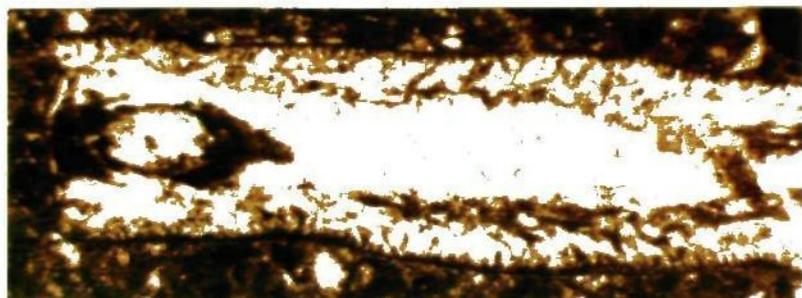
3.90



3.91



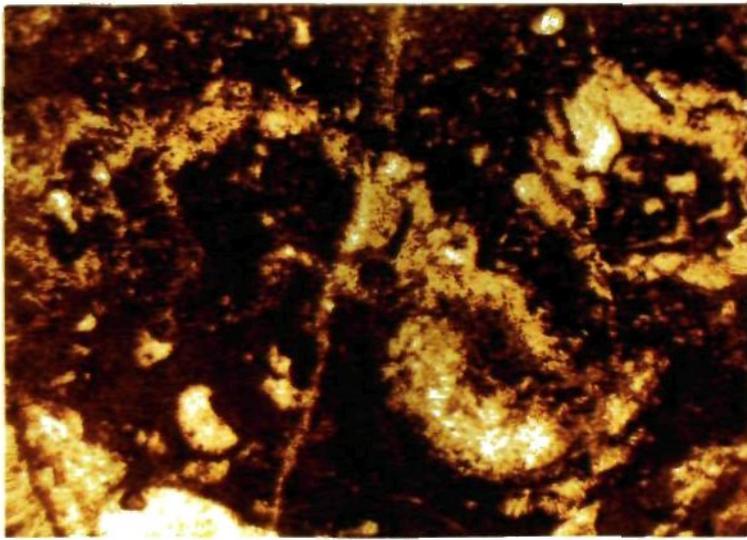
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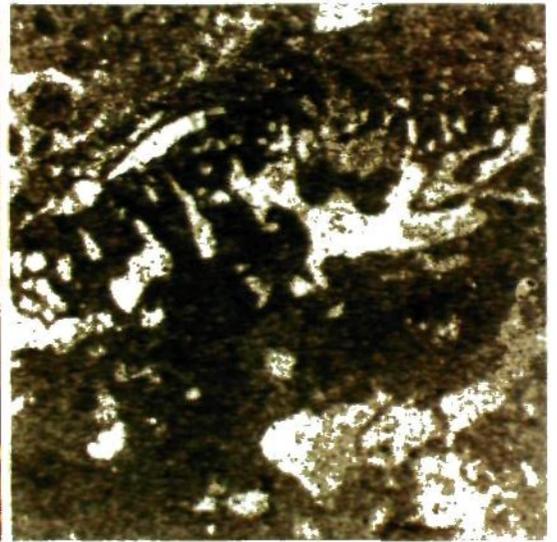
3.93

PLATES 3.94 - 3.98

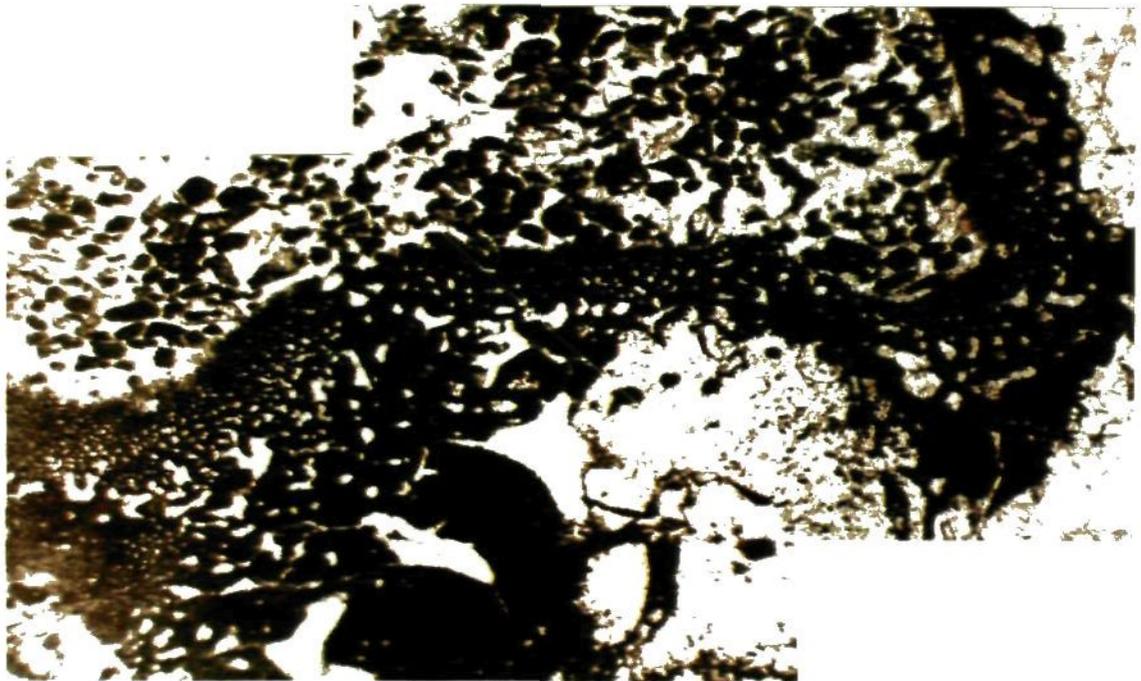
- Plate 3.94: *Ethelia alba*, x40. WM(JDS)96.
- Plate 3.95: *Lithocodium aggregatum*, x40. MS11.
- Plate 3.96: *Lithocodium aggregatum*, x16. BK54.
- Plate 3.97: *Lithocodium aggregatum*, x40. BK54.
- Plate 3.98: *Lithocodium aggregatum*, x16. WM55.



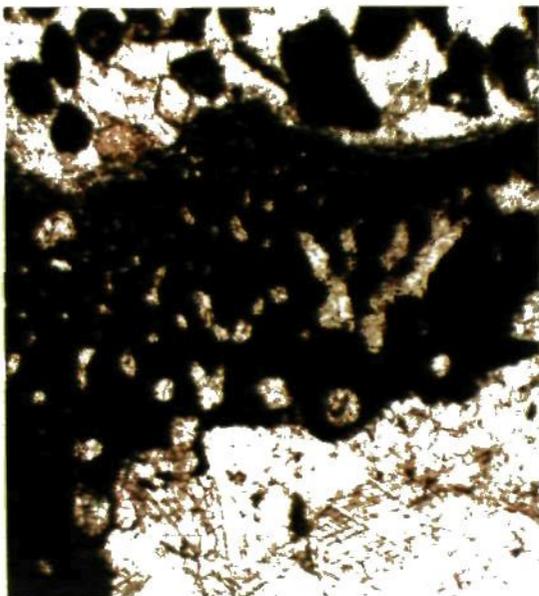
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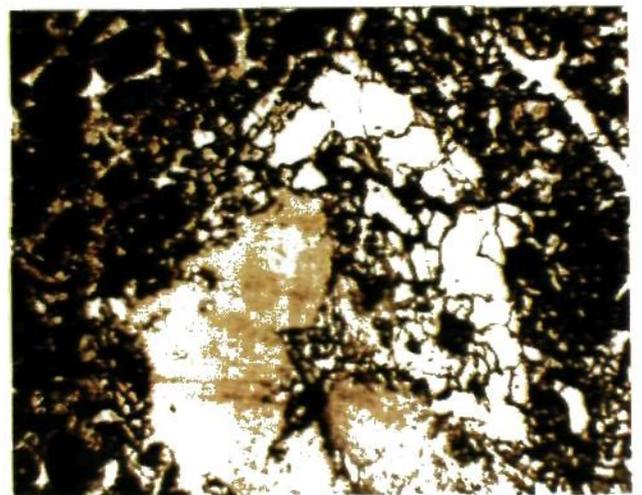
3.95



3.96



3.97



3.98

PLATE 3.99 - 3.104

Plate 3.99: *Lithocodium aggregatum*, x40. WM55.

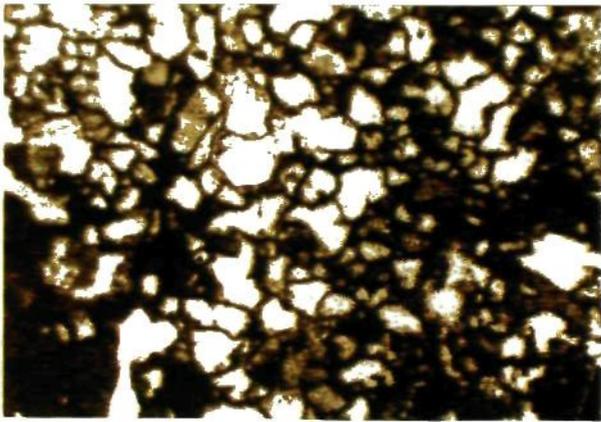
Plate 3.100: *Lithocodium aggregatum*, x40. WM55.

Plate 3.101: *Lithocodium aggregatum*, x40. WM55.

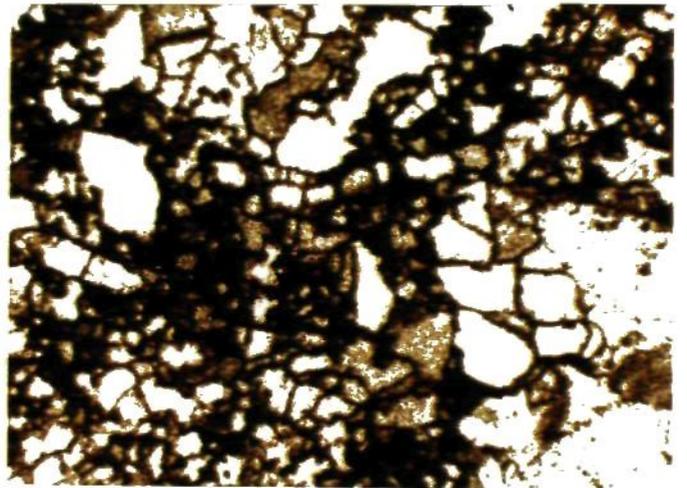
Plate 3.102: *Lithocodium aggregatum*, x40. WM55.

Plate 3.103: *Lithocodium aggregatum*, x40. MS11.

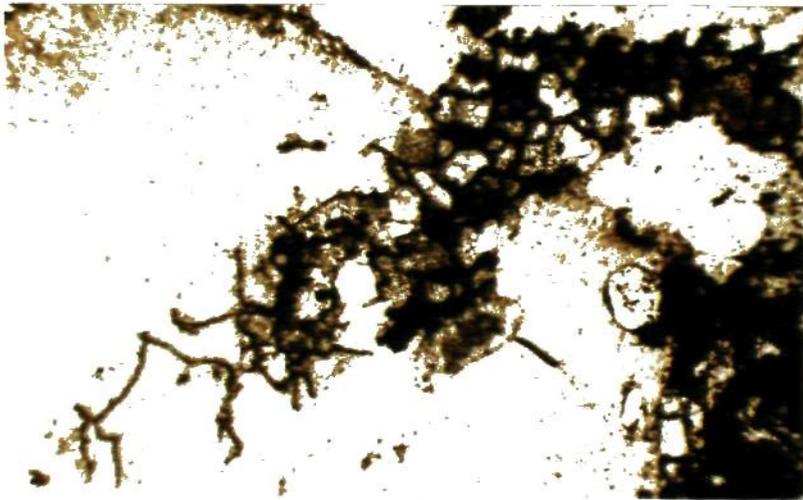
Plate 3.104: *Lithocodium aggregatum*, x40. K13.



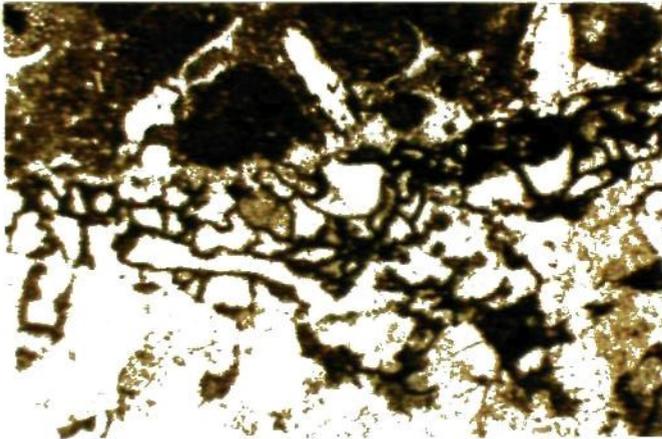
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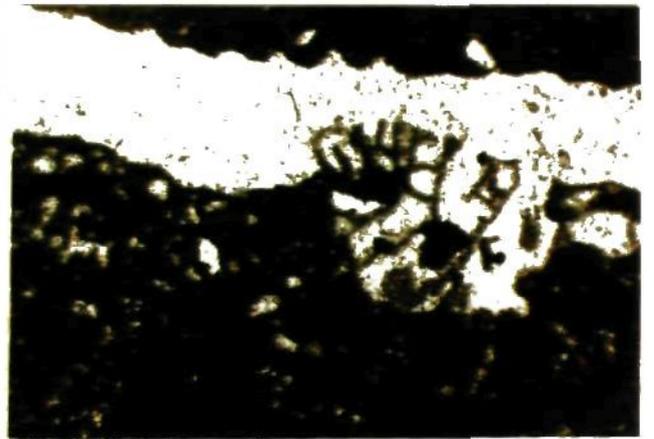
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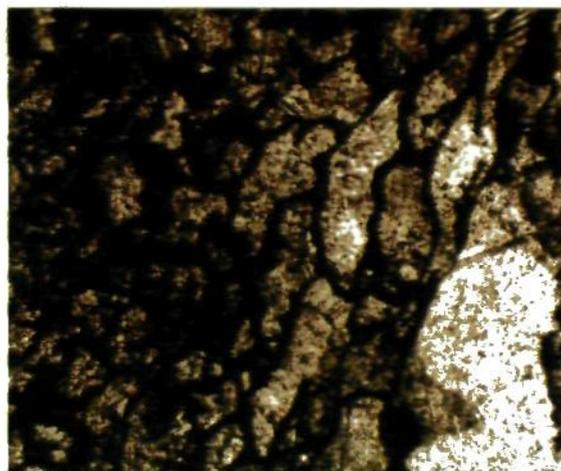
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3.102



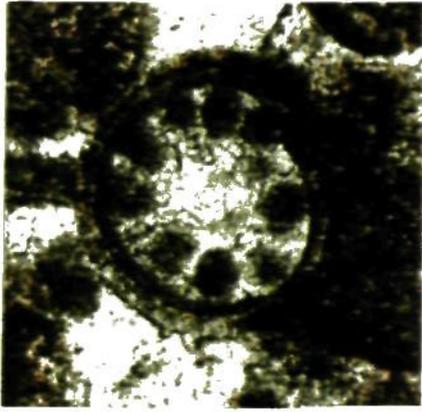
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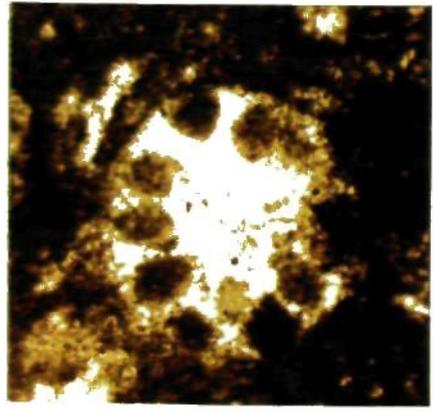
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PLATES 3.105 - 3.108

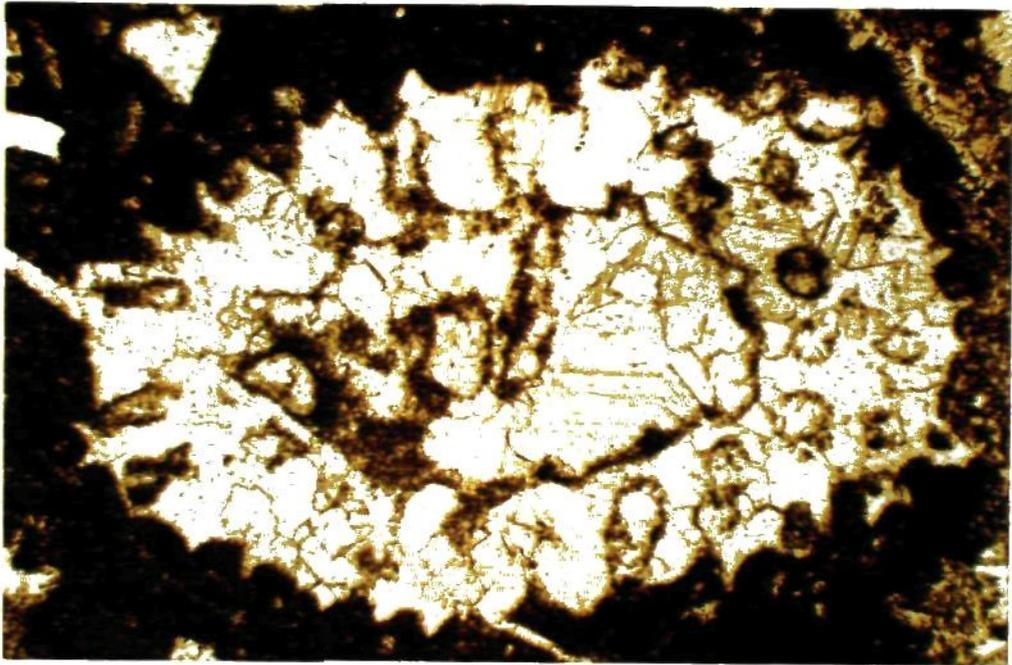
- Plate 3.105: *Acicularia antiqua*, x100. JMD2a.
- Plate 3.106: *Acicularia antiqua*, x100. WM105.
- Plate 3.107: *Acroporella assurbanipali*, x40. WM103.
- Plate 3.108: *Acroporella assurbanipali*, x40. WM103.



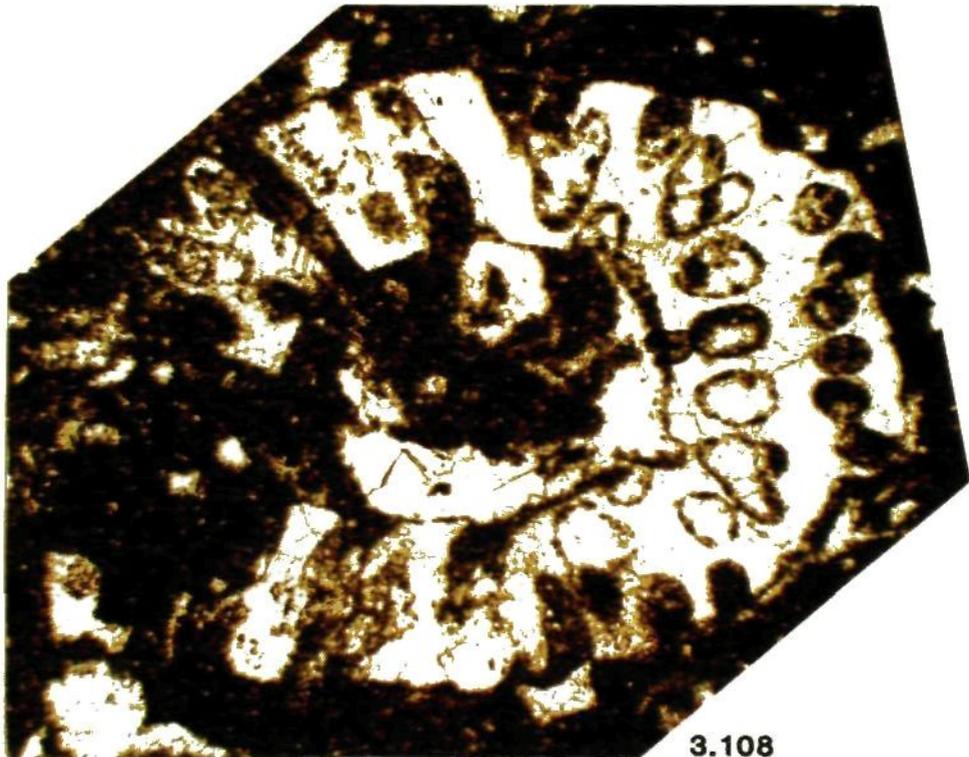
3.105



3.106



3.107



3.108

PLATES 3.109 - 3.114

Plate 3.109: *Acroporella assurbanipali*, x16. WM103.

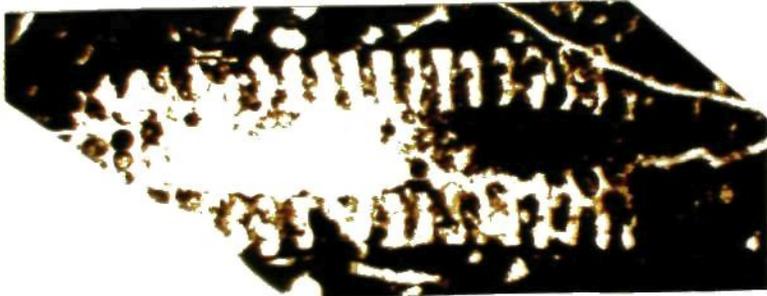
Plate 3.110: *Acroporella assurbanipali*, x32. WM103.

Plate 3.111: *Acroporella assurbanipali*, x40. WM103.

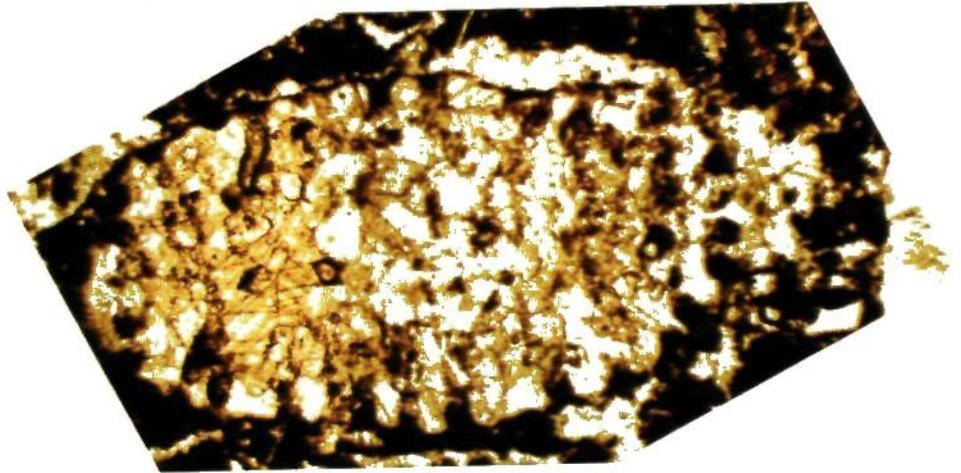
Plate 3.112: *Acroporella assurbanipali*, x40. WM103.

Plate 3.113: *Acroporella radoicici*, x40. WM48.

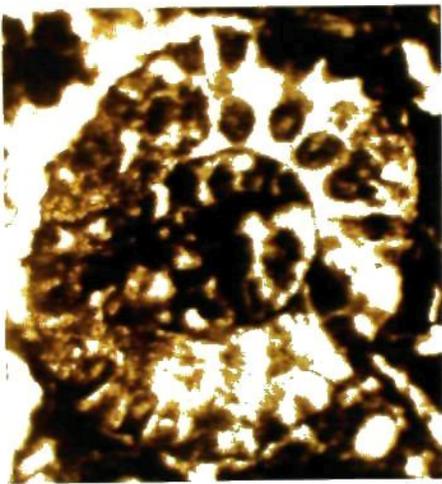
Plate 3.114: *Acroporella radoicici*, x40. WM48.



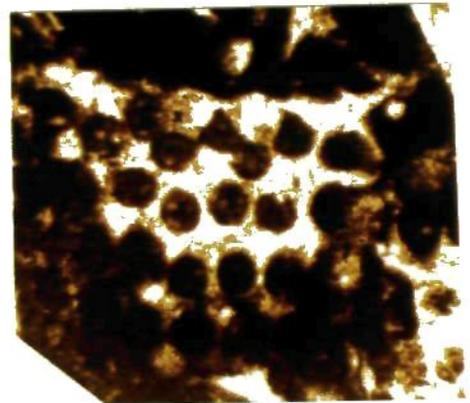
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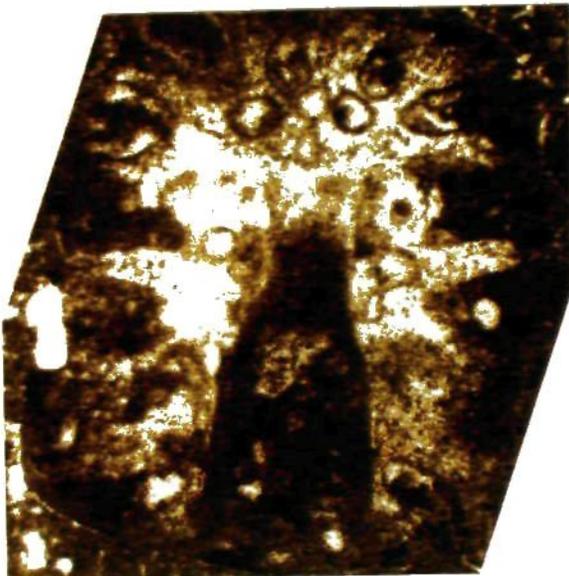
3.110



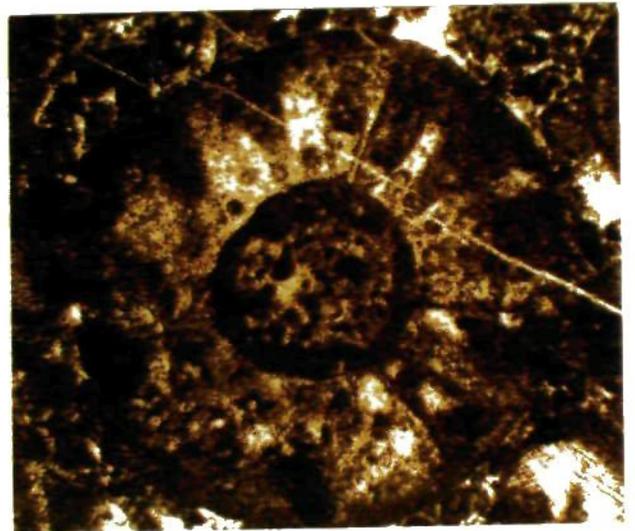
3.111



3.112



3.113



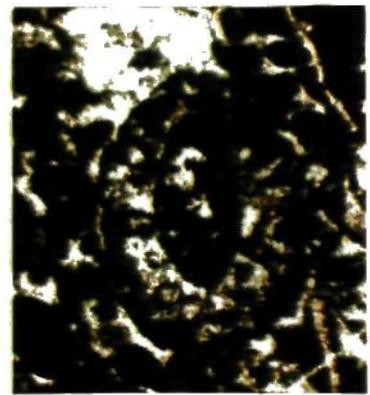
3.114

PLATE 3.115 - 3.121

- Plate 3.115: *Acroporella radoicici*, x40. WM48.
- Plate 3.116: *Acroporella radoicici*, x40. WM(JDS)103.
- Plate 3.117: *Acroporella radoicici*, x40. WM48.
- Plate 3.118: *Actinoporella podolica*, x40. WM103.
- Plate 3.119: *Actinoporella podolica*, x40. WM103.
- Plate 3.120: *Actinoporella podolica*, x40. WM103.
- Plate 3.121: *Actinoporella podolica*, x100. MS22.



3.115



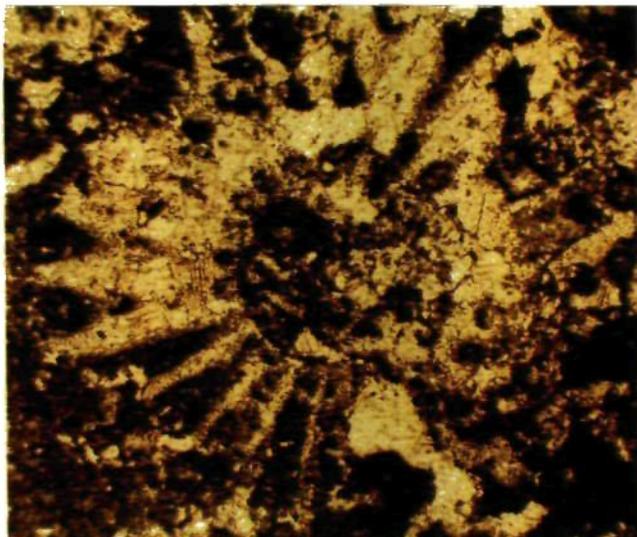
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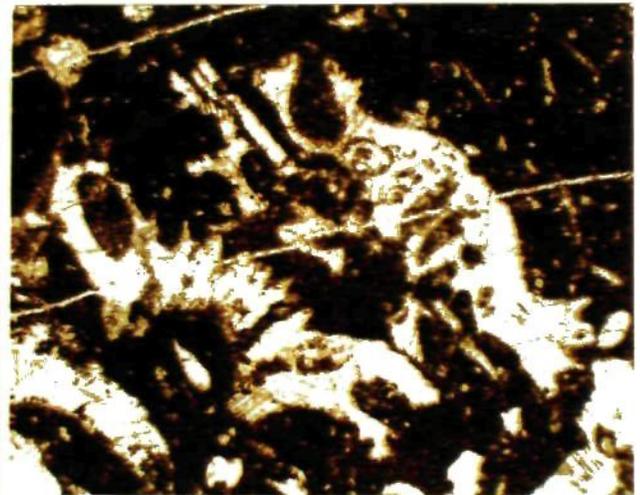
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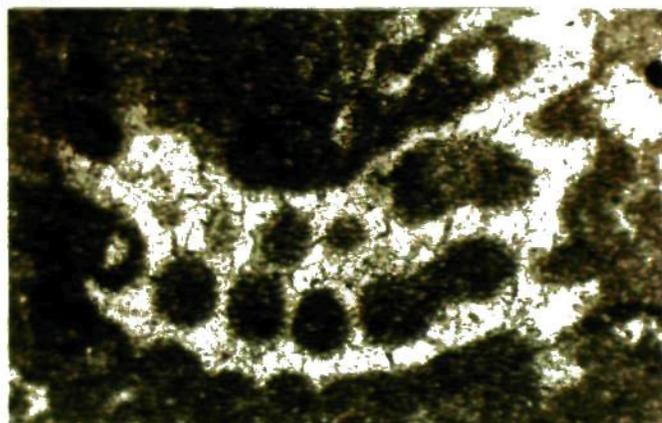
3.118



3.119



3.120



3.121

PLATES 3.122 - 3.127

Plate 3.122: *Actinoporella podolica*, x40. MS22.

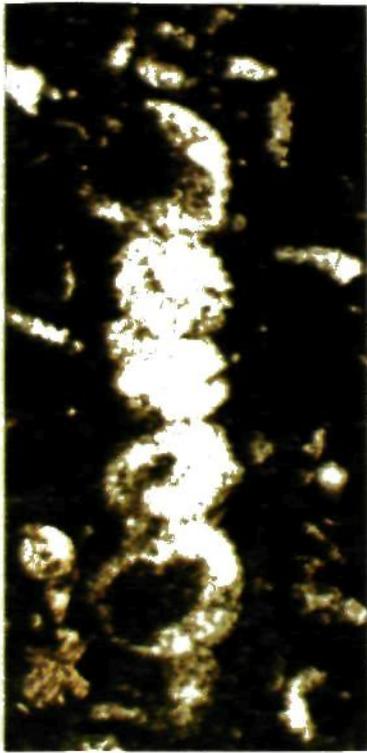
Plate 3.123: *Actinoporella podolica*, x40. MS24.

Plate 3.124: *Clypeina parvula?*, x100. BK59.

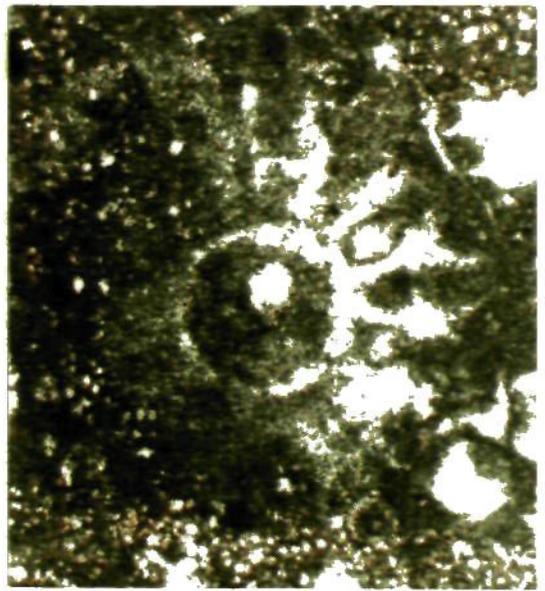
Plate 3.125: *Clypeina parvula?*, x100. B94.

Plate 3.126: *Clypeina (?) solkani?*, x100. B42.2.

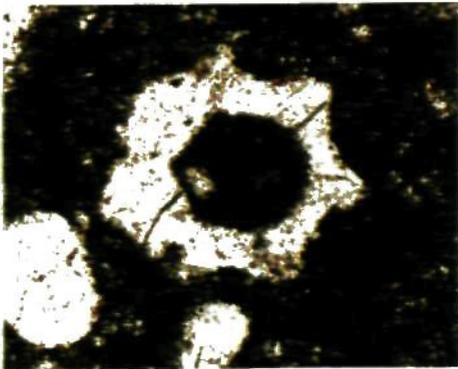
Plate 3.127: *Coptocampylodon lineolatus*, x100. MS11.



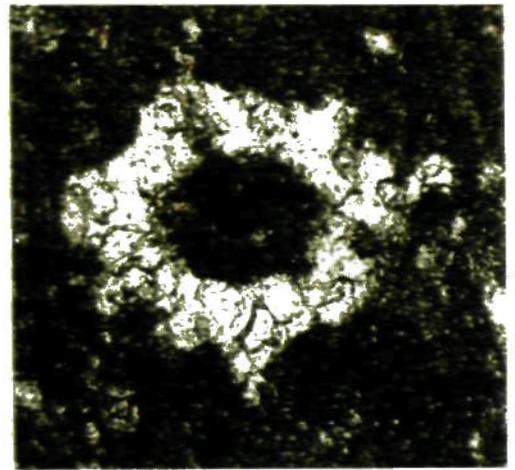
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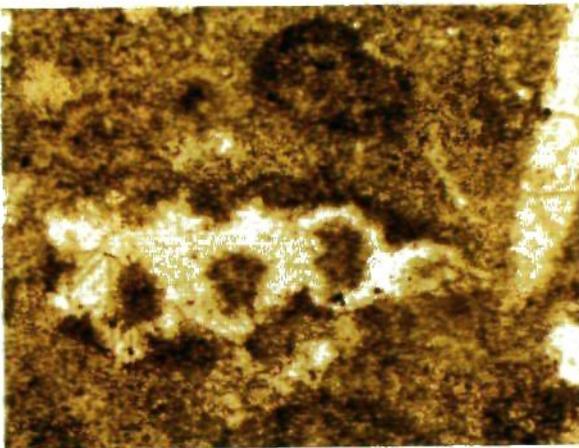
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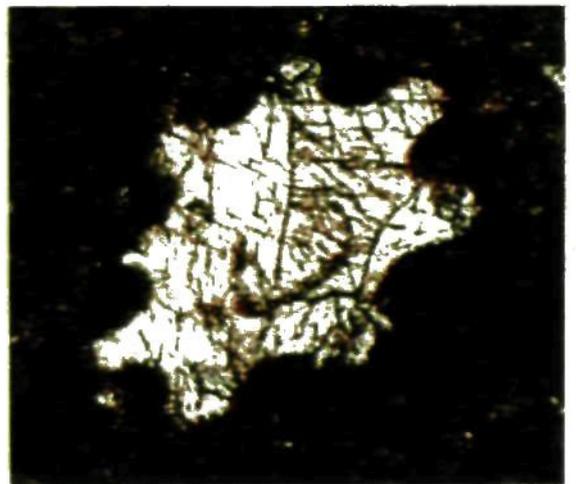
3.124



3.125



3.126



3.127

PLATES 3.128 - 3.135

Plate 3.128: *Coptocampylodon lineolatus*, x100. WM(JDS)135.

Plate 3.129: *Coptocampylodon lineolatus*, x40. MS11.

Plate 3.130: *Cylindroporella arabica*, x100. BK41.

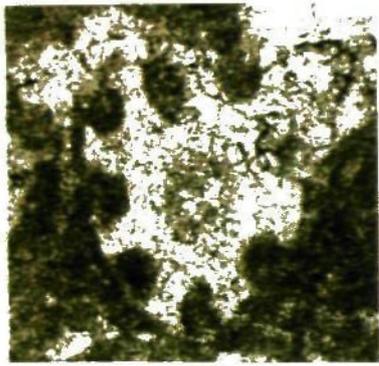
Plate 3.131: *Cylindroporella arabica*, x40. MS4.2.

Plate 3.132: *Cylindroporella arabica*, x100. WM(JDS)85A.

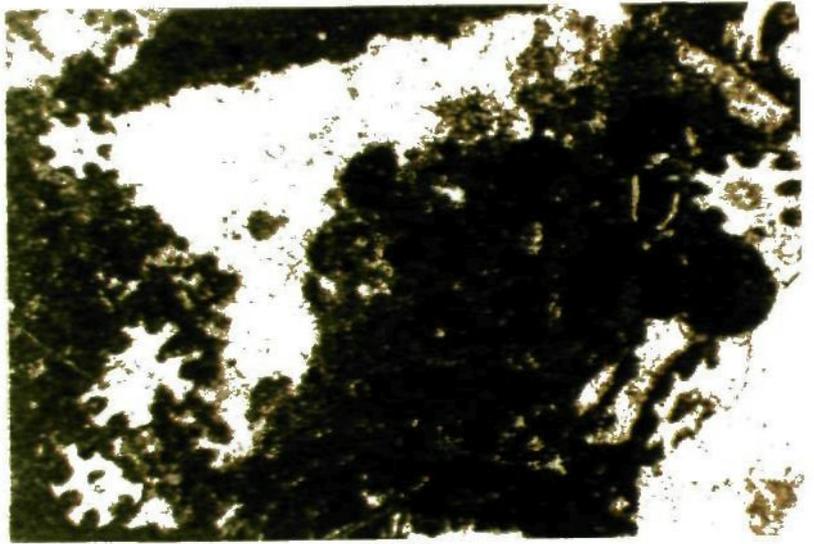
Plate 3.133: *Cylindroporella arabica*, x40. WM(JDS)109.

Plate 3.134: *Cylindroporella arabica*, x100. WM(JDS)85A.

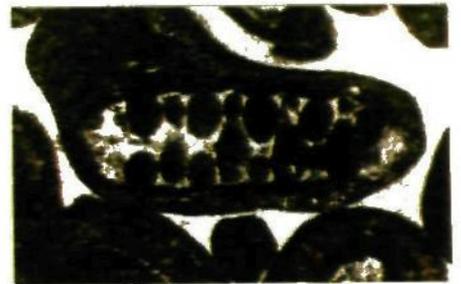
Plate 3.135: *Cylindroporella sugdeni*, x100. MS24.



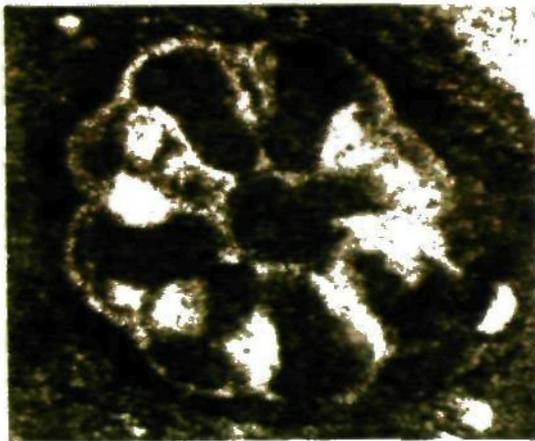
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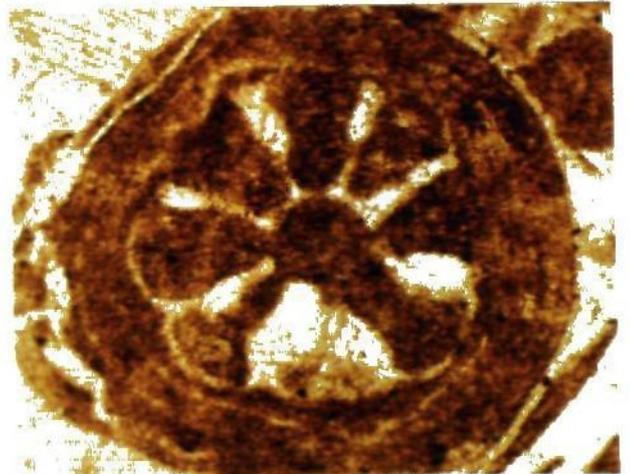
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3.131



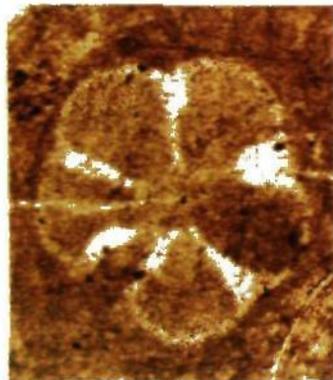
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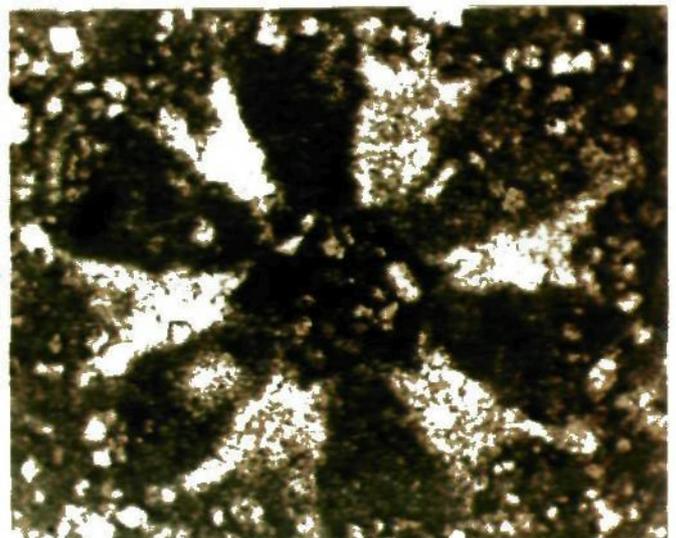
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3.133



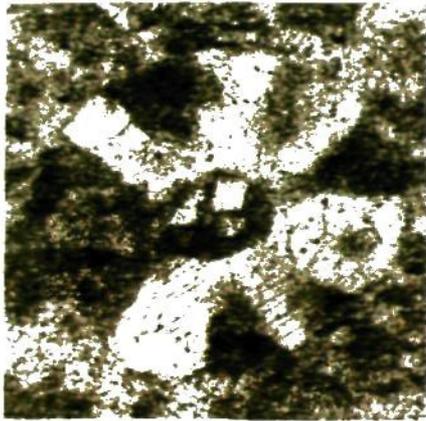
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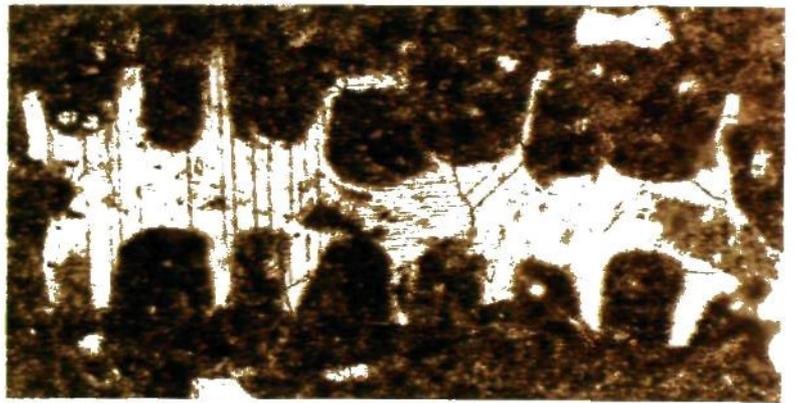
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PLATES 3.136 - 3.145

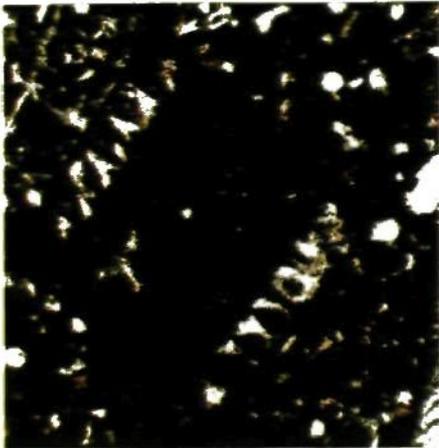
- Plate 3.136: *Cylindroporella sugdeni*, x100. B90.
- Plate 3.137: *Cylindroporella sugdeni*, x90. WM56.
- Plate 3.138: *Neomeris cretacea*, x40. WM(JDS)83.
- Plate 3.139: *Salpingoporella muehlbergii*, x40. WM105.
- Plate 3.140: *Salpingoporella muehlbergii*, x40. WM105.
- Plate 3.141: *Salpingoporella muehlbergii*, x100. WM105.
- Plate 3.142: *Salpingoporella muehlbergii*, x100. WM105.
- Plate 3.143: *Salpingoporella* sp. A., x100. MS27.
- Plate 3.144: *Salpingoporella arabica*, x100. BK64.
- Plate 3.145: "*Salpingoporella*" *dinarica*, x40. Topotype specimen.



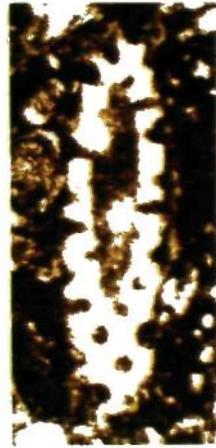
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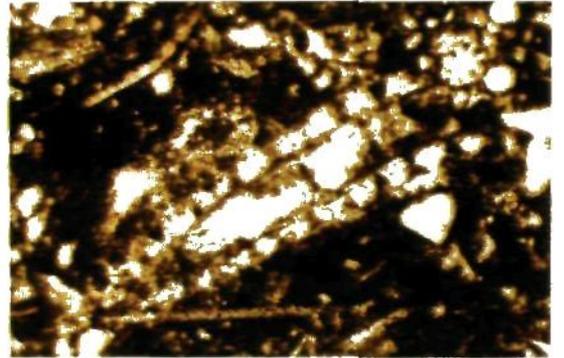
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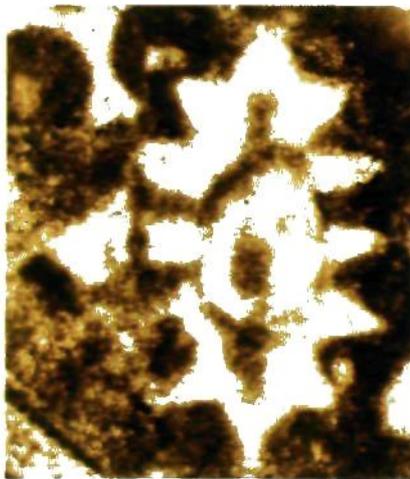
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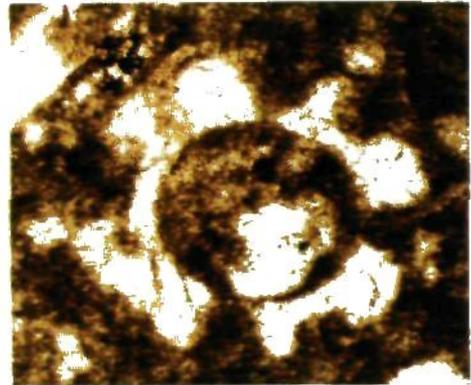
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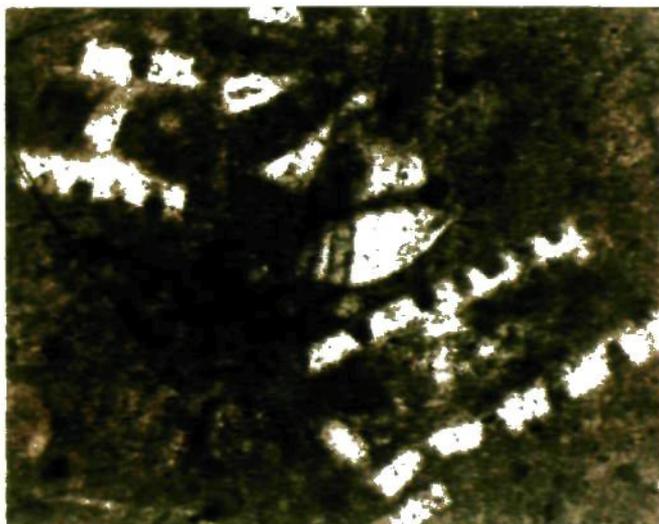
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3.141



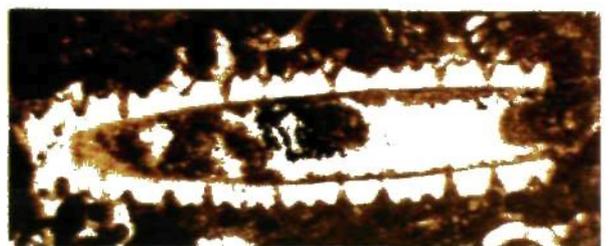
3.142



3.143



3.144



3.145

PLATES 3.146 - 3.151

Plate 3.146: "*Salpingoporella*" *dinarica*, x40. Topotype specimens.

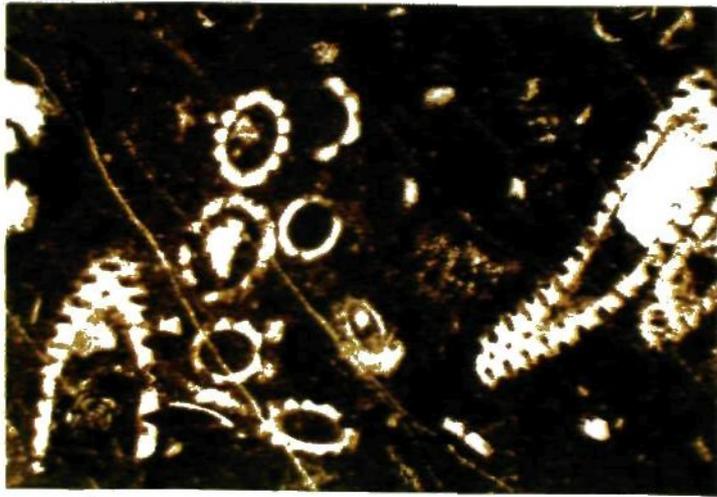
Plate 3.147: "*Salpingoporella*" *dinarica*, x100. Topotype specimens.

Plate 3.148: "*Salpingoporella*" *dinarica*, x100. Topotype specimen.

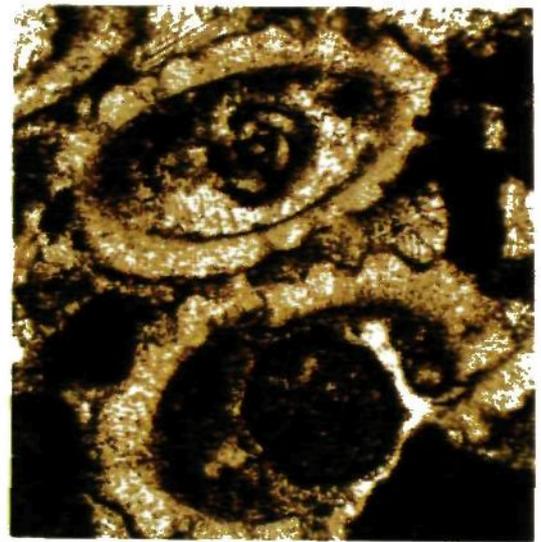
Plate 3.149: "*Salpingoporella*" *dinarica*, x100. WM105.

Plate 3.150: "*Salpingoporella*" *dinarica*, x100. B90.

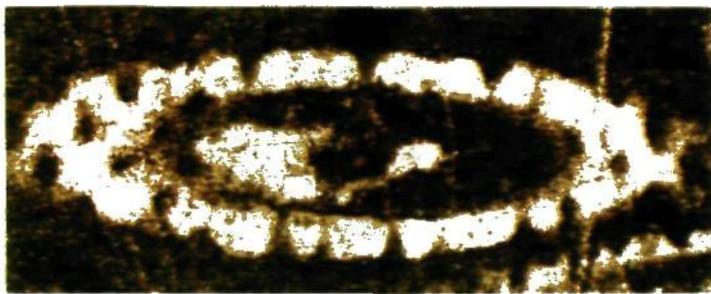
Plate 3.151: "*Salpingoporella*" *dinarica*, x100. B94.



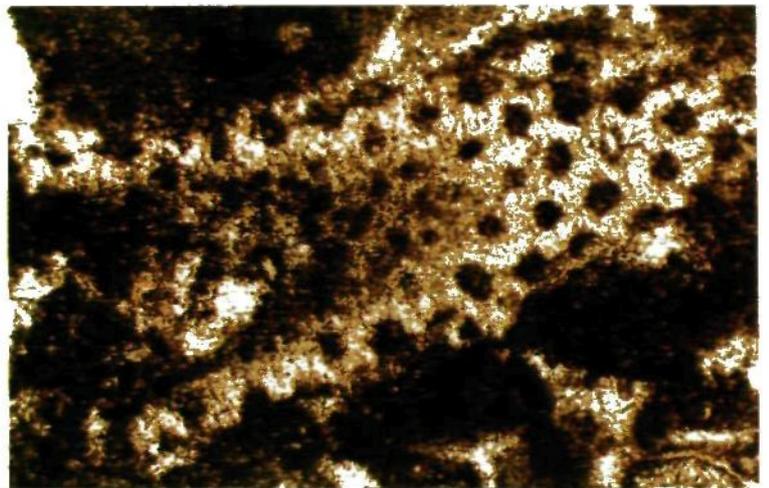
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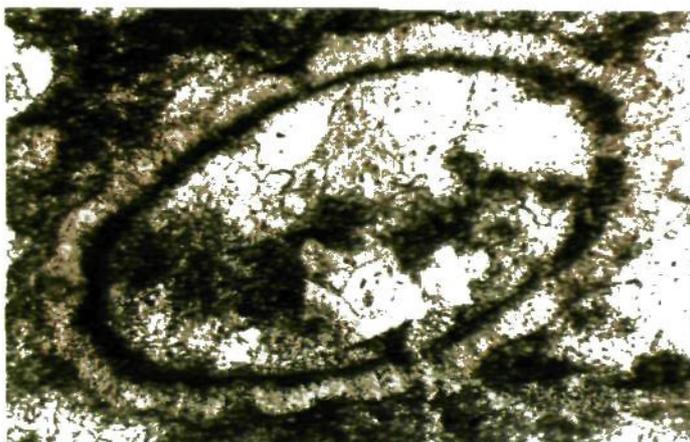
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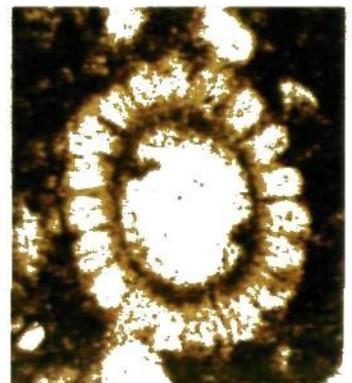
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3.149



3.150



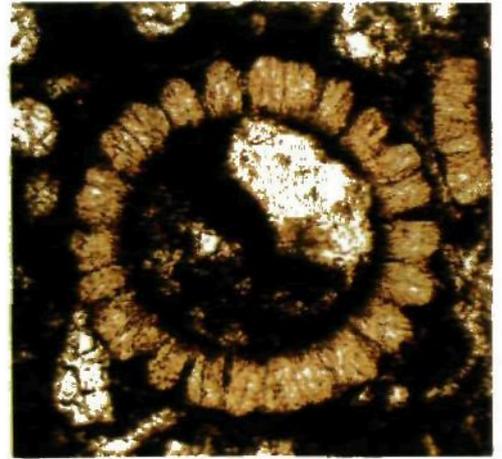
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PLATES 3.152 - 3.159

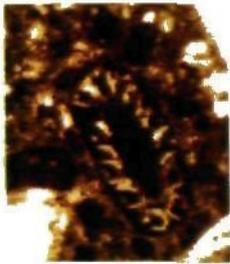
- Plate 3.152:        "*Salpingoporella*" *dinarica*, x100. B90.
- Plate 3.153:        "*Salpingoporella*" *dinarica*, x100. WM105.
- Plate 3.154:        *Salpingoporella johnsoni*, x40. WM(JDS)83.
- Plate 3.155:        *Salpingoporella pygmaea*, x40, B53.
- Plate 3.156:        *Salpingoporella pygmaea*, x100. B53.
- Plate 3.157:        *Salpingoporella pygmaea*, x100. B53.
- Plate 3.158:        *Salpingoporella pygmaea*, x100. MS51.
- Plate 3.159:        *Salpingoporella pygmaea*, x100. WM54.



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3.153



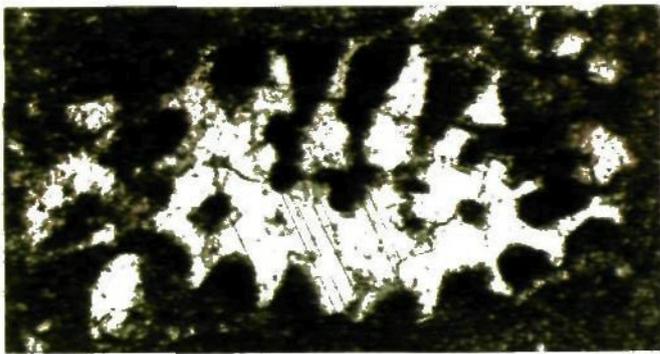
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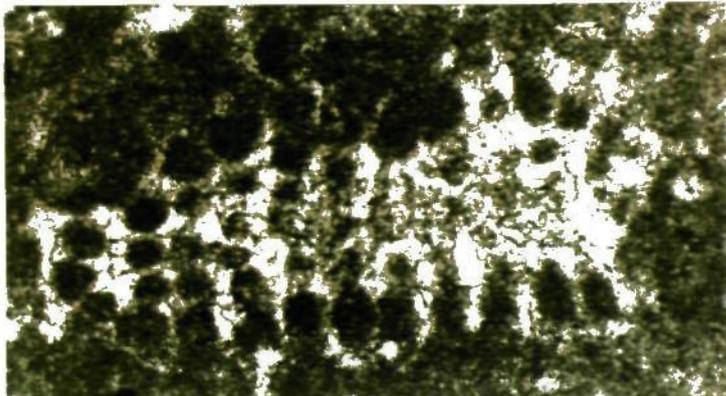
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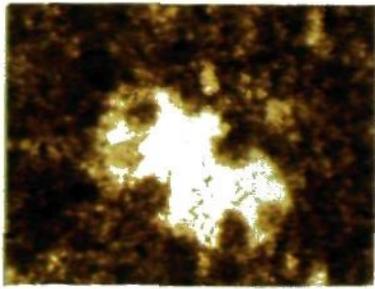
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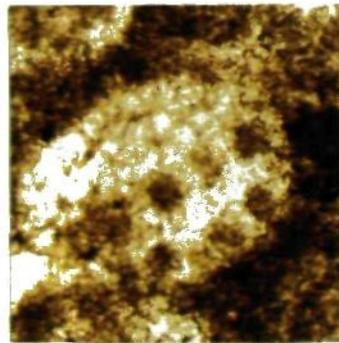
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PLATES 3.160 - 3.169

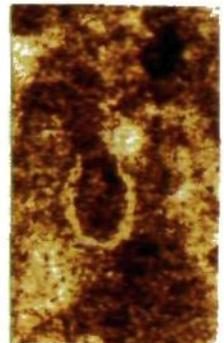
- Plate 3.160: *Terquemella* sp. A., x100. WM105.
- Plate 3.161: *Terquemella* sp. A., x100. WM105.
- Plate 3.162: *Calpionella alpina*, x100. WM(JDS)5.
- Plate 3.163: *Calpionella alpina*, x400. WM(JDS)5.
- Plate 3.164: *Calpionellopsis elongata*, x100. WM(JDS)6A.
- Plate 3.165: *Calpionellopsis elongata*, x100. WM(JDS)6A.
- Plate 3.166: *Calpionellopsis elongata*, x100. WM(JDS)6A.
- Plate 3.167: *Calpionellopsis elongata*, x400. WM(JDS)6A.
- Plate 3.168: *Crassicollaria parvula*, x100. WM(JDS)5.
- Plate 3.169: *Crassicollaria parvula*, x100. WM(JDS)5.



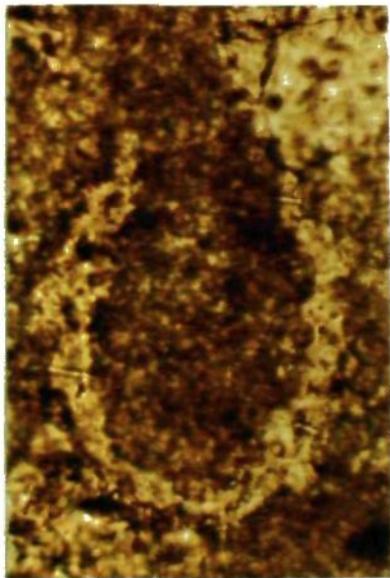
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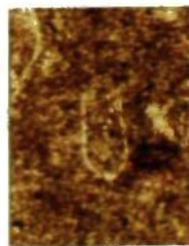
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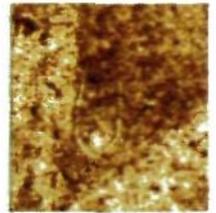
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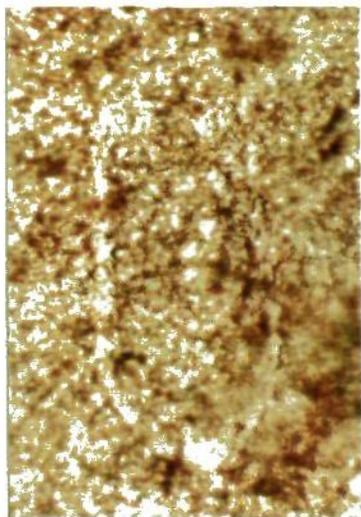
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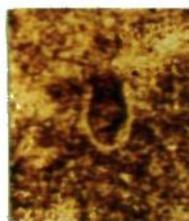
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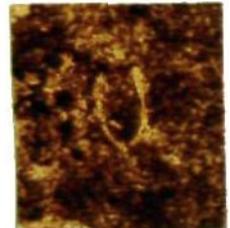
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# 10

## The biostratigraphy and microfacies of the Early to mid-Cretaceous carbonates of Wadi Mi'aidin, Central Oman Mountains.

M. D. Simmons and M. B. Hart

### ABSTRACT

The autochthonous successions of the oil-bearing Cretaceous carbonates in the Oman Mountains are mainly exposed in three areas: Musandam, Jebel Akhdar, and Saih Hatat. On the southern flank of Jebel Akhdar, Wadi Mi'aidin provides a well-exposed, accessible section through the carbonate succession of Early to mid-Cretaceous age. This succession is described and the microfacies illustrated. The stratigraphic distribution of the Foraminifera and calcareous algae is presented for the first time, despite this succession being used by many oil geologists as a reference for correlation throughout the Oman Mountains.

### INTRODUCTION

The Oman Mountains form a distinct crescent along the north of the country. To the south lies

the interior gravel plain, while to the north of the mountains there is a narrow strip of fluvial/aeolian sediments which border the Gulf of Oman (see Figure 10.1). The region is famous as the site of perhaps the best preserved ophiolite complex in the world: the Semail Ophiolite. This ophiolite complex and the underlying allochthonous thrust units known as the Hawasina Series override an *in situ* Mesozoic carbonate platform succession that rests unconformably on a pre-Permian basement. Details of this geologically complex area are presented in Glennie *et al.* (1974), which remains the key text on the geology of this region.

Within the autochthonous succession, the Early to mid-Cretaceous is represented by an important sequence of carbonate rocks which provide both the source rock and the reservoir for the Natih and Fahud oil fields. An understanding of this succession is the purpose of this account.

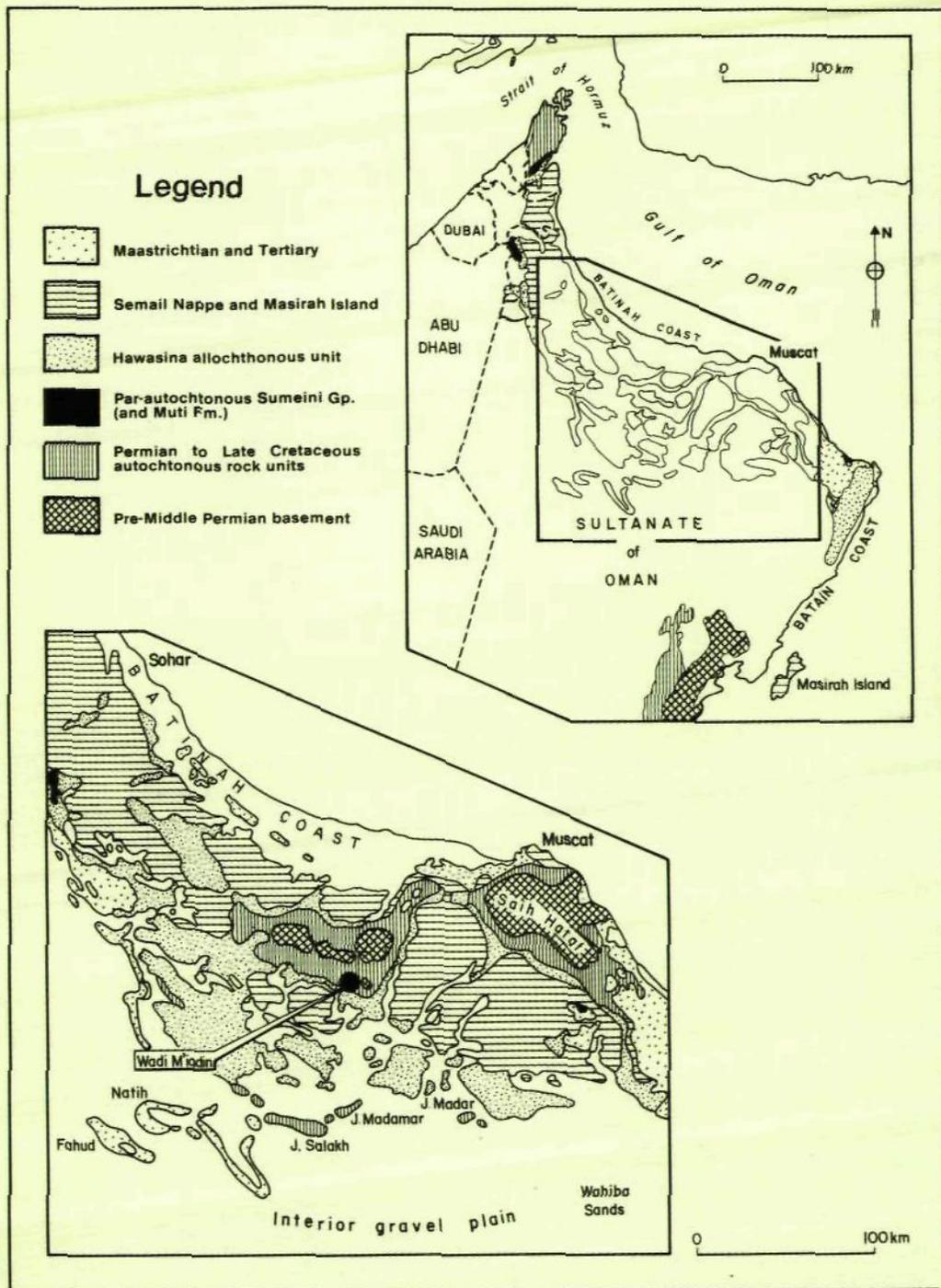


Fig. 10.1 — Location of the Oman Mountains with an enlargement of the area investigated by the authors. The Wadi Mi'adin section is indicated by ●, and the other sections that have been sampled are located at Jebel Madar, Jebel Salakh, Jebel Madamar, and the other wadis around Jebel Akhdar. Note the location of the Fahud and Natih oilfields. Modified after data presented in Glennie *et al.* (1974).

Wadi Mi'aidin cuts into the southern side of the Jebel Akhdar dome (see Figure 10.1) 15 km east of Nizwa and 10 km west of Izki. The wadi cuts through a number of rock types from Cambrian basement beds near its source, to allochthonous Hawasina Series sediments at its mouth. However, the wadi is noted for its exposures of Mesozoic autochthonous sediments of the Hajar Super-group, making it the most extensively studied locality in the Oman Mountains. Previously published descriptions of the section are given by Wilson (1969) and Glennie *et al.* (1974).

Although Early to mid-Cretaceous autochthonous carbonates are well exposed at other localities in the Oman Mountains and have been studied as part of our research, the succession at Wadi Mi'aidin forms a biostratigraphic reference section, which acts as the key to understanding the regional stratigraphy.

### GEOLOGICAL SETTING

The greater part of the Oman Mountains is formed by the outcrops of the Semail Ophiolite and the Hawasina Series. The main outcrops of the Mesozoic autochthonous succession can be seen in (from north to south-east) Musandam, Jebel Akhdar, and Saih Hatat. The latter two areas are presently exposed as a result of Early Neogene doming, probably as a response to halokinetic movements in the pre-Permian basement. Both these dome-like structures are on a very large scale, with the mountains of Jebel Akhdar almost attaining a height of 3000 m above sea level. Minor doming of the autochthonous succession is also seen along the southern edge of the Oman Mountains where only the very tops of the structures stand above the otherwise flat gravel plain. These features, at Jebel Madar, Jebel Salak, and Jebel Madamar are aligned with the major oil-producing structures of Fahud and Natih. These localities, and others around the Jebel Akhdar dome, have been studied as part of our overall research. This has shown that between Wadi Mi'aidin and other sections in the Oman Mountains area, there are subtle variations in the

thickness and facies types of the Early to mid-Cretaceous succession; notably a thinning and marked diachroneity of formations to the north.

The southernmost corner of Jebel Akhdar is flanked by hills of the Semail Ophiolite. At some localities the ophiolite and the underlying allochthonous Hawasina Series lie directly on the Early to mid-Cretaceous carbonates, whilst at others there is an intervening shale of Late Cretaceous age (the Aruma Group; Muti and Fiqa Formations). Emplacement of the allochthonous units is reportedly Campanian in age (Glennie *et al.* 1974), as overlying the ophiolite is a coarse pebbly sandstone of Maastrichtian age, followed by a succession of Cainozoic carbonates.

Early to mid-Cretaceous carbonates outcrop for 2–3 km along the floor of Wadi Mi'aidin (Figures 10.2–10.6). They are underlain by similar carbonates of the Jurassic Sahtan Group and unconformably overlain by deeper-water sediments of the Late Cretaceous Muti Formation.

The sediments which are the subject of this study range in age from basal Cretaceous to Cenomanian, and are lithostratigraphically grouped into the Thamama and Wasia Groups. These lie within the Hajar Super-group of Glennie *et al.* (1974). The succession is further subdivided into a number of formations (see Figure 10.6 for a summary of the lithostratigraphy and sedimentology). These formations are known not to be exact (time or lithological) equivalents to the same formations described elsewhere in the Middle East. The sequence is dominated by shallower-water carbonates which follow slightly deeper-water carbonates of earliest Cretaceous age.

A major disconformity separates the Thamama Group, which is earliest Cretaceous–Early Aptian in age, from the Wasia Group, which is Early/Middle Albian–Middle/Late Cenomanian in age. The two groups thus have separate microfossil assemblages and were deposited in separate but similar sedimentary environments. The Thamama and Wasia Groups therefore represent the first two

depositional cycles recognized by Harris *et al.* (1984) in the Cretaceous of the Arabian Peninsula.

The Thamama Group sediments at Wadi Mi'aidin represent the progradation of a carbonate ramp system. The type of environment of deposition envisaged is similar to the 'ramps with barrier ooid shoal complex' (type 'E') described by Read (1985). The distal slope of the ramp was downwarped in the Early Creta-

ceous to produce the somewhat deeper water sediments of the Rayda and Salil Formations. These pass into slope sediments and eventually the oolitic barrier shoal sediments of the Habshan Formation. Behind this barrier, bioclastic/pelloidal wackestones and packstones were deposited in very shallow lagoonal environments, now represented by the Lekhair, Kharaib, and Shuaiba Formations. The shallow, backshoal, nature of these formations is



Fig. 10.2 — Wadi Mi'aidin: The Thamama Group (Rayda-Shuaiba Formations) on the west side of the wadi.



Fig. 10.3 — Wadi Mi'aidin: Massively bedded limestones of the Shuaiba Formation overlying the thinly bedded limestones of the Kharab Formation.

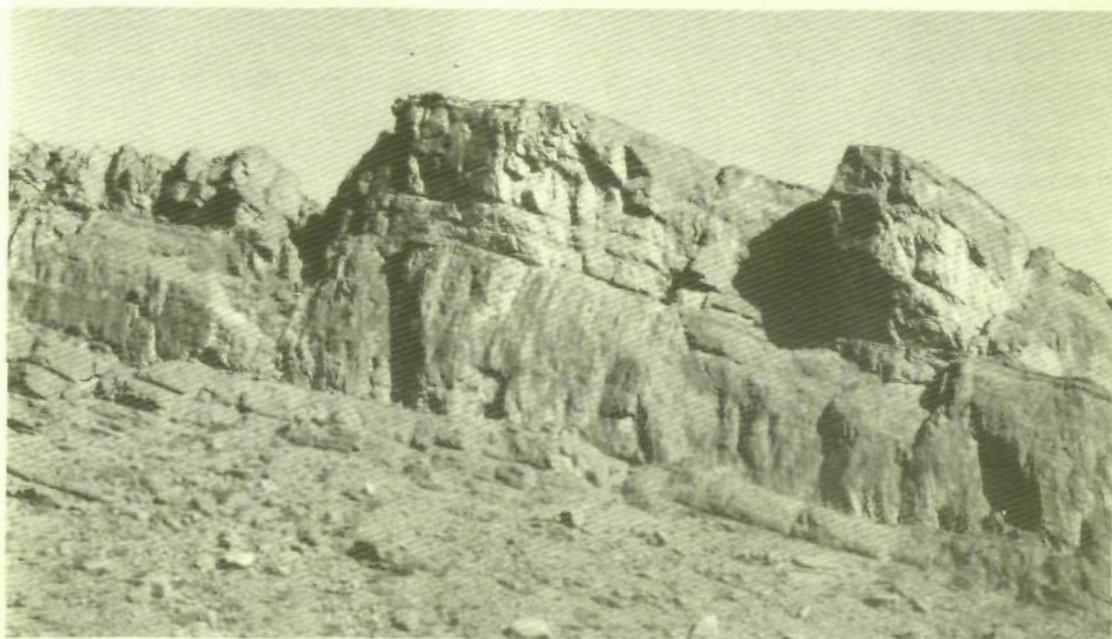


Fig. 10.4 — Wadi Mi'aidin: Massively bedded limestones of the Natih Formation overlying the scree-covered outcrop of the Nahr Umr Formation on the east side of the wadi.

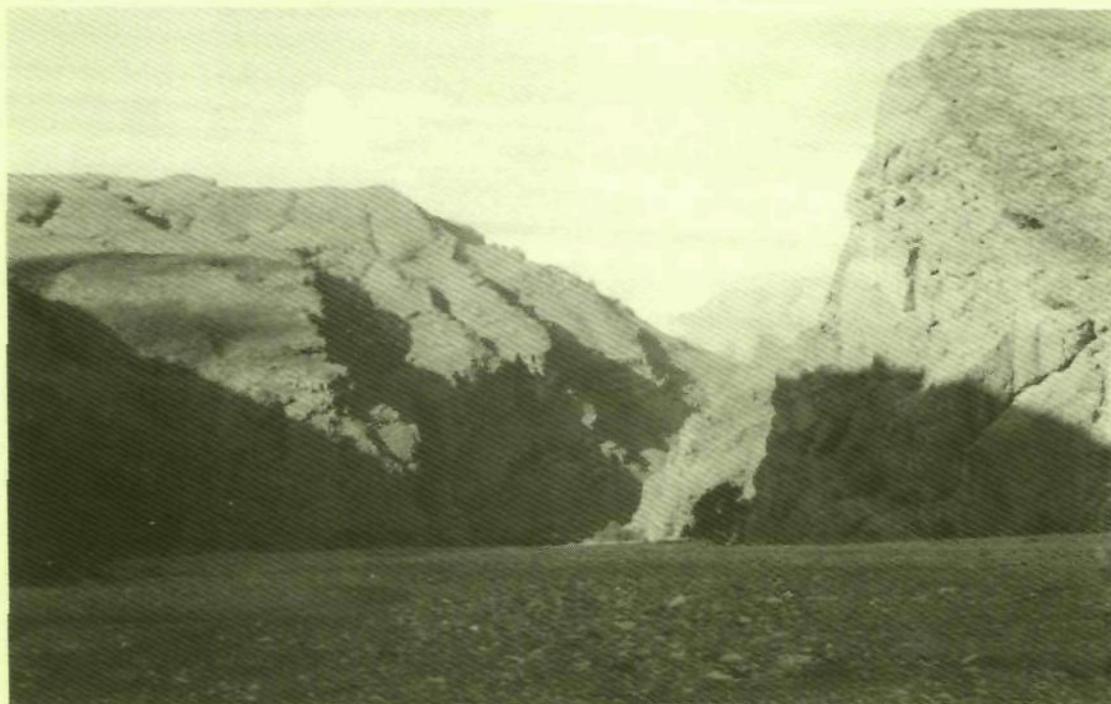


Fig. 10.5 — Wadi Mi'aidin: General view of the wadi looking north, with the Natih Formation in the foreground.

confirmed by the association of larger Foraminifera, dasyclad algae, and biostromes of *toucasid* and *monopleurid* ridists.

The Wasia Group may also represent deposition in a carbonate ramp environment. The Albian *Nahr Umr Formation* represents slow sedimentation on a shallow platform, with clastic input from the Arabo-Nubian shield. Reworking of the fine clastic sediments during storms developed many local hiatuses of short duration (Harris *et al.* 1984). The overlying Natih Formation represents deposition in the type of carbonate environment envisaged by Burchette & Britton (1985) for the deposition of the Mishrif Formation in Abu Dhabi. This model describes a carbonate platform rimmed by coarse bioclastic shoals or radiolitid rudist biostromes. Behind these, backshoal bioclastic packstones and platform lagoon benthonic foraminiferal mudstones develop. In front of the shoals/biostromes bioclastic slope deposits

occur, passing into planktonic foraminiferal wackestones within intrashelf basins. These facies are developed in the Natih Formation at Wadi Mi'aidin with the exception of the deeper-water planktonic foraminiferal wackestones. However, this facies can be seen at other localities in the Oman Mountains area, presumably where subsidence at the seaward margin of the ramp was greater.

At some localities to the south of Jebel Akhdar the uppermost Natih Formation consists of fine-grained lime mudstones/wackestones with planktonic Foraminifera and ammonites indicating deeper-water, open marine environments in the earliest Turonian. At Wadi Mi'aidin the youngest Natih Formation sediments are of Middle-?Late Cenomanian age. Therefore the deep-water sediments are not present, presumably removed in the erosion prior to the deposition of the Muti Formation.

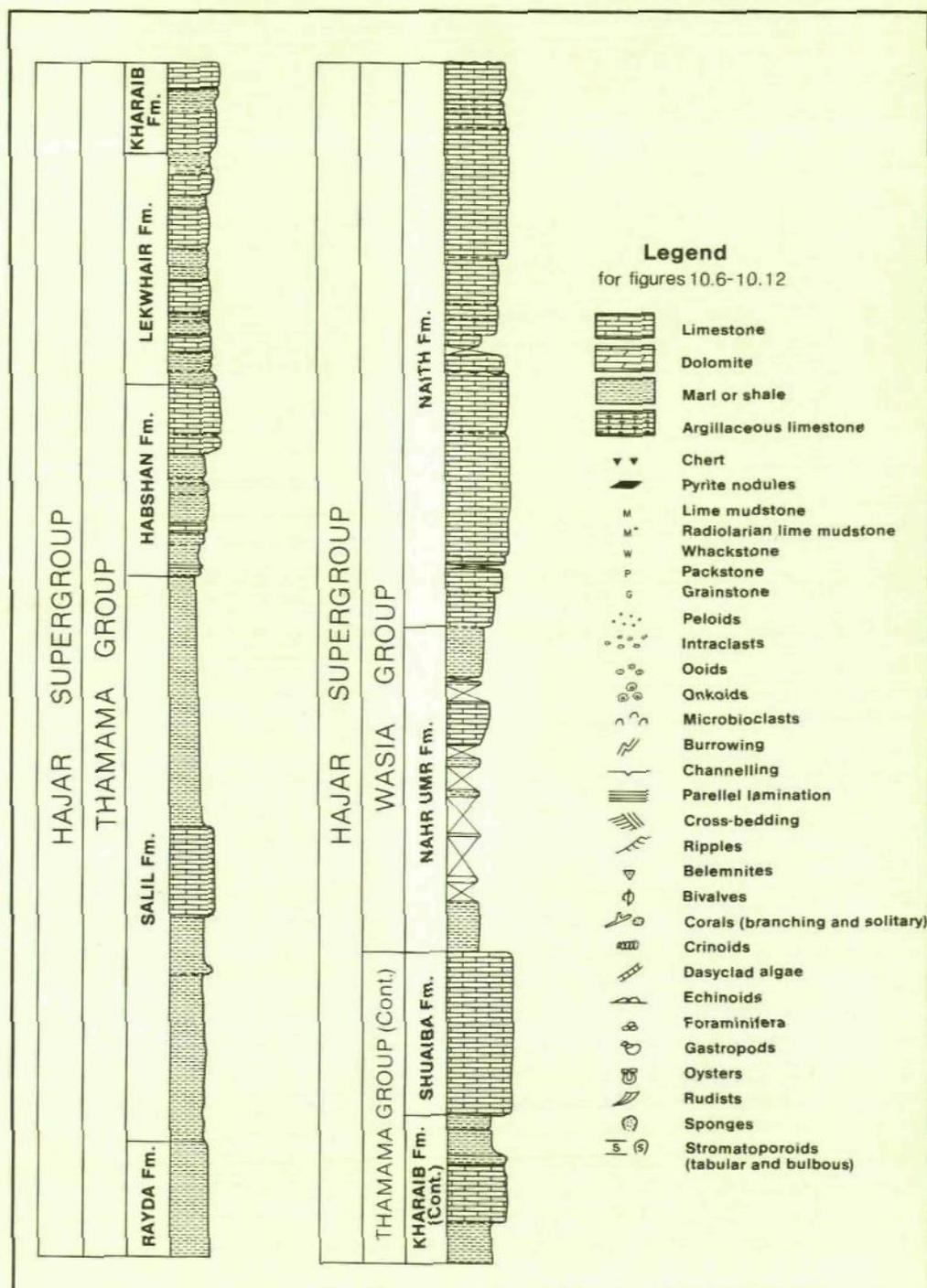


Fig. 10.6— Outline lithostratigraphy of the Wadi Mi'aidin succession. The thickness of this measured section is approximately 1500 m. Figures 10.6-10.12 are based on field data and drawn sections provided by Dr. J. D. Smewing.

## MICROFOSSIL ASSEMBLAGES

Despite relatively intense exploration by oil companies in the Middle East, there are few publications describing the Cretaceous biostratigraphy of this area. Important publications include Henson (1948), Sampo (1969), and El-Naggar & Al-Rifay (1972, 1973). Recently Harris *et al.* (1984) produced a micropalaeontological zonation scheme for the Cretaceous of the Arabian Peninsula.

Publications concerning the micropalaeontology of the Cretaceous rocks of the Oman Mountains are extremely scarce. Although Glennie *et al.* (1974) outlined the microfauna present in the autochthonous Cretaceous carbonates, they went into very little detail. Other publications on the geology of the Oman Mountains which mention some of the microfossils occurring in the rocks described here include Hudson & Chatton (1959) and Ricateau & Riche (1980).

The lack of publications on Cretaceous microfossil assemblages in the Middle East is unfortunate. This area thus remains almost unknown in terms of Tethyan palaeogeography, palaeoecology, and biostratigraphy. Correlation of the highly developed biostratigraphic schemes of Southern Europe (e.g. Neumann & Schroeder 1981 and Saint-Marc 1977) to the Middle East is required, and study of some of the endemic faunas is also needed.

The microfossil assemblages present in the Early to mid-Cretaceous carbonates of the Oman Mountains have strong similarities with those described from elsewhere within the Tethyan region, although diversity tends to be less than those of the 'Peri-Mediterranean' region. Strong comparisons can be drawn with the assemblages in the Urgonian limestones of Southern France, and the Cretaceous of Iberia and the Mediterranean area. Although each region does have endemic faunal elements, geographically widespread biostratigraphic correlation is possible.

The microfossil assemblages from Oman are very closely comparable to those described from Early to mid-Cretaceous sediments of

other parts of the Middle East, e.g. Iran (Sampo 1969), Kuwait (El-Naggar & Al-Rifay 1972, 1973), and Lebanon (Saint-Marc 1974, 1981, Basson & Edgell 1971).

The earliest Cretaceous part of the Thamama Group (Rayda and lower Salil Formations) contains a microfossil assemblage consisting of calpionellids, calcified radiolarians, sponge spicules, and rare planktonic Foraminifera. The upper part of the Salil Formation also contains rare planktonic Foraminifera, but with benthonic forms, presumably transported down the slope of the carbonate ramp. The Habshan-Shuaiba Formations contain a classic Early Cretaceous Tethyan microfauna and flora of orbitolinids, lituolids, cuneolinids, milliolids, and dasyclad and gymnocodioid algae. The mid-Cretaceous Wasia Group is dominated by orbitolinids in its lower part, but passes into assemblages also containing trocholinids, lituolids, and gymnocodioid algae. In the upper part of the Natih Formation alveolinids replace orbitolinids as the dominant foraminiferal component of the microfossil assemblage.

## MICROFACIES

The distribution of carbonate microfacies/microfossil assemblages within the Thamama and Wasia Groups is shown in Figures 10.7-10.9.

The microfacies present can be simplified into a number of associations. The associations present in each formation are as follows:

*Rayda Formation:* This formation consists of pelagic mudstones and wackestones, equivalent to standard microfacies 3 of Wilson (1975) and Flugel (1982). There are a variety of subfacies. The lower beds of the formation are micrites with common calcified radiolarians and some small benthonic and planktonic Foraminifera. Sponge spicules and echinoderm fragments are also present. There is often evidence for secondary partial dolomitisation. Some units are burrowed and contain less fauna. Overlying these units is a micrite with abundant calpionellids, echinoderm debris, and microbioclasts.

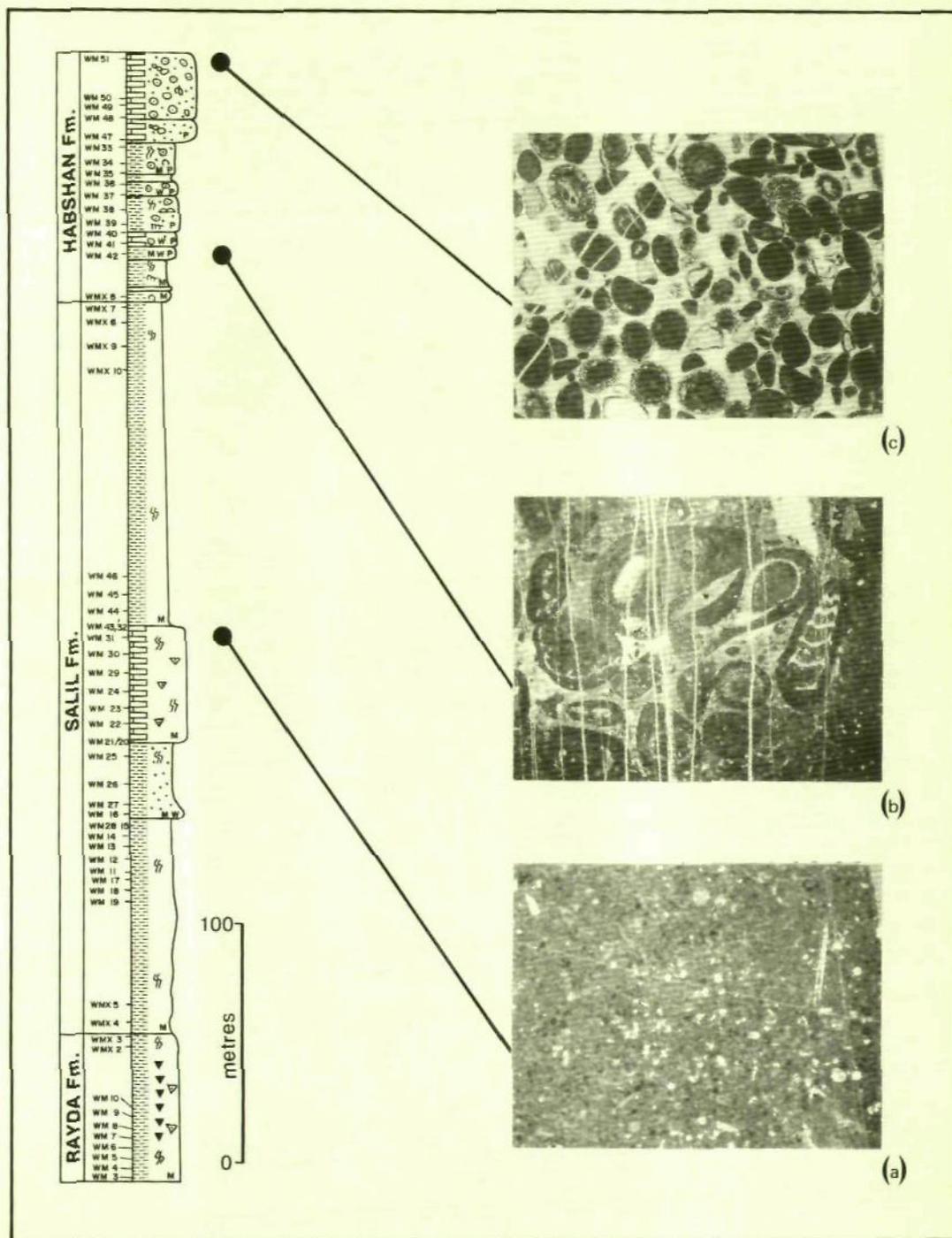


Fig. 10.7 — Representative microfacies seen in the Rayda, Salil, and Habshan Formations, Wadi Mi'aidin.

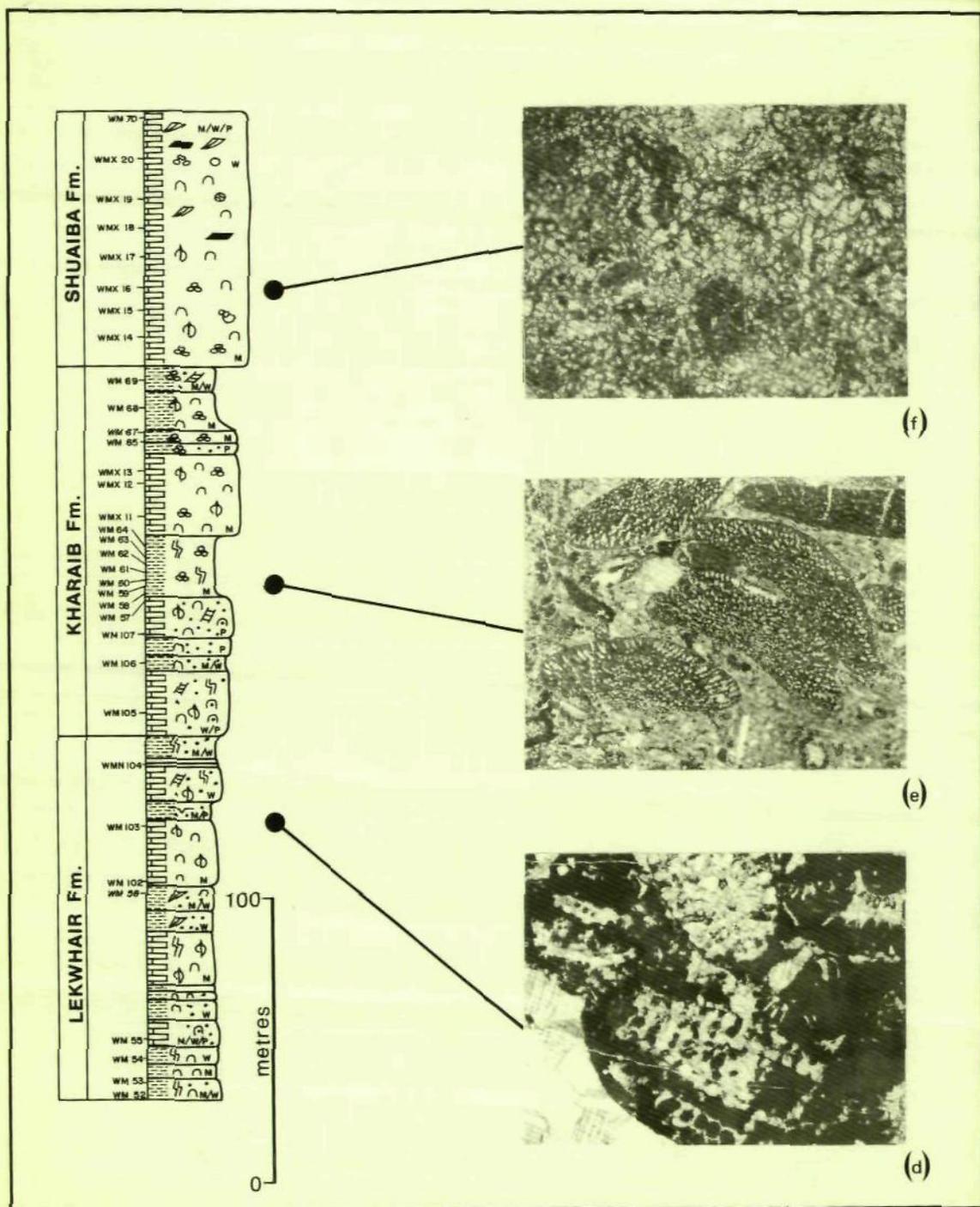


Fig. 10.8 — Representative microfacies seen in the Lekwhair, Kharab and Shuaiba Formations, Wadi Mi'aidin.

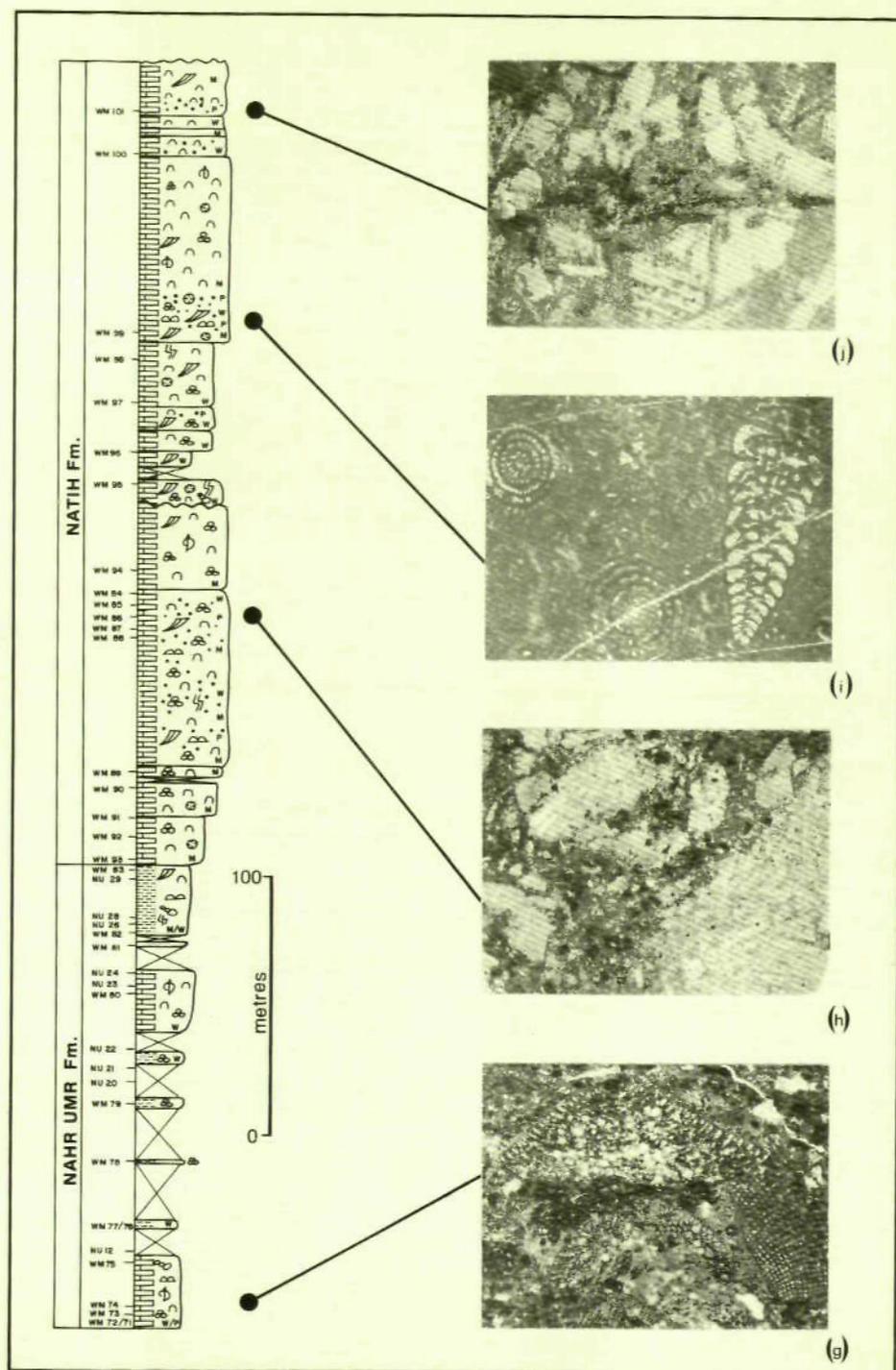


Fig. 10.9 — Representative microfacies seen in the Nahr Umr and Natih Formations, Wadi Mi'aidin.

The calpionellid wackestone is in turn overlain by micrites with varying abundances of microbioclasts. In the field this formation is characterised by the presence of cherts. Deposition of this formation is thought to have taken place at the deep shelf margin of the Thamama ramp.

**Salil Formation:** The greater part of this formation consists of pelagic mudstones and wackestones, with microbioclasts, calcified radiolaria, and rare planktonic Foraminifera. Burrowing is common, and burrow infills include faecal pellet grainstones and dolosparites. Some horizons contain quite abundant microbioclasts or are peloidal packstones. These units probably represent derived sediment from higher regions of the carbonate ramp slope. Some of the bioclasts can be recognised as fragments of shallow-water benthonic Foraminifera.

**Habshan Formation:** The lowest units of this formation are bioclastic wackestones with microbioclasts, lituolids, and large echinoderm and mollusc fragments.

The overlying units of this formation consist of high-energy deposits which indicate deposition of the flanks of, or within, the oolitic shoal which rimmed the margin of the Thamama ramp. A wide range of microfacies are represented. Carbonate microfacies present include highly burrowed peloidal packstones with abundant micritized dasyclad algae, *Bouenia* sp. and mollusc debris, and oolitic — peloidal packstones with micritized ooids, cortoids, and large echinoderm and mollusc fragments. Micritisation is very common in this formation, with micritised ooids and macrofossil fragments surrounded by micrite envelopes being abundant. This suggests a shallow-water environment of deposition. Superficial ooids are also common.

Faecal peloid grainstones are present, and these often contain cortoids, lituolids and echinoderm and mollusc fragments. Intraclasts and lithoclasts are also moderately common allochems in this formation. High-energy, shallow-water conditions of deposition are indicated for this formation.

The uppermost units of the Habshan Formation are oolitic grainstones (the ooids are usually partly micritised), ooid — peloid packstones/grainstones, and faecal peloid grainstones. Intraclasts, mollusc debris, and benthonic Foraminifera are rarer allochems. These units usually have a sparite cement, indicating that the original micritic matrix has been winnowed out. The oolitic units are equivalent to standard microfacies 15 of Wilson (1975) and Flugel (1982). Standard microfacies type 11 (grainstones with coated bioclasts in sparry cement) also occurs in the upper part of this formation. These microfacies suggest deposition in facies zone 6 of Wilson (1975) with winnowed platform edge sands and oolitic shoals — all areas with constant wave action, at or above wave base.

**Lekwhair Formation:** The microfacies present in this formation represent relatively quiet-water deposition in a back-shoal environment.

Bioclastic wackestones and packstones (standard microfacies 9 and 10 of Wilson (1975)) are dominant. These include burrowed micrites with mollusc debris and/or dasyclad algae. Micritisation of allochems is common. Burrows often have a dolosparite infilling.

Dasycladacean grainstones (standard microfacies 18 of Wilson (1975)) are a feature of this formation. They indicate very shallow environments of deposition, possibly in lagoon channels.

Another typical microfacies of this formation is that of micritic wackestones with highly fragmented gymnocodioid and dasyclad algal remains and some benthonic Foraminifera. This is the 'Algal Debris Facies' of the Middle East, first described by Elliott (1958).

**Kharab Formation:** Peloidal grainstones, algal — Foraminifera packstones, and orbitolinid packstones characterise the microfacies present in this formation. Algae are less common than in the Lekwhair Formation. Orbitolinid packstones often also contain lituolids and *Salpingoporella dinarica* Radoicic, and may be partially dolomitised. Burrowing is a common feature.

Within the orbitolinid packstones the orbitolinids are often micritised. Mollusc debris (notably oyster) is a quite common allochem.

This formation shows a large-scale cyclicity of microfacies; two bioclastic wackestones are underlain and overlain by orbitolinid packstones. Shallow back-shoal conditions of deposition are suggested, with the orbitolinid packstones perhaps deposited in broad lagoonal channels.

*Shuaiba Formation*: The lowest beds in this formation are *Bacinnella-Lithocodium* boundstones, overlain by packstones with *Bacinnella-Lithocodium* fragments, Foraminifera (including orbitolinids) and peloids. The upper part of the formation largely consists of faecal peloid packstones and grainstones with some Foraminifera (equivalent to standard microfacies 16 of Wilson (1975)). These units are usually burrowed. There are also thin interbedded *Bacinnella-Lithocodium* boundstones. *Bacinnella-Lithocodium* boundstones are known to be a typical feature of the lower part of the Shuaiba Formation of Abu Dhabi (Alsharhan 1985).

The highest beds of the Shuaiba Formation often contain rudist bivalve fragments and orbitolinids in peloidal packstones. The large mollusc fragments are often encrusted by algae. Deposition in low-energy, shallow-water conditions is suggested by these microfacies.

*Nahr Umr Formation*: The greater part of the Nahr Umr Formation consists of alternations between *Orbitolina* wackestones and packstones. The orbitolinids are often micritised and form up to 90% of the allochems present. Gymnodiacyd algae and lituolids are less common allochems. Thin mudstones often overlie the wackestones. There appear to be repeated fining-up sequences of packstone-wackestone-mudstone within this formation.

The uppermost units of the Nahr Umr Formation are bioclastic packstones with abundant mollusc debris (standard microfacies 12 of Wilson (1975)).

*Natih Formation*: The lowest units of this formation are burrowed bioclastic wackestones

with mollusc debris, Foraminifera especially *Orbitolina*, and gymnodiacyd algae. These are overlain by packstones with a similar microfaunal content and some peloids.

These units are in turn overlain by rudist packstones—floatstones (equivalent to standard microfacies 5 of Wilson (1975)) and peloidal-intraclast packstones. These sediments were deposited in high-energy conditions and can be compared to lithofacies association 3 of the Mishrif Formation of Abu Dhabi described by Burchette & Britton (1985). Deposition in a platform margin shoal environment in close proximity to a radiolitic rudist bioherm is suggested.

The sediments overlying the bioclastic shoal facies are alveolinid-chrysalidinid-mollusc debris wackestones, overlain by packstones and wackestones with alternating abundances of alveolinids, gymnodiacyd algae, and mollusc debris. These microfacies are similar to lithofacies association 6 of Burchette & Britton (1985) and represent deposition in a shallow, quiet-water platform lagoon environment.

In the upper part of the formation thin bioclastic packstones occur. These contain either abundant rudist fragments (as in the sediments below) or oyster shells. The rudist packstones probably represent periods when back-shoal skeletal sands were extended, as areas of intra-lagoonal biostromal growth occurred. This model of deposition has been proposed for similar rudist packstones in the platform lagoon facies of the Mishrif Formation of Abu Dhabi by Burchette & Britton (1985).

## BIOSTRATIGRAPHY

Figures 10.10–10.12 show the occurrence of selected microfossil species in the Early-mid-Cretaceous succession exposed at Wadi Mi'aidin. Plates 10.1–10.5 illustrate some of these forms.

The succession at Wadi Mi'aidin has been comprehensively sampled, with samples generally being taken at a maximum interval of 10 metres. At critical intervals sampling has been

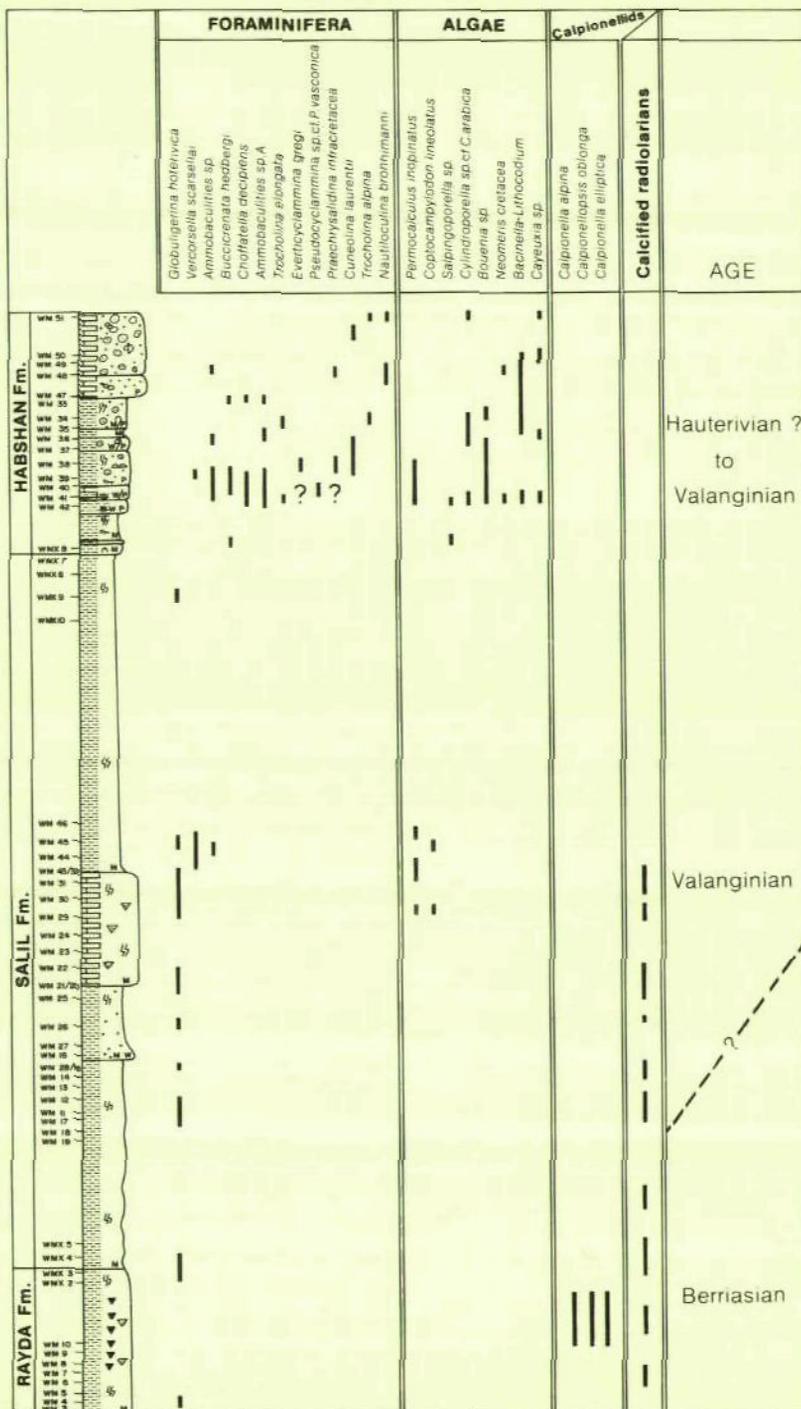


Fig. 10.10 — Distribution of selected taxa in the Rayda, Salil and Habshan Formations, Wadi Mi'aidin.

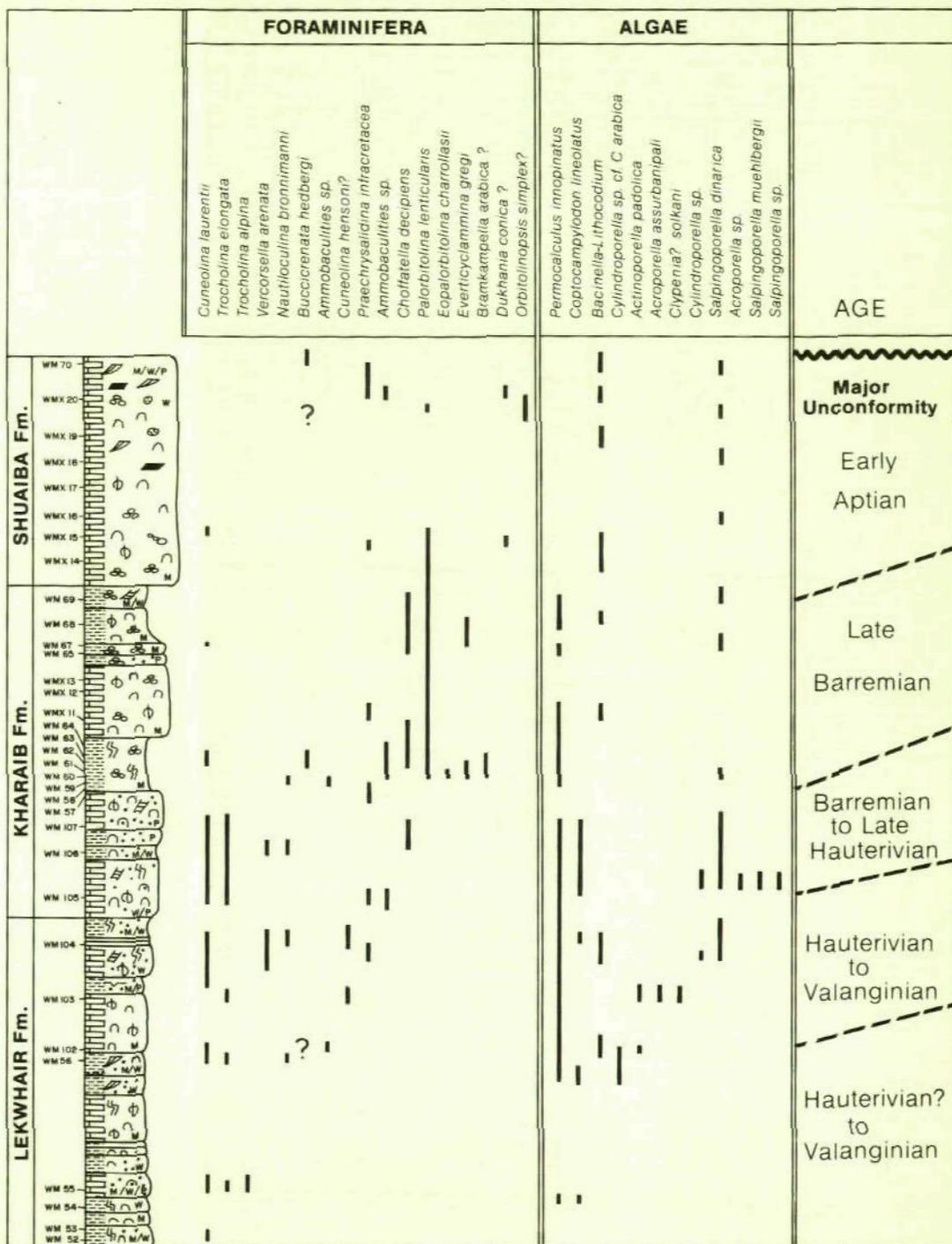


Fig. 10.11 — Distribution of selected taxa in the Lekwhair, Kharaib, and Shuaiba Formations, Wadi Mi'aidin.

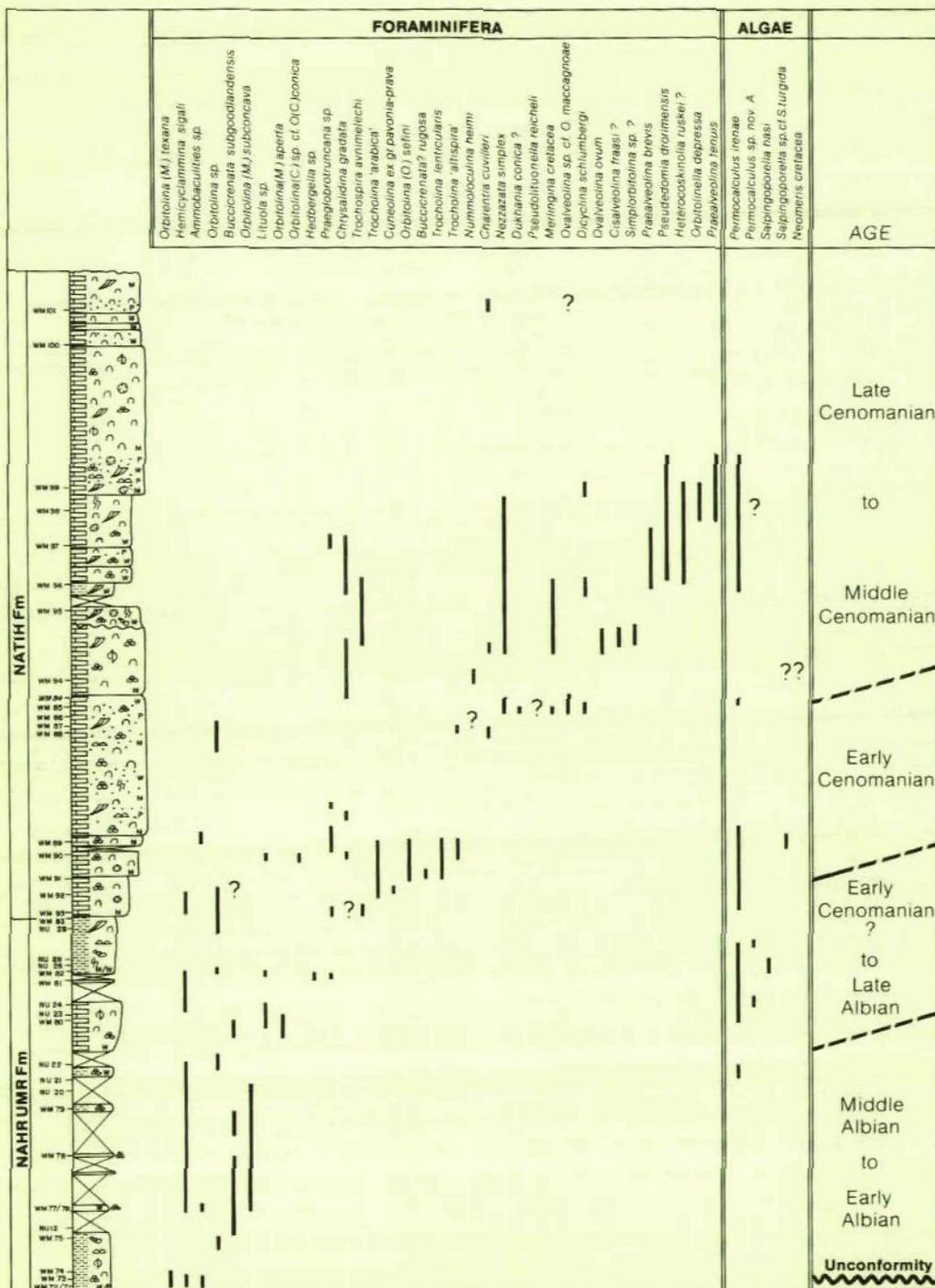


Fig. 10.12 — Distribution of selected taxa in the Nahr Umr and Natih Formations, Wadi Mi'aidin.

much more closely spaced. All the microfossils described here have been identified in thin-section.

No biozones are formally proposed for the Wadi Mi'aidin succession. It would be impracticable to do so for only one locality, since the lateral extent and significance of such biozones would remain unproven. However, it can be seen from the occurrence charts that a number of clearly recognisable assemblage zones and/or species range zones could be described; for example, a number of zones based on the range of orbitolinid species. Our studies of other exposures of Early to mid-Cretaceous carbonates in the Oman Mountains have shown that many of these biozones are of some lateral extent. Furthermore, many equate with zones described for other parts of the Middle East (e.g. Harris *et al.* 1984). However, studies of some of the assemblage zones have revealed that they have a marked diachroneity across the Oman Mountains area, particularly when compared to ages derived from the study of the rudist bivalve faunas (P. W. Skelton, *pers. comm.*).

Age subdivision of the Wadi Mi'aidin succession can be achieved fairly precisely by biostratigraphic means. However, age control on many of the species used to date the succession is derived from occurrences largely in the Mediterranean area. It may be shown eventually that the ranges of some of these species may differ for the Middle East. Until now age determinations of benthonic microfaunas and floras from the Middle East have been, at best, tentative, with there being little ammonite or other well established palaeontological age control.

The microfossil assemblage for each age interval recognised in the Wadi Mi'aidin succession is discussed below:

**Berriasian:** A Berriasian age is ascribed to sediments of the Rayda Formation, and questionably the lower part of the Salil Formation. A very age diagnostic calpionellid assemblage occurs within the Rayda Formation. In particular, the

presence of *Calpionella elliptica* Cadisch points to a 'mid' Berriasian age. This species is typical of calpionellid zone C ('mid' Berriasian) in the Western Alps (Remane 1971). Co-occurring with *C. elliptica* are *Calpionella alpina* Lorenz and *Calpionellopsis oblonga* (Cadisch). Also occurring in this interval are calcified radiolarians and planktonic Foraminifera which appear to be attributable to *Globuligerina hoterivica* (Subbotina).

**Valanginian:** A Valanginian age is ascribed to the middle and upper parts of the Salil Formation. Sediments of Valanginian age are first recognised in the sequence with the first occurrence of the algae *Percalculus inopinatus* Elliott and *Coptocampylodon lineolatus* Elliott, and the Foraminifera *Vercorsella scarsellai* (De Castro). Although the ranges of these species are poorly known they have not been recorded in Berriasian sediments. Also occurring in this interval are calcified radiolarians and *G. hoterivica*.

**Valanginian-?Hauterivian:** A Valanginian-questionably Hauterivian age is ascribed to sediments of the Habshan Formation and lower part of the Lekwhair Formation. Within parts of the Habshan and lower Lekwhair Formations there is a relatively great diversity of both Foraminifera and algae. However, none of the species present indicate a precise age. Two species present have conflicting ranges. *Neomeris cretacea* Steinmann has a range of Hauterivian-Danian (M. Conrad, *pers. comm.*), whilst *Cylindroporella arabica* Elliott has a Kimmeridgian-Valanginian range (Masse and Poignant 1971, Elliott 1968). The *Cylindroporella* species we describe as *C. sp. cf. C. arabica* is very similar to the original description of Elliott (1957). Other species present in this interval are quite long-ranging but many are known to occur in the Valanginian. On balance a Valanginian age is preferred, but a Hauterivian age cannot be discounted. The top of this interval is thus taken at the last occurrence of *C. sp. cf. C. arabica*.

Other significant algal occurrences are; *P. inopinatus*, *C. lineolatus*, *Bouenia* sp., the

encrusting codiacid (?) complex *Bacinella-Lithocodium*, and *Cayeuxia* sp.

Significant foraminiferal occurrences are those of *Buccicrenata hedbergi* (Maync), *Chofatella decipiens* Schlumberger, *Ammobaculites* sp. A, *Trochoina elongata* (Leupold), *T. alpina* (Leupold), *Everticyclammina gregi* (Henson), *Pseudocyclammina* sp. cf. *P. vasconica* Maync, *Praechrysalidina infracretacea* Luperto Sinni, *Cuneolina laurentii* Sartoni and Crescenti, and *Nautiloculina brönnimanni* Arnaud-Vanneau & Peybernes.

This microfossil assemblage is very similar to that described from sediments of Valanginian-Hauterivian age in southwest Iran by Sampo (1969).

**Valanginian-Hauterivian:** A Valanginian-Hauterivian age is ascribed to sediments of the upper part of the Lekwhair Formation. Considering the age of the overlying interval (Late Hauterivian-Early Barremian), it seems likely that at least part of this succession is of Early Hauterivian age.

Within this interval there is a fairly diverse microfossil assemblage similar to that of the underlying interval. However, the possible Valanginian indicator *C.* sp. cf. *C. arabica* is absent. None of the microfauna or flora shows positive evidence for a Hauterivian age, with most of the species being fairly long-ranging Early Cretaceous forms.

The most age diagnostic species occurring in this interval is the dasyclad algal *Acroporella assurbanipali* Elliott. According to Elliott (1968), this species is recorded from the Valanginian-Hauterivian of Iraq.

Other significant algal occurrences are *P. inopinatus*, *C. lineolatus*, *Bacinella-Lithocodium*, *Actinoporella podolica* Alth, *Clypenia? solkani* Conrad & Radiocic(?), and *Salpingoporella dinarica* Radioicic (= *Hensonella cylindrica* Elliott). The range of *S. dinarica* is thought to be Valanginian-Aptian (Elliott 1968).

Significant foraminiferal occurrences are *C. laurentii*, *T. elongata*, *Vercorsella arenata*

Arnaud-Vanneau, *N. brönnimani*, *Ammobaculites* sp. A, *Cuneolina hensoni* Dalbiez(?), and *P. infracretacea*.

**Late Hauterivian-Barremian:** A Late Hauterivian-Barremian age is ascribed to the lower part of the Kharab Formation. This interval contains a number of fairly long-ranging species, but an age younger than Barremian is precluded by the age of the overlying interval which is Late Barremian. The occurrence of the dasyclad alga *Salpingoporella muehlbergii* (Lorenz) indicates that this interval can be no older than Late Hauterivian (Conrad & Peybernes 1976, Bassoullet *et al.* 1978).

Other significant algal occurrences in this interval are *P. inopinatus*, *C. lineolatus*, *S. dinarica*, and also undetermined species of *Salpingoporella*.

Significant foraminiferal occurrences are *C. laurentii*, *T. elongata*, *V. arenata*, *N. brönnimani*, *P. infracretacea*, and *C. decipiens*.

**Late Barremian:** A Late Barremian age is ascribed to the upper part of the Kharab Formation, although probably not the uppermost beds.

The base of this interval is marked by the first appearance of orbitolinds in the sequence. The interval is characterised by the presence of 'primitive' forms of *Palorbitolina lenticularis* (Blumenbach). *P. lenticularis* has a range of Late Barremian-Early Aptian (Schroeder 1975). However, Gusic (1981) demonstrated that 'primitive' forms of *P. lenticularis* (i.e. those without peri-embryonic chamberlets) characterise the Late Barremian, whilst 'advanced' forms (those with peri-embryonic chamberlates) characterise the Early Aptian. It is therefore suggested that this interval with 'primitive' *P. lenticularis* can be assigned to a Late Barremian age.

Supportive evidence for this age determination comes from the occurrence of *Eopalorbitolina charrollasii* Schroeder & Conrad. This species has only been recorded from Late Barremian strata (Schroeder & Conrad 1967, Arnaud-Vanneau 1980). Until now this species

was thought to be endemic to the Western Alps (Moullade *et al.* 1985).

Other species occurrences do not conflict with the age assignation given. Other foraminiferal occurrences include *C. laurentii*, *N. brönnimani*, *B. hedbergi*, *Ammobaculites* sp. A., *P. infracretacea*, *C. decipiens*, and *E. gregi*. Forms somewhat similar to *Bramkampella arabica* Redmond also occur.

Significant algal occurrences are *P. inopinatus*, *Bacinella-Lithocodium*, and *S. dinarica*.

**Early Aptian:** An Early Aptian age is ascribed to the Shuaiba Formation and possibly the uppermost Kharab Formation.

This interval is characterised by the presence of 'advanced' forms of *P. lenticularis*. As stated above, these are typical of the Early Aptian. The actual base of this interval is difficult to define since transitional forms of *P. lenticularis* occur in the uppermost Kharab Formation. Certainly all the occurrences of *P. lenticularis* in the Shuaiba Formation are clearly advanced forms. The top of this interval is marked by an unconformity with the overlying Early-Middle Albian interval of the Nahr Umr Formation.

Other significant foraminiferal occurrences in this interval are *C. laurentii*, *B. hedbergi*, *N. brönnimani*?, *P. infracretacea*, *C. decipiens*, *E. gregi*, and forms similar to *Dukhanian conica* Henson and *Orbitolinopsis simplex* (Henson). *O. simplex* (= *Iraqia simplex*) is thought to be restricted to the Early Aptian (Moullade *et al.* 1985).

Significant algal occurrences are *S. dinarica* and *Bacinella-Lithocodium*.

**Early-Middle Albian:** An Early-Middle Albian age is ascribed to the lower part of the Nahr Umr Formation. The base of this interval is an unconformity with the underlying Shuaiba Formation of Early Aptian age.

The interval is characterised by the occurrence of two species of *Orbitolina*. These are *O. [Mesorbitolina] texana* (Roemer) and *O. (M.) subconca* Leymerie. Both these species range from the Late Aptian-Middle Albian

(Schroeder & Neumann 1985). However, their co-occurrence with *Hemicyclammina sigali* Maync in this interval demonstrates an Early-Middle Albian age. *H. sigali* has not been reported from strata older than Albian (Bengtson & Berthou 1982). The specimens of *O. (M.) texana* which occur at the base of this interval are fairly primitive and suggest an Early Albian age. They also have a large number of sponge spicules agglutinated to their tests (so called 'calcite eyes' (Douglass 1960)), which is a distinctive local feature.

Faunal diversity is very low in this interval. No algae occur, and the only significant foraminiferal occurrence other than those described above is that of *Buccicrenata subgoodlandensis* (Vanderpool).

**Late Albian:** A Late Albian age is ascribed to the upper part of the Nahr Umr Formation.

This interval has a relatively diverse fauna compared to the underlying interval. Significant foraminiferal occurrences are *H. sigali*, *B. subgoodlandensis*, *Orbitolina [Mesorbitolina] aperta* (Erman), *Hedbergella* sp., and *Praeglobotruncana* sp.,

Significant algal occurrences are *Permocalculus irenae* Elliott, *Permocalculus* sp. nov. A, and *Salpingoporella hasi* Conrad, Radoicic, & Rey.

*O. [M.] aperta* is not known from strata older than Late Albian (Schroeder & Neumann 1985). Also, no species of *Praeglobotruncana* are known older than Late Albian (Robaszynski & Caron 1979). The presence of *S. hasi* supports a Late Albian age determination. This species is known from the Late Albian-Early Cenomanian of Portugal and Yugoslavia (Conrad *et al.* 1976).

**Early Cenomanian:** An Early Cenomanian age is ascribed to the lower part of the Natih Formation.

This interval has a diverse fauna. Significant foraminiferal occurrences are *H. sigali*, *Praeglobotruncana* sp., *Chysalidina gradata* d'Orbigny, *Trochospira avnimelechi* Hamaoui & Saint-Marc, *Trocholina 'arabica'* Henson, *Tro-*

*cholina 'altispira'* Henson, *Trocholina lenticularis* Henson, *Cuneolina* ex gr. *pavonia* d'Orbigny, *Orbitolina (Orbitolina) seifini* Henson, *Buccicrenata? rugosa* (d'Orbigny), *Charentia cuvilleri* Neumann and *Orbitolina* sp. cf. *O. (Conicorbitolina) conica* (d'Archiac).

Significant algal occurrences are *P. irenae* and *Salpingoporella* sp. cf. *S. turgida* (Radoicic); Conrad, Praturon, & Radoicic.

Although some of the above forms are quite long-ranging, several are typically associated with Cenomanian strata (Saint-Marc 1981, Schroeder & Neumann 1985), giving the assemblage a Cenomanian aspect. *H. sigali* is not known from strata younger than Early Cenomanian (Bengtson & Berthou 1982).

The base of this interval is taken at the first appearance of *T. avnimelechi*, which is restricted to the Cenomanian (Schroeder & Neumann 1985).

*Middle-Late Cenomanian*: A Middle to Late Cenomanian age is ascribed to the middle and upper parts of the Natih Formation.

This interval is characterised by a very diverse fauna of Foraminifera. Some of the significant species present are *Praeglobotruncana* sp., *C. gradata*, *T. avnimelechi*, *Nummuloculina heimi* Bonet, *C. cuvilleri*, *Nezzazata simplex* Omara, *Merlingina cretacea* Hamaoui & Saint-Marc, *Ovalveolina* sp. cf. *O. maccagnoae* De Castro, *Dicyclina schlumbergeri* Munier-Chalmas, *Ovalveolina ovum* (d'Orbigny), *?Cisalveolina fraasi* (Gumbel), *Simplorbitolina* sp.?, *Praealveolina brevis* Reichel, *Pseudodominia drorimensis* Reiss, Hamaoui, & Ecker, *?Heteroskinolia ruskei* Saint-Marc, *Orbitolina depressa* Henson, and *Praealveolina tenuis* Reichel.

Algal occurrences include *P. irenae* and possibly *Permocalculus* sp. nov. A.

Several of the species present have a range restricted to the Middle-Late Cenomanian. These include *O. Ovum*, *P. brevis*, and *P. tenuis* (Schroeder & Neumann 1985). The assemblage present is very similar to that from the Middle-Late Cenomanian of Lebanon (Saint-Marc

1981) and from the Cenomanian of South West Iran (Sampo 1969).

The base of this interval is taken at the first appearance of *M. cretacea*, which has a Middle-Late Cenomanian range. The top of the interval is the top of the Wasia Group at this locality.

## CONCLUSIONS

The Early to mid-Cretaceous carbonate succession exposed at Wadi Miáidin represents deposition during the progradation of two separate carbonate platforms, to produce the Thammama and Wasia Group sediments. A varied number of microfacies are present, and these relate to depositional environments on the platforms, particularly the proximity and position with regard to barriers — either bioherms or oolitic shoals. Fore barrier, barrier, and back barrier microfacies can be recognised.

A large number of microfossil species have been recognised in the succession. These have allowed the sequence to be subdivided quite precisely, into age related intervals. The Thammama Group has been shown to be of Berriasian—Early Aptian age at this locality, whilst the Wasia Group has been shown to be of Early/Middle Albian—Middle/?Late Cenomanian age. A major unconformity separates these two lithostratigraphic units.

The microfossil assemblages present (Foraminifera, calcareous algae, and calpionellids) are similar to those described from other parts of Cretaceous Tethys, in particular the Mediterranean area and other sections described from the Middle East.

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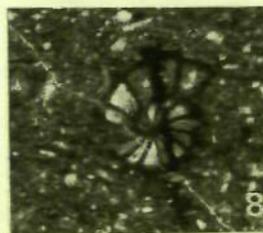
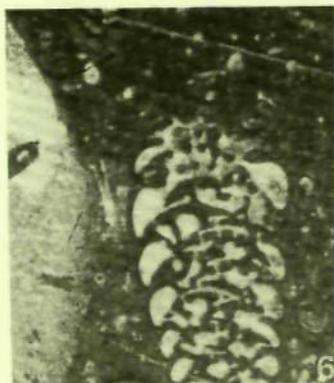
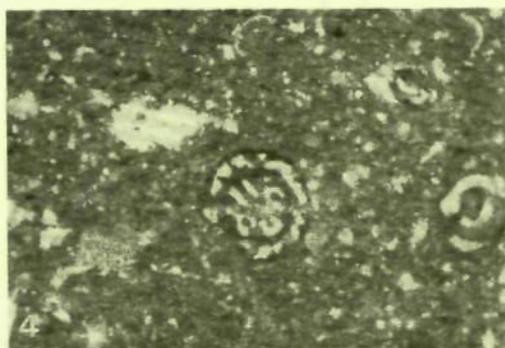
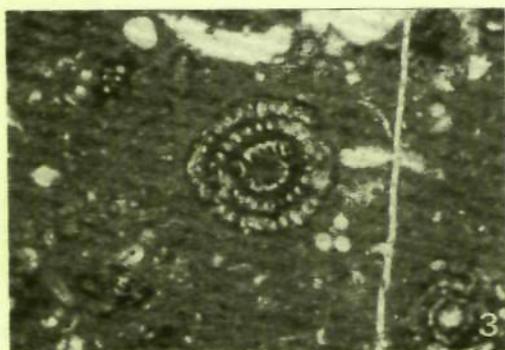
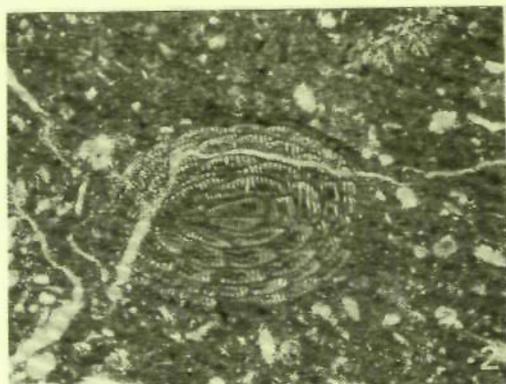
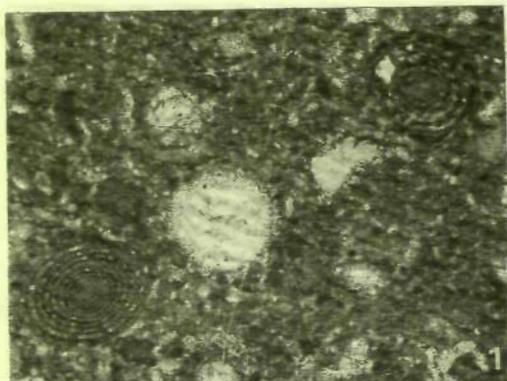
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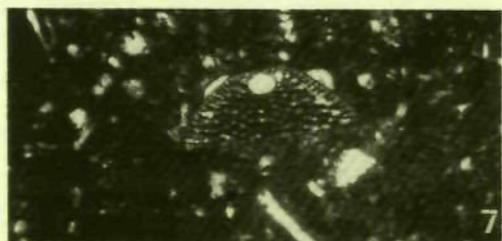
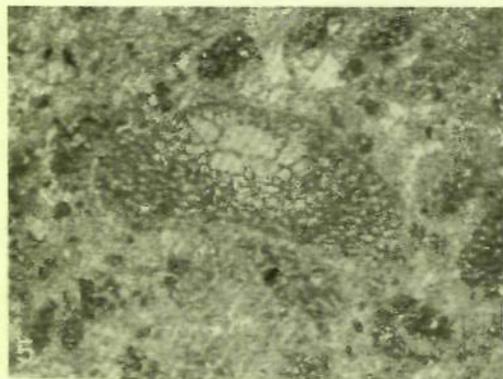
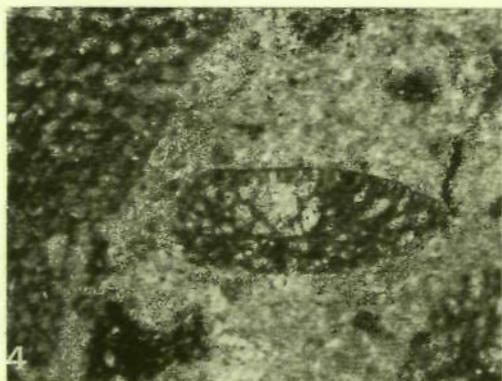
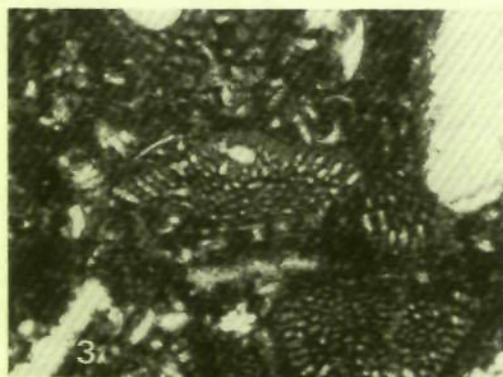
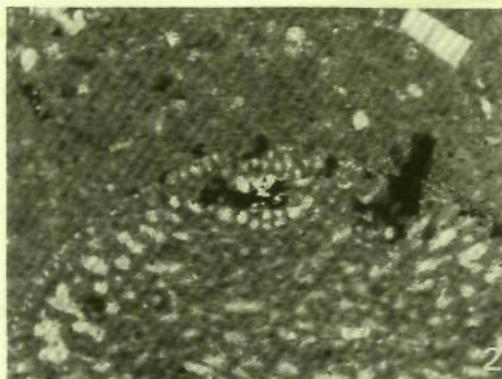
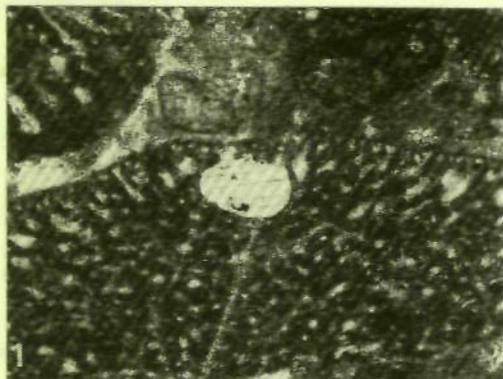
**Plate 10.1**

- Fig. 1 — *Pseudedomia drorimensis* Reiss, Hamaoui, & Ecker,  $\times 14$ , Natih Formation, Wadi Mi'aidin.  
Fig. 2 — *Praealveolina tenuis* Reichel,  $\times 14$ , Natih Formation, Wadi Mi'aidin.  
Fig. 3 — *Ovalveolina ovum* (d'Orbigny),  $\times 20$ , Natih Formation, Wadi Mi'aidin.  
Fig. 4 — *Ovalveolina* sp. cf. *O. maccagnoae* De Castro,  $\times 20$ , Natih Formation, Wadi Mi'aidin.  
Fig. 5 — *Praechrysalidina infracretacea* Luperto Sinni,  $\times 14$ , Habshan Formation, Wadi Mi'aidin.  
Fig. 6 — *Chrysalidina gradata* d'Orbigny,  $\times 14$ , Natih Formation, Wadi Mi'aidin.  
Fig. 7 — *Nautiloculina brönnimanni* Arnaud-Vanneau & Peybernes,  $\times 20$ , Habshan Formation, Wadi Mi'aidin.  
Fig. 8 — *Nezzazata simplex* Omara,  $\times 20$ , Natih Formation, Wadi Mi'aidin.



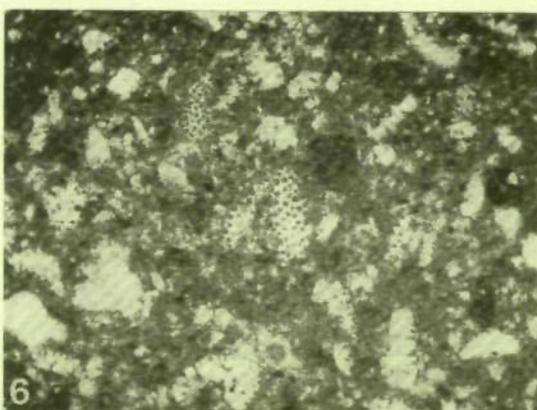
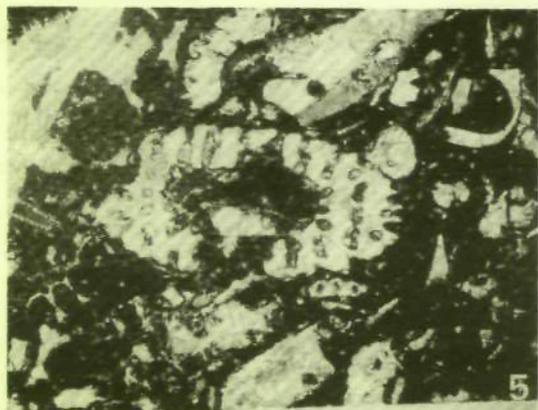
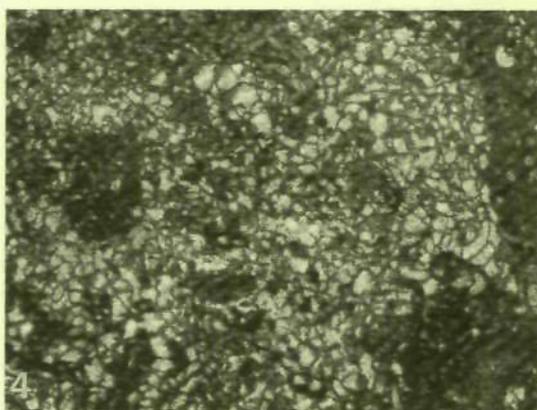
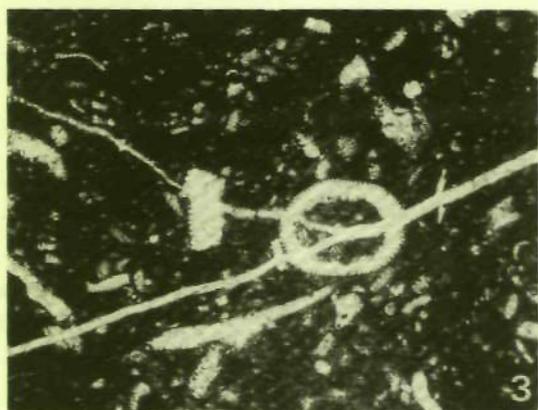
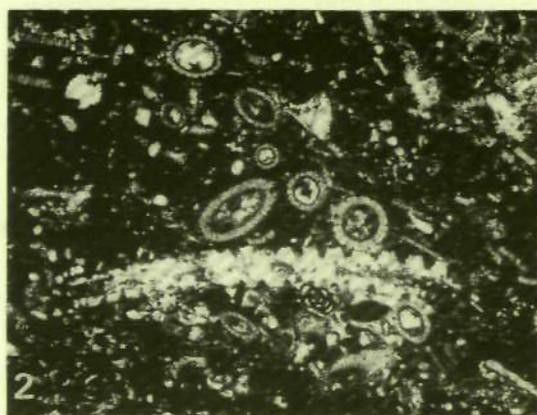
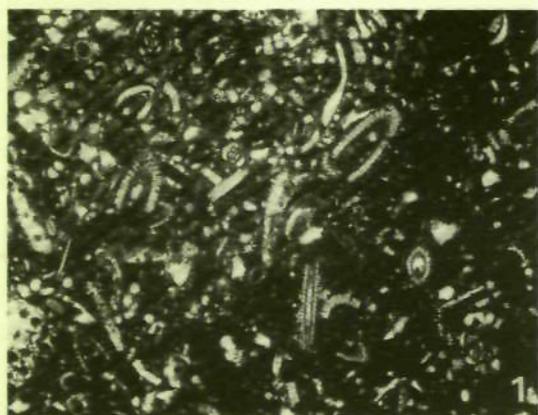
**Plate 10.2**

- Fig. 1 — *Palorbitolina lenticularis* (Blumenbach), ×55, Kharab Formation, Wadi Mi'aidin.  
Fig. 2 — *Orbitolina (Mesorbitolina) subconcava* Leymerie, ×55, Nahr Umr Formation, Wadi Mi'aidin.  
Fig. 3 — *Orbitolina (Orbitolina) sefini* Henson, ×20, Natih Formation, Wadi Mi'aidin.  
Fig. 4 — *Orbitolina (Mesorbitolina) texana* (Roemer), ×55, Nahr Umr Formation, Wadi Mi'aidin.  
Fig. 5 — *Orbitolina (Mesorbitolina) aperta* (Erman), ×20, Nahr Umr Formation, Wadi Mi'aidin.  
Fig. 6 — *Eopalorbitolina charrollasii* Schroeder & Conrad, ×55, Hanshan Formation, Wadi Mi'aidin.  
Fig. 7 — *Palorbitolina lenticularis* (Blumenbach), ×20, Kharab Formation, Wadi Mi'aidin.



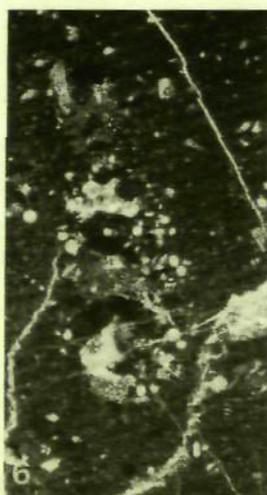
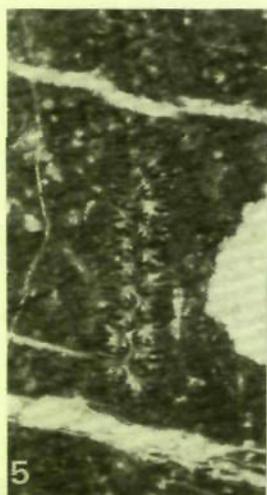
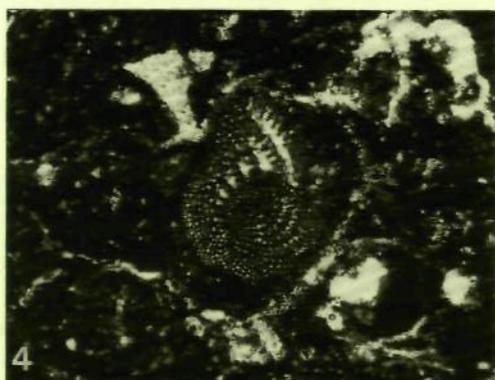
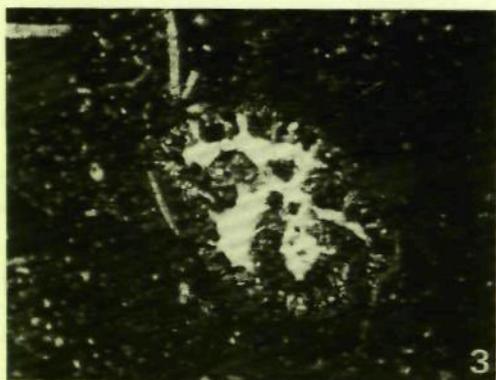
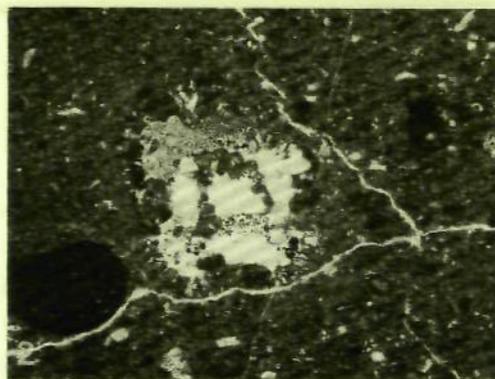
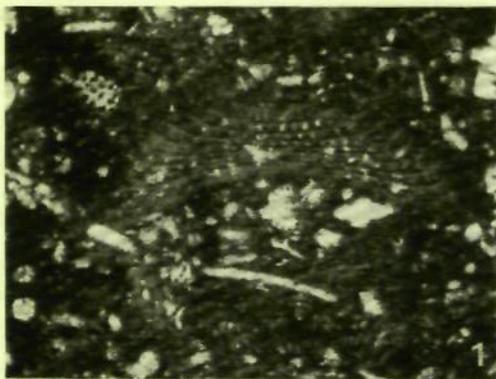
**Plate 10.3**

- Fig. 1 — *Salpingoporella dinarica* Radoicic, ×14, Lekwhair Formation, Wadi Mi'aidin.  
Fig. 2 — *Salpingoporella dinarica* Radoicic and *Salpingoporella muehlbergii* (Lorenz), ×14, Kharaiib Formation, Wadi Mi'aidin.  
Fig. 3 — *Permocalculus irenae* Elliott, ×14, Nahr Umr Formation, Wadi Mi'aidin.  
Fig. 4 — *Bacinella* — *Lithocodium*, ×14, Lekwhair Formation, Wadi Mi'aidin.  
Fig. 5 — *Acroporella assurbanipali* Elliott, ×14, Lekwhair Formation, Wadi Mi'aidin.  
Fig. 6 — *Permocalculus* sp. nov. A, ×20, Nahr Umr Formation, Wadi Mi'aidin.



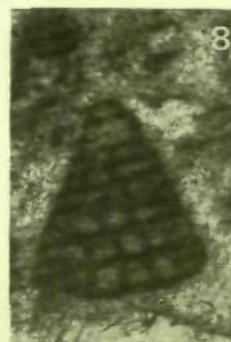
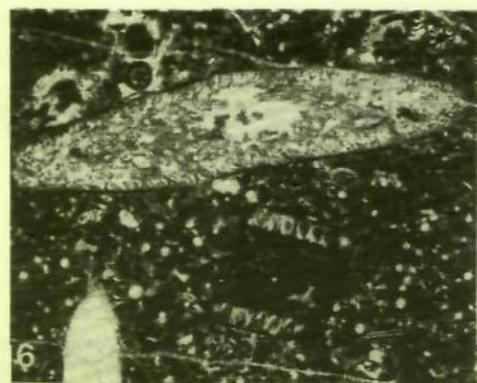
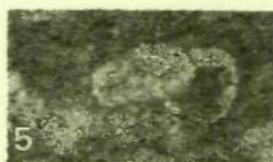
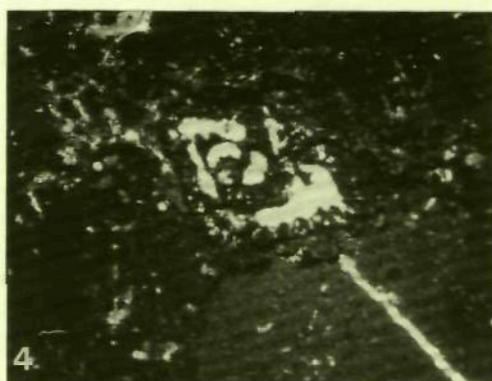
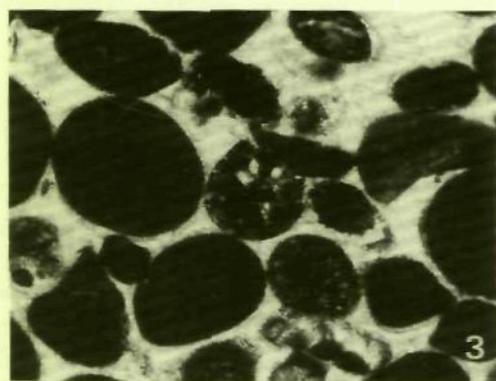
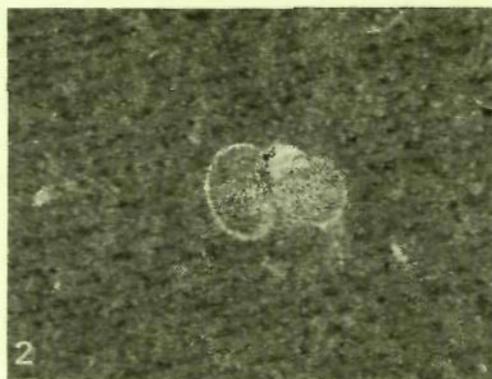
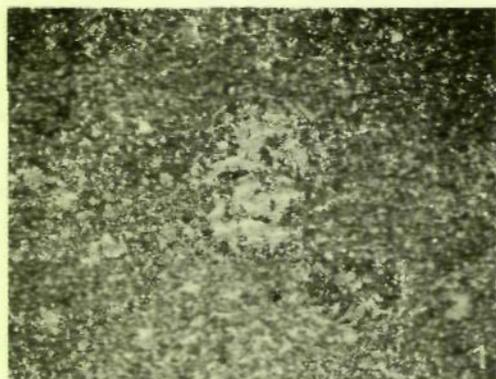
**Plate 10.4**

- Fig. 1 — *Orbitolinella depressa* Henson, ×20, Natih Formation, Wadi Mi'aidin.  
Fig. 2 — *Buccinrenata hedbergi* (Maync), ×20, Habshan Formation, Wadi Mi'aidin.  
Fig. 3 — *Buccinrenata hedbergi* (Maync) ×20, Habshan Formation, Wadi Mi'aidin.  
Fig. 4 — *Choffatella decipiens* Schlumberger, ×20, Kharai Formation, Wadi Mi'aidin.  
Fig. 5 — *Dicyclina schlumbergeri* Munier-Chalmas, ×20, Natih Formation, Wadi Mi'aidin.  
Fig. 6 — *Ammobaculites* sp., ×14, Lekwhair Formation, Wadi Mi'aidin.  
Fig. 7 — *Hemicyclammina sigali* Maync, ×20, Nahr Umr Formation, Wadi Mi'aidin.



## Plate 10.5

- Fig. 1 — *Buccicrenata subgoodlandensis* (Vanderpool), ×14, Nahr Umr Formation, Wadi Mi'aidin.  
Fig. 2 — *Globuligerina hoterivica* (Subbotina), ×55, Salil Formation, Wadi Mi'aidin.  
Fig. 3 — *Cyclindroporella* sp. cf. *C. arabica* Elliott, ×20, Habshan Formation, Wadi Mi'aidin.  
Fig. 4 — *Buccicrenata? rugosa* (d'Orbigny), ×14, Natih Formation, Wadi Mi'aidin.  
Fig. 5 — *Praeglobotruncana* sp., ×70, Nahr Umr Formation, Wadi Mi'aidin.  
Fig. 6 — *Neomeris cretacea* Steinmann and *Bouenia* sp. ×14, Habshan Formation, Wadi Mi'aidin.  
Fig. 7 — *Cuneolina laurentii* Sartoni & Crescenti, ×55, Lekwhair Formation, Wadi Mi'aidin.  
Fig. 8 — *Vercorsella arenata* Arnaud-Vanneau, ×100, Lekwhair Formation, Wadi Mi'aidin.



Cenomanian echinoids, larger foraminifera and calcareous algae from the Natih formation, central Oman Mountains

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Within the Natih Formation (late Albian-early Turonian) of the Oman Mountains, there occurs a distinctive, correlatable horizon with an abundant and moderately diverse echinoderm fauna. This horizon occurs within Member c of the Natih formation and can be assigned a latest middle Cenomanian age based on the associated microfossil assemblage which is dominated by alveolinids and gymnocodi-acian algae. The depositional environment of this echinoderm-rich bed was probably back barrier, close to radiolitic rudist biostromes and bioclastic shoals which fringed the upper Natih shelf edge. Nine species of echinoid are described, most of which are new records for the Arabian Peninsula. One new species, *Pedinopsis sphaerica*, is erected. *Coenolectypus larteti* dominates the assemblage and occurs together with *Stereocidaris sarracenarum*, *Tetragramma variolare*, *Heterodiadema lybica*, *Pedinopsis humei*, *P. desori*, *P. sphaerica*, *Hemiasper syriacus* and *H. cubicus*. The composition of the genus *Pedinopsis* is critically reviewed and a new subgenus, *Sinaiopsis*, erected. Many of the species have previously been reported from Egypt, the Sinai Peninsula and Israel.

KEY WORDS: Oman; Cenomanian; echinoids; foraminifera; algae; carbonate shelf.

### 1. Introduction

The Sultanate of Oman occupies the easternmost corner of the Arabian Peninsula. The Oman Mountains form a prominent arcuate range in the northern part of the country. The mountains largely comprise a sequence of thrust sheets, mainly of Mesozoic Tethyan marine sediments and volcanics (the Hawasina and Haybi complexes and the Sumeini Group), overlain by the Semail Ophiolite slab. These were emplaced during the Campanian onto an autochthonous sequence consisting of Precambrian to Cambrian basement overlain by Permian to Late Cretaceous sediments largely of shelf origin (the Hajar Super-group). Unconformably overlying the thrust sequence are marine Maastrichtian and Palaeogene sediments which today crop out mainly around the mountain flanks. The regional geology is further detailed in Glennie *et al.* (1974), Glennie (1977) and Hughes-Clarke (1988). Figure 1 presents a simplified geological map for the Oman Mountains region.

The autochthonous Cretaceous shelf sequence forming part of the Hajar Super-group, from which the studied fauna and flora were collected, crops out in four main areas (Figure 1); the Musandam Peninsula, the tectonic windows of Jebel Akhdar and Saih Hatat, and the isolated jebels to the south of the main mountain belt (i.e. Jebel Nahdah, Jebel Salak, Jebel Madamar and Jebel Madar). This paper describes a moderately diverse and well preserved Cenomanian echinoid fauna from a distinctive bed within the Natih Formation (the uppermost part of this autochthonous Cretaceous shelf sequence) which is known to occur on the southern side of Jebel Akhdar and at the jebels to the south of the main mountain belt. The majority of the macrofauna was collected from outcrops at the western end of Jebel Madamar (see Figures 2, 3).

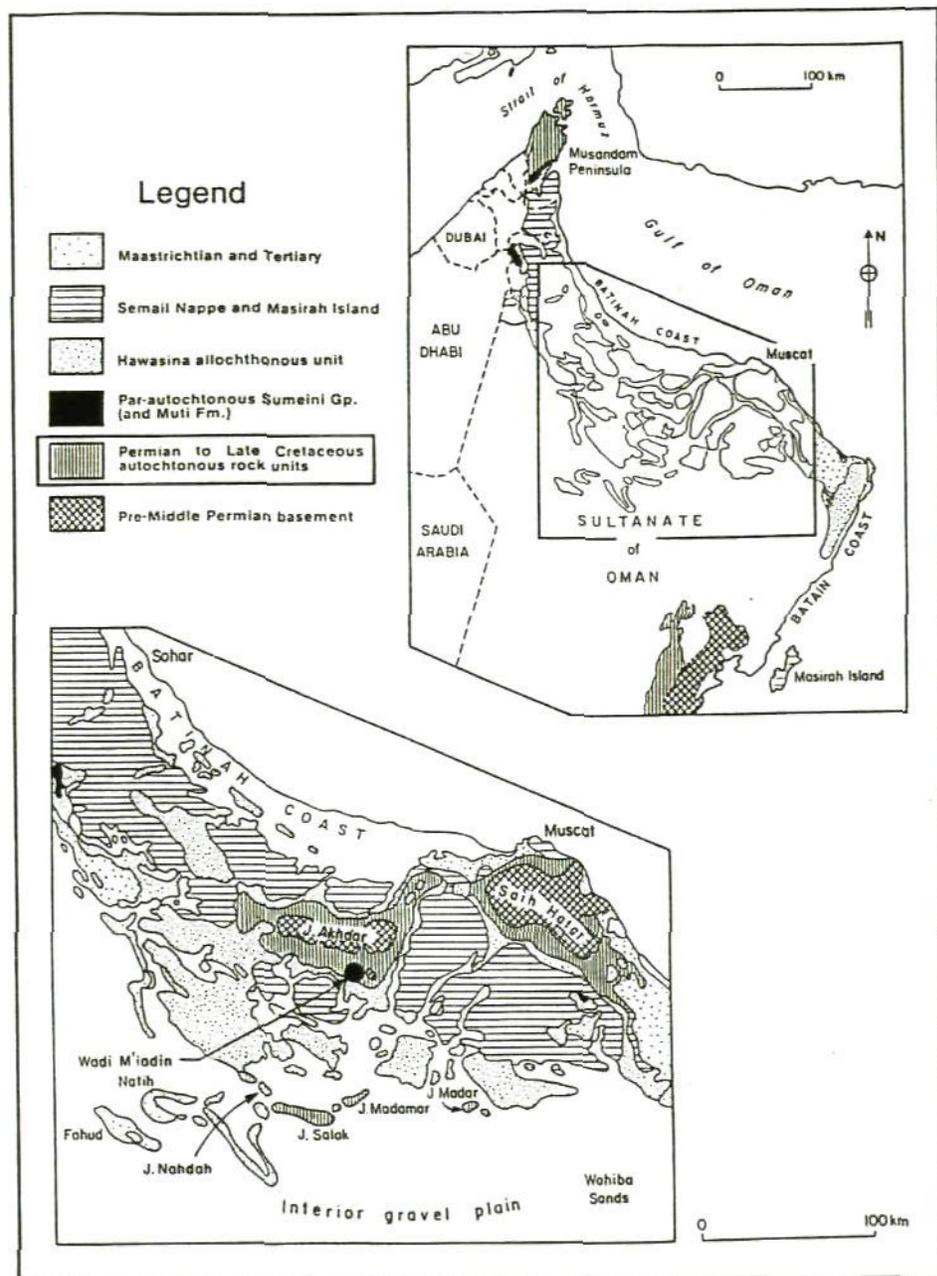


Figure 1. Simplified geological map of the Oman Mountains. The echinoid-rich horizon described in this paper occurs within the Permian to Late Cretaceous autochthonous sediments. The localities mentioned in the text are indicated. Figure modified from Simmons & Hart (1987).

Little has been published on the echinoid faunas of the Oman Mountains region and adjacent areas. Carter (1852) described Late Cretaceous sediments outcropping in the Hadramaut region of south-east Oman. Duncan (1865) described the echinoid fauna from these sediments which are largely of Cenomanian age. Duncan's determinations are in need of revision, but the fauna that he documented, now housed in the British Museum (Natural History), shares no species in common with

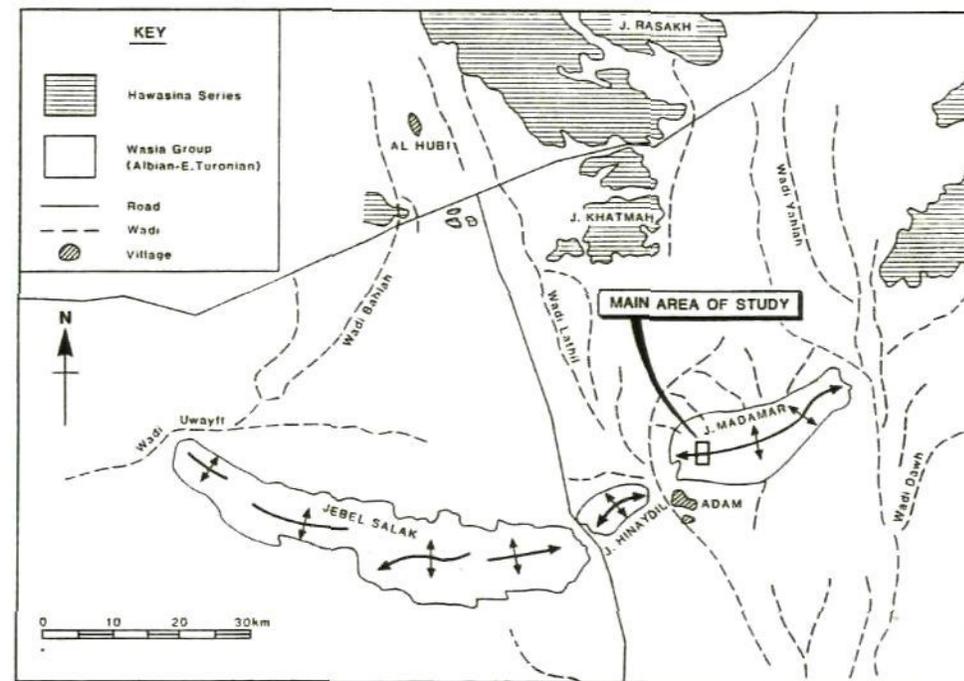


Figure 2. Map showing the location of the Jebel Salak and Jebel Madamar anticlines. The main source of the material described herein is from the western end of Jebel Madamar.



Figure 3. View of the Natih Formation at the western end of Jebel Madamar. The Echinoid Marker Bed is indicated by the letters 'EMB'.

the fauna described here and appears to be somewhat older. Lees (1928) described a few Campanian/Maastrichtian species from northern Oman and also listed *Salenia scutigera* Gray as present in Cenomanian beds in Dhofar. He also described a few Early Cretaceous species from northern Oman, including a new species, *Heteraster musandamensis*, from Aptian limestones of the Musandam Peninsula. Kuhn (1929), in his description of the palaeontology and stratigraphy of Oman, only listed the echinoid species described by Duncan (1865) from the Cenomanian of Hadramaut and mentioned a few other species from the Campanian/Maastrichtian. Clegg (1933) described echinoderms from the Cretaceous and Tertiary of the Persian Gulf (including Oman) collected by the Geological Survey of India. He described two species from unspecified levels in the Late? Cretaceous (almost certainly Campanian/Maastrichtian): *Holectypus khamirensis* from Khamir in Iran and *Pyrina arabica* from near Khalhat in Oman. A diverse Late Cretaceous echinoid fauna was described from southern Iran by Cotteau & Gauthier (1895) but this was almost entirely Campanian/Maastrichtian in age and only two possible Cenomanian species were recorded by them. Similarly, Kier (1972) described the Cretaceous echinoids from the Riyadh district of Saudi Arabia which consisted of a diverse Campanian/Maastrichtian echinoid fauna but no Cenomanian species. Ali (1989) has described an echinoid fauna of similar age from the United Arab Emirates. Roman *et al.* (1989) has recently published faunal lists of Cretaceous and Tertiary echinoids from the Dhofar region of southern Oman and discussed their biogeographical relationships. This includes fifteen Albian/Cenomanian species, but only three are common to the fauna described here.

There are few publications on the Cenomanian micropalaeontology of Oman. Glennie *et al.* (1974) outlined the microfauna present in the partly Cenomanian Wasia Group, but did not go into any detail. Simmons & Hart (1987) have produced one of the more detailed studies to date, describing the biostratigraphy and microfacies of the Early-Middle Cretaceous carbonates exposed at Wadi Mi'aidin, whilst Scott (in press) has described the chronostratigraphic setting for the entire Cretaceous of the Oman Mountains. There are more publications concerning the Cenomanian micropalaeontology of other regions of the Middle East. Those of importance to this study include Sampo (1969), Kalantari (1986; Iran), and Saint-Marc (1974, 1981; Lebanon).

## 2. Stratigraphic setting

The echinoid-bearing horizon that is the focus of this study occurs within the Natih Formation, which forms the upper part of the Wasia Group (Owen & Nasr, 1958) in the Oman Mountains region. This group is widely recognized throughout the Gulf region and represents the second major depositional cycle recognised by Harris *et al.* (1984) in the Cretaceous of the Arabian Peninsula. The Wasia Group contains numerous cycles of varying orders of magnitude, some at least being driven by eustatic sea-level changes (Scott, in press). The lower boundary of the Wasia Group (Figure 4) is marked by a major disconformity between limestones of the Shuaiba Formation (Kahmah Group), which in the Central Oman Mountains are early Aptian in age (Simmons & Hart, 1987; Scott, in press), and the shales and marls of the Nahr Umr Formation (Wasia Group), which are Albian in age (Simmons & Hart, 1987; Hughes-Clarke, 1988). The upper boundary of the Wasia Group (Figure 4) is marked by a hiatus between the mainly carbonate Natih Formation, which locally may be as young as earliest Turonian (Simmons & Hart, 1987; Scott,

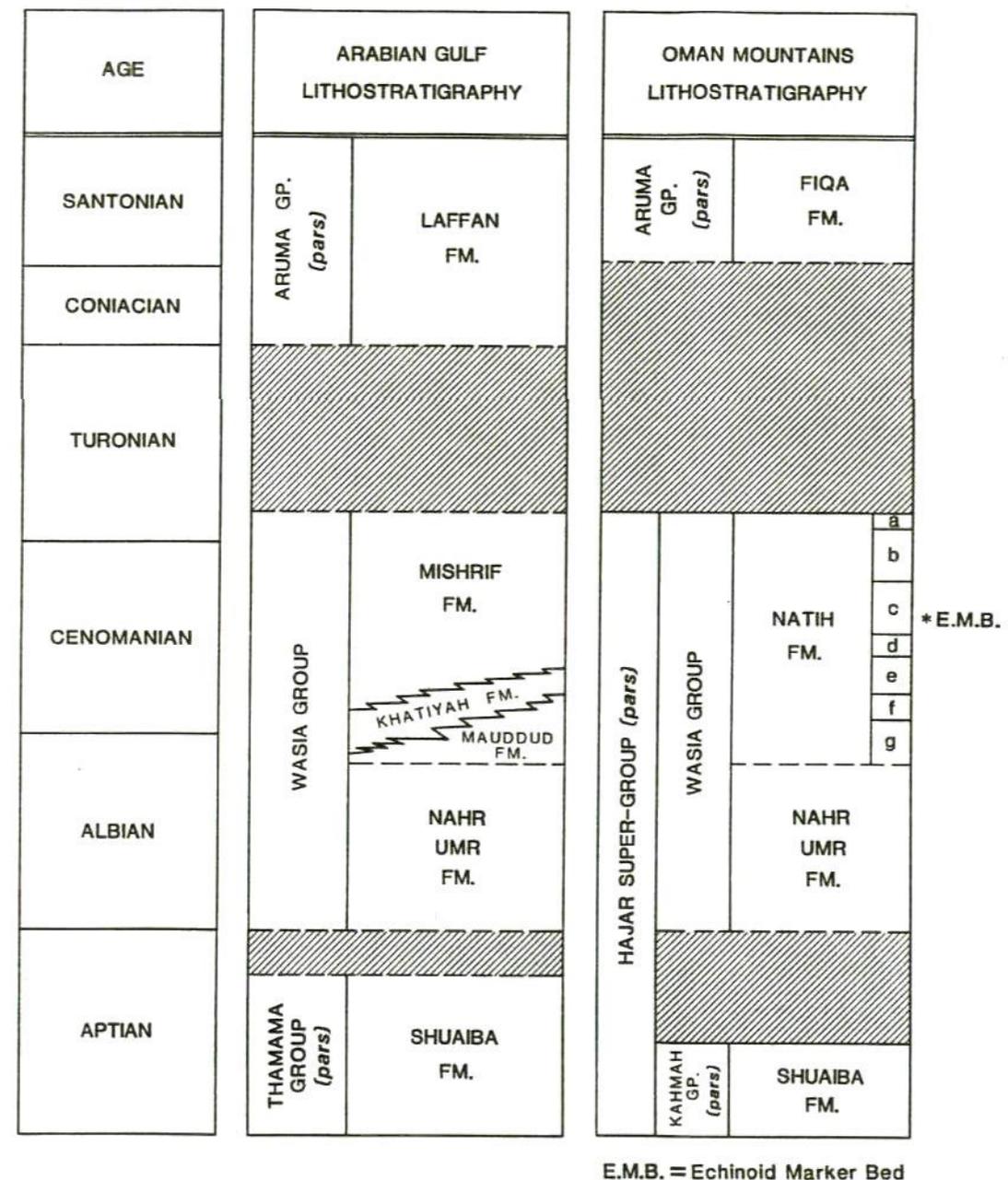


Figure 4. Lithostratigraphy of Aptian to Santonian sediments in the Arabian Gulf and Oman Mountains region.

in press; Kennedy & Simmons, in prep.) and the overlying shaly Fiqa Formation (Aruma Group), which is Santonian to Campanian in age (Hughes-Clarke, 1988). In Oman, the Wasia Group is thus divided into a lower argillaceous unit, the Nahr Umr Formation, and an upper carbonate unit, the Natih Formation. The contact between these two formations is transitional (Hughes-Clarke, 1988).

Type and reference sections of the Natih Formation were described by Hughes-Clarke (1988). The surface reference section at Wadi Mi'aidin on the southern side of Jebel Akhdar (see Figure 1) was the subject of a biostratigraphic and microfacies study by Simmons & Hart (1987). They concluded that at this locality the formation was? late Albian/early Cenomanian-late Cenomanian. To the south of this locality the formation may be as young as earliest Turonian (Simmons & Hart, 1987; Scott, in press; Kennedy & Simmons, in prep.), although this is disputed by Hughes-Clarke (1988) and others.

Tschopp (1967), in his original description of the Wasia Limestone Formation (= Natih Formation) in the subsurface of the Fahud oilfield, recognized seven members within the formation which he termed a to g. Some authors (e.g. Harris & Frost, 1984) have suggested that these members are not recognizable in the surface outcrop sections because of facies variations. However, Scott (in press) has shown that the seven-fold subdivision of the Natih Formation into members can be applied to the outcrop sections, and has redescribed the members in terms of the facies seen in the outcrops around and to the south of Jebel Akhdar. It would appear that the echinoderm-rich horizon forming the subject of this study occurs within Member c (Figure 4).

The Natih Formation is equivalent to the Mauddud, Khatiyah (or Shilaif) and Mishrif Formations identified in the Arabian Gulf region. However, precise correlation to these formations is problematic (Harris & Frost, 1984; Brennan, 1985, 1986; O'Connor & Patton, 1986; Hughes-Clarke, 1988; Alsharhan & Nairn, 1988) because of apparently diachronous and localized intrashelf basin deposits that accumulated during the Cenomanian-Turonian period in this region. The preferred correlation used in this study is shown on Figure 4. This shows that the Mauddud Formation correlates with Members g, f and e of the Natih Formation, whilst the Mishrif Formation correlates with Members d, c, b and a (see also Harris & Frost, 1984; Alsharhan & Nairn, 1988). A hardground surface is located at the top of Member e at several localities in the Oman Mountains which probably correlates with a regional disconformity between the Mishrif and Mauddud Formations, the boundary between two regionally recognized cycles of deposition; the Nahr Umr-Mauddud cycle and the Wara-Mishrif cycle (Alsharhan & Nairn, 1988). This disconformity can also be recognized in Oman by a marked break in isotopic signatures (Wagner, in press). The basinal Khatiyah Formation of Abu Dhabi is less easily correlated with the Oman Mountains sections. Scott (in press) has suggested correlation with a bituminous horizon in the lower part of Member e of the Natih Formation. There is some biostratigraphic support for this in that both the Khatiyah Formation of Abu Dhabi and the Member e of the Natih Formation contain the planktonic foraminifera *Favusella washitensis* Carsey, which ranges no higher stratigraphically than middle Cenomanian (Caron, 1985). Basinal sediments occurring higher in the Natih Formation (e.g. Member b) have no direct relative to the formations seen in Abu Dhabi. Member b of the Natih Formation contains a late Cenomanian-earliest Turonian planktonic foraminiferal assemblage (Simmons & Hart, 1987; Scott, in press; Kennedy & Simmons, in prep.) suggesting that it cannot be biostratigraphically correlated with the Khatiyah Formation of Abu Dhabi.

The Natih Formation thus consists of two separate cycles of deposition separated by a disconformity surface corresponding to the Mishrif-Mauddud boundary. The echinoderm-rich horizon lies within Member c of the Natih Formation which corresponds to a level within the Mishrif Formation of the Arabian Gulf region.

### 3. Microfossil assemblages and biostratigraphy

The echinoid-rich bed within Member c of the Natih Formation forms a distinctive horizon which can be correlated across much of the Central Oman Mountains. Field geologists operating in the region have termed it the "Echinoid Marker Bed". The lithofacies adjacent to this marker bed appear to be constant, and biostratigraphic studies demonstrate that the microfauna and flora associated with the horizon are similar at all localities where it was examined. Within the limits of biostratigraphic resolution the bed appears to be synchronous.

The Echinoid Marker Bed was noted at five localities during the course of this study: Wadi Mi'aidin, Jebel Nahdah, Jebel Salak, Jebel Madamar and Jebel Madar (see Figure 1). It probably occurs at other localities on the south side of Jebel Akhdar, but on the northern side of Jebel Akhdar, the upper part of the Natih Formation is absent, presumably a result of differential pre-Aruma Group erosion and the effects of local faulting, so the Echinoid Marker Bed does not occur. The majority of the echinoderm fauna described in the subsequent section of this paper is from Jebel Madamar, where the echinoids are most abundant and easily collected, whilst the microfossil assemblages were studied from all the localities mentioned above. There are only minor differences between the microfossil assemblages associated with the Echinoid Marker Bed recorded at all these localities. For the sake of brevity, the microfossil assemblages are considered as being from one composite section, a range chart for which is given as Figure 5.

The lower part of the Natih e Member occurs in two distinct lithofacies across the Central Oman Mountains. At some localities (e.g. Jebel Madamar) it occurs as a bituminous thinly bedded limestone, which in thin-section contains abundant planktonic foraminifera (*Favusella washitensis*, *Hedbergella delrioensis* (Carsey) and *Praeglobotruncana stephani* (Gandolfi)) and calcispheres (*Pithonella* spp.), together with locally reworked benthonic microfaunas. This indicates deposition in deep outer shelf conditions, corresponding to an arm of the Khatiyah intrashelf basin. At other localities (e.g. Wadi Mi'aidin) the lower part of Member e is a platform bioclastic limestone dominated by benthonic foraminifera, notably species of *Orbitolina*. In both facies, microfauna from the lower part of Member e suggests an early-middle Cenomanian age.

The upper part of Member e is developed in platform limestone facies across all the Central Oman Mountains. A fairly diverse microfauna is present together with the gymnocodiacean alga *Permocalculus irenae* Elliott (Figure 6l, m). Benthonic foraminifera present in this part of the succession include *Orbitolina conica* (d'Archiac), forms from the *Orbitolina sefimi-concava* plexus, rare *Trocholina arabica* Henson and *Trocholina altispira* Henson, *Dicyclina schlumbergeri* Munier-Chalmas, *Dukhania conica* Henson (Figure 6d), *Chrysalidina gradata* d'Orbigny, *Mayncina orbigny* (Cuvillier & Szakall), two distinctive new species of orbitolinid here referred to as Orbitolinid A (Figure 6i) and B (Figure 6j), and *Orbitolinella depressa* Henson (Figure 6h). *Nezzazata simplex* Omara (Figure 6f), *Merlingina cretacea* Hamaoui (Figure 6g), *Taberina bingistani* Hamaoui & Saint-Marc, *Trochospira avnimelechi* Hamaoui and *Biplanata peneropliformis* Hamaoui & Saint-Marc are present and occur in abundance together near the top of the member. Alveolinids also occur at the top of Member e: *Ovalveolina ovum* d'Orbigny, forms from the *Praealveolina cretacea-brevis* plexus, and a distinctive and often abundant new species of *Cisalveolina*, here referred to as *Cisalveolina* sp. A (Figure 6a). Questionable

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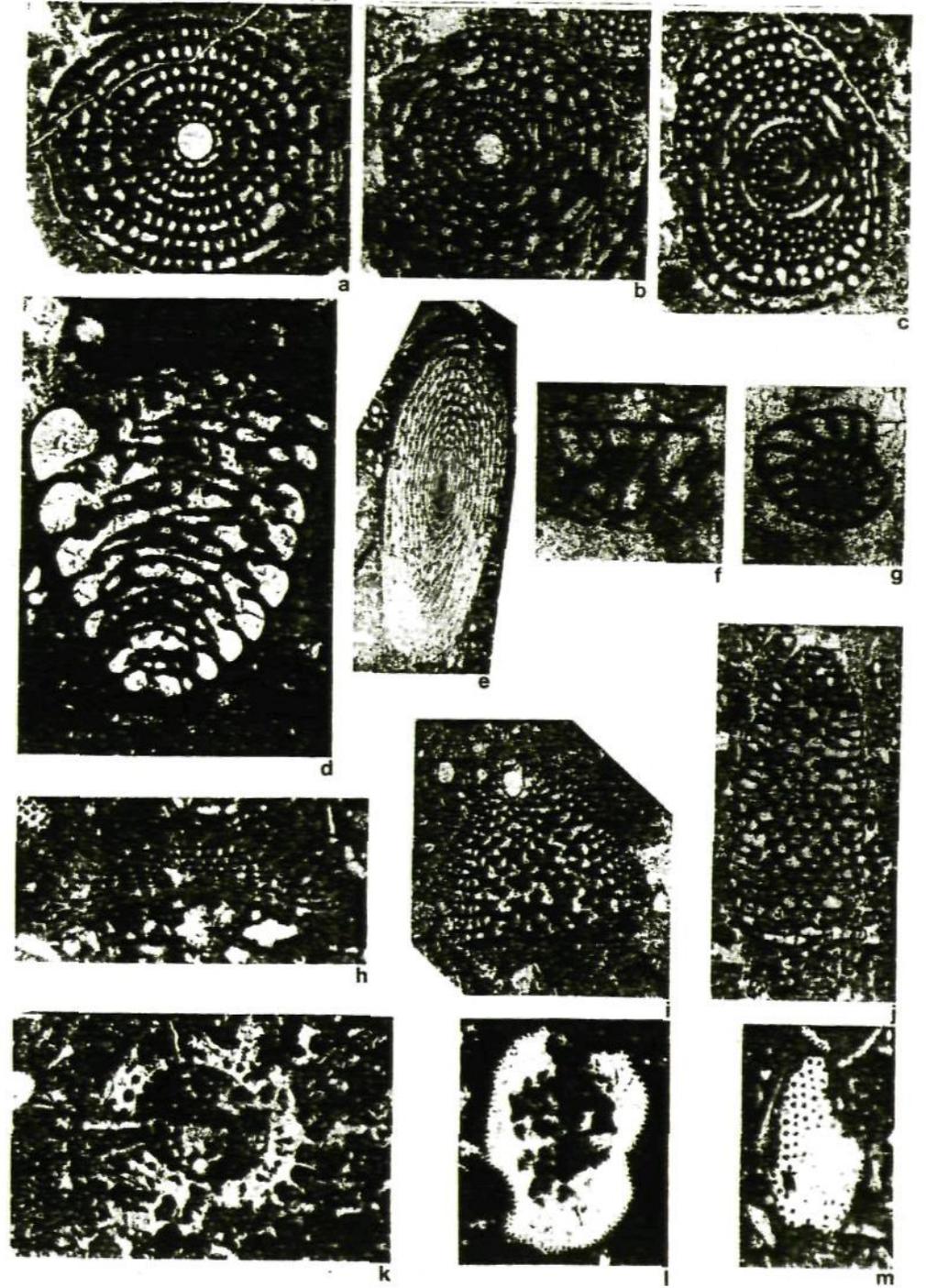
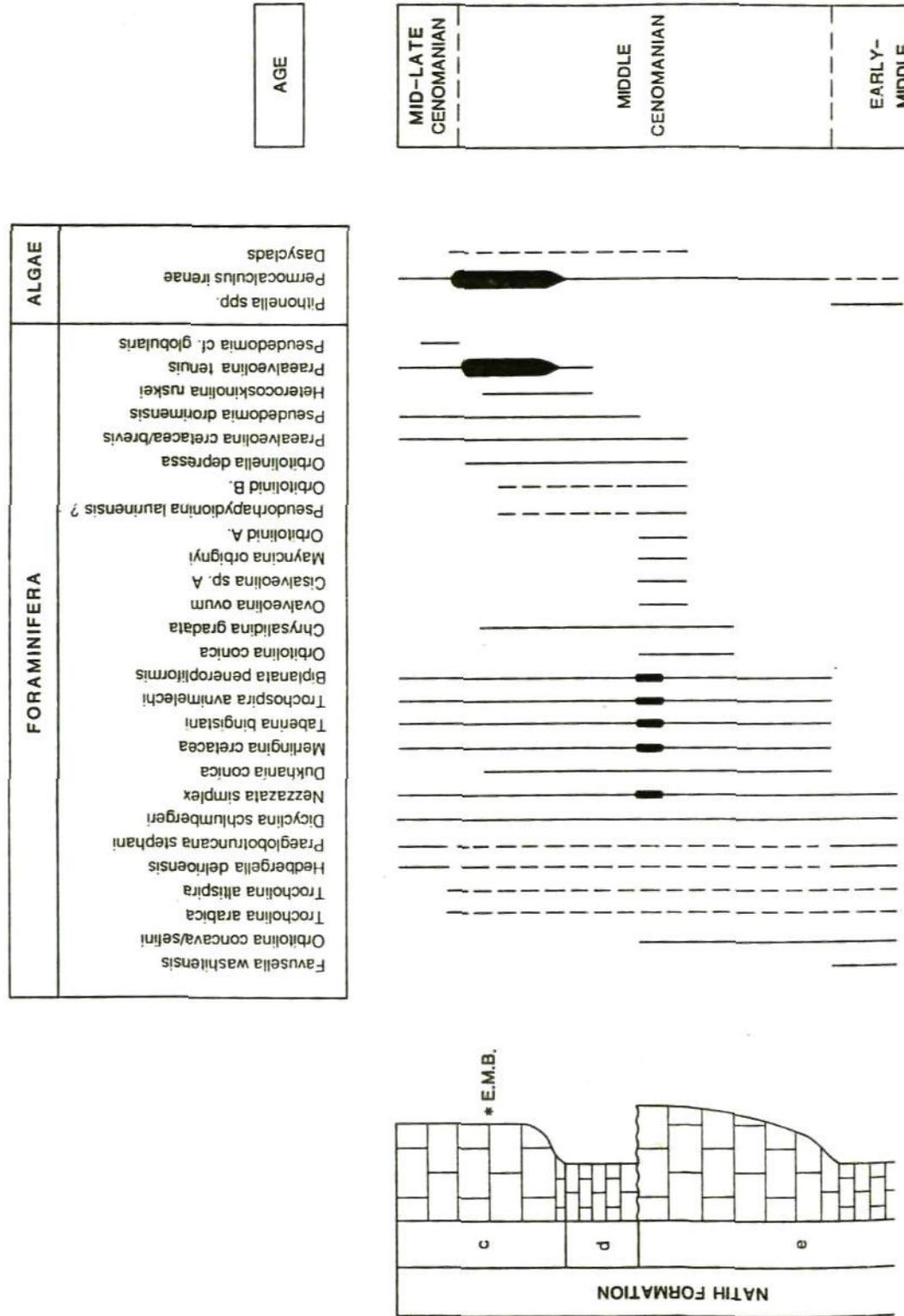


Figure 6. Foraminifera (a-j) and calcareous algae (k-m) from the Natih Formation, central Oman Mountains. a, *Cisalveolina* sp. A,  $\times 20$ . b, c, *Pseudodomia* cf. *globularis* Smout,  $\times 20$ . d, *Dukhanina conica* Henson,  $\times 20$  (possibly a transitional form to *Chrysalidina gradata*). e, *Praaevalveolina tenuis* Reichel,  $\times 5$ . f, *Nezzazata simplex* Omara,  $\times 20$ . g, *Merlingina cretacea* Hamouei,  $\times 20$ . h, *Orbitolinella depressa* Henson,  $\times 20$ . i, Orbitolid A,  $\times 20$ . j, Orbitolid B,  $\times 20$ . k, unidentified dasycladacean alga,  $\times 20$ . l, m, *Permolcalculus irenae* Elliott,  $\times 20$ .

specimens of *Pseudorhapydionina laurinensis* (De Castro) are also present. Unidentified dasycladacean algae (Figure 6k) occur in this part of the succession, but are rare.

The overlap of orbitolinids and alveolinids in the upper part of Member e forms a distinctive, correlatable horizon, which, considering the species involved, is indicative of middle Cenomanian age (Schroeder & Neumann, 1985). This is supported by the abundance of nezzazatid species, similar to the middle Cenomanian of Lebanon (Saint-Marc, 1981). The base of this clearly middle Cenomanian interval is taken at the first local inception of *Merlingina cretacea* which is known to range no older than middle Cenomanian (Schroeder & Neumann, 1985). The following species occurring within the upper part of Member e also have supposedly pan-Tethyan inceptions in the middle Cenomanian: *Ovalveolina ovum*, *Chrysalidina gradata*, *Praealveolina brevis/cretacea* and *Pseudorhapydionina laurinensis*, the latter species being virtually restricted to this sub-stage (Schroeder & Neuman, 1985). *Trocholina arabica*, *Trocholina altispira*, *Orbitolina sefini/concava* and *Orbitolina conica* range no higher than middle Cenomanian.

Although a major unconformity surface occurs at the top of Member e, there is no major change in the microfossil assemblages across this boundary, and the overlying unit (Member d) is also considered to be middle Cenomanian in age. Thus this non-deposition event was short-lived and probably corresponds to the so-called 'Mid-Cenomanian non-sequence' (Carter & Hart, 1977), which can be correlated across much of Tethys (Hart & Simmons, in prep.). This in turn may relate to the major intra-Cenomanian sea-level fluctuation and sequence boundary recognised by Haq *et al.* (1987).

The microfauna from Member d is broadly similar to that described from the upper part of member e. With the exception of the new taxon Orbitolinid B, no orbitolinids range up into Member d. Similarly *Ovalveolina ovum* and *Cisalveolina* sp. A do not range above the hardground at the top of Member e. However, *Praealveolina cretacea/brevis* is present as are *Chrysalidina gradata*, *Dukhanina conica*, *Orbitolinella depressa*, *Permocalculus irenae* and rare unidentified dasycladacean algae. Trocholinids are present, but are rare, whilst *Nezzazata simplex*, *Merlingina cretacea*, *Trochospira avnimelechi* and *Biplanata peneropliformis* are present, but are less common than in Member e. *Pseudedomia drorimensis* Reiss, Hamaoui & Ecker, *Heterocoskinolina ruskei* Saint-Marc and *Praealveolina tenuis* Reichel (Figure 6e) all have their local inceptions within Member d. At some localities *Hedbergella delrioensis* and *Praeglobotruncana stephani* are sporadically present.

The lower part of Member c, which contains the Echinoid Marker Bed, has a microfossil assemblage very similar to Member d. However, *Praealveolina tenuis* and *Permocalculus irenae* (and possibly some new species of *Permocalculus*) become extremely abundant, particularly within, and directly adjacent to the Echinoid Marker Bed. Most of the taxa described from Member d, range up to and occur within, and just above, the Echinoid Marker Bed, although they may be somewhat scarce. The presence of *Trocholina arabica*, *Trocholina altispira*, *Heterocoskinolina ruskei* and questionable specimens of *Pseudorhapydionina laurinensis* all indicate an age no younger than middle Cenomanian (Saint-Marc, 1978; Schroeder & Neumann, 1985). The overlap with *Praealveolina tenuis* indicates more specifically a latest middle Cenomanian age (Schroeder & Neumann, 1985). This is supported by the nature of the overall microfossil assemblage which is comparable to the middle Cenomanian of other parts of the Middle East (Sampo 1969; Saint-Marc, 1978, 1981; Kalantari, 1986). Additionally the echinoid fauna itself is indicative of a

middle Cenomanian age (see subsequent section), whilst at Jebel Salak, middle Cenomanian ammonites have been found some distance above the Echinoid Marker Bed (Kennedy & Simmons, in prep.). A latest middle Cenomanian age for the Echinoid Marker Bed is in agreement with the work of Scott (in press), who, by graphic correlation to European and Gulf Coast sections, places the middle-late Cenomanian boundary within Natih Member b.

Above the Echinoid Marker Bed, in the upper part of Member c, the microfossil assemblage decreases in abundance and diversity. *Hedbergella delrioensis* and *Praeglobotruncana stephani* are present, whilst *Dicyclina schlumbergeri*, *Nezzazata simplex*, *Merlingina cretacea*, *Taberina bingistani*, *Trochospira avnimelechi* and *Biplanata peneropliformis* occur but are not common. *Permocalculus* is present as are alveolinids; *Praealveolina tenuis*, *Praealveolina cretacea/brevis* together with *Pseudedomia drorimensis*. Of note is the presence of *Pseudedomia* cf. *globularis* Smout (Figure 6b, c). *Pseudedomia globularis* was originally described by Smout (1963) from the Campanian of Iraq. However, Hottinger (pers. comm., 1989) has evidence that *Pseudedomia globularis* was originally considered to be a Cenomanian species when first discovered by Iraq Petroleum Company biostratigraphers. The specimens noted here are very similar to the types, suggesting that further research is required to determine the true age range of this species. Overall the fauna from this part of the succession indicates a middle-late Cenomanian age (Saint-Marc, 1981; Schroeder & Neumann, 1985). No clearly middle Cenomanian species are present.

#### 4. Depositional environment

The Wasia Group was deposited on a carbonate ramp (*sensu* Read, 1985). The lower part, the Nahr Umr Formation, is believed to represent slow sedimentation on a shallow platform, with clastic input from the Arabo-Nubian shield (Harris *et al.*, 1984). The overlying Cenomanian Natih Formation represents deposition on a carbonate platform rimmed by coarse bioclastic shoals or radiolited rudist biostromes (Simmons & Hart, 1987; Skelton & Simmons, in prep.). Landwards from these barriers there was a platform lagoon with benthonic foraminiferal mudstones, whilst oceanwards the shoals passed into bioclastic slope deposits and then into planktonic foraminiferal intrashelf, basinal wackestones (Glennie *et al.*, 1974; Harris *et al.*, 1984; Simmons & Hart, 1987).

The upper part of the Natih Formation (containing the echinoid bed) comprises alveolinid-molluscan-algal debris wackestones which are overlain by packstones and wackestones with varying abundances of algae, alveolinids, and molluscan and echinoderm debris. Rudist biostromes associated with bioclastic shoals are also locally developed. In the upper part of the formation at localities to the south of the main mountain belt, pelagic wackestones and packstones are developed with abundant calcispheres and planktonic foraminifera. Simmons & Hart (1987) noted that such microfacies are similar to the Mishrif Formation in Abu Dhabi as described by Burchette & Britton (1985), and represent deposition in a shallow, quiet-water, platform lagoon environment, passing into shelf-edge barrier facies, and further seawards, into deeper water, intra-shelf basin conditions. At all localities where it was seen, the echinoid bed is associated with biostromal radiolited rudist beds and thinly bedded bioclastic packstones containing abundant rudist and/or oyster fragments. The latter facies may represent periods of extension of back-barrier skeletal sands and the development of intra-lagoonal biostromes.

As noted above, the upper part of the Natih Formation containing the Echinoid

Marker Bed correlates with the Mishrif Formation of the Arabian Gulf. The depositional environment of this formation has been described by a number of authors, notably Burchette & Britton (1985), Jordan *et al.* (1985) and Reulet (1982). Harris & Frost (1984) described upper Natih Formation in the region of the Fahud oilfield in terms of Mishrif depositional environments. All of these authors have described the same basic depositional model for the Mishrif Formation (and hence the upper Natih Formation of the Oman Mountains). It can be summarized as a carbonate shelf with a marked barrier (rudist biostromes and/or bioclastic shoals) prograding into a deeper intrashelf basin.

Reulet (1982) recognized several distinct facies within the Mishrif Formation of Iraq: (i) open outer shelf–basin mudstones–packstones with planktonic foraminifera and calcispheres, (ii) outer peri-reefal wackestones–grainstones with echinoderms, alveolinids and algae, (iii) barrier deposits including packstones–grainstones of rudist debris forming shoals, and more rarely, true rudist bioherms, (iv) inner peri-reefal wackestones–packstones of rudist debris and other bioclasts, (v) inner shelf subtidal, lagoon mudstones and wackestones with a diverse microfauna and (vi) intertidal peloidal–bioclastic wackestones and packstones with miliolids and gastropods. Similar lithofacies associations were recognized by Burchette & Britton (1985) in the Mishrif Formation of Abu Dhabi.

According to the model of Reulet (1982) a biofacies of common *Permocalculus*, *Praealveolina*, nezzazatids, coarse rudist and coral debris, and echinoids, as found in the Echinoid Marker Bed, is likely to represent deposition in 'peri-reefal' conditions either directly behind or in front of a barrier (facies ii and iv above). We favour a depositional position directly behind the barrier rimming the Mishrif (= upper Natih) shelf. This is because the Echinoid Marker Bed lies within a progradational shelf sequence, where below it are coarse rudist biostromes representing the barrier, and above it are *Exogyra*-rich lagoonal wackestones, with a moderately diverse microfauna. It is unlikely that true reefal barriers developed to rim the upper Natih shelf. Instead bioclastic shoals developed which were stabilized by radiolited rudists, and were capped by caprinid rudists. Although not bioherms, these shoals/biostromes formed an effective hydrodynamic barrier to the upper Natih shelf. This type of barrier may have also been prevalent in the Mishrif shelf of Abu Dhabi (Burchette & Britton, 1985) and Iraq (Reulet, 1982). Jordan *et al.* (1985, p. 431), whilst referring to 'reefs' in the Mishrif of Dubai, also stated that "The reefs are discontinuous and may be more a series of near-reef shoals than ecologic reefs".

The dominance of alveolinids also points to a back-barrier depositional environment (Henson, 1950; Hottinger, 1973; Saint-Marc, 1982; Pautal, 1987; Racey, in prep.), whilst the abundance of gymnocodiacean algae (*Permocalculus*) suggests deposition in outer shelf conditions of moderate water depth (5–20 m?), either in front of, or behind a barrier. The echinoid assemblage, which is dominated by holoctypoids, also suggests deposition in conditions close to a barrier. Modern-day holoctypoids occupy niches directly behind reefs in areas of coarse reef talus (Rose, 1976). The predominance of epifaunal regular echinoids and scarcity of burrowing spatangoids suggests that the sediment was consolidated, perhaps algal bound.

## 5. The echinoid fauna

Nine species of echinoid were collected from the Echinoid Marker Bed at Jebel Madamar, ?*Temnocidaris* (*Stereocidaris*) *sarracinarum* Fourtau, *Tetragramma variolare* (Brongniart), *Pedinopsis humilis* Fourtau, *P. sinaica* (Agassiz & Desor), *Pedinopsis*

*sphaerica* sp. nov., *Heterodiadema lybica* (Agassiz & Desor), *Hemiaster syriacus* Conrad, *Hemiaster cubicus* Cotteau and *Coenoholotypus larteti* (Cotteau), most of which have not previously been reported from the Arabian Peninsula. *Pedinopsis sphaerica*, *H. lybica* and *C. larteti* were also collected from Jebel Madar, while *H. lybica*, *C. larteti*, *H. syriacus* and *T. variolare* were collected from Jebel Salak. In terms of specimens, *C. larteti* greatly outnumbers other species at Jebel Madamar, *H. lybica* being the only other species present in any abundance. At Jebel Madar the faunal composition is similar, but at Jebel Salak *H. lybica* and *C. larteti* occur in equal abundance, with subsidiary *T. variolare*.

Faunas of similar age are known from North Africa (Algeria; Cotteau *et al.*, 1878: Egypt (Sinai Peninsula); Fourtau, 1914, 1921), the Middle East (Israel, Jordan; Blanckenhorn, 1925; Bandel & Geys, 1985), and India (Chiplonkar & Badve, 1972) as well as from Europe. Interestingly none of the species described here is known to occur in India, but most are recorded from Sinai. Of the nine species, eight are definitely known from Sinai and the ninth may be present. Six of these species are also known from Jordan/Israel and five from Algeria (Figure 7). Only two of the Omani species are found in Portugal and southern France. Clearly then there can have been little barrier to dispersal between Oman and Sinai during the middle Cenomanian but much less interchange between Oman and south western Europe. Roman *et al.* (1989, p. 282) suggested that during the Albian–Cenomanian there existed an eastern Mediterranean sub-province comprising the area circumscribed by Egypt, Iran and Somalia. Our results are consistent with this view and demonstrate that the Cenomanian fauna of Oman Egypt and the Middle East is very similar.

## 6. Systematic descriptions

Class Echinoidea Leske, 1778

Subclass Cidaroidea Claus, 1880

Order Cidaroida Claus, 1880

Family Cidaridae Gray, 1825

Genus *Temnocidaris* Cotteau, 1863

*Temnocidaris* (*Stereocidaris*) *sarracinarum* (Fourtau, 1921)

Figure 8a.

1921 *Stereocidaris sarracinarum* Fourtau, p. 6, pl. 3, fig. 10.

**Diagnosis.** A *Stereocidaris* with five interambulacral plates in a column, the top bearing only a rudimentary tubercle. Ambital and adapical plates about as tall as broad with large circular areoles occupying most of the plate. Scrobicular circles tangential at the ambitus; separated adapically. Extra-scrobicular tuberculation absent except adapically where a single row of miliary tubercles may occur along the interradial margin.

**Material.** One specimen, BMNH E83119, from the Echinoid Marker Bed at Jebel Madamar.

**Description.** The single specimen is 24.5 mm in diameter and 14.5 mm in height (60% of the test diameter). It is incomplete and rather badly weathered in places.

The apical disc is not seen. Ambulacra are sinuous and about 13% of the test diameter in width. The central tuberculate zone forms about 60% of the width of an ambulacrum. Ambulacral pores are non-conjugate and the two pores are separated

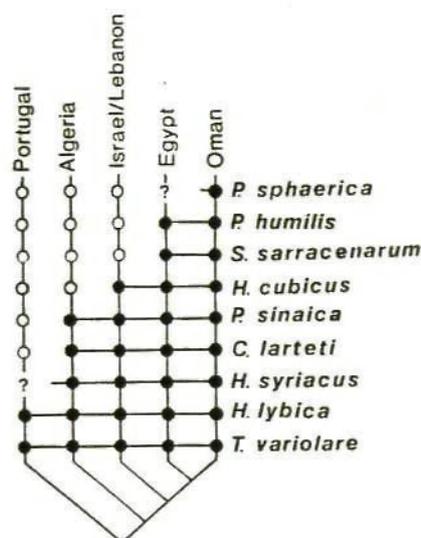


Figure 7. Geographical distribution of Oman echinoid species given in the form of an area cladogram. Filled circles = taxon present; open circles = taxon not recorded; ? = taxon may be present but material inadequate.

by a raised partition that is slightly narrower than the diameter of a single pore. Each ambulacral plate has a large navelonate primary tubercle adjacent to the pore pair and two smaller secondary tubercles placed one above the other per radially.

There are five interambulacral plates in a column, the most adapical of which bears a small rudimentary tubercle surrounded by numerous equal-sized miliaries. The other plates each have a perforate, non-crenulate primary tubercle surrounded by a large circular areole that occupies most of the plate. Scrobicular circles on adoral plates are tangential or confluent and leave no room for extrascrobicular tuberculation. Adapically a single row of secondary tubercles and miliaries is present along the interradiial and adapical margins of plates outside the scrobicular circle. Plate sutures are clearly marked and slightly incised. There are small angular pits at interradiial triple suture junctions.

The peristome is small and subpentagonal, measuring 42% of the test diameter.

**Remarks.** This species was established by Fourtau (1921) on the basis of two 18 mm diameter specimens from the Cenomanian of the northern Sinai (Egypt). It is clearly differentiated from other species of *Temnocidaris* (*Stereocidaris*) on account of the large size of its primary interambulacral tubercles and virtual absence of secondary tuberculation outside the scrobicular circles. This is a juvenile feature in cidarid development, but, by the equivalent size, other *T.* (*Stereocidaris*) species have extensive zones of miliary granulation on interambulacral plates (Smith & Wright, 1989). The specimen described here differs slightly from the types in having only two secondary tubercles on ambulacral plates, whereas Fourtau described four irregular rows developed at the widest part of the ambulacrum. Possibly in his specimen the two tubercles that are positioned one above the other in the Oman specimen are offset slightly in the types. However, the differences seem slight and in other cidarid species considerable variation may be encountered in the precise arrangement of secondary tubercles on ambulacral plates (Smith & Wright, 1989).

Subclass Euechinoidea Bronn, 1860  
 Cohort Echinacea Claus, 1876  
 Family Pseudodiadematidae Pomel, 1883  
 Genus *Tetragramma* Agassiz, 1840  
*Tetragramma variolare* (Brongniart, 1822)  
 Figure 8b.

1822 *Cidarites variolaris* Brongniart, p. 84, 390 (*partim*); pl. 5, fig. 9.  
 1985 *Tetragramma variolare* (Brongniart); Geys, p. 135 (see for full prior synonymy).

**Diagnosis.** A *Tetragramma* with ambulacral compounding of four elements at the ambitus and above but only three elements adorally. There are two equal-sized primary tubercles on ambital plates from about 15–40 mm test diameter.

**Material.** BMNH E83120, a single, incomplete specimen from the Echinoid Marker Bed at Jebel Madamar; BMNH E83279-82, four specimens from Jebel Salak.

**Description.** This species is very well known and needs little description. The Oman specimens reach almost 40 mm in diameter and approximately 17 mm in height (40% of the diameter). Ambulacral pores, which are arranged in weak arcs of four at the ambitus and immediately subambitally, become biserial adapically. The four most adoral plates are trigeminate, but all other plates are quadrigeminate. In quadrigeminate plates the upper of the two middle elements is a demi-plate. At the ambitus there are two equal-sized interambulacral tubercles which occupy virtually the entire width of the plate.

**Remarks.** This species is widespread in occurrence, being reported from the Cenomanian of North Africa (Algeria, Tunisia and Egypt), the Middle East (Syria, Lebanon, Israel and Jordan) as well as Europe (see Geys, 1985). It has also recently been reported from Albian/Cenomanian of Dhofar, southern Oman by Roman *et al.*, (1989). There are subtle differences in test shape between the populations found in Britain and France and those of North Africa and the Middle East. In comparison with populations from Wilmington, England for example (Smith *et al.*, 1988, the Oman specimen has slightly coarser interambulacral tuberculation and the ambitus lies at mid-height. In the Wilmington population and in most of the French material examined the ambitus lies above mid-height so that in profile the test has a broad, flat top and a slightly narrower base. However, these differences are not consistently developed.

Genus *Heterodiadema* Cotteau, 1864  
*Heterodiadema lybica* (Agassiz & Desor, 1846)  
 Figures 8c–g, 9, 10.

1846 *Hemicidaris lybica* Agassiz & Desor, p. 338.  
 1980 *Heterodiadema lybica* (Agassiz & Desor); Geys, p. 449, pl. 8 [includes a full synonymy].

**Diagnosis.** A depressed *Heterodiadema* (height about 50% of diameter) in which both ambulacral and interambulacral primary tubercles decrease abruptly and markedly in size at the ambitus.

**Age and distribution.** A widespread species known from the Cenomanian and Turonian of southern Europe, North Africa and the Middle East; possibly also from the Campanian of Belgium (Geys, 1980). The type comes from the Cenomanian of Egypt.

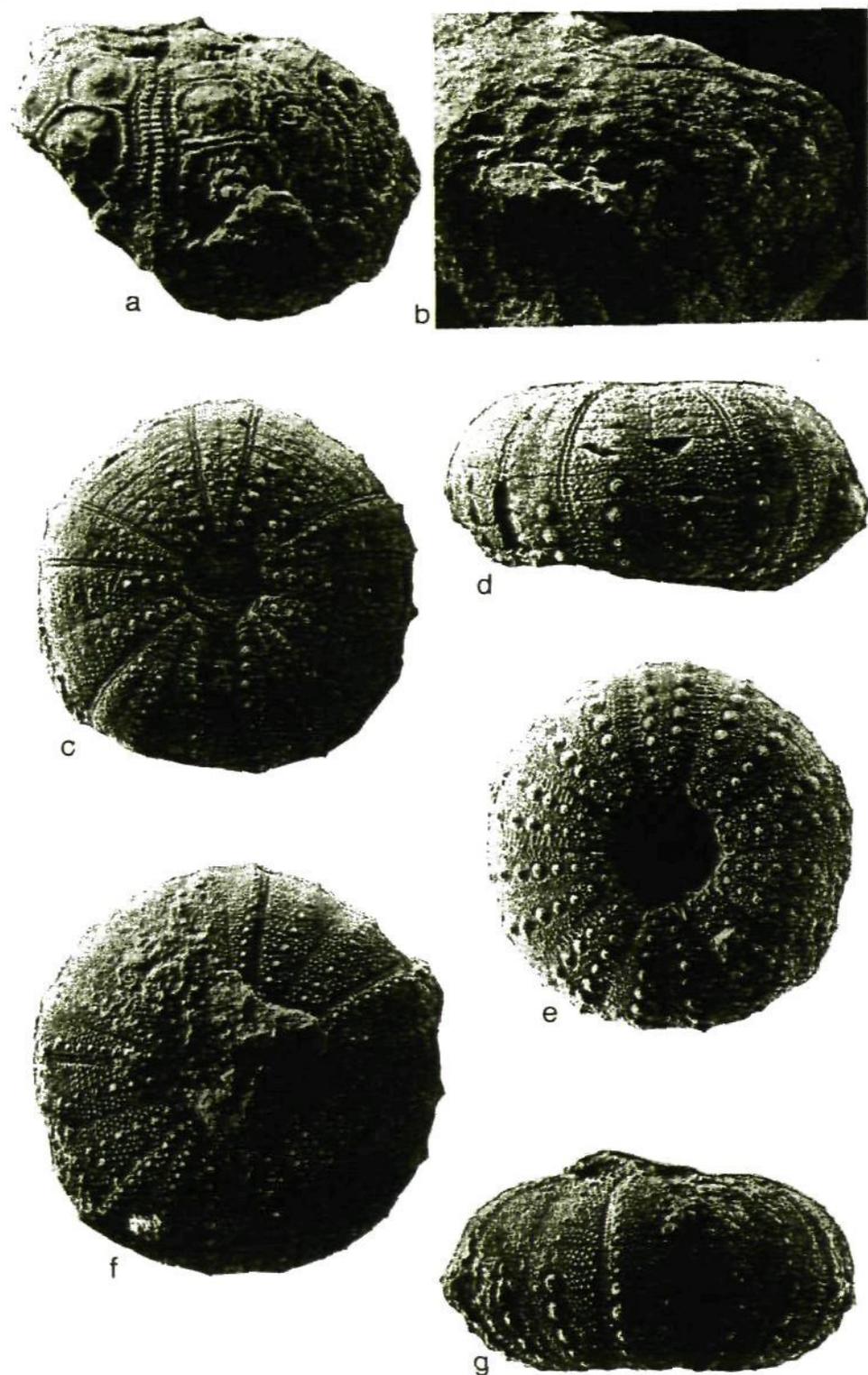


Figure 8. All specimens from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian of Jebel Madamar. a, *Temnocidaris* (*Stereocidaris*) *sarracinarum* (Fourtau), BMNH E83119,  $\times 2$ . b, *Tetragramma variolare* (Brongniart), BMNH E83120,  $\times 2$ . c-g, *Heterodiadema lybica* (Agassiz & Desor): c, d, adapical and lateral views of BMNH E83121,  $\times 1.5$ ; e, f, g, oral, adapical

**Material.** Nine well preserved specimens, BMNH E83121-5, E83290-3, from the Echinoid Marker Bed at Jebel Madamar form the basis for the following description. A number of other specimens were collected from here and from Jebel Salak and Jebel Madar.

**Description.** Tests are 15.3–36.3 mm in diameter and are subpentagonal in outline, the angles of the pentagon being radial. Test height is 40–53% of the test diameter (mean = 46%, SD = 3.8%, N = 9; Figure 9). In profile the sides are strongly inflated and the ambitus is at mid-height. Both the apex and the peristome are slightly invaginated.

No specimen retains plating of the apical disc. The outline of the disc is highly distinctive, resembling a key-hole with four small interradiial notches in interambulacra 1–4 and a deep, narrow cleft penetrating well into the posterior interambulacrum (Figure 8c). The width of the apical disc is 22–32% of the test diameter. In large individuals, 30–35 mm in test diameter, the top two plates of interambulacra 1–4 are separated by a sharp, clearly defined notch created by the genital plates. In the posterior interambulacrum, however, up to five adapical plates are separated and the notch is slightly pinched adapically. The notches increase in size

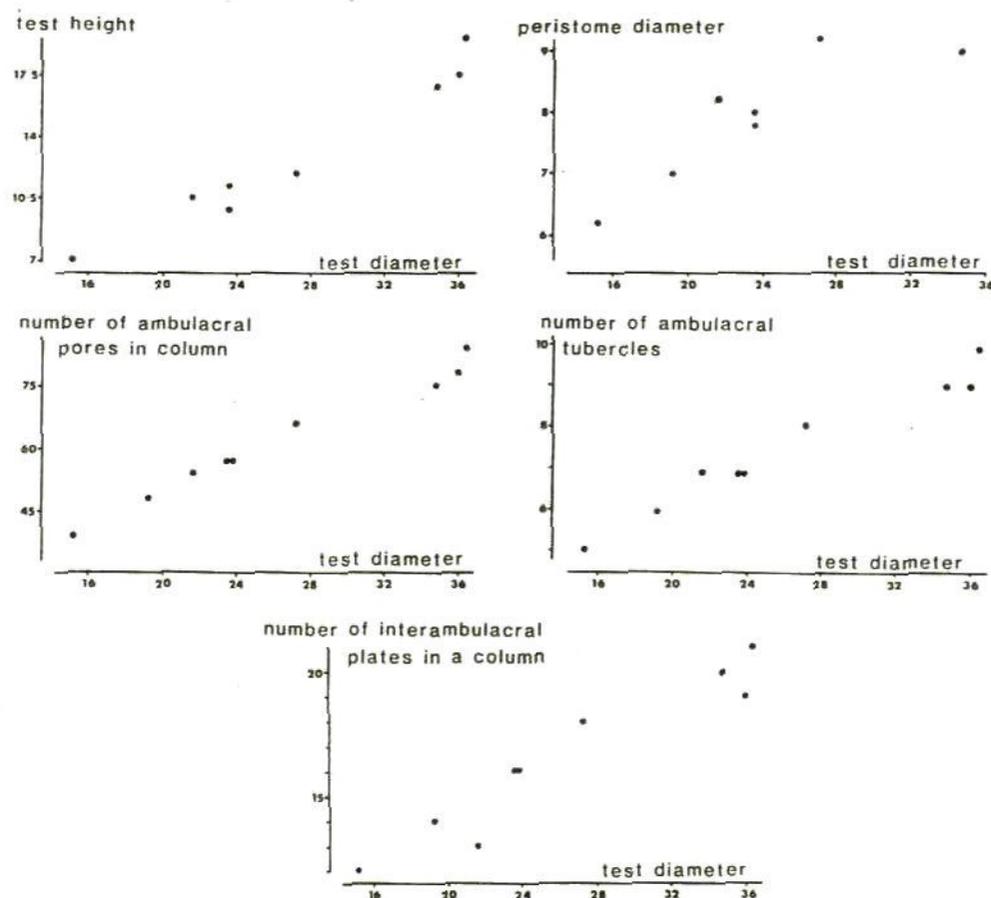


Figure 9. Biometric data on *Heterodiadema lybica* (Agassiz & Desor) from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian of Jebel Madamar. All measurements in millimetres.

during growth. In a 15-m-diameter individual, genital plates 1–4 hardly notch the interradial sutures while the posterior notch is broad, open and only separates the most adapical two interambulacral plates. By 21 mm test diameter genital plates 1–4 form distinctive notches at the interradial sutures and the posterior notch is more clearly differentiated, slightly pinched adapically and separates the three most adapical interambulacral plates in each column. The length of the apical disc also grows relative to the test diameter. In a 15-mm individual, the length of the spical disc is only 11% of the test diameter whereas, by 35 mm, it is 18–20% of the test diameter.

Ambulacral width is 21–23% of the test diameter at the ambitus. There are 40 ambulacral pores in a column at 15 mm test diameter rising to 78–83 at about 35-mm test diameter (Figure 9). Pores are uniserial throughout, with a tendency to become weakly arcuate in triads towards the peristome. All plates are compound triads in which the three elements reach the perradial suture. The central of the three plates in each triad is distinctly pinched towards the centre (Figure 10), particularly on ambital plates. Primary tubercles are perforate and crenulate adorally but imperforate and with either little or no crenulation adapically. There is a single large primary tubercle on each oral compound plate up to the ambitus. Those on the lowest three of four plates have non-contiguous areoles but above this, areoles are contiguous and elliptical rather than circular in outline. A narrow band of perradial miliaries occupies the centre of the ambulacrum. At the ambitus there is an abrupt decrease in the size of primary tubercles, which suddenly become less than half the diameter of adoral tubercles (Figures 8d, g, 10). Tubercles remain small to the apex. Primary tubercles are situated on the adradial margin of the plate adjacent to the pore zone and there is a broad perradial band of equal-sized miliary tubercles some 6–10 abreast. Adapically the primary tubercles are non-contiguous and are separated by a band of miliary tubercles. There are five large oral tubercles at 15 mm test diameter, 7 at 22 mm diameter and 9 or 10 at 35–36 mm test diameter (Figure 9). Four to five ambulacral pore pairs lie opposite at ambital interambulacral plate.

Interambulacral plates are wide and low. There are 12 plates in a column at 15 mm test diameter, rising to 19–21 at about 35 mm test diameter (Figure 9).

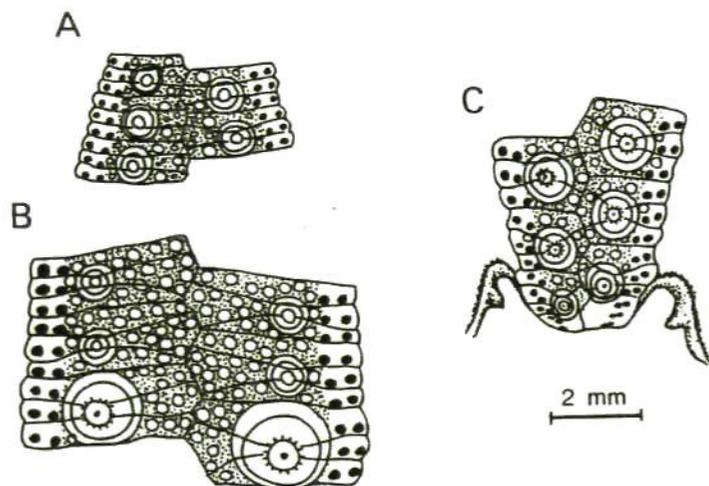


Figure 10. Camera lucida drawings of ambulacral plating in *Heterodiadema lybica* (Agassiz & Desor), BMNH E83122, from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian of Jebel Madamar. A, adapical plating; B, ambital plating; C, adoral plating (note shape of buccal notches).

Adoral primary tubercles are large, perforate and crenulate, adapical ones are much smaller, imperforate and hardly crenulate. Primary tubercles lie at the centre of interambulacral plates and there are well-developed bands of miliaries both adradially and interradially. On an ambital plate of larger specimens there are approximately five miliaries abreast interradially and three or four abreast adradially. Close to the peristome the primary tubercles are non-confluent, with narrow bands of miliaries separating adjacent areoles. But over most of the oral surface, up to the ambitus, areoles are confluent. At the ambitus there is an abrupt decrease in the size of primary tubercles and adapical tubercles are less than half the diameter of ambital tubercles (Figure 8d, g). Adapically, tubercles are all non-confluent and miliaries are arranged in semi-regular horizontal rows. In the most adapical five or so plates the primary tubercles may enlarge slightly. There is a narrow granule-free interradial 'naked zone' developed toward the apex. At the ambitus, ambulacral primary tubercles are only slightly smaller than interambulacral primary tubercles.

The peristome forms about 40% of the test diameter in 15 mm-sized individuals but becomes proportionally smaller during growth (Figure 9), reducing to only 26% of the test diameter at about 35 mm. It is circular in outline but incised by very deep buccal notches that penetrate as far as the fifth ambulacral pore pair. The notch is partitioned (Figure 10c) and has a well-developed rim. Buccal notches are poorly developed at 15 mm test diameter but become deeper and sharper at test size increases. In large specimens a naked channel extends from the tip of the buccal notch adambitally for a further three interambulacral plates (Figure 8e), indicating that in *H. lybica* the coelomic expansion sacs were large and recumbent.

*Remarks.* This species has been described and figured on several occasions but its growth has not previously been documented biometrically. The abruptness with which primary tubercle size decreases at the ambitus varies from population to population. In the Oman sample the change is extremely abrupt whereas in other populations, such as those from Batna, Algeria, the change tends to be less abrupt and tubercle size decreases gradually adapically. There is, however, no sharp distinction between the two and all intermediates can be found. The imperforate nature of aboral primary tubercles has not previously been noted.

The species differs from *H. ouremense* Loriol, from the Cenomanian of Portugal, in shape, *H. ouremense* having an almost globular test. *H. bigranulatum* Gregory, from the Cenomanian of the Sinai Peninsula, Egypt, appears to be a poorly preserved juvenile of *H. lybica*. *H. lybica* is known from the Cenomanian of southern Europe, north Africa and the Middle East, and has been reported as far afield as the Karakorum Mountains and Niger (Geys, 1980).

#### Genus *Pedinopsis* Cotteau, 1863

*Diagnosis.* Regular echinoid with perforate, feebly crenulate tubercles. Both ambulacral and interambulacral tubercles small, with primary tubercles not much differentiated from secondary tubercles; these arranged in horizontal rows. Ambulacral plates compound; trigeminate adorally, quadrigeminate or polygeminate at ambitus and above with only the principal element in each compound plate reaching the perradial suture. Pore-pairs arranged biserially adapically but uniserial adorally. Apical disc much smaller than peristome.

*Type species.* *Pedinopsis meridianensis* Cotteau, 1863 by original designation.

*Range.* Neocomian to Coniacian/Santonian unspecified.

*Remarks.* *Pedinopsis* is readily recognized by its very complex ambulacral compounding in which all but the principal element are demi-plates. It resembles *Tetragramma* in having ambulacral pores arranged biserially adapically, but in *Tetragramma* ambulacral compounding never includes more than four elements and all elements reach the perradial suture. Furthermore, *Tetragramma* is a very much more coarsely tuberculate and has a very much larger apical disc that is similar in size to the peristome.

Several species of *Pedinopsis* have been described and these can be separated into three discrete groups based on their style of ambulacral compounding. In members of the first group, characterized by *P. desori* (Coquand, 1862), only the four or so most adoral ambulacral plates are trigeminate; the other adoral plates are quadrigeminate and the adapical plates are composed of six elements. Biserial pore arrangement extends from the apex to well below the ambitus. The type species, *P. meridianensis* Cotteau, belongs here and is based on a large specimen with a row of up to eight interambulacral tubercles on ambital interambulacral plates. Its compound plates comprise six elements and the biserial arrangement of ambulacral pores extends virtually to the peristome. It is stated to come from Neocomian beds in France. Also included are the Cenomanian *P. humilis* Fourtau and *P. sphaerica* nov., differentiated from *P. desori* on general shape and on the size and degree of invagination of the peristome. *P. texana* Cook, from the Upper Albian of Texas also belongs here, but appears virtually indistinguishable from *P. derori* in morphology and is probably best treated as synonymous. The same is true of the Lower Cenomanian *P. weisti* Wright from England. *P. pondi* Clark from the Coniacian/Santonian Austin Chalk of Texas is the youngest member known (Cooke, 1953).

In the second group, which contains only *P. sinaica* (Agassiz & Desor), ambulacra are trigeminate adorally and quadrigeminate adapically, while pores are arranged uniserially adorally and become biserial adapically. Complex polygeminate compounding is not developed.

A closely related species is *Dumblea symmetrica* Cragin, from the Upper Albian of Texas and Mexico (Cooke, 1955). This species resembles *Pedinopsis* in having rows of small equal-sized tubercles on ambulacral and interambulacral plates and in having biserially arranged pores from the apex to subambitally. Only the primary element in each compound plate reaches the perradial suture. *Dumblea* differs from *Pedinopsis* in having compound plating of triads throughout. Two species *P. yarboroughi* and *P. engerrandi*, both from the Fredericksburg Group, Albian, of Texas, also belong here and were described by Iken (1940, p. 14). Cooke (1946, p. 212) treated these as synonymous and noted that they were 'very similar' to *P. symmetrica* [= *Dumblea symmetrica*] but were tentatively maintained as valid species because they were found at a different stratigraphical level. In addition, the Egyptian species *P. torrendi* Cotteau may belong here although it is poorly known. It was redescribed by Fourtau (1921, p. 34) and differentiated from other species of *Pedinopsis* by having three adradial and three interradial columns of tubercles.

These species are clearly closely related on account of their biserial pore arrangement, similarity of demiplating and style of tuberculation, but they differ in the detailed construction of compound plates. This allows the recognition of three subgenera within *Pedinopsis*, *P. (Pedinopsis)* [type species *P. meridianensis* Cotteau] for species with compound ambulacral plates constructed of six elements adapically and four adorally; *P. (Dumblea)* Cragin [type species *Dumblea symmetrica* Cragin] for species with trigeminate compound plating throughout; and *P. (Sinaioopsis)* nov.

[type species *Pedina sinaica* Agassiz & Desor] for species with trigeminate compound plating adorally and quadrigeminate compound plating adapically.

Subgenus *Pedinopsis (Pedinopsis)* Cotteau, 1863

Type species. *Pedinopsis meridianensis* Cotteau, 1863.

*Diagnosis.* *Pedinopsis* with polygeminate ambulacral plate compounding ambitally and adapically comprising six elements. Quadrigeminate plate compounding usually developed adorally and trigeminate plating confined to the most adoral two to four compound plates.

*Range.* Neocomian to Coniacian/Santonian, Europe, U.S.A., North Africa, Middle East.

*Pedinopsis (Pedinopsis) humilis* Fourtau, 1921

Figures 12, 14a-c.

1921 *Pedinopsis humilis* Fourtau, p. 33, pl. 5, fig. 2.

*Diagnosis.* A large, wheel-shaped *Pedinopsis* with pores arranged biserially except in the adoral half of the lower surface. Adapical and ambital plates include occluded elements. One large primary ambulacral tubercle on each plate. Ambital interambulacral plates broad, with a row of four equal-sized tubercles occupying most of the plate height.

*Material.* One specimen, BMNH E83282, from the Echinoid Marker Bed at Jebel Madamar.

*Age and distribution.* The two syntypes come from the Lower Cenomanian of Jebel el Helal, Egypt. The Oman specimen is late middle Cenomanian in age. No other material has been reported.

*Description.* The unique specimen is rather badly weathered removing much surface detail. The test is flat and wheel-shaped (Figure 14c), being 38 mm in diameter and 14 mm in height (37% of test diameter). It is slightly pentagonal in outline and has a rounded margin, with the ambitus at about mid-height. The apical disc is small and approximately circular in outline, being 6 mm in diameter (16% of the test diameter). No apical disc plates remain in position.

Ambulacra are 8.5 mm in width at the ambitus (22% of the test diameter). Pores are arranged biserially from the apex to half-way towards the peristome on the oral surface, where they become arranged into arcs of four. The pore-pairs are very closely packed together and elements in compound plates often become occluded from one or other of the sutures, or indeed from both (Figure 12a-b). The pore zone is broad adapically and at the ambitus, occupies about half of the plate width. Plate compounding is illustrated in Figure 12. One large primary tubercle lies centrally on each compound plate; details of any finer tuberculation have been lost through weathering. There are more than 80 pore pairs in a column (adoral part of ambulacrum not seen).

Interambulacra have a width about 40% that of the test diameter. Ambital plates are wide and short with a row of four equal-sized tubercles on each plate which occupy much of the plate height (Figure 14c). Miliary granules occur along the upper and lower plate edge.

The peristome is not exposed.

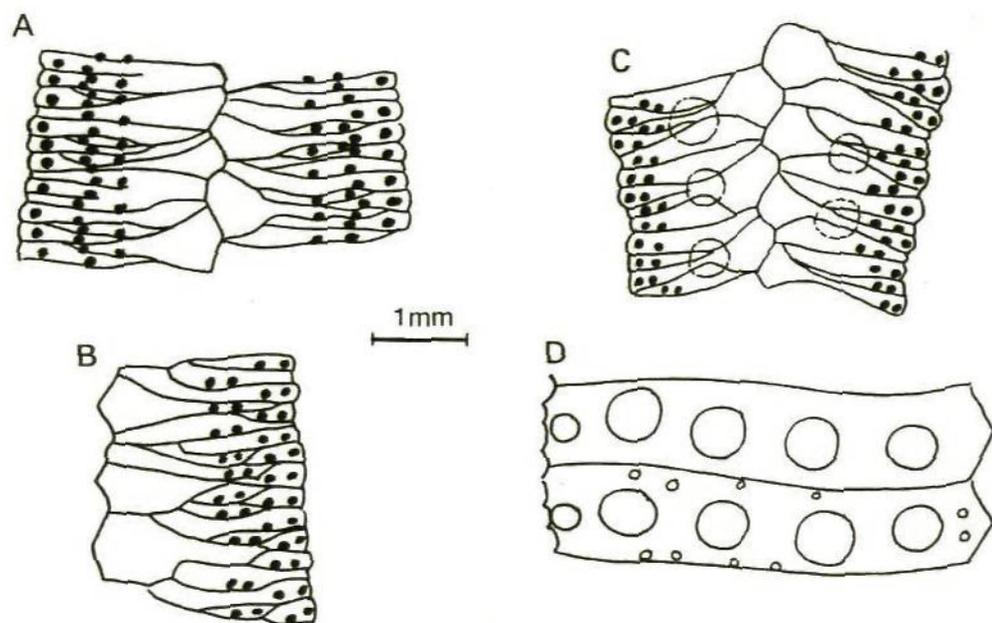


Figure 11. Camera lucida drawings of plating and tuberculation in *Pedinopsis (Pedinopsis) humilis* Fourtau: BMNH E83283, from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian of Jebel Madamar. A, adapical ambulacral plating; B, ambital ambulacral plating; C, adoral ambulacral plating. D, ambital interambulacral plates (perradial suture to the right) showing the position and size of the principal tubercles. All to same scale.

**Remarks.** The Oman specimen is identical to the types described and figured by Fourtau (1921) from the Lower Cenomanian of Egypt. It resembles *P. desori* and *P. sphaericus* in having six elements in aboral and ambital ambulacral compound plates and four adorally, but differs in having much wider and shorter interambulacral plates each with a row of four equal-sized tubercles at the ambitus; the primary tubercle is not obviously differentiated from the rest. Furthermore, in ambital and adapical compound plates some elements are occluded from both the adradial and perradial suture, a feature not seen in other species. Finally, its wheel-like shape is also characteristic.

*Pedinopsis (Pedinopsis) sphaerica* sp. nov.

Figures 11a–e, 13.

?1921 *Pedinopsis desori* Coquand; Fourtau, p. 32.

**Diagnosis.** A globular species of *Pedinopsis*, almost as tall as wide, with pores arranged biserially from subambitally to the apex. Peristome small and not at all invaginated.

**Types.** Holotype BMNH E83127, paratype BMNH E83128, designated here.

**Origin of name.** In allusion to the highly distinctive test shape.

**Age and distribution.** The types come from the Echinoid Marker Bed at Jebel Madamar, late middle Cenomanian in age. A third, poorly preserved specimen comes from a similar horizon at Jebel Madar. Possibly also known from the Cenomanian of Egypt (see discussion).

**Description.** The types are 23 and 27 mm in diameter and circular in outline. Test height is 20 and 23 mm (85–87%) of test diameter. In profile the test is almost perfectly circular, with a small flat base and apex (Figure 11c, e). The ambitus is at mid-height. Plates of the apical disc are missing in both specimens and must have been rather loosely attached to the corona. The apical disc is circular in outline and 16–17% of the test diameter in diameter.

Ambulacra are broad and straight, tapering gradually adorally and rather abruptly adapically. At the ambitus they are 19–22% of the test diameter in width. The pore zones are relatively narrow, leaving a broad perradial zone of tubercles forming about 67% of the ambulacral width. Pores are undifferentiated and are biserially arranged from the apex to a little below the ambitus. Towards the peristome pore-pairs are arranged in arcs of three. The change in pore arrangement occurs about 8 or 9 compound plates away from the peristome. There are about 140–150 pore pairs in a column and 29–31 compound plates. Plate compounding is highly complex (Figure 13). At the apex the very first few plates are simple and all reach the perradial suture. However, there rapidly develops a compounding style involving six elements, only one of which reaches the perradius (Figure 13a). This coincides with the development of a clear biserial arrangement of pore-pairs. Below the ambitus, where the biserial pore arrangement starts to disappear, only four elements are included in a compound plate, three of which are occluded from the perradial suture (Figure 13c). In the most adoral few plates compounding involves just three elements, only the lowest of which is occluded from the perradial suture (Figure 13d). Here pores become offset into strong arcs forming a phyllode. On the lower surface each compound plate has a moderately large primary tubercle situated close to the pore zone. This is situated on the largest of the three plates but also overlaps one of the smaller elements. Towards the ambitus this primary tubercle decreases in size and comes to lie almost entirely on the largest of the elements in each compound plate, though still encroaching over one of the smaller elements (Figure 13e). On ambital plates two horizontal rows of two or three smaller secondary tubercles and scattered miliaries occur perradial to the primary tubercle (Figure 13e). Primary tubercles continue to the apex, but are small and confined entirely to the largest of the elements in the compound plate. They are hardly differentiated from other small tubercles on ambulacral plates from the ambitus adapically. Ambulacral and interambulacral plates are similar in height at the ambitus and are arranged opposite rather than alternately.

Interambulacral plates are wide and low, more than four times as wide as tall at the ambitus. There are 27 plates in a column at 23 mm test diameter and 28 at 27 mm. Adorally each plate carries three large perforate, crenulate tubercles which occupy most of the plate (Figure 13h). The largest of these is the central tubercle. Away from the peristome, first the adradial and later the interradian tubercle diminish in size rapidly, leaving only a single larger tubercle situated on the centre of the plate. This primary tubercle also diminishes in size away from the peristome so that by the ambitus it occupies only a small part of the plate height and is only slightly larger than the numerous other small tubercles and miliaries that cover the surface (Figure 13f). This continues to the apex where the primary tubercle is barely distinguishable.

The peristome is circular and not invaginated. Its diameter is 36% of the test diameter and there are small, but sharply incised, buccal notches with a thickened rim.

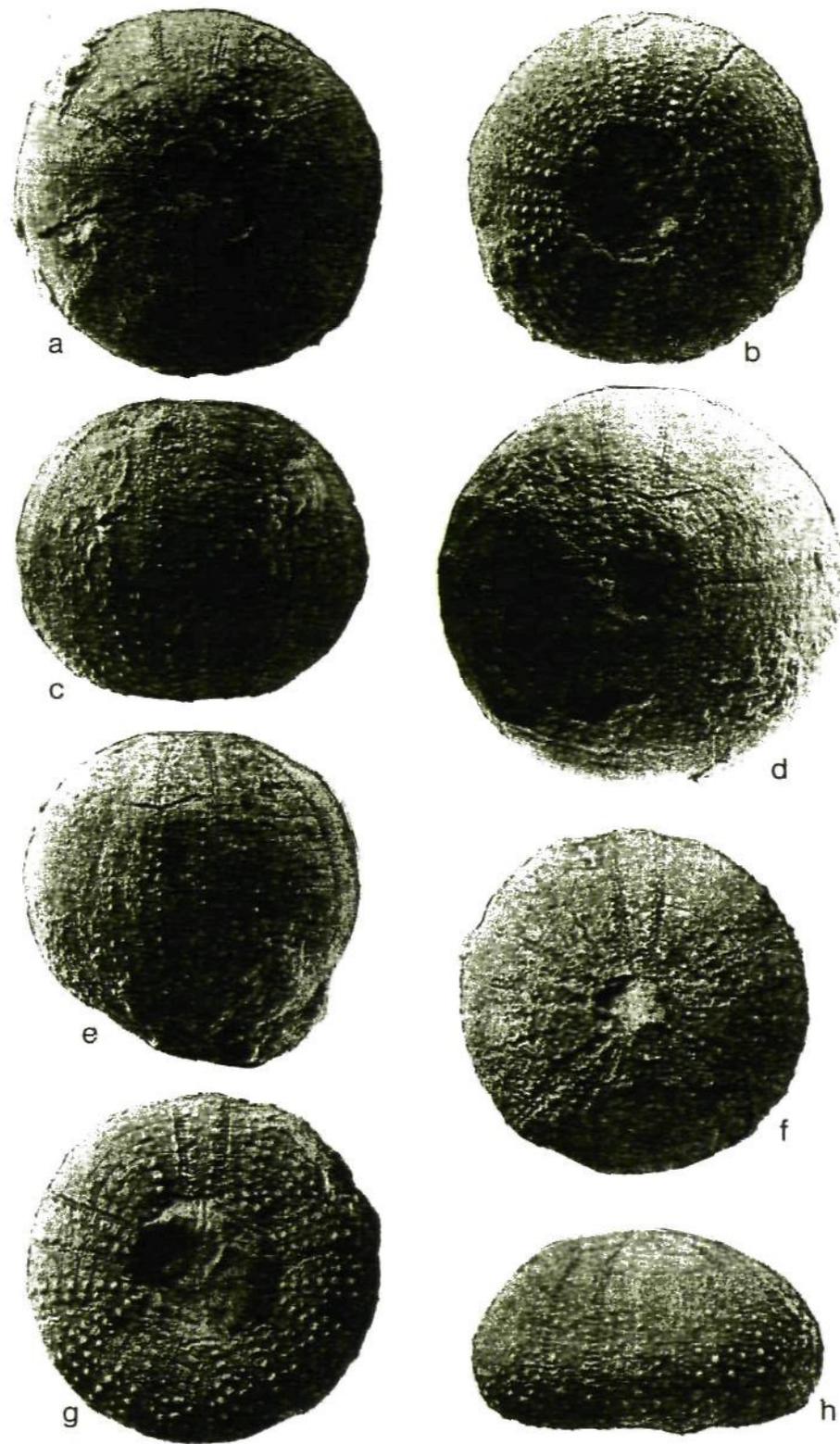


Figure 12. All specimens from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian of Jebel Madamar. a-e, *Pedinopsis (Pedinopsis) sphaerica* sp. nov.; a-c, apical, oral and lateral views of BMNH E83127,  $\times 2$ ; d, e, apical ( $\times 2$ ) and lateral ( $\times 1.5$ ) views of BMNH E83128. f-h, *Pedinopsis (Sinaiopsis) sinaica* (Agassiz & Desor), BMNH E83289, apical, oral and lateral views,  $\times 2$ .

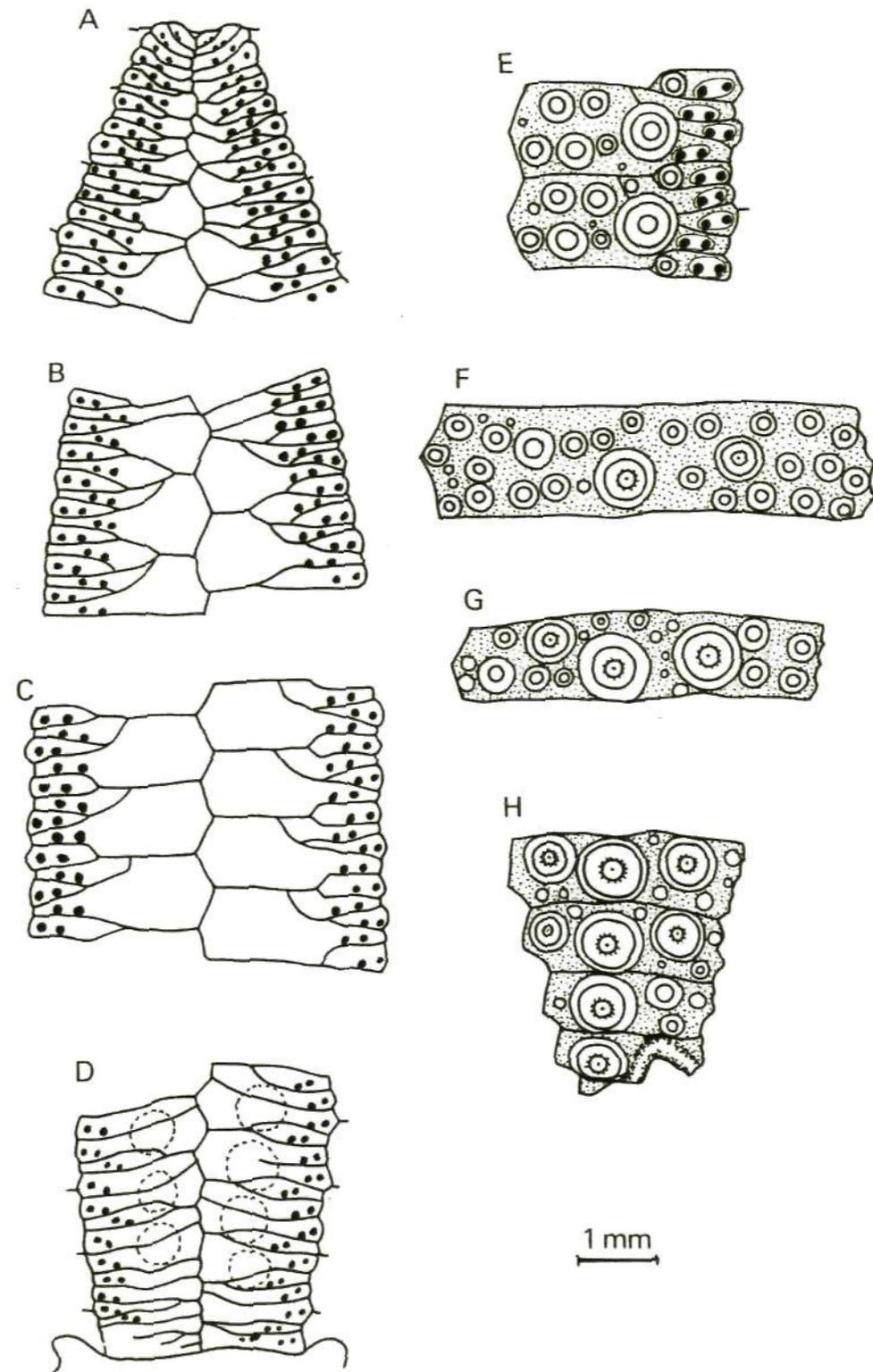


Figure 13. Camera lucida drawings of plating and tuberculation of *Pedinopsis (Pedinopsis) sphaerica* sp. nov. A, adapical ambulacral plating, apex at top; B, supra-ambital ambulacral plating; C, sub-ambital plating; D, adoral plating, peristomial margin at bottom; E, ambital ambulacral tuberculation; F, ambital interambulacral plate, interradius to the left; G, adoral interambulacral plate, interradius to the left; H, adoral interambulacral plates, peristomial margin at bottom. A-C & E-H, BMNH E83128; D, H, BMNH E83127; all to same scale.

*Remarks.* *P. desori* comes closest to this species but differs in having a subconical profile and a larger and noticeably invaginated peristome. Test height in *P. desori* is no more than about 60% of the test diameter. The type of *P. desori* comes from North East Algeria, and additional specimens were illustrated by Cotteau (1865) (though these are inaccurately illustrated in depicting an unnaturally large peristome) and by Blanckenhorn (1925). The small, globular, badly preserved specimen described by Fourtau (1921) as *P. desori*, from the Cenomanian of Egypt, is probably the same as our Oman species but no illustration was given and the type has not been seen. *P. sinaica* (Agassiz & Desor, 1847) is easily distinguished both on test shape and on style of ambulacral compounding. *P. humilis* Fourtau, which is also found at this horizon, is easily distinguished by its wheel-shaped test and has more complex ambulacral compounding in which occluded elements are present.

Subgenus *Pedinopsis* (*Sinaioopsis*) nov.

*Diagnosis.* *Pedinopsis* with biserially arranged pores adapically only. Ambulacral plating trigeminate adorally, becoming quadrigeminate adapically.

*Type species.* *Pedina sinaica* Agassiz & Desor, 1847, p. 67.

*Age and distribution.* Cenomanian of Algeria, Egypt, Israel and Oman.

*Pedinopsis* (*Sinaioopsis*) *sinaica* (Agassiz & Desor, 1847)  
Figures 11f–h, 15, 16

1847 *Pedina sinaica* Desor; Agassiz & Desor, p. 67.

1852 *Echinus syriacus* Conrad, in Lynch, p. 212, pl. 1, fig. 1, pl. 22, fig. 127.

1914 *Pedinopsis sinaea* Fourtau, p. 18, pl. 2, figs 3–4.

1925 *Pedinopsis sinaica* Des?; Blanckenhorn, p. 89.

*Diagnosis.* Subconical, somewhat inflated in profile, with one primary tubercle differentiated on each ambulacral and interambulacral plate.

*Age and distribution.* Cenomanian of Lebanon, Israel, Egypt, Algeria and Oman.

*Material studied.* One specimen from the Echinoid Marker Bed, Natih Formation, late middle Cenomanian of Jebel Madamar.

*Description.* The test is circular in outline and subconical in profile, with swollen sides and the ambitus lying slightly below mid-height (Figures 11a–c). Test diameter is 25.3 mm and test height 14.2 mm (56% of the diameter).

The apical disc is relatively small and approximately circular, 18% of the test diameter. No apical disc plates are preserved in position.

Ambulacral width is 16% of the test diameter at the ambitus. Pore-pairs are strictly unigeminate adorally and ambitally but become biserially arranged towards the apex. All plates up to the ambitus are trigeminate and, except for the lowest two or so plates, only one of the three elements reaches the perradial suture (Figure 15a). Above the ambitus, where pore-pairs start to become biserially arranged, there is a fourth element in each compound plate (Figure 15b). This style of compounding continues to the apex. There is a single larger primary tubercle on each compound plate lying close to the pore zone. This tubercle straddles two of the three elements in trigeminate plates and two or three elements in quadrigeminate plates. A secondary tubercle, about half the diameter of the primary, lies at the lower perradial edge of each plate. The remainder of the compound plate has scattered miliaries (Figure 15a).

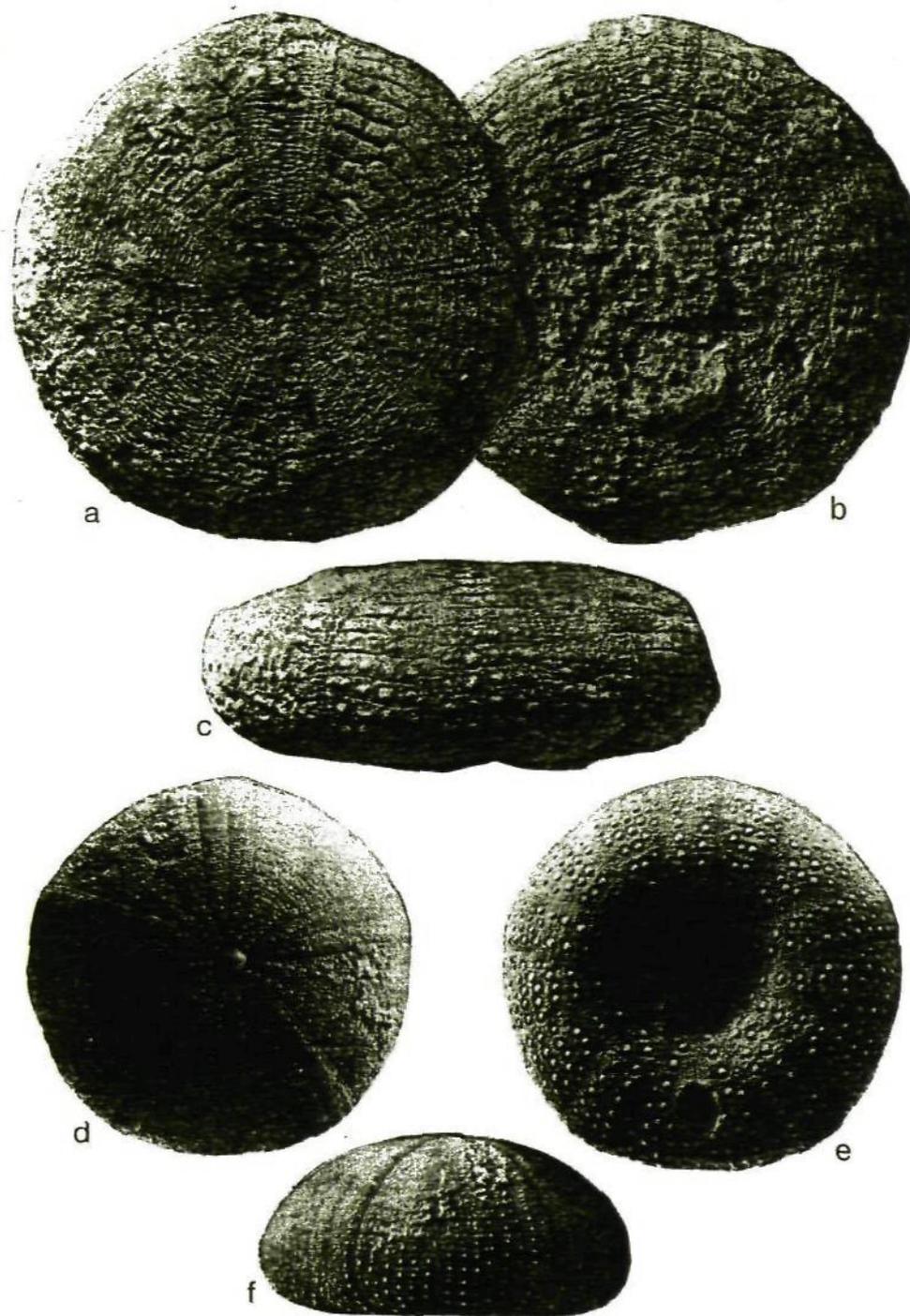


Figure 14. All specimens from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian, at Jebel Madamar,  $\times 2$ ; a–c, *Pedinopsis* (*Pedinopsis*) *humilis* Fourtau, BMNH E83283, oral, apical and lateral views,  $\times 2$ . d–f, *Coenoholactypus larteti* (Cotteau), BMNH E83129, oral, apical, and lateral views.

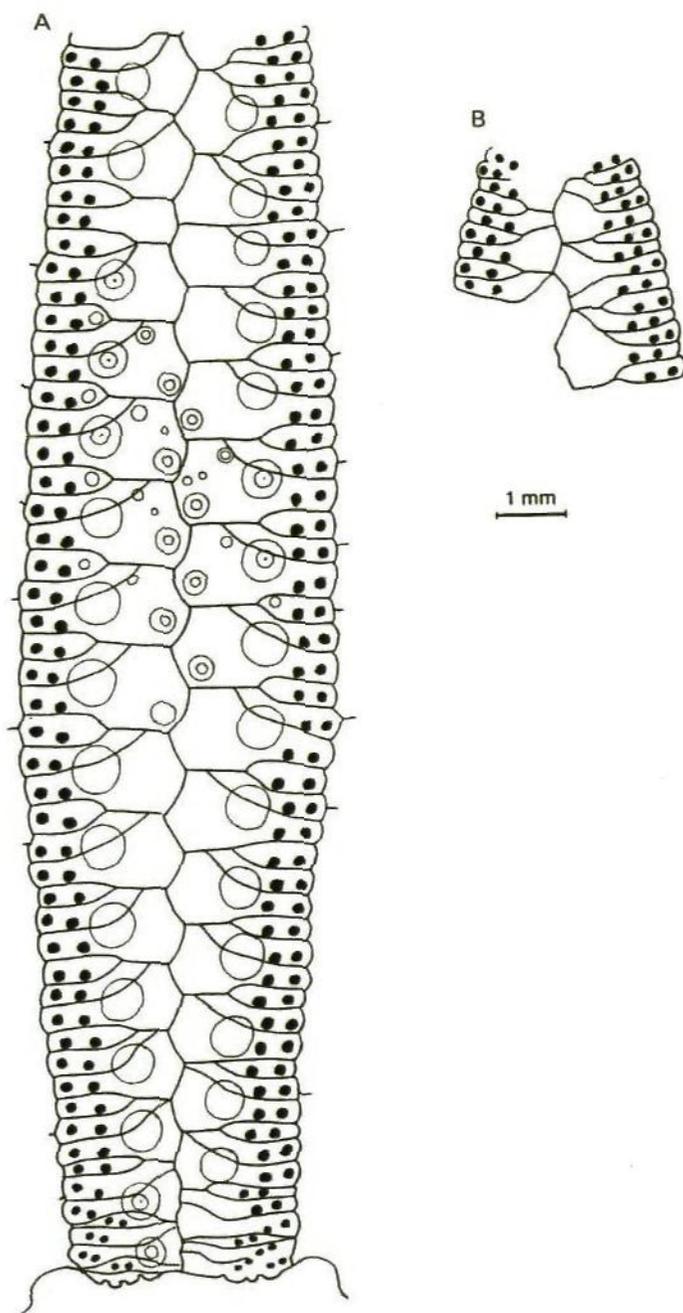


Figure 15. Camera lucida drawings of *Pedinopsis (Sinaiopsis) sinaica* (Agassiz & Desor), BMNH E83289, from the Echinoid Marker Bed, Unit c, Natih Formation, late middle Cenomanian, at Jebel Madamar. Ambulacral plating: A, plating from peristome (bottom) to half-way up the adapical surface; B, plating close to the apex.

Interambulacral plates are rather long and low, ambital plates having a height that is 30% of their length. One larger primary tubercle is differentiated but is relatively small in comparison with the plate (Figure 16). It occupies only about half of the plate height and is situated centrally towards the adoral plate margin. On either side on ambital plates there are two smaller secondary tubercles (about 60% of the primary tubercle's diameter) offset towards the upper edge of the plate (Figure 16). The remainder of the plate surface is covered in sparse tertiary tubercles and miliaries.

The peristome is moderately large, 46% of the test diameter, and somewhat invaginated. Shallow buccal notches are present.

*Remarks.* *P. sinaica* can be distinguished readily from the two other species of *Pedinopsis* that occur at this level by its shape, tuberculation and pattern of ambulacral compounding. *P. sphaerica* is virtually globular and has a slightly smaller peristome that is not at all invaginated. Interambulacral tuberculation is rather similar but there are more secondary ambulacral tubercles in *P. sphaerica*. Trigeminate plating extends much higher in *P. sinaica* at an equivalent test size and the biserial arrangement of pores is restricted to the adapical portion of the test. *P. humilis* is very much more depressed in form, has larger interambulacral tubercles, more equal in size and occupying very much more of the plate height. It has quadrigeminate plating adorally and polygeminate plating adapically with occluded elements in each compound plate.

The species was first described from the Cenomanian of Sinai, Egypt, and has also been reported from Algeria (Cotteau *et al.*, 1878).

Cohort Irregularia Larteille, 1825  
 Order Holectypoida Duncan, 1889  
 Family Holectypidae Lambert, 1899  
 Genus *Coenholectypus* Pomel, 1883  
*Coenholectypus larteti* (Cotteau, 1869)  
 Figures 14d-f, 17, 18

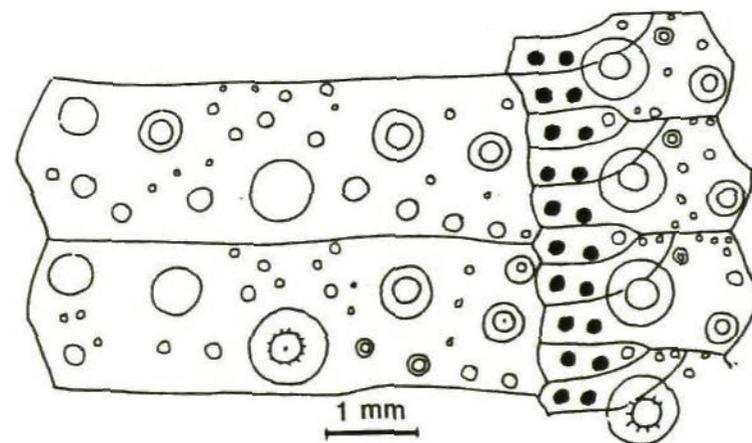


Figure 16. Camera lucida drawing of ambital (right) and interambulacral (left) tuberculation in *Pedinopsis (Sinaiopsis) sinaica* (Agassiz & Desor), BMNH E83289, from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian, at Jebel Madamar.

- 1869 *Holoctypus larteti* Cotteau; Cotteau, p. 537, text-fig.  
 1873 *H. larteti* Cotteau; Lartet, p. 81, pl. 9, figs 21–22.  
 1877 *H. larteti* Cotteau; Lartet, p. 155, pl. 14, figs 1–5.  
 1879 *H. chauveneti* Cotteau, Peron & Gauthier, p. 172, pl. 12, figs 3–6.  
 1897 *H. larteti* Cotteau; Loriol, p. 17, pl. 6, fig. 9.  
 1906 *H. larteti* Cotteau; Gregory, p. 226.  
 1909 *H. chauveneti* Peron & Gauthier; Fourtau, p. 102.  
 1912 *H. dowsoni* Fourtau, p. 160, pl. 2, fig. 5.  
 1914 *H. larteti* Cotteau; Fourtau, p. 44, pl. 3, fig. 8.  
 1914 *H. larteti* Cotteau race *sinaea* Fourtau, p. 46, pl. 4, figs 1–4.  
 1914 *H. larteti* Cotteau var. *Dowsoni* Fourtau; Fourtau, p. 47.  
 1921 *H. larteti* Cotteau; Fourtau, p. 55.  
 1921 *H. larteti* Cotteau race *sinaea* Fourtau; Fourtau, p. 55.  
 1925 *H. larteti* Cotteau; Blanckenhorn, p. 90, pl. 7, figs 10–11.  
 1925 *H. larteti* var *major* Blanckenhorn, p. 91, pl. 7, fig. 12.  
 non 1989 *H. (Caenholoectypus) larteti* Cotteau; Ali, p. 401, fig. 5(10).

**Diagnosis.** An inflated species of *Coenholoectypus* with a rounded ambitus and the periproct small and opening between plates 4a, b and 8a, b about midway between the peristome and ambitus.

**Material studied.** Fifteen well preserved specimens, BMNH E83129–43, from the Echinoid Marker Bed at Jebel Madamar, were used in the biometric study. Other material comes from Jebel Madar and Jebel Salak.

**Age and distribution.** This is the most abundant species in the Echinoid Marker Bed at Jebel Madamar. It is also known from the Cenomanian of Egypt, North Africa and the Middle East and has been recorded by Roman *et al.* (1989) from the Cenomanian of Dhofar, southern Oman.

**Description.** Tests range in size from 19 to 29.3 mm in diameter. Test height is 44–61% of the test diameter (mean = 51%, SD = 4.2%, n = 15; Figure 17). The test is circular in outline and has a low conical profile with a well-rounded ambitus that lies 30–40% of test height above the base (Figure 14f). The peristome is deeply invaginated because of the curvature of the test.

The apical disc is small, often somewhat elevated and the diameter is 8–11% of the test diameter (mean = 9%, SD = 0.9%, n = 14). All five genital plates are perforate at these sizes. Genital 2 is at least twice as large as other genital plates and occupies the centre of the apical disc. The madrepores are confined to genital 2, which is usually domed and has a spongy appearance. Gonopores are positioned centrally on the other genital plates. In most specimens ocular plates I, IV and V do not abut genital plate 2 (Figure 18b, c). However, in one large specimen genital plate 2 is extremely large and genital plates alternate with ocular plates around the periphery (Figure 18d). Ocular plates are only slightly smaller than adjacent non-madreporic genital plates.

The ambulacra form 14–17% of the test width at the ambitus. They are composed of simple narrow plates from the subambitus adapically, but distinct triads are developed adorally. Below the ambitus the middle plate in each triad is much enlarged and one or both of the other plates are occasionally occluded from the perradial suture (Figure 18a). Ambulacral pores are undifferentiated and are arranged uniseriably throughout. There are 85 pores in a column at about 20 mm test diameter, increasing to 118 at 29 mm test diameter (Figure 17). There are three and

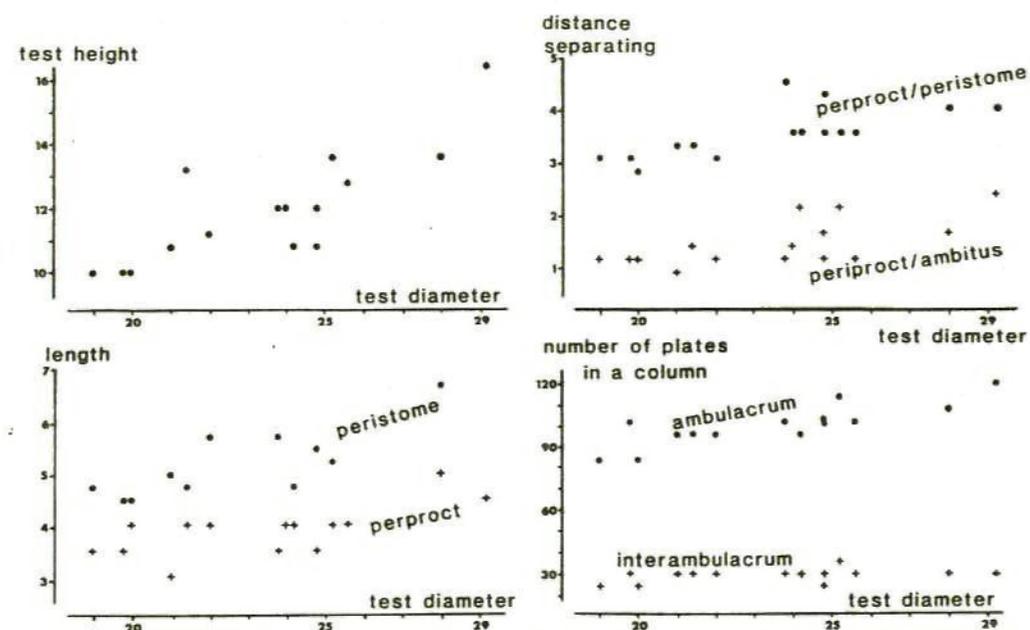


Figure 17. Biometric data on *Coenholoectypus larteti* (Cotteau) from the Echinoid Marker Bed, Member c, Natih Formation of Jebel Madamar. All measurements in millimetres.

a half to four ambulacral plates opposite a single ambital interambulacral plate. One third of the ambulacral plates lie below the ambitus.

Interambulacral plates are very broad and low at the ambitus. There are 25 plates in a column at about 20 mm test diameter, rising to 32 or 33 at about 29 mm test diameter (Figure 17). 45% of the interambulacral plates occur beneath the ambitus. The most adapical plates have a single differentiated primary tubercle but other plates have up to six equal-sized tubercles arranged in an offset row (Figure 14d–f). Over the remainder of the plate there are semi-regular horizontal rows of miliaries.

The periproct is small, longitudinally elongate and pointed both adorally and adapically (Figure 18a). It is situated about midway between the peristome and the ambitus. Its width is 65–80% of its length (mean = 72%, SD = 4.6%, N = 14), and its length 14–20% of the test diameter (mean = 17%, SD = 1.7, N = 15; Figure 17). The distance separating the periproct from the peristome is 14–19% of the test diameter (mean = 15%, SD = 1.5%, N = 15; Figure 17) and this is composed of the first four, or occasionally five interambulacral plates. The periproct lies between plates 4a, b and 8a, b, or rarely between plates 5a, 4b and 9a, 8b. The distance separating the adapical end of the periproct and the ambitus is 4–9% of the test diameter (mean = 6%, SD = 1.3, N = 15) (Figure 17) and is slightly shorter than the distance from the periproct to the peristome. The peristome is circular and 20–26% of the test diameter in diameter (mean = 23%, SD = 1.8%, N = 11; Figure 17). Buccal slits are sharp and well defined. The peristome is deeply invaginated and the oral surface pulvinate (Figure 14e, SD = 1.3%, N = 15; Figure 17) and is slightly shorter than the distance from the periproct to the peristome. The peristome is circular and 20–26% of the test diameter in diameter (mean = 23%, SD = 1.8%, N = 11; Figure 17). Buccal slits are sharp and well defined. The peristome is deeply invaginated and the oral surface pulvinate (Figure 14e).

Internally there are feeble thickenings of the test along the adradial margins of

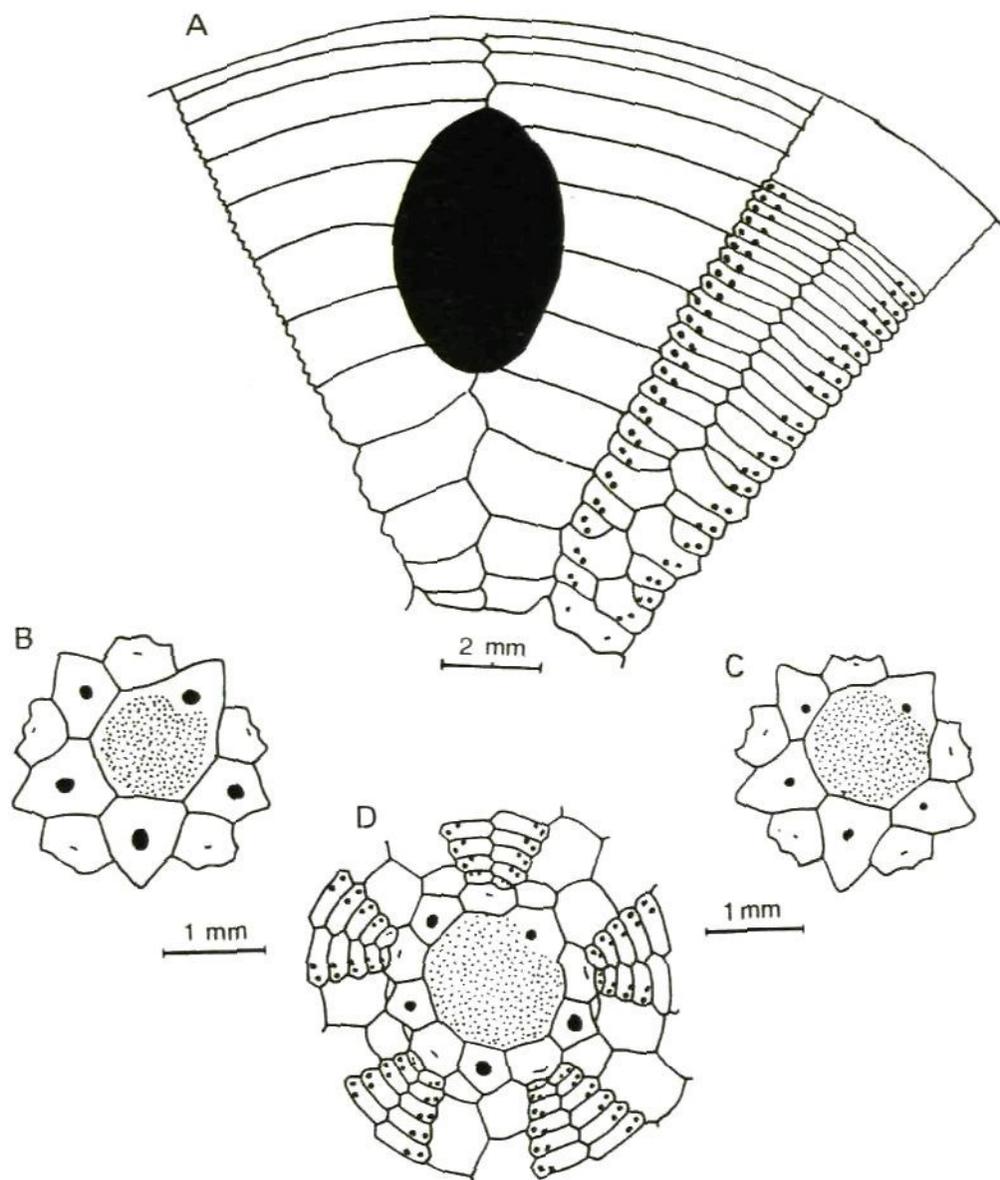


Figure 18. Camera lucida drawings of plating in *Coenholectypus larteti* (Cotteau), from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian at Jebel Madamar. A, BMNH E83130, oral surface-posterior interambulacrum with periproct and adjacent ambulacrum; scale bar = 2 mm. B–D, apical disc plating, scale bar = 1 mm; B, BMNH E83131; C, BMNH E83129; D, BMNH E83132.

interambulacra on the oral surface, where plates thicken to about twice their usual thickness. However, these appear as low undulose features on the interior of the test and not as sharply defined buttresses. There are marked interambulacral ridges forming a perignathic rim to the peristome, but the structure of this area is not clearly seen and it is not known how large these are in comparison to the auricles.

**Remarks.** This species was first described from Syria by Cotteau (1869). It is readily distinguished from other species by its inflated shape and rounded profile and by the

small size and position of its periproct. A number of subspecies have been described in the literature, but all seem to fall within the range of variation encountered within single populations. The species is known from the Cenomanian of Algeria, where it was described under the name *Holectypus chauveneti*, and from Egypt and the Sinai Peninsula, Israel, Jordan and Syria. Previous authors have described this species under the generic name *Holectypus*. However, it is here transferred to the genus *Coenholectypus* because it has five gonopores, not four. Ali (1989, figure 5(10)) illustrated a *Coenholectypus* from the supposed Maastrichtian of the United Arab Emirates. The figure shows only the aboral surface and is completely undiagnostic. Its apical disc structure is different from that of *C. larteti* having five equally developed genital plates and it is probably just a depressed form of *C. inflatus* (Cotteau & Gauthier).

Order Spatangoida Claus, 1860  
Family Hemiasteridae Clark, 1917  
Genus *Hemiaster* Agassiz, 1847  
*Hemiaster syriacus* (Conrad, 1852)  
Figures 19a–d, 20

1852 *Holaster syriacus* Conrad, in Lynch, p. 212, pl. 1, fig. 2.  
1877 *Hemiaster orbignyianus* Lartet, p. 150, Pl. 13, figs 11, 12.  
1878 *H. gabreilis* Cotteau, Peron & Gauthier, p. 116, pl. 4, figs 9–12.  
cf. 1888 *H. lusitanicus* Loriol, p. 100, pl. 19, figs 1–7.  
cf. 1888 *H. subtilis* Loriol, p. 106, pl. 21, figs 1–3.  
1912 *H. cf. gabreilis* Fourtau, p. 62.  
1914 *H. gabreilis* var. *aegyptiaca* Fourtau, p. 74, pl. 6, fig. 7.  
1925 *H. syriacus* Conrad; Blanckenhorn, p. 103, pl. 8, figs 33–35.

**Diagnosis.** Oval, depressed species of *Hemiaster* tapering slightly posteriorly with the periproct visible from above. Posterior petals about two-thirds the length of anterior petals; both rather narrow and reaching two-thirds of the way to the ambitus. Apical disc lies slightly posterior of centre. Anterior ambulacrum narrow, parallel-sided, anterior notch virtually absent. Peristome crescentic.

**Material.** Three specimens, BMNH E83144–5, E83284, one of which is crushed, from Jebel Madamar; one, BMNH E83285, from Jebel Salak.

**Description.** Tests are 17–27 mm in length and 15–24 mm in breadth (83–88% of length). The widest part of the test lies slightly in front of the midpoint, 40–45% of test length from the anterior border. Test height is 60–65% of test length and the tallest part of the test lies well to the posterior midway between the apical disc and the periproct. The test slopes anteriorly to a rounded anterior margin and there is a slight tallon posteriorly (Figure 19c).

The apical disc is compact with four gonopores. It is slightly longer than broad. Genital plate 2 is long and narrow and separates the two posterior genital plates (Figure 20c). Other genital plates are small and sub-equal and are largely filled by their gonopore. The posterior two ocular plates abut. The apical disc lies about 55% of the test length from the anterior margin.

The petals are more or less straight and are arranged almost cross-like (Figure 19a). The anterior pair reach about two-thirds of the way from the apex to the ambitus while the posterior pair are shorter and reach only slightly more than half way. Anterior petals are 1.5 times as long as the posterior petals. Pores are elongate

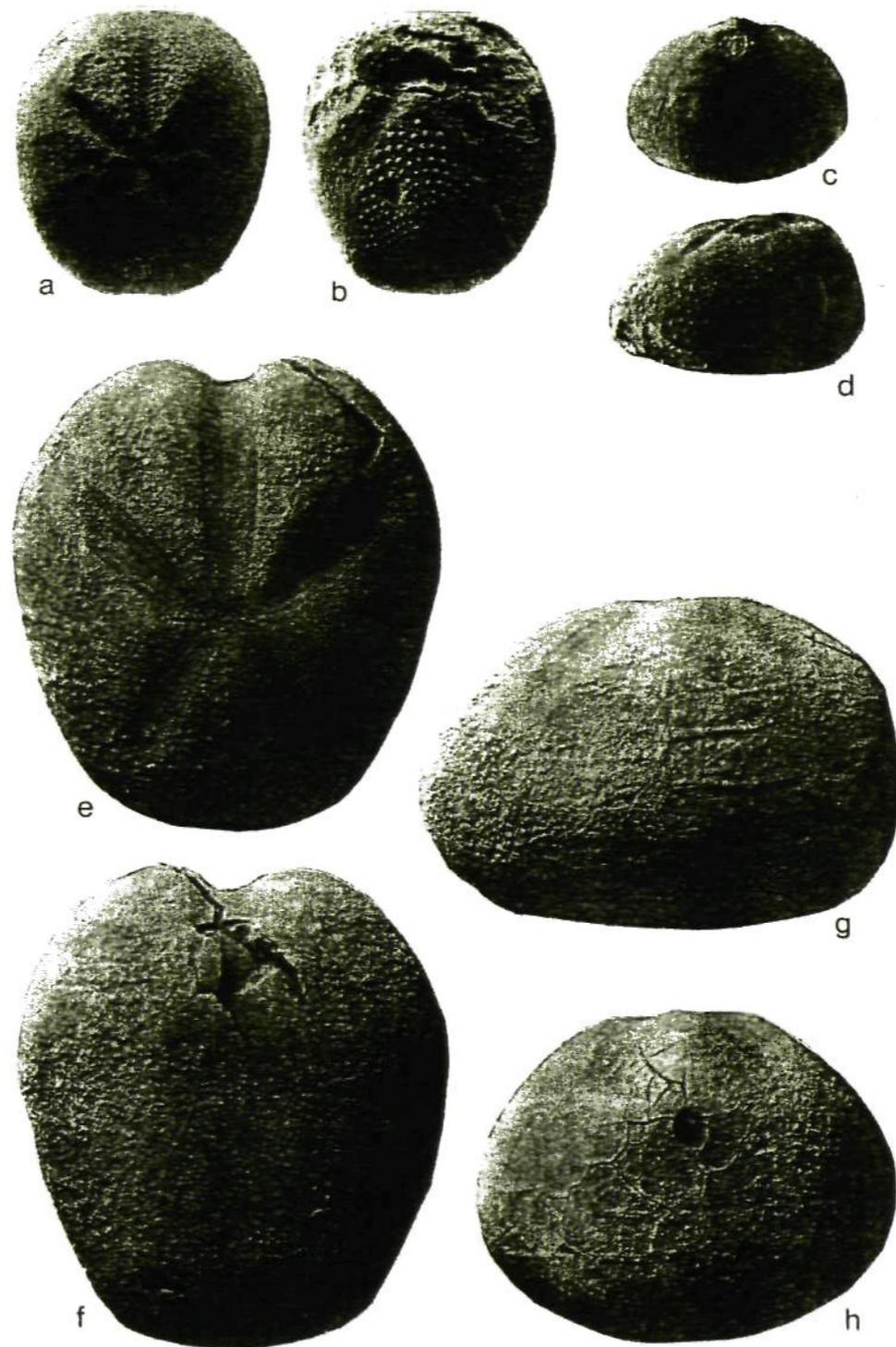


Figure 19. All specimens from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian, at Jebel Madamar; MDNM  $\times 2$ . a-d, *Hemiaster syriacus* (Conrad), BMNH E83144; oral, apical, lateral and posterior views. e-h, *Hemiaster cubicus* Agassiz & Desor, BMNH E83286; oral, apical, lateral and posterior views.

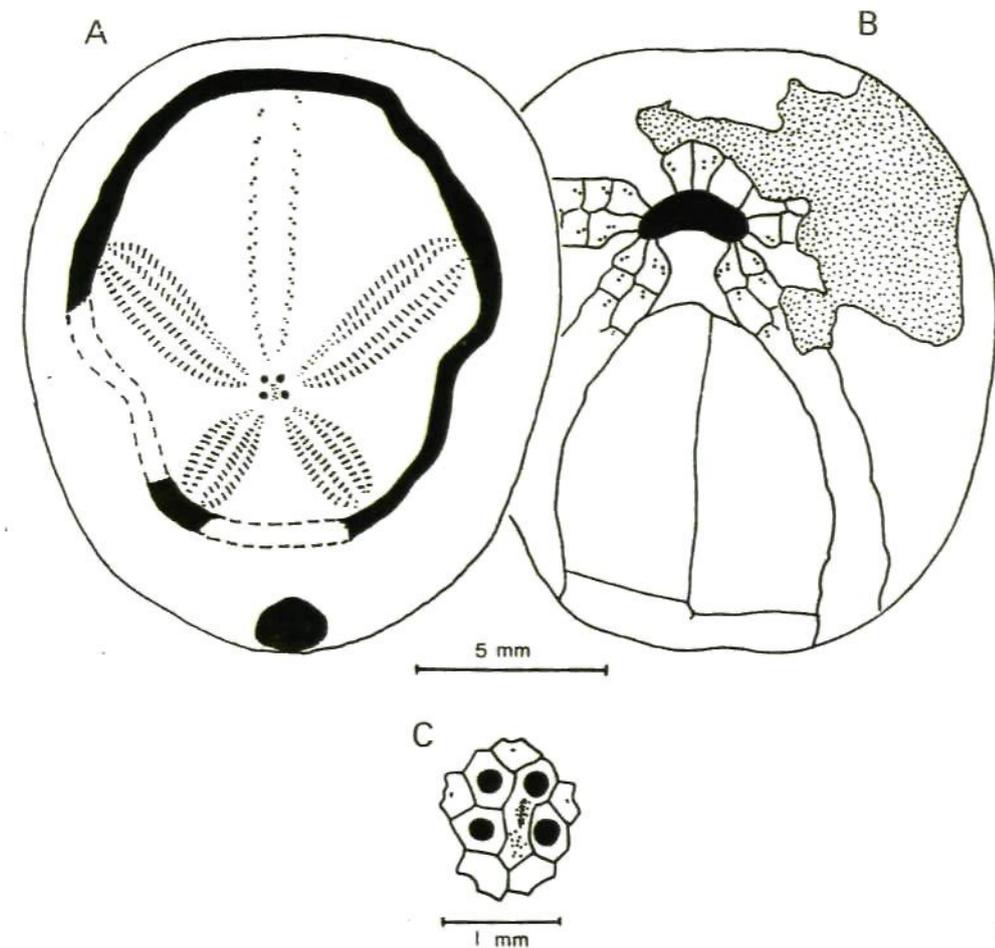


Figure 20. Camera lucida drawings of *Hemiaster syriacus* (Conrad), BMNH E83144, from the Echinoid Marker Bed, Member late middle Cenomanian, at Jebel Madamar. A, B, apical and oral views; black band = peripetalous fasciole (dashed segments inferred); stippled region = damaged part of test. C, apical disc plating.

slits, characteristic of species of *Hemiaster*. The anterior ambulacrum lies in a shallow groove adapically but this depression more or less disappears by the ambitus. The frontal groove is narrow and parallel-sided.

The peripetalous fasciole is thickest at the base of the anterior petals. It forms a semicircle around the anterior of the test and bends sharply behind the anterior petals (Figure 20a).

The periproct is visible from above and lies very high on the test, its base being 75% of the test height above the base. It is relatively small and slightly elongate vertically. The peristome lies 70% of the test length from the posterior and is crescentic in outline due to projection of the labrum. The labral plate is short and broad (Figure 20b).

*Remarks.* The taxonomy of Cenomanian species of *Hemiaster* is in dire need of revision. In the past a large number of specific names have been erected based on one or a few specimens only and largely distinguished on subtle differences in shape. There are no biometric studies of populations from single localities for any North

African or Middle East species. This means that the validity of many of these nominal species is questionable. Unfortunately only four specimens from Oman were collected and it is not possible to establish the variation in morphology quantitatively. The Oman specimens appear identical in all respects to specimens described by Conrad, in Lynch (1852), and latter by Blanckenhorn (1925) from Syria under the name *Hemiaster syriacus*. They also bear a very close resemblance to specimens from the Sinai Peninsula and from Algeria described under the name *Hemiaster gabrielis* Cotteau *et al.* (1878). As noted by Fourtau (1914, p. 75), certain species from the Cenomanian of Portugal described by Loriol (1888) also appear to be virtually identical, namely *H. lusitanicus* and *L. subtilis*. Proper biometric analysis of populations of these species is required before we can be certain whether or not they are conspecific.

*Hemiaster cubicus* Agassiz & Desor, 1847

Figures 19e–h, 21

1847 *Hemiaster cubicus* Desor; Agassiz & Desor, p. 124.

1855 *Hemiaster cubicus* Desor; Orbigny, p. 237, pl. 879, figs 1–7.

1914 *Hemiaster cubicus* Desor; Fourtau, p. 67, pl. 6, figs 1–5.

1921 *Hemiaster cubicus* Desor; Fourtau, p. 87.

1925 *Hemiaster cubicus* Desor; Blanckenhorn, p. 99, pl. 8, figs 28, 29.

**Diagnosis.** A *Hemiaster* with long, sub-equal petals reaching about 3/4 of the way to the ambitus. Apical disc sub-central. Peristome very far forward, directed anteriorly and largely covered by the labrum in oral view. Labral plate very long and narrow.

**Age and distribution.** Very common in the Cenomanian of Egypt and Israel; unknown from Algerian or European Cenomanian.

**Material studied.** Three specimens, BMNH E83286–8, all from the Echinoid Marker Bed at Jebel Madamar. One specimen is incomplete, the other two are large, complete individuals and form the basis for the following description.

**Description.** The test is subquadrate in outline with a moderately deep and well-defined anterior sulcus (Figure 19e–h). The posterior of the test is squarely truncated and the widest point on the test lies slightly anterior of mid-length. The two complete specimens have test lengths of 35 and 36 mm, maximum widths of 31 and 34.5 mm (89–96% of test length) and heights of 24 and 26 mm (69–72% of test length). In profile the posterior is vertically truncated and the anterior well rounded. The highest point on the test more or less coincides with the apical disc and the upper surface is gently domed (Figure 19g).

The apical disc lies more or less centrally. Its anterior edge lies 47–49% of the test length from the front of the test. It is tetrabasal and genital 2 extends posteriorly separating the posterior two genital plates (Figure 21). The apical disc is much broader than long.

The anterior ambulacrum lies in a moderately deep sulcus that continues to the peristome. There are about 24 small, rather widely spaced pores in each column between the ocular and the peripetalous fasciole, which lies slightly above the ambitus. The petals are long, deeply sunken and sub-equal in length. The posterior petals are some 82–90% of the length of the anterior petals. There are just over 50 pore-pairs in the anterior petals and about 46 in the posterior petals. The anterior petals reach 80–82% of the radial length to the ambitus, while the posterior petals reach about 70% of the radial length. The angle formed between the anterior two

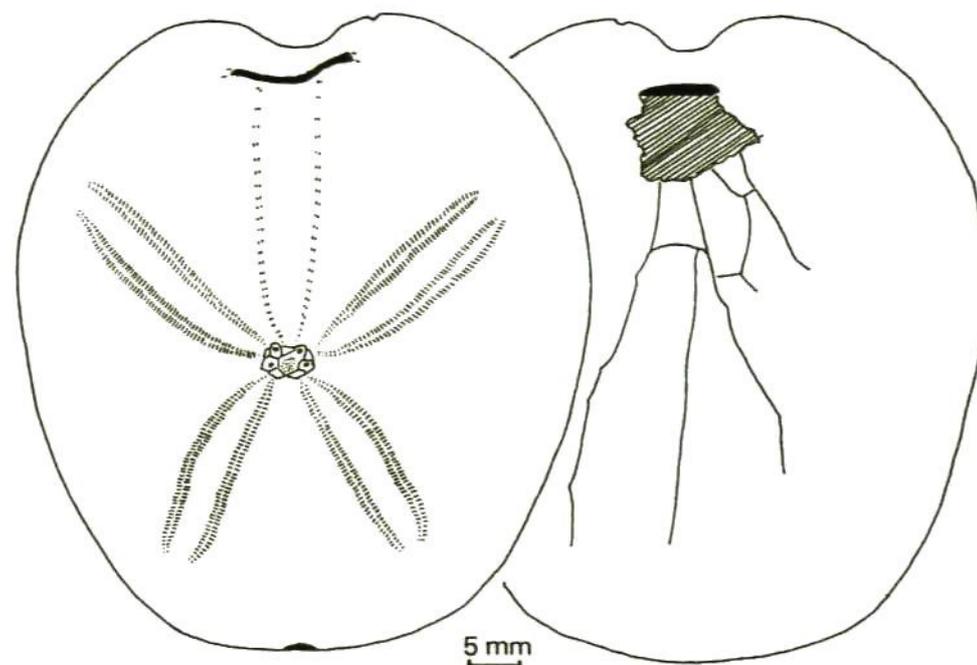


Figure 21. Camera lucida drawings of *Hemiaster cubicus* Agassiz & Desor, BMNH E83286, from the Echinoid Marker Bed, Member c, Natih Formation, late middle Cenomanian, at Jebel Madamar: apical and oral views. Black band = peripetalous fasciole; lined area = missing part of test.

petals is  $115^\circ$  while that between the posterior two petals is  $65^\circ$ . There is a peripetalous fasciole but only the anterior portion is preserved, due to weathering. This lies close to the ambitus.

The lower surface is gently rounded. Plating on the oral surface is largely obscured. The peristome, which is about 3.5 mm in width, lies very close to the anterior border and is directed forwards. The distance between the frontal edge of the peristome and the anterior is only about 5% of the test length. The peristome is largely hidden from sight in oral view because it is orientated almost vertically and covered by the labral plate. The labrum is extremely long and slender, and appears to have been about 7 mm in length (the anterior is missing in the specimen that shows plating arrangement). The interradial plastronal suture is inclined towards ambulacrum V.

The periproct is relatively small (12% of the test height) and slightly elongate vertically. It lies towards the top of the posterior surface, its base being about 58–66% of the test height above the base.

**Remarks.** *H. cubicus* is a very distinctive species because of its long, sub-equal petals, and very anterior and forward-pointing peristome that, in oral view, is largely hidden from sight. The extreme length of the labral plate is also unusual. No other species of *Hemiaster* can be confused.

The species was first described on the basis of material from the Cenomanian of Egypt, where it is common. It has also been reported from the Cenomanian of Palestine (Blanckenhorn, 1925).

## 7. Conclusions

1. A relatively rich and diverse fauna, consisting of six regular and three irregular echinoids, is present in the Cenomanian Natih Formation of northern Oman. This horizon, termed the Echinoid Marker Bed, forms a distinct, correlatable unit within that region.

2. Cenomanian microfossils are described from this region for the first time. These allow for precise dating of this horizon as late middle Cenomanian. A number of these taxa are not known outside the Middle East region.

3. Microfauna, microflora and lithofacies analyses suggest that the Echinoid Marker Bed represents pre-reefal deposits lying immediately behind a rudist shoal/biostrome complex fringing the Natih carbonate shelf. The preponderance of regular echinoids over irregular echinoids suggests that the sediment must have been predominantly algal bound.

4. The echinoid fauna is very similar to the fauna of the Sinai Peninsula and the Lebanon/Syria region. Eight of the nine species are also known from the Sinai Peninsula. Faunal links with the western Mediterranean region are much weaker.

5. The composition of the genus *Pedinopsis* is reviewed and three species groups recognised and distinguished at subgeneric level. The new subgenus *Sinaiopsis* is erected.

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On Lithocodium Elliott; its palaeobiological and stratigraphical  
significance

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**ABSTRACT** - Lithocodium aggregatum Elliott (with its synonyms, Bacinella irregularis Radoičić and Pseudolithocodium carpaticum Mišić), Radoicicinellopsis sterna (Radoičić) and Bacinellacodium calcareus Dragastan are referred to the new subfamily Lithocodioidae of the family Codiaceae (marine, chlorophycean, calcareous algae). The significance which has been ascribed to these taxa by past authors is assessed. Radoicicinellopsis is proposed as a new genus. Lithocodium is redescribed and its diagnosis is emended. The importance of this alga in palaeoenvironmental interpretation and fossil hydrocarbon accumulation is noted.

**INTRODUCTION**

Lithocodium aggregatum was first described as a new genus and new species by Elliott (1956, 1957) using specimens obtained in thin section from

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"Lower Cretaceous" limestones of the Rumaila No.4 well, Iraq. The taxon, which was firmly referred to the codiacean algae, was subsequently recorded to occur abundantly in the top of the Iraqi Ratawi Formation with Pseudocyclammina lituus (Dunnington et al., 1959), of probable Hauterivian age, and at least as high stratigraphically as the Albian in that country (Elliott, 1963). L. aggregatum was also reliably recorded in the Early Cretaceous limestones of Iran (Kalantari, 1986, text-fig. 85.1), from the Lekhwair Formation (broadly equivalent to the Ratawi Formation) of Oman (Simmons & Hart, 1987) and abundantly in the succeeding Kharaib and Shuaiba Formations (Barremian - Aptian) of the southern Arabian Gulf (Alsharhan, 1985; Alsharhan & Nairn, 1986; Simmons & Hart, 1987). This species has also been found in the upper Aptian of Lebanon (Basson & Edgell, 1971), and in limestones as old as Berriasian - Valanginian in Sharjah, U. A. E. (Connally & Scott, 1985). Eastwards, L. aggregatum has been recorded from the Cenomanian - Turonian of central Afghanistan (Kaever, 1965), from the late Aptian of north India (Cherchi et al., 1984) and from the early Cretaceous of China (Mu Xi-nan, 1986). The species is also known westwards, from southern Europe (Urgonian of Bulgaria, Chrishev & Bakalova, 1974; early Cretaceous of the Italian central Apennines, Praturlon, 1964; Aptian of southern Italy, Luperto Sinni, 1979; Late Jurassic to Cenomanian in southern French Aquitaine, Bouroullec & Deloffre, 1968; Valanginian - Gargasian of the French eastern Pyrenees, Jaffrezo, 1975; Oxfordian - Portlandian of Portugal, Ramalho, 1971), but it does not yet appear to have been found in northern Europe or, with certainty, in North Africa or America; it has been recorded, but not illustrated, from the early Cretaceous of Cuba, Texas and the Blake Escarpment (Johnson, 1968, 1969).

Quite independently of the proposal of Lithocodium, Radoičić (1959) had published, also as a new genus and new species, Bacinella irregularis, based upon thin-sections of "algae incertae sedis" in "Barremian-Aptian" limestones of Bosnia and Serbia, in the Yugoslav Dinarides. These findings were confirmed (Radoičić, 1960) and B. irregularis was recorded from many Early Cretaceous limestones of southern Europe (e.g., the Valanginian - Aptian of S.W. Italy, Sartoni & Crescenti, 1962; early to late Aptian limestones of S. Italy, Chiocchini & Mancinelli, 1977; Valanginian to Bedoulian limestones in Provence, Masse, 1976) as well as in rocks of about the same age from more eastern localities (the Shuaiba Formation, Aptian, of Oman, Hughes Clarke, 1988; the Valanginian to Hauterivian limestones, with Pseudocyclammina lituus, in Iran, Sampo, 1969; early Cretaceous limestones in China, Mu Xi-nan, 1986). Occurrences in limestones as old as Late Jurassic have also been recorded from southern Europe (Portugal, "Upper Oxfordian/Kimmeridgian" to Valanginian, Ramalho, 1971; the French eastern Pyrenees, late Jurassic - Late Urgonian, Jaffrezo, 1975; the late Jurassic to Cenomanian of Aquitaine, Bouroullac & Deloffre, 1968; "Portlandian" of central Italy, Barattolo & Pugliesi, 1987; Tithonian to Barremian near Bucarest in Roumania, Dragastan, 1966; unspecified Upper Jurassic limestones of mainland Greece, Zambetakis-Lekkas & Karotsieris, 1986). Bacinella has also been recorded from the Triassic (Samuel et al., 1972, p.129; Borza, 1975, pl.4) but these records are yet to be confirmed.

Like Lithocodium, B. irregularis seems not to have been recorded with any reliability from northern Europe, Africa or America. The two taxa have remarkably similar confirmed recorded ranges; both are certainly known in the late Jurassic - middle Cretaceous limestones of Tethys, in the Portugal to China area. Even if other species, originally assigned to these genera,

are included, the main pattern of distribution is not significantly changed; Endo (1961) reported L. japonicum and L. morikawai, both new species, from Upper Jurassic limestones of Japan (Johnson, 1964), and Radoičić (1972) described as new B.? sterni from Cenomanian limestone in Yugoslavia (Conrad et al., 1977).

The similarity of stratigraphic range and palaeogeographical distribution is paralleled by that of the morphology of the type specimens of the principal taxa concerned. Elliott (1956) illustrated microphotographs of three specimens of L. aggregatum, which represented the holotype (1956, pl.1, fig. 5) and two paratypes (loc. cit., figs. 2 and 4) from the same subsurface sample. Together, they clearly showed the character believed to typify Lithocodium - an encrusting or nodose growth-mode in a codiacean with a subdermal skeletal structure similar to that of regularly segmented genera (like Halimeda). One of the paratypes (loc.cit., fig.4) particularly well showed that the inner, irregularly oriented but coarse filaments could be surrounded by an outer layer of much finer, sub-radial filaments, and that, in both layers, the filaments could be separated by calcified tissues as thick, or even thicker than, the filaments themselves. This paratype is very similar indeed to the holotype of Bacinella irregularis Radoičić.

When Radoičić (1959) first described B. irregularis, she published photomicrographs of two specimens from different localities, the holotype (1959, pl.3, fig. 1) and one paratype (loc. cit., fig.2). Although Radoičić noted that the "subdermal structure" (that is, the outer layer filamentous arrangement) could be "similar to that one of the species Lithocodium aggregatum Elliott" (Radoičić, 1959, p.92), she did not clearly attempt to distinguish between them. The holotype of B. irregularis is morphologically

very similar indeed to L. aggregatum, as noted above, and is distinguishable only by the more frequent occurrence in the former of thin walls separating the adjacent cells of particular filaments. This difference is one of degree; thin walls separate adjacent cells while thickly calcitised tissues separate adjacent filaments in both specimens, in both the outer and the inner layers of the thalli. A more clearly recognisable difference between the taxa appears to be shown by the morphology of the illustrated paratype of B. irregularis (Radoičić, 1959, pl.3, fig.2). In this specimen, only the inner layer of the thallus is seen (no cortex is visible), and all the filaments are of the coarser kind and are very randomly arranged, with no clear directions of growth; their cells are divided only by thinly calcitised walls, and walls of equally thin calcification may separate adjacent filaments. It is this "vacuolated" and apparently poorly organised structure, regardless of the precise morphology of the holotype, which has been taken by many authors to typify Bacinella. This is in spite of the fact that "systematic distinction based essentially on the degree of calcification appears to be wrong" (Bassoulet et al., 1977) in any member of the Chlorophyta.

Variation in the degree of calcification was even used by Mišik (1979) for the distinction of his new genus Pseudolithocodium (typified, monotypically, by P. carpaticum Mišik n.sp.) which was clearly corticate, like Lithocodium, but in which "the tubes of [the] cortical layer are densely packed, not submerged in micrite" (Mišik, 1979, p.709). In other words, the thickness of the calcified tissues between the filaments of the cortex of "Pseudolithocodium" is no greater than it was between the filaments in the subcortical parts of the paratype Bacinella irregularis. It is clear, from these specimens alone, that the degree of calcification

varied in forms with and without a cortex, and that it would seem to be unwise to use an observed degree as the basis for a taxonomic distinction. Such taxa would be difficult to distinguish in many other fossil assemblages.

Although some authors (e.g., Alsharhan, 1985; Luperto Sinni, 1979; Poignant, 1968; Simmons & Hart, 1987) have concluded that Lithocodium and Bacinella are synonymous genera of the Codiaceae, others (e.g., Barattolo & Pugliese, 1987; Bouroullec & Deloffre, 1968; Elliott, 1963; Jaffrezo, 1975; Ramalho, 1979) have considered them as separable, probably distinct genera of that same suprageneric group. Some (e.g., Chrishev & Bakalova, 1974; Johnson, 1968, 1969) have been willing to refer Lithocodium to the Codiaceae, but have been unhappy to consider Bacinella as anything but "algae incertae sedis"; Radoičić (1959) is unclear but probably belonged to this group of workers. Opposed to this view is that of those who believe that Lithocodium and Bacinella were of organic origin, but not from the Codiaceae (Segonzac & Marin, 1972). Previous systematic assignments of Lithocodium-Bacinella have encompassed both the green and the red algae. Both the Codiaceae and Dasycladaceae, the marine families of the Chlorophyta, are skeletally aragonitic, and only the Corallinaceae of the Rhodophyta are calcitic (e.g., Wray, 1977). No published photomicrograph, or unpublished but studied specimens, give any indication that L. aggregatum or B. irregularis were anything but primarily calcitic. This is discussed further in this paper. The taxa have also been considered to belong to zoological phyla, and have been referred to orders as diverse as the stromatoporoids and the foraminifera (see, e.g., Maurin et al., 1985). Masse (1976) has suggested that these microfossils were of botanical but

multiple origin, comparable to the algal symbioses seen in terrestrial lichens.

Maurin et al. (1985) and Camoin and Maurin (1988), basing their decisions on material from the Upper Cretaceous of Tunisia, the Lower Cretaceous of Sicily and the Middle East, and the Upper Jurassic of Sumatra, claimed that the origin was universally microbial; they extended the stratigraphic significance of "bacinellid-textures" to include everything from Precambrian to Recent, but admitted that "the debate is not closed". There can be no doubt that the microstructures commonly known as Lithocodium and Bacinella are common in micritic, calcareous, apparently well oxygenated, marine sediments of Mesozoic age in Tethys; if their origin is merely microbial, why are they confined to these Tethyan, Mesozoic carbonates? Why do not identical microstructures occur equally commonly in argillites, in the Americas, and in sediments of Tertiary and even Quaternary-Recent age? Again, if their origin is merely microbial, why is there such a narrow size-limitation on the "vesicles" of both Lithocodium and Bacinella, when both, it is presumed, would be merely lithified bubbles of (calcareous!) mud following microbial gas-generation? The "bacinellid-texture" developed in stromatolites may even there have an algal origin (Wright & Wright, 1985); true Lithocodium-Bacinella specimens are, as shown below, nodular-encrusting and are not at all stromatolitic (or mud-mound-like) even in gross growth-plan. As for the bacterial genesis of the calcium carbonate itself, nothing can be proved: as would be expected, all the specimens of the Mesozoic microfossils that we have studied have undergone recrystallisation to some degree (not excluding obvious dolomitisation!) and this may obscure resemblance to any of the biogeochemically produced carbonate grains shown in her 38 plates by Castanier (1987); grains which

resemble lithified (or SEM coated?) bacteria may, of course, be found, but bacteria are present on all organisms, living and dead. The aseptic alga would be unique.

In this paper, we attempt to demonstrate the identity of Lithocodium aggregatum, Pseudolithocodium carpaticum and Bacinella irregularis, the place these microfossils have within the Codiaceae, their significance in the interpretation of palaeoenvironments, their role in producing high intraparticle porosity, and, therefore, their importance as primary producers of porous limestone petroleum reservoirs in the Middle East.

#### **MATERIALS AND METHODS**

The problem was highlighted by the need to study the Early Cretaceous sequences (the Shuaiba, Kharai, Lekhwa and Habshan Formations) retrieved during field geology in Oman (Simmons & Hart, 1987) and during oil-well drilling in the United Arab Emirates (particularly in offshore and onshore Abu Dhabi). Core-slab successions from eleven selected wells were studied macroscopically in the laboratories of ADNOC. In total, the work has provided many thousands of field, core and cuttings samples of limestones which have been routinely examined in thin section for their entire assemblages of fossil microfauna and microflora. Many of the sections of well cores were routinely stained with Alizarin Red-S, and impregnated with resin, to identify dolomite and ferroan calcite and to enable quantification of crystallography and porosity.

Additional material, similarly studied, was obtained from the southern Apennines, Italy; these limestones displayed well-preserved sections of Lithocodium-Bacinella but the specimens were solidly infilled with

secondary, sparitic calcite. Most of the specimens available from the Middle East lacked such solid infilling, and some (especially from the Lekhwair formation) seemed to possess a total lack of secondary infilling; these, especially, were studied under S. E. M.

#### THE IDENTITY OF LITHOCODIUM AND BACINELLA

As noted above, the holotype and paratype thin-sections of Lithocodium aggregatum (Elliott, 1956) undoubtedly refer to the same species and they are not to be separated from the holotype thin-section of Bacinella irregularis (Radoičić, 1959). This was emphasised and most clearly shown by Segonzac & Marin (1972), who illustrated every conceivable morphological intermediate between the holotypes of the two taxa, using only Aptian limestone specimens from north-east Spain. Such morphological intermediates are also illustrated here (Plates 1-5). There can be no doubt that Lithocodium aggregatum Elliott is the senior synonym for all such forms. Similarly, L. aggregatum, for the reasons noted above, must be regarded as the senior synonym of Pseudolithocodium carpaticum Mišik.

Ramalho (1971, pl. 29, fig.1) has illustrated a remarkably well preserved nodule formed by Lithocodium (reproduced Text-figure 1), in which the pattern of growth of the alga may be noted. This nodule shows no erosion or abrasion from any post-mortem transportation; it was probably buried virtually in situ in the calcite-mud which now forms the micritic matrix of its rock. The posture and structure of the nodule shows that it has nothing in common with the layered, unstructured stromatolites of gaseous, microbial origin (c.f. Maurin et al., 1985). A smaller nodule of Rivularia (a) forms the base upon which the Lithocodium grows (organic nodules

typically form such bases - e.g., sponge skeletons as shown by Cherchi et al., 1984, pl. 1, or microgastropods, as on Plate 4, Fig. 4 - but they provide substrates for initial algal colonisation, as they are always too small to have provided decaying bases for adequate microbial flatulence of the kind favoured by Maurin et al., 1985). The Rivularia nodule is partly covered (b) by thick-walled cortical and near-cortical Lithocodium skeleton and partly (c) by thin-walled medullary structures. The latter show at least four successive layers of cortical development (d) now embedded in the skeleton of the thallus. The last-formed cortical structures (e) are thickest-walled, but lie directly on top of poorly calcified, "vacuolated" medulla (f). Laterally to the main thallus growth direction, no recognisable cortex structures are apparent.

From this and similar specimens, problems of identity are isolated:

- (1) Although some specimens have every appearance of possessing a codiacean cortex of fine, subradial filaments, such specimens may also appear to lack a siphonate, filamentous medulla. As pointed out by Segonzac & Marin (1972, p.334) "Lithocodium présente une aberration apparente de structure, avec une base cloisonnée et un sommet siphonné. Il ne rentre dans aucune catégorie actuelle or fossile." This is not typically Codiacean, if the preserved skeletal structure is a true reflection of the original tissues.
- (2) Other specimens, like the paratype of Bacinella irregularis, appear to lack any cortical skeletal structure and merely consist of irregularly arranged, coarse (but with little apparent consistency of size), "medullary" siphons or filaments, which may be septate. This appears to be an opposite condition from that noted as (1), above, but would be easily derived from sections of specimens cut across the thallus, at right angles

to the direction of thallus growth, where the cortical, terminal structure is not yet developed.

Such apparent contradictions are easily explained not only by the specimen described above but by the characteristic property of the Codiaceae to calcify secondarily, after the complete growth of soft tissue, and then perhaps to calcify only partially. Partial calcification may leave some tissue without a calcareous skeleton. This is commonest in those Codiacea where the thallus is composed of erect tufts (e.g., Halimeda, Boueina, etc.): as Johnson (1969, p.35) so clearly put it, "calcification .. begins at, or just inside, the outer margin and works inward. Older segments may be completely calcified, but many specimens show only partial calcification with the central structure not preserved."

We believe that Lithocodium-Bacinella answers the following description:

- (a) It grew as an essentially encrusting codiacean, and was not erect and tufted,
- (b) It developed a nodular thallus in which only the terminal zone of growth developed cortical structures,
- (c) It may have been only partially calcified and that calcification began internally; consequently, the medulla is always calcified, but the cortex may be fully calcified (Plate 1, Figs. 1-4, and Plate 3, Fig. 1, as in the paratypes of L. aggregatum and the holotype of B.irregularis), or only partly calcified (as shown by Praturlon, 1964, fig. 28).
- (d) Even where the medullary or cortical calcification appears to have been complete (in the sense that all tissues possessed a skeleton), the degree of calcification was variable, in that in some areas (or

specimens) the calcified layers were relatively thin, but in other areas (or specimens) they were relatively thick.

- (e) Thinly calcified walls, in particular, may have been skeletally discontinuous (e.g., Plate 4, Fig. 2). The absence of a skeletal wall does not mean that the living alga also lacked a wall of uncalcified tissue in that place; the absence of such skeletal walls gives the visual impression that many filamentous spaces are much larger than the filaments which occupied them, but it should not be interpreted to mean that the filaments, themselves, were so large.

We believe that all of the above apply not only to the Late Jurassic - Albian species Lithocodium aggregatum Elliott (and, of course, to its synonym Bacinella irregularis Radoičić) but also to the Jurassic synonyms called L. morikawai Endo and L. japonicum Endo. "Bacinella?" sterni Radoičić (as figured by Radoičić, 1972) followed the same pattern of growth and calcification in the Cenomanian, and differed from true Lithocodium only in the great reduction (almost to terminal absence) of the cortex. We distinguish, below, this species under a separate generic name (Radoicicinellopsis nov.) but in the same new subfamily, Lithocodioidea; we cannot agree with Masse (1979) in the transfer of this species to the Porostromata. The opposite morphological trend is displayed by the Tithonian - Aptian taxon with a variably calcified medulla but a heavily calcified cortex, distinguished as Bacinellacodium calcareus by Dragastan (1985); the principal difference from Lithocodium, that in Bacinellacodium the cortical filaments are distinctly thinner, longer and more parallel, is essentially a difference of degree, not of kind. The medulla is essentially the same in both genera, but may be very weakly calcified in

Bacinellacodium. In the latter genus, the overall structure is distinctly Codiacean, with strong medulla - cortex differentiation. It confirms our allocation of Lithocodium itself to the family Codiaceae. Between these genera, we are distinguishing not just degrees of calcification of components of the thallus, but the extent of primary development of the cortex itself: thick and solely terminal in Bacinellacodium, much reduced and repetitious in Lithocodium, but reduced even to a non-filamentous state in Radoicicinellopsis. This is not to be confused with the recognition of different degrees of calcification in different specimens of Lithocodium, where the degree of cortical development is essentially always the same. All of these genera are now referred (below) to the same, new subfamily, Lithocodioidea.

Of course, all of the Codiaceae can be readily distinguished from the members of the family Rivulariaceae Rabenhorst 1865, of the division Cyanophyta, as the latter have no medulla/cortex differentiation at all but merely possess regularly diverging filaments which are orientated subparallel to the long axis of the thallus (e.g., as in Rivularia (Roth) Agardh itself, which, according to Dragastan (1985), is a senior synonym of the commonly recorded genus Cayeuxia Frollo).

All these codiacean taxa appear to constitute a recognisably distinct group of Codiaceae, of common Late Jurassic - Cretaceous stratigraphic Tethyan range, and they often occur in association. Consequently, it is appropriate to recommend that fossils of the family Codiaceae be considered to comprise the following subfamilies of the Chlorophyta (the names following the standards outlined by Jeffrey, 1973; Wray, 1977; Voss et al., 1983, articles 16-19).

## SYSTEMATIC TAXONOMY

Class CHLOROPHYCEAE Kuetzing, 1843:

Order SIPHONALES Wille, 1884:

Family Codiaceae (Trevisan) Zanardini 1843:

### Subfamilies:

(1) Halimedoidea nov. subfam.: thallus of erect tufts, regularly segmented; typically with filaments differentiated into an inner medulla and continuous outer cortex; typically with calcification of tissues between filaments, initially at or near the outer margin of the cortex; the medulla may be calcified, in whole or in part, or it may remain uncalcified; the calcareous skeleton is primarily aragonite; includes Halimeda, Boueina, Arabicodium, Carpathicodium, etc.

(2) Lithocodioidea nov. subfam.: thallus is encrusting, initially at least, and the fully-grown thallus may be nodose to subcylindrical in form; it is initially calcified at earliest tissue growth stages, but later it may lack uniformity of the extent of calcification and may remain uncalcified in parts of the thallus; filaments are differentiated into those of an internal medulla and terminally the thallus has an external, usually filamentous cortex of increased calcification; the calcareous skeleton is probably primarily calcite; includes Lithocodium Elliott, Bacinellacodium Dragastan and Radoicicinellopsis nov.

Subfamily Lithocodioidea nov.

Lithocodium Elliott, 1956, emend.

Lithocodium Elliott, 1956, p.331

Bacinella Radoičić, 1959, p.89

Pseudolithocodium Mišik, 1979, p.709

Descriptive diagnosis:

A Codiacean genus of the subfamily Lithocodioidea (as defined above); initially encrusting, but the thallus may in later growth become subconical, subcylindrical or nodose in shape; the subdermal tubular filaments of the medulla are irregularly arranged, and encrust each other in various directions which are dominantly subparallel to each other and are broadly oblique to, or nearly at right-angles to, the long axis of the encrusting or nodular thallus; the subdermal filaments may bifurcate or trifurcate or variously ramify, and broaden before and during ramification, and are consequently of variable diameter; subdermal filaments are irregularly septate; in the area of terminal growth, the filaments narrow, become subparallel to the long-axis of growth of the previously-formed encrustation or nodule (i.e., they become subperpendicular to the planes of the subdermal filaments) and become heavily encrusted with microgranules of calcium carbonate to form a relatively heavily calcified cortex; in the cortex, the relatively narrow tubular filaments also bifurcate, trifurcate or variously ramify, but they diminish in diameter as they do so, so that the outermost cortical filaments (which have undergone the most ramifications) are the narrowest; the cortical filaments are terminated by a continuous thin sheet of calcium carbonate and are not open to the exterior, but this terminal sheet may be followed by resumed (originally lateral, then supraterminal) growth of subdermal filaments which are followed by another cortical development.

Remarks:

Lithocodium differs from Bacinellacodium Dragastan in possessing distinctly shorter and broader cortical filaments, and the walls of the subdermal filaments of the medulla are more strongly and continuously calcified; the medulla of Bacinellacodium is much reduced. In Lithocodium the cortex is relatively reduced, and is present typically only at the terminal growth-stage area of the thallus. Radoicicinellopsis nov. differs in its much more greatly reduced cortex (which may, in fact, be nonfilamentous even in terminal growth stages); the medulla of that genus is very much enlarged.

Lithocodium aggregatum Elliott emend.

Plates 1-5

Lithocodium aggregatum Elliott, 1956, pp.331-332, pl. 1, figs. 2, 4-5.

Bacinella irregularis Radoičić, 1959, pp.89, 92, pl.3, figs.1-2.

Pseudolithocodium carpaticum Mišik, 1979, pp. 709-710, pl.2, figs.2-8.

Descriptive diagnosis:

A species of the genus Lithocodium as defined above, in which the cortex is regularly formed and possesses two or more (usually three or more) phases of branching and diminution in size of the cortical filaments. The cortical filaments are circular or subcircular in cross-section, but those of the medulla are of irregular cross-section shape. The thalli are 1 to 5cm thick.

Remarks:

This genus may subjectively be monotypic. As noted by Johnson (1969, p.38), "L. regularis" Johnson, 1968, was a complete error: "unfortunately the author identified this as an alga by mistake. It is a foraminifer." The Jurassic taxa L. japonicum Endo and L. morikawai Endo, 1961, do not seem to be separable at species level from the range of variation observed in Early Cretaceous specimens of L. aggregatum.

The thallus of L. aggregatum may consist of a few, broad medullar-cortex growths (as depicted in Text-figure 1, derived from Ramalho, 1971) and this morphologically grades into forms where there are many, narrow but otherwise similar growths (Plate 1, fig.1). Even in such thalli, the medullary filaments are septate (Plate 1, fig. 2; Plate 2, figs. 1, 4), and they are distinctly tubular (Plate 2, fig.3). They ramify diversely with marked broadening of their diameters (Plate 1, figs. 3,4; also Plate 2, fig. 2, where one tube quadrifurcates, the two outer ramifications rapidly bending into the specimen, one of the two inner ramifications later doing the same, and the remaining branch continuing on a path in the same plane as the original tube), but this apparent broadening may also result from incomplete calcification of the walls of the medullary filaments (Plate 2, fig.4). These medullary, subdermal filaments are stacked upon each other, often encrusting earlier-formed medullae in subparallel planes (Plate 3, figs. 2-4). The cortical filaments are heavily calcified and they are distinctly narrower than the previously formed, subdermal filaments (Plate 1, figs. 1-4; Plate 3, fig. 1) but they may be seen to branch even in thin-section (Plate 1, fig. 4). When it is cut obliquely, the complete, nodular thallus is usually seen, in random thin-section of its host limestone, to contain a subdermal (or, at least, initially formed) mass of broad, thinly-walled and relatively weakly calcified medullary filaments, and dermal,

cortical filaments which are distinctively heavily calcified, more clearly subparallel in direction, and which diminish in diameter towards the exterior of the thallus; such a section is characteristic of both the genus and its type species (Plate 4, fig.1).

The growth of the medullary filaments begins upon a substratum which is often biogenic (Rivularia sp., Text-figure 1; gastropod, Plate 4, fig.4) and which is soon encased in these filaments (Plate 1, fig.1; Plate 4, fig.4). Other biogenic, skeletal fragments may be similarly encapsulated during the growth of the medulla; examples include miliolid and textulariid foraminiferan tests (Plate 4, fig.2) and other calcareous algae (Plate 4, fig. 3, shows Thaumtoporella parvovesiculifera (Raineri) (= Polygonella incrustata Elliott) which now lies parallel to the previously formed subdermal filaments, seen lower right of the photograph, but which is encased by subsequently formed, but similar filaments on the other side). Where relatively large biogenic skeletal fragments have been previously bored, the medullary filaments of encrusting L. aggregatum may fill these borings so closely that the impressions may be gained, erroneously, the the encrusting alga had, itself, created the borings! Such a specimen is shown on Plate 5, fig. 2, and this must be compared to other specimens which have been previously bored, obviously by other organisms (e.g., Plate 5, fig.1, where the echinoderm clast shows earlier, much finer borings and corrosion, possibly by sponges and bacteria), and those which have been widely fractured, not bored at all (Plate 4, fig.3). Those calcareous skeletal fragments which form initial substrates for encrustation, and which are longest in contact with the L.aggregatum filaments (as well as being the most obvious source of calcium carbonate for the calcification of the

growing alga), may show no boring or corrosion at all (e.g., Plate 4, fig.4).

As noted above, in the Introduction to this paper, the type horizon of Lithocodium aggregatum Elliott is probably Hauterivian in age, and that the species ranges from Late Jurassic (probably Oxfordian, certainly Tithonian) to Albian, in clean micritic marine limestones of Tethys.

Radoicicinellopsis nov.gen.

Type species: Bacinella? sterni Radoičić, 1972

Descriptive diagnosis:

A Codiacean genus of the subfamily Lithocodioidea (as defined above), initially encrusting but which, in later growth, becomes nodulose or subconical in shape; medullary, subdermal filaments are encrusting, oriented in various directions which are dominantly subparallel to each other and which are nearly at right-angles to the long-axis of the thallus; the cortex is (or successive cortices are) very thin and usually reduced to a thickened layer (or layers) of calcification.

Remarks:

Radoicicinellopsis differs from the other genera of the Lithocodioidea by the great reduction in its cortex. Biostratigraphically, it is the youngest (and last) known genus of this subfamily.

Radoicicinellopsis sterni (Radoičić)

Bacinella? sterni Radoičić, 1972, pp. 228-229, figs. 1 a-c.

#### Description:

A species of the genus which has thalli of 4-6 mm (rarely up to 10mm) diameter and which terminally divides into two or more lobes, with densely encrusting medullary filaments, each about 0.2 mm in diameter.

#### Remarks:

The type specimens were obtained by Radoičić (1972) from micritic, marine limestones of the (probably lowest) Cenomanian, exposed at Urladanas, Yugoslavia. No other records are yet known.

As the genus is monotypic, the morphocharacters of the species are not, as yet, clearly separable from those of the genus.

#### **PALAEOENVIRONMENTAL SIGNIFICANCE**

All the records of Lithocodium aggregatum (and its synonymous references to Bacinella irregularis) which are cited in the Introduction above, and which give sufficient information for the palaeoenvironment under which the microfossils were deposited to be assessed, indicate that all known occurrences of this alga are from marine, micritic limestones. This, like the additional comments noted below, is in complete agreement with the observations we, ourselves, have made in the routine examination and record of many thousands of samples from the Mediterranean area and from the Middle East. If the limestones are sparitic, the Lithocodium specimens are found encased in micrite, and they are clearly allochthonous, having been transported and redeposited from micritic environments. These occurrences are rare; in situ specimens, in which no apparent abrasion or erosion has

occurred, are found in abundance in calcareous, micritic limestone of mudstone or wackestone packing. However, Lithocodium (or any other taxa of the Lithocodioidea) has never been found by us, and its occurrence has never been substantiated, in any argillaceous rock. Specimens are known only in "clean" carbonates.

The micritic matrix in which Lithocodium occurs indicates low palaeocurrent velocities (broadly equivalent to those which would allow settlement of argillaceous mud, and therefore probably not exceeding about 10 cm/sec speeds), and, therefore, the occurrences are unlikely to be commonly in inner-shelf palaeoenvironments, but more likely to have been in water deeper than this. This agrees with the lack of association of Lithocodium with acknowledged shallow-water Codiacea (such as Arabicodium, Boueina, etc), but with its occurrence with deeper-water dasyclads (Acicularia, Salpingoporella, etc), and the calcitic (possibly also dasyclad) "Hensonella" cyndrica Elliott (vel "Salpingoporella" dinarica Radoičić). This is also in agreement with our palaeodepth-estimations using associated foraminifera. Other palaeoenvironmental estimates (palaeosalinity, palaeotemperature) based on associated foraminifera and other microfossils are in line with the conclusions given below. Also, the palaeogeography is that which clearly associates the known occurrences of Lithocodium with Tethys; the Lithocodioidea are not known from more boreal or austral deposits.

As a result, we estimate that the palaeoenvironment favoured by Lithocodium was that of a warm, fully marine, well oxygenated, calcium carbonate rich, mid-shelf sea (possible palaeodepths of abundant, in situ specimens ranging from ca. 15 m to ca. 60m b.s.l.). This is quite different

from that which would be concluded from the opinions published by Maurin et al. (1985).

#### RESERVOIR PROPERTIES OF LITHOCODIUM

Lithocodium (as defined in this paper) is common or abundant at many horizons in the Early Cretaceous of the Arabian Peninsula. Simmons and Hart (1987) and Hughes-Clarke (1988) have recorded it from the Lekhwair, Kharaib and Shuaiba Formations of Oman, whilst Alsharhan (1985; 1987) and Alsharhan and Nairn (1986) have described it from the Thamama Group of Abu Dhabi.

The genus is most prolific at two levels in the subsurface Thamama Group of Abu Dhabi; within the lowermost Shuaiba Formation (Aptian), termed Reservoir Zone A by ADCO for the onshore region, Reservoir Zone 1A by ADMA for the offshore region and units A and B by Alsharhan (1987), and within the lower Lekhwair Formation (Valanginian - Hauterivian) at horizons termed Reservoir Zones F, G and H by ADCO for the onshore region, and Reservoir Zone 4 or Zakum Member by ADMA for the offshore region. As can be seen from this, prolific Lithocodium buildups seem to be associated with so called "Reservoir Zones".

Examination of these intervals reveals that Lithocodium often dominates the biofacies of the reservoir zone horizon, but is less common in the sediments surrounding the reservoir zone, termed "dense zones" by the operating companies. Lithocodium recorded from the dense zones is usually present as clearly reworked nodules or fragments. Within the reservoir zones themselves, Lithocodium forms major biostromes of layered encrustations, which are laterally continuous and may vary from a few centimetres to a metre in thickness. In thin-section they give the

appearance of boundstones or packstones with abundant coalescing

Lithocodium nodules.

Within the reservoir zones, only the medulla structure of the Lithocodium organism is often present (i.e. that often described as "Bacinella") (see Plate 5, figs. 3-4). However the cortical structure may be preserved, more commonly in the Shuaiba Formation (see Plate 1, figs. 1-3). Often the medulla structure of Lithocodium is infilled by secondary calcite spar (Plate 1, fig. 4, Plate 4, fig. 2). However, in samples from the subsurface of Abu Dhabi, particularly those from the reservoir zones of the Lekhwair Formation, the vesicles remained unfilled by calcite and thus develop significant intraparticle porosity (see Plate 5, figs. 3-4). Porosities between 30 and 40% may be developed locally, although permeabilities are variable. These porosities may be enhanced by leaching associated with the development of hiatus surfaces within the Lekhwair and Shuaiba Formation. As an example, the Zakum field of offshore Abu Dhabi produces oil from Reservoir Zone 4 (Zakum Member) of the Lekhwair Formation (Beydoun, 1988) which is associated with Lithocodium accumulations. Moshier *et al.* (1988) have described the role of intraparticle porosity in Lithocodium within the Shuaiba Formation of Sharjah in the development of the giant gas and condensate reservoir of the Sajaa field.

Clearly therefore, the development of Lithocodium buildups may be beneficial for the reservoiring of large hydrocarbon accumulations. These Lithocodium buildups have an associated fauna of Lenticulina, Pseudocyclammina, Neotrocholina, echinoderm debris and occasionally small hedbergellid planktonic foraminifera. It is suggested that such buildups developed in response to moderate increases in relative water depth. Such water depth increases may themselves be eustatically controlled on

carbonate platforms such as that of the Early Cretaceous of Arabia. The prediction of major Lithocodium accumulations is thus of importance in hydrocarbon exploration. This can be facilitated by the detailed study of sequential palaeoenvironmental change, with particular emphasis on water depth, within a sequence. Of course, the retention of porosity in such buildups is controlled by diagenesis which may be independent of primary depositional controls.

#### ACKNOWLEDGEMENTS

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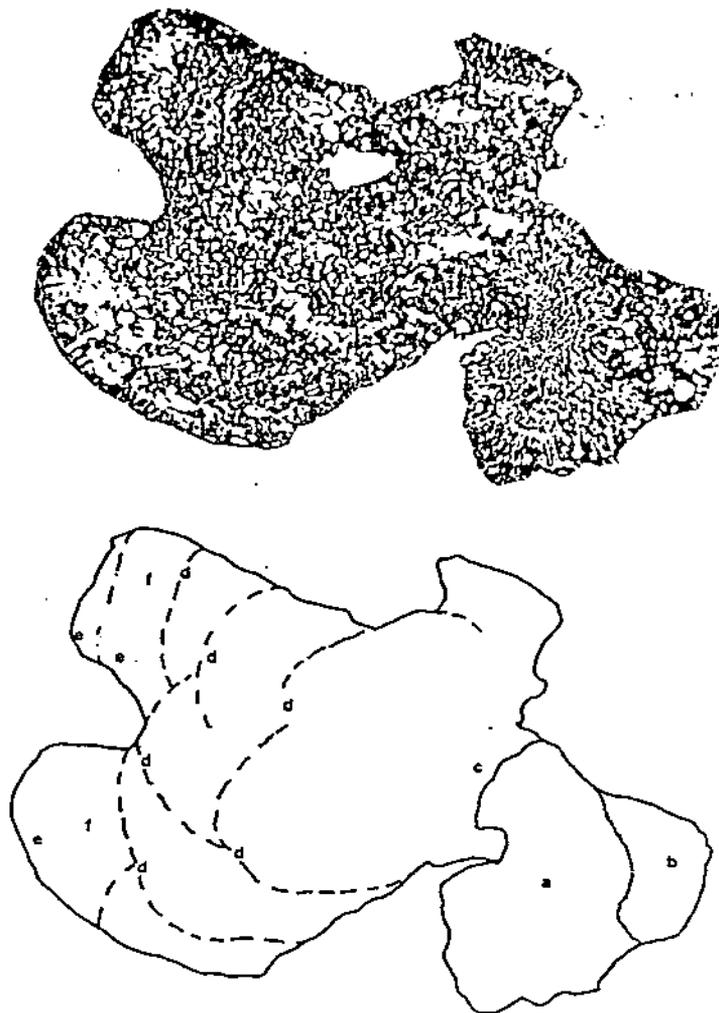
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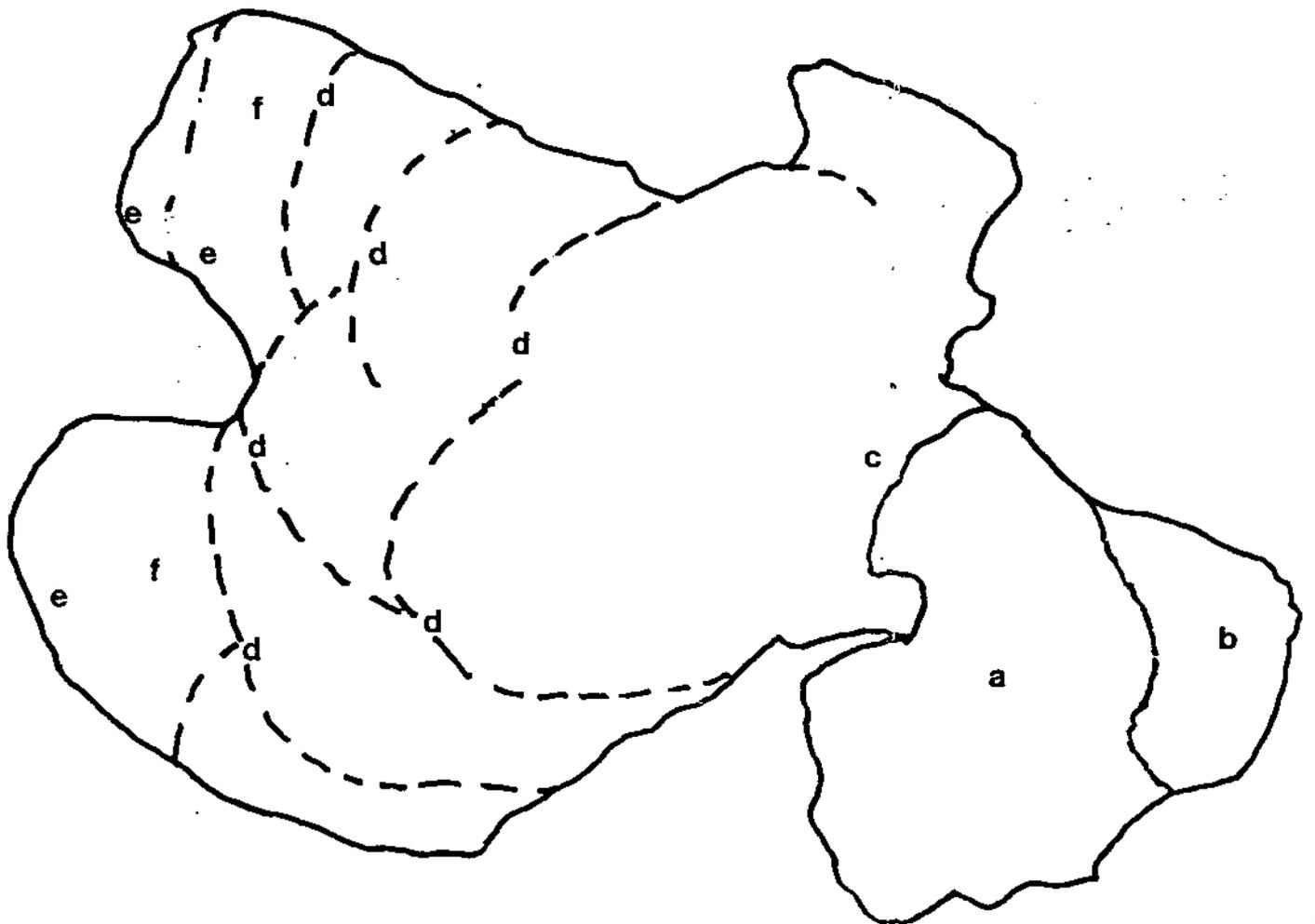
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TEXT FIGURE 1

(reduced to 85 mm = 1 column breadth)



## Explanation of Plate 1

### Lithocodium aggregatum Elliott

Fig. 1 Photomicrograph (x16), Shuaiba Formation, subsurface Abu Dhabi.

Fig. 2 Photomicrograph (x40), Shuaiba Formation, subsurface Abu Dhabi.

Fig. 3 Photomicrograph (x40), Shuaiba Formation, subsurface Abu Dhabi.

Fig. 4 Photomicrograph (x13), Shuaiba Formation, Wadi Bani Kharus, Oman Mountains.

## Explanation of Plate 2

### Lithocodium aggregatum Elliott

Fig. 1 Scanning electron micrograph (x50), Shuaiba Formation,  
subsurface Abu Dhabi.

Fig. 2 Scanning electron micrograph (x140), Shuaiba Formation,  
subsurface Abu Dhabi.

Fig. 3 Scanning electron micrograph (x100), Shuaiba Formation,  
subsurface Abu Dhabi.

Fig. 4 Scanning electron micrograph (x80), Shuaiba Formation,  
subsurface Abu Dhabi.

### Explanation of Plate 3

#### Lithocodium aggregatum Elliott

Fig. 1 Scanning electron micrograph, back-scattered electrons (x25), Shuaiba Formation, subsurface Abu Dhabi.

Fig. 2 Scanning electron micrograph, back-scattered electrons (x140), Shuaiba Formation, subsurface Abu Dhabi.

Fig. 3 Scanning electron micrograph, back-scattered electrons (x75), Shuaiba Formation, subsurface Abu Dhabi.

Fig. 4 Scanning electron micrograph (x32), Shuaiba Formation, subsurface Abu Dhabi.

Explanation of Plate 4

Lithocodium aggregatum Elliott

Fig. 1 Photomicrograph (x16), Shuaiba Formation, subsurface Abu Dhabi.

Fig. 2 Photomicrograph (x40), Aptian, Southern Apennines, Italy.

Fig. 3 Photomicrograph (x40), Lekhwair Formation, subsurface Abu Dhabi.

Fig. 4 Photomicrograph (x16), Shuaiba Formation, subsurface Abu Dhabi.

Explanation of Plate 5

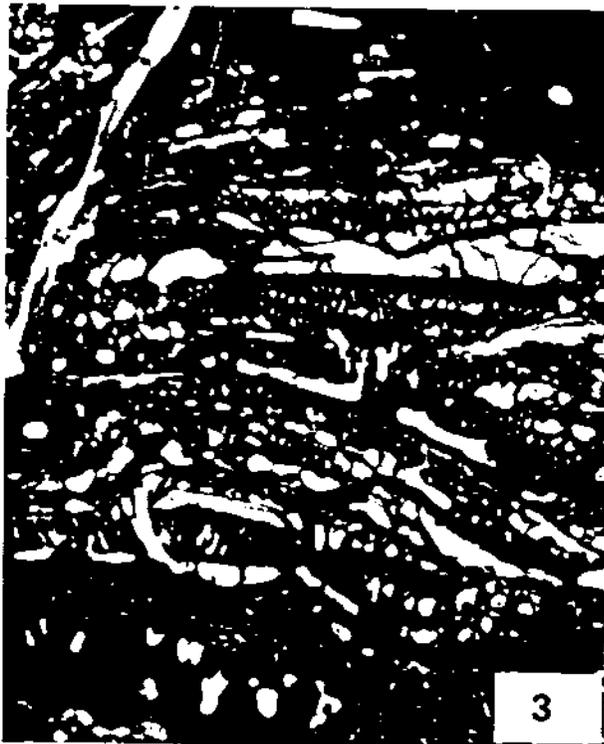
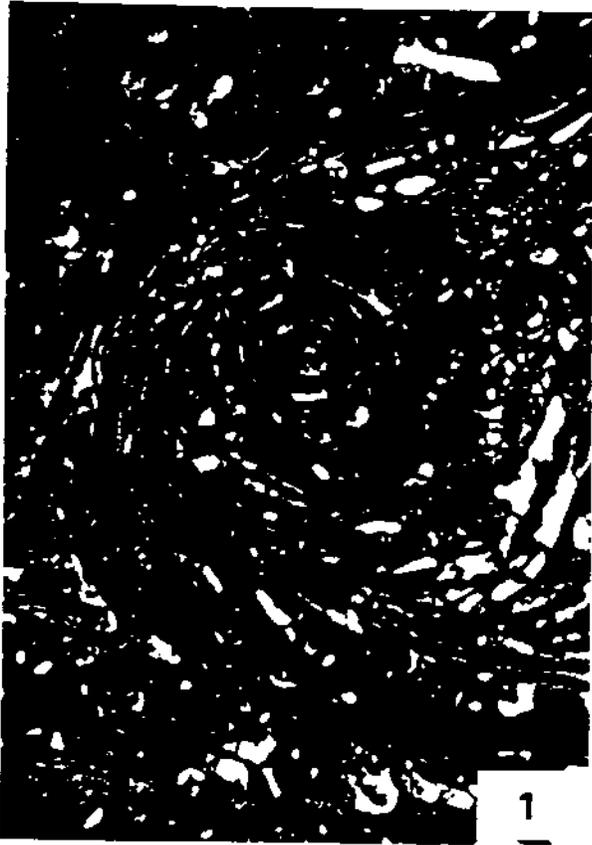
Lithocodium aggregatum Elliott

Fig. 1 Photomicrograph (x40), Lekhwair Formation, Wadi Mi'aidin,  
Oman Mountains.

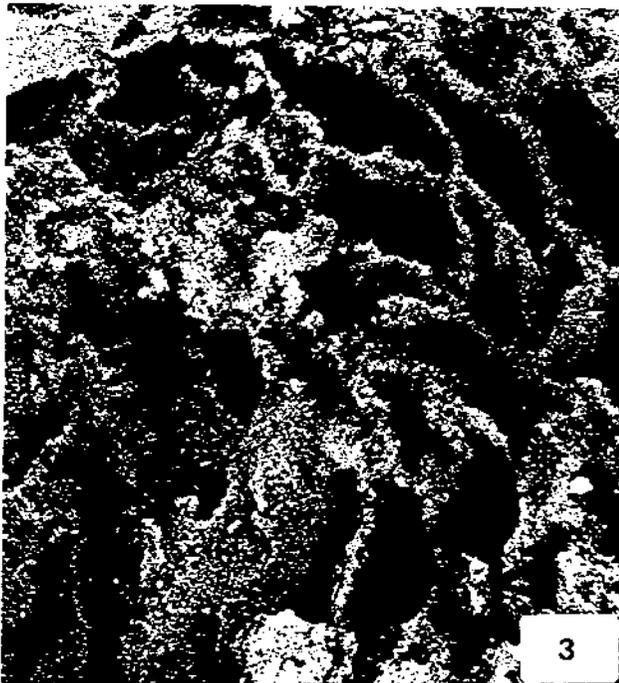
Fig. 2 Photomicrograph (x40), Habshan Formation, Wadi Bani  
Kharus, Oman Mountains.

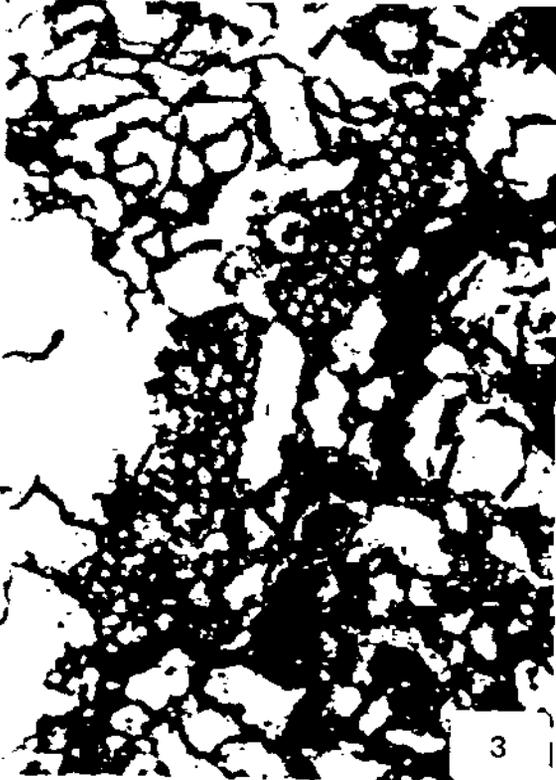
Fig. 3 Photomicrograph (x40), Lekhwair Formation, subsurface Abu  
Dhabi.

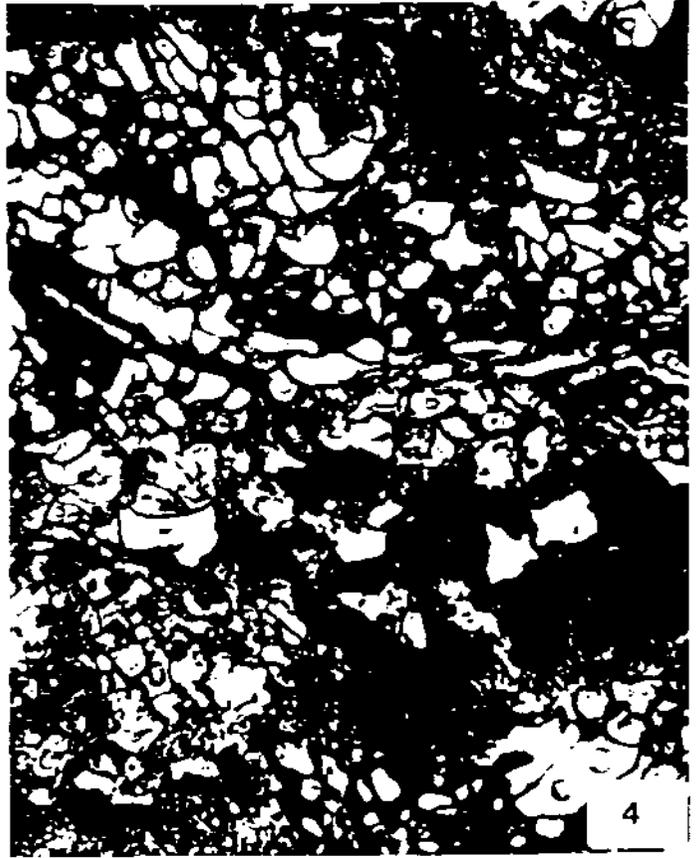
Fig. 4 Photomicrograph (x16), Lekhwair Formation, subsurface Abu  
Dhabi.











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## EARLY-MID CRETACEOUS LARGER FORAMINIFERA IN MIDDLE EASTERN BIOSTRATIGRAPHY

by

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### KEY WORDS

Benthic foraminifera, Cretaceous, Middle East, Palaeoecology, Palaeozoogeography.

### ABSTRACT

Early-mid Cretaceous larger Foraminifera (orbitolinids, alveolinids, cyclamminids, cuneolinids, etc) have been shown to be extremely useful in constructing biostratigraphic zonation schemes within the Tethyan region. However, the stratigraphic ranges and palaeogeographic distribution of these Foraminifera has only been extensively studied in the "Peri-Mediterranean" region. There are relatively few publications dealing with this subject for the Middle East, despite intense oil company exploration.

This presentation synthesizes the available data on stratigraphic ranges and palaeogeographic distribution of Early-mid Cretaceous larger Foraminifera in the Middle East, and incorporates new data, in particular, from Oman. An attempt is made to correlate the existing biostratigraphic zonation schemes for the Mediterranean region to those of the Middle East.

The presentation shows that :

- 1) Larger Benthonic Foraminifera provide the most practical biostratigraphic zonation of most Early-mid Cretaceous sediments in the Middle East.
- 2) This zonation is correlatable with similar zonation schemes for the Mediterranean region, although certain differences do exist.
- 3) Certain Foraminifera previously thought endemic to the Mediterranean region also occur in the Middle East. However, there are forms endemic to the Middle Eastern region.
- 4) The microfaunas of the Middle East are not yet known to be as diverse as those of the Mediterranean area. This has palaeoecological and palaeozoogeographic implications.

The type species of the genus *Orbitolina* D'Orbigny, 1850 (Foraminifera)

5500638

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**ABSTRACT**—A number of species have been suggested as type species of the genus *Orbitolina* d'Orbigny, 1850, notably *Madreporites lenticularis* Blumenbach, 1805, *Orbulites concava* Lamarck, 1816 and *Orbitolina gigantea* d'Orbigny, 1850. It is shown that the correct type species is *Orbitolina gigantea*, although this is in fact a species of coral. Consequently in order to preserve the concept of *Orbitolina* as a foraminiferal genus, we herein recommend to the ICZN the proposal of *Orbulites concava* as a replacement type species. This would negate the need for a major revision of orbitolinid taxonomy and allows the genus *Palorbitolina* Schroeder, 1963 to remain valid.

## INTRODUCTION

The typically Tethyan, Cretaceous larger foraminiferal genus *Orbitolina* was erected by d'Orbigny in 1850. Because of uncertainty in the original designation of a type species for this genus, a number of species have since been referred to as "type species". This has led to some confusion concerning the taxonomic concept of the genus and may have rendered other genera invalid because of problems with type species priority. In particular, the commonly used generic name *Palorbitolina* Schroeder, 1963 has been thought by some to be invalid, because the type species of that genus, *Madreporites lenticularis* Blumenbach, 1805, has been described, e.g. by Douglass, Loeblich and Tappan (1964), as the type species of *Orbitolina*. If this were the case it would have tremendous taxonomic implications. Not only would the name *Palorbitolina* be unavailable, but most species commonly regarded as belonging to *Orbitolina* would have to be assigned to a new genus. This is because Schroeder (1964a,b; 1975) has shown that *Palorbitolina* is morphologically and phylogenetically distinct from *Orbitolina*. Therefore if the true nature of *Orbitolina* is that commonly regarded as *Palorbitolina* (i.e. that of the species *lenticularis*), then other species thought today to be *Orbitolina* (e.g. *O. concava* (Lamarck, 1816) (*Orbulites*) or *O. texana* (Roemer, 1849) (*Orbitulites*)) could not belong to that genus because of the observations of Schroeder (*opp. cit.*).

To clarify these problems a detailed examination of the original description of the genus *Orbitolina* and subsequent type species designations has been carried out.

## DISCUSSION

### Original designation

The first problem to address in this review is to establish if d'Orbigny designated a type species for *Orbitolina* in his original 1850 description.

*Orbitolina* is first mentioned on page 143 of volume 2 of the "Prodrome de Paléontologie stratigraphique universelle des animaux mollusques & rayonnés faisant suite au cours élémentaire de Paléontologie et de Géologie stratigraphiques". There is no mention of *Orbitolina* in either volume 1 or 3 of this book.

The entry on page 143 reads:

"ORBITOLINA, d'Orb., 1847. Ce sont des Orbitolites à côtés inégaux, l'un encroûte, l'autre avec des loges.

\*342. *lenticulata*, d'Orb., 1847. *Orbitolites lenticulata*, Lamarck, 1816; Lamouroux, 1821, pl. 72, fig. 13-16. Perte-du-Rhône (Ain), St-Paul-de-Fenouillet (Aude).

In this text "d'Orb., 1847" refers to the manuscript date. *Orbitolites lenticulata* Lamarck 1816 is synonymous with *Madreporites lenticularis* Blumenbach, 1805, variously referred to *Orbitolina* or *Palorbitolina*.

It is important to note that volume is arranged in stratigraphic order. Hence the first species mentioned under *Orbitolina* is *lenticulata* in the section "Foraminifères", within the chapter "19e étage - Albien".

Within the subsequent chapters the following species are listed:

20e étage - Cenomanien; pages 184-185:

"ORBITOLINA, d'Orb., 1847. Voy. t.2, p.148.

\*743. *plana*, d'Archiac, 1837, Mém. Soc. géol. de France, t.2., p.178. France, Fouras, La Malle (Var).

\*744. *mamillata*, d'Archiac, 1837, id., t.2, p.178. Fouras.

\*745. *concava*, Lamarck, 1816. Anim. sans vert., 2, Michelin, 1842, Icon. zoophyt., p.28, pl.7, fig. 9 (mala). *Orbitolina conica*, d'Orbigny, France, Ballon, St-Paulet, près le Pont-St-Esprit, Fouras."

22e etage - Senonien; pages 279-280:

"ORBITOLINA, d'Orb., 1847. Voy. p.148.

\*1350. *gigantea*, d'Orb., 1847. Espèce qui atteint jusqu'à 10 centimètres de diamètre; concave en dessous, convexe en dessus. France, Royan, Pérignac (Charente-Inférieure).

\*1351. *radiata*; d'Orb., 1847. Espèce pourvue de rayons qui convergent du bord au centre. France, Royan."

In total six species are listed under the genus *Orbitolina* in stratigraphic order. D'Orbigny does not indicate any particular species to be the type, and the stratigraphic nature of the volume implies that the first mentioned species under a genus is not necessarily the type.

It is clear, therefore, that no type species was designated for *Orbitolina* by d'Orbigny, and that *lenticulata* (= *lenticularis*) is not automatically the type species simply because it is listed first. This was first noted by Schroeder (1963) in a paper which established *lenticularis* as type species of the new subgenus (later genus) *Palorbitolina*.

Unfortunately, Douglass (1960a,b), Hofker (1963; 1966a,b) and most importantly Douglass, Loeblich and Tappan (1964) in the definitive "Treatise on Invertebrate Paleontology" regard *Madreporites lenticularis* Blumenbach, 1805 as type species. According to the last-named authors (page C309); *Orbulites lenticulata* Lamarck, 1816 (= *Madreporites lenticularis* Blumenbach, 1805) is the type species of the genus by original designation (monotypy).

As demonstrated above there is neither an original type species designation by d'Orbigny, nor is the genus monotypic in the reference containing the original description.

#### Subsequent designation

All six species recorded by d'Orbigny (1850) under *Orbitolina* have equal claim as type species. According to Article 69(a) of the International Code of Zoological Nomenclature (ICZN) (Ride *et al.*, 1985), the first published designation of a type species subsequent to the original publication of the genus should be regarded as the only valid one.

There are, in fact, several subsequent quotations which could be regarded as designations of a type species for *Orbitolina*.

(i) According to Parker and Jones (1860:35) "the conical, hemispherical and flattened forms of *Orbitolina* so common in the Cretaceous deposits, and known under twelve or more different names, are referable to one specific type, namely the *O. concava*, Lamarck, sp. and to this type not only these large . . ." However, this

quotation, nor any that follow it in the text, is not really valid as a type designation, as these authors were not using type in the sense of "type species of a genus", but rather as an indication of the "typical form of a species." Indeed on page 38 we read "we regard it (*O. concava*) as the type of a species including numerous varieties". In their recent monograph of foraminifera genera, Loeblich and Tappan (1988:166) cited this reference by Parker and Jones (*op. cit.*), as a valid subsequent designation of a type species, and thus regarded *Orbulites concava* Lamarck, 1816, as the correct type species of *Orbitolina*. As noted above, we cannot agree with their opinion that the Parker and Jones reference is a valid subsequent designation, although for different reasons, as will be shown, we would recommend that *O. concava* be regarded as type species.

(ii) Ellis and Messina (1940 *et seq.*) reported that *Orbitolina lenticularis* Blumenbach, 1805 was designated as type species by Dollfus (1905). They regarded this designation as invalid because a species named *lenticularis* was "not among the species originally included under the generic name by d'Orbigny." In fact d'Orbigny (1850:143) cited *Orbitolites lenticulata* Lamarck, 1816, which is synonymous with *Madreporites lenticularis* Blumenbach, 1805.

The reference "Dollfus, 1905" of Ellis and Messina relates to a review by that author on a paper published by Prever (*in Prever and Silvestri*, 1905). In this review Dollfus (1905:232) pointed out: "Il [= Prever] considère que le Genre *Dictyocornis* [he means *Dictyocornus*] Blackenhorst, fondé pour quelques espèces d'Égypte, est bien rigoureusement synonyme [with *Orbitolina*]; il le compare aux Genres voisins et commence par établir que le type du G. *Orbitolina* est *O. lenticularis* Blum. sp. (*Madreporites*) 1796, espèce de la Perte du Rhône." However, the second half of this statement made by Dollfus is wrong; Prever has never designated *O. lenticularis* as type species of *Orbitolina*. On the contrary, *O. lenticularis* belongs to the species which were eliminated by this latter author (1905:469; "il lavoro di revisione compiuto, mi ha obbligato a distruggere parecchie delle specie già istituite ed anche di quelle or nominate, ed in cambio a crearne delle nuove").

(iii) Cushman (1928:182) designated *Orbitolina gigantea* d'Orbigny as type species of *Orbitolina*. Subsequently Douvillé (1933:199) demonstrated that this species is a coral belonging to the genus *Cyclolites* Lamarck.

(iv) Davies (1939:786) pointed out that "*O. concava* seems to be the form best indicated in the 'Prodrome' itself. It is also the best for studying the genus, being usually better preserved as well as much larger than *O. lenticularis*. It should obviously, in my opinion, be taken as the type of *Orbitolina*."

Davies (*op. cit.*) therefore selected *O. concava* as type species. By doing so he hoped to alleviate the taxonomic problems caused by Cushman's designation of the coral *O. gigantea* (= *Cyclolites*) as type species. In fact Cushman in the 1950 edition of his text, named *O. concava* as the type species. A number of other workers have also agreed with Davies's opinion that *O. concava* should be regarded as the type species of *Orbitolina*. These include Henson (1948) and Sahni and Sastri (1957).

(v) Thalmann (1950:509) proposed *Orbitolina texana* (Roemer, 1849) (= *Orbitulites texanus* Roemer, 1849) as a substitute type species in place of *Orbitolina concava*. However, since this species is not among those originally included under the generic name by d'Orbigny, it can be immediately excluded from consideration as a type species (ICZN Article 69a). (vi) Douglass (1960a:28) and Douglass, Leoblich and Tappan (1964:C309) considered *Orbitolina lenticularis* to be the type species of the genus. Douglass (*op. cit.*) is of the opinion that "only one species is referred to the genus in this, the original description. The genus as described is therefore monotypic, even though five other species are referred to it in later sections of the volume." As demonstrated above, the stratigraphic nature of the "Prodrome" implies that the first mentioned species under a genus is not necessarily the type. For this reason, the arguments of Douglass and Douglass *et al.* (*op. cit.*), which were also followed by Hofker (1963:220; 1966b:9), are invalid (see also Schroeder, 1963:351).

#### CONCLUSIONS AND RECOMMENDATIONS

It is clear that despite the arguments of Douglass (1960a), Hofker (1963) and Douglass, Leoblich and Tappan (1964), no original designation of a type species of *Orbitolina* was made by d'Orbigny (1850), nor was the genus monotypic in the original description. Hence, *Madreporites lenticularis* (= *Orbitolina lenticularis*) is not automatically the type species.

The first designation of a type species is that of Cushman (1928), who nominated *Orbitolina gigantea* d'Orbigny, 1850. According to Douville (1933) this taxon is a species of the coral genus *Cyclolites*. In strict observance of the International Code of Zoological Nomenclature, *Orbitolina* d'Orbigny, 1850 is a synonym of *Cyclolites* Lamarck, 1801 (see Wells, 1956:F386).

If one accepts this situation, then the numerous species regarded as belonging to *Orbitolina* would have to be assigned to a new genus. Therefore we recommend the suppression of *Orbitolina gigantea* as type species and the recognition of *Orbitolina concava* as replacement type species of *Orbitolina*, as originally suggested by Davies (1939). This will negate the need for a major revision of orbitolinid taxonomy and allow

the genus *Palorbitolina* to remain valid. In this context an official application has been made to the International Commission on Zoological Nomenclature to implement the above recommendations (Case 2663, Schroeder and Simmons, 1988).

It is worth noting that *Orbitolina concava* (= *Orbitulites concava* Lamarck, 1816) is not the same taxon as *Orbitolites concava* Lamarck, 1801. As demonstrated by Parker and Jones (1860) and Schroeder (1962), the earlier named species (in fact a bryozoan) cannot be considered as the type of *Orbitolina concava*. Hence it is *Orbitolina concava* (Lamarck, 1816) that should be regarded as the valid type species of the genus *Orbitolina*.

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## Case 2663

***Orbitolina* d'Orbigny, 1850 (Foraminiferida): proposed confirmation of *Orbulites concava* Lamarck, 1816 as the type species**

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**Abstract.** The purpose of this application is the confirmation of the nominal species *Orbulites concava* Lamarck, 1816 as type species of *Orbitolina* d'Orbigny, 1850. The first type species designated is now known to be a coral, but the designation supported here maintains the Tethyan, Cretaceous foraminiferal genus *Orbitolina* in its established meaning.

1. *Orbitolina* is first mentioned on p. 143 of volume 2 of d'Orbigny's *Prodrome de Paléontologie*. . . There is no mention of *Orbitolina* in either volume 1 or 3 of this book. In total, six species are listed under the genus, in stratigraphic order. He listed them as follows: (i) (p. 143) *lenticulata* d'Orbigny, 1847; (ii) (p. 184) *plana* d'Archiac, 1837; (iii) (p. 184) *mamillata* d'Archiac, 1837; (iv) (p. 185) *concava* Lamarck, 1816; (v) (p. 279) *gigantea* d'Orbigny, 1847 and (vi) (p. 280) *radiata* d'Orbigny 1847. D'Orbigny does not indicate any particular species to be the type. It must be noted here that in the text of the *Prodrome* the date 1847 refers to the date of the manuscript, which was actually published in 1850.

2. All six species recorded by d'Orbigny (1850) under *Orbitolina* have equal claim as type species. According to Article 69a of the Code, the first published designation of a type species subsequent to the original publication of the genus should be regarded as the only valid one. There are several subsequent quotations which could be regarded as designations of a type species for *Orbitolina*, and these are discussed in paragraphs 3-8 below.

3. According to Parker & Jones (1860, p. 35) 'the conical, hemispherical and flattened forms of *Orbitolina* so common in the Cretaceous deposits, and known under twelve or more different names, are referable to one specific type, namely the *O. concava*, Lamarck, sp. and to this type not only these large . . .'. However, neither this quotation, nor any that follow it in the text, are valid as a type designation, as these authors were not using 'type' in the sense of 'type species of a genus', but rather as an indication of the 'typical form of a species'. Indeed on p. 38 we read 'we regard it [*O. concava*] as the type of a species including numerous variety's'. In their recent monograph of foraminifera genera, Loeblich & Tappan (1988, p. 166) cited this reference by Parker & Jones as a valid designation of a type species, and thus regarded *Orbulites concava* Lamarck, 1816 (p. 197) as the correct type species of *Orbitolina*. As noted above, we cannot agree with their opinion that the Parker & Jones reference is a

valid designation, although for different reasons, as will be shown, we suggest that *O. concava* be recognised as the type species.

4. Ellis & Messina (1940 et seq.) reported that *Orbitolina lenticularis* (Blumenbach, 1805) was designated as type species by Dollfus (1905, p. 232). They regarded this designation as invalid because a species named *lenticularis* was 'not among the species originally included under the generic name by d'Orbigny'. In fact d'Orbigny (1850, p. 143) mentioned *Orbitolites lenticulata* Lamarck, 1816, which Schroeder (1963) noted is synonymous with *Madreporites lenticularis* Blumenbach, 1805. The Dollfus reference relates to a review by that author of a paper published by Prever (in Prever & Silvestri, 1905). In this review Dollfus pointed out: 'Il [Prever] considère que le Genre *Dictyocornis* [he means *Dictyoconus*] Blanckenhorn, fondé pour quelques espèces d'Égypte, est bien rigoureusement synonyme [with *Orbitolina*]; il le compare aux Genres voisins et commence par établir que le type du G. *Orbitolina* est *O. lenticularis* Blum. sp. (*Madreporites*) 1796, espèce de la Perte du Rhône'. However, the second half of this statement made by Dollfus is wrong; Prever never designated *O. lenticularis* as type species of *Orbitolina*. On the contrary, *O. lenticularis* belongs to the species which were eliminated by this latter author (1905, p. 469): 'Il lavoro di revisione compiuto, mi ha obbligato a distruggere parecchie delle specie già istituite ed anche di quelle or nominate, ed in cambio a crearne delle nuove' [As a result of this revision, I have been obliged to destroy quite a lot of species already established and also quite a lot of those just mentioned and to create new ones instead]. It is clear that neither Dollfus nor Prever designated a type species.

5. Cushman (1928, p. 182) designated *Orbitolina gigantea* d'Orbigny as type species of *Orbitolina*. Subsequently Douvillé (1933, p. 199) demonstrated that this species is a coral belonging to the genus *Cyclolites* Lamarck, 1801.

6. Davies (1939, p. 786) pointed out that '*O. concava* seems to be the form best indicated in the *Prodrome* itself. It is also the best for studying the genus, being usually better preserved as well as much larger than *O. lenticularis*. It should obviously, in my opinion, be taken as the type of *Orbitolina*'. Davies therefore selected *O. concava* as type species. By doing so he hoped to alleviate the taxonomic problems caused by Cushman's designation of the coral *O. gigantea* [= *Cyclolites*] as type species, and in fact Cushman in the 1950 edition of his text named *O. concava* as the type species. A number of other workers have also agreed with Davies' opinion that *O. concava* should be regarded as the type species of *Orbitolina*. These include Henson (1948) and Sahni & Sastri (1957), and we also suggest that this designation be accepted.

7. Thalmann (1950, p. 509) proposed '*Orbitolina texana* Roemer, 1849' [*Orbitulites texanus* Roemer, 1849] as a substitute type species in place of *Orbitolina concava*. However, this species is not among those originally included under the generic name by d'Orbigny.

8. Douglass (1960a, p. 28) and Douglass, Loeblich & Tappan (1964, p. C309) considered *Orbitolina lenticularis* to be the type species of the genus. Douglass [op. cit.] is of the opinion that 'only one species is referred to the genus in this, the original description. The genus as described is therefore monotypic, even though five other species are referred to it in later sections of the volume'. However, as pointed out in para. 1 above, six species were included in d'Orbigny (1850), and so the arguments of Douglass (1960a,b) and of Douglass et al. [op. cit.], which were also followed by Hofker (1963, p. 220; 1966a, p. 204; 1966b, p. 9), are invalid (see also Schroeder, 1963, p. 351).

9. *Madreporites lenticularis* Blumenbach, 1805 (Heft 8 [80]) (= *Orbitolina lenticulata*) is the type species by monotypy of *Palorbitolina* Schroeder, 1963 (p. 348). This genus was shown by Schroeder (1964a,b; 1975) to be morphologically and phylogenetically distinct from *Orbitolina*.

10. As there was no type by original designation, nor was the genus monotypic in the original description, Cushman's 1928 designation of *Orbitolina gigantea* d'Orbigny makes *Orbitolina* d'Orbigny, 1850 a junior objective synonym of the coral genus *Cyclolites* Lamarck, 1801 (see Wells, 1956, p. F386). If one were to accept this situation, the numerous species regarded as belonging to *Orbitolina* would have to be assigned to a new genus. Therefore we request the suppression of *Orbitolina gigantea* as type species of *Orbitolina* and the recognition of *Orbitolina concava* as type species, as originally suggested by Davies (1939). This solution negates the need for a major revision of orbitolinid taxonomy, and allows the genus *Palorbitolina* Schroeder, 1963 to remain valid, with *Madreporites lenticularis* as its type species by monotypy. *Palorbitolina* and *Orbitolina* are often abundant in Early and Middle Cretaceous platform carbonates of the Tethyan realm and recognition of their constituent species is extremely valuable in biostratigraphic studies of such sediments. As biozonation schemes can be developed using these taxa (e.g. Schroeder, 1975), it is important that their names be conserved in their accustomed usage.

11. Parker & Jones (1860) and Schroeder (1962) pointed out that *Orbitolina concava* [= *Orbulites concava* Lamarck, 1816] is not the same taxon as *Orbitolites concava* Lamarck, 1801; the earlier named species is now referred to the bryozoan genus *Lunulites*.

12. The International Commission on Zoological Nomenclature is accordingly asked:

- (1) to use its plenary powers to set aside all designations of type species for the nominal genus *Orbitolina* d'Orbigny, 1850 prior to that of *Orbulites concava*, Lamarck, 1816 by Davies (1939);
- (2) to place on the Official List of Generic Names in Zoology the following names:
  - (i) *Orbitolina* d'Orbigny, 1850 (gender: feminine), type species by designation by Davies (1939) *Orbulites concava* Lamarck, 1816;
  - (ii) *Palorbitolina* Schroeder, 1963 (gender: feminine), type species by monotypy *Madreporites lenticularis* Blumenbach, 1805;
- (3) to place on the Official List of Specific Names in Zoology the following names:
  - (i) *concava* Lamarck, 1816, as published in the binomen *Orbulites concava* (specific name of the type species of *Orbitolina* d'Orbigny, 1850);
  - (ii) *lenticularis* Blumenbach, 1805, as published in the binomen *Madreporites lenticularis* (specific name of the type species of *Palorbitolina* Schroeder, 1963).

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