1991

Tectonics and sedimentation in the Devonian and carboniferous rocks of SW Devon, England.

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http://hdl.handle.net/10026.1/723

http://dx.doi.org/10.24382/3374
University of Plymouth

TECTONICS AND SEDIMENTATION IN THE DEVONIAN AND CARBONIFEROUS ROCKS OF SW DEVON, ENGLAND

Volume 1

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A thesis submitted in partial fulfilment of the requirements of the Council for National Academic Awards for the degree of Doctor of Philosophy

August 1991

Polytechnic South West

I declare that this work is the result of my own independent investigations, that it has not been accepted in substance for any degree nor is it being concurrently submitted in candidature for any other degree.

R. D. SEAGO ....

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ABSTRACT

TECTONICS AND SEDIMENTATION IN THE DEVONIAN AND CARBONIFEROUS ROCKS OF SW DEVON, ENGLAND

Robert David Seago

Detailed mapping of the rocks to the north and south of Plymouth reveals a sedimentary sequence deformed by a series of folds and thrusts. Two structural zones exist each with a different style of deformation. In the Lower to Upper Devonian rocks of the southern zone, slip vectors, vergence and facing of D1 folds indicate that the transport direction is to the north west. The northern zone, comprising Upper Devonian and lower Carboniferous strata, extends into central Devon and east Cornwall and the geometry and facing of the early folds in these rocks indicate a transport direction to the south or south east. D1 folds generally verge north but are downward facing towards the south. The two structural zones confront each other at an E-W trending line which passes through Cargreen to the north of Plymouth. The confrontation is interpreted as a northerly dipping backthrust produced by underthrusting of the Carboniferous foreland basin flysch deposits which become inverted and backthrust towards the south.

The above sequence of events is dependent on a thin-skinned tectonic model and can be incorporated into the well established Early Carboniferous plate tectonic setting. Parameters indicating strike slip movement can also be incorporated within the envisaged thrust regime. These are thought to have been generated by differential movement related to the shape of the Variscan Front. The oblique trend of the Variscan Front to the regional transport direction observed in Southern Ireland, Wales and England, where it trends WNW-ESE, is thought to be a function of lateral buttressing against the Irish and London/Brabant Massifs during NW transport of thrust sheets.

Re-mapping in the Plymouth area has also led to modifications of the Devonian stratigraphy and sedimentology of the Lower Devonian. The previously named Dartmouth Beds/Slates have been re-named the Dartmouth Group and comprise the Renney Rocks, Wembury, Yealm and Warren Formations. The latter pass upwards, by interdigitation, into the Meadfoot Group which in turn consists of the Bovisand and Staddon Grit Formations. Overlying the Meadfoot Group is the Plymouth Group which is divided into the Jennycliff Slate Formation, Plymouth Limestone Formation, Compton Slate Formation and the Saltram Slate Formation. The division of the previously named Plympton Formation into the two latter formations has allowed more control on structural mapping in the area north of Plymouth. The recognition of repeated stratigraphy and its further subdivision indicates that, due to thrusting, the sequences are much thinner than previously thought.

The sedimentological character of the Dartmouth Group implies deposition in an alluvial setting and sub-environments include channels, sheetflow, overbank flow and lake deposition. Debris flows indicate that the area was periodically unstable. It is envisaged that deposition took place on a wet alluvial plain with rare drying out. The deposits probably represent a distal setting to the more proximal Old Red Sandstone alluvial deposits of South Wales. Higher up the sequence the Meadfoot Group records a major marine transgression across the area (Bovisand Formation) with a minor regressive pulse represented by the Staddon Grit Formation. The boundary conditions of these two formations has been examined and the sedimentology of this part of the sequence indicates the presence of a series of offshore bar forms. They are thought to represent mouth bar sequences related to the overlying deltaic sequence of the Staddon Grit Formation.

Analysis of the onshore New Red Sandstone indicates the presence of a topographic high in the Start area. This local palaeogeographic detail can be related to the regional offshore Permian Basin form.

ACKNOWLEDGEMENTS

Firstly I would like to thank Tim Chapman, my supervisor, for his guidance, enthusiasm and thought-provoking comments. I am also grateful to Malcolm Hart, Ian Tunbridge and Mary Ford for additional support and encouragement and to the technical staff, Graham, Roger, Maggie, Spike, John and Huw of the Polythechnic South West. My time in Plymouth would not have been the same without the friendship of Steve, Tim, Rod, Ailbhe and Meriel. Over the last year John Smewing, Director of Earth Resources Institute, Swansea, has been generous in allowing me the time to work on my thesis. I would also like to thank Rebecca for her assistance during the compilation stages of the thesis. My parents' support during my time in higher and further education has been invaluable and I cannot thank them enough.

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CHAPTER 1
INTRODUCTION

1.1 LOCATION

The main area of study is located in the SW corner of Devon, between Plymouth and Torbay, in the South Hams district of SW England (Fig. 1.1) (see also Appendix 2 for more detailed maps). However, the study area also extends to the north of Plymouth and Torbay into central SW Devon, around Tavistock and Bovey Tracey respectively. Data from here is supplemented by observations in the Lydford Gorge, Tavistock, Mary Tavy, and St. Mellion areas (Fig. 1.1). For comparison, other less detailed studies have been carried out on the north Cornish coast around Newquay, on the west side of Plymouth Sound (Fig 1.1) and offshore SW England.

Due to the poor inland exposure, the majority of field data have been obtained from the coastal exposures. The shape of the South Hams coast and the course of the River Tamar allows the examination of two cross-strike traverses through the Devonian and Carboniferous strata. These provide ample data for cross section construction and stratigraphical/ sedimentological analysis.

1.2 SUMMARY OF WORK UNDERTAKEN

The initial aims of this project were to investigate the lithostratigraphy, sedimentology and structure of the Lower Devonian sequences of the South Hams district of SW Devon. However, due to increased research into the development of the Carboniferous basins of SW England the study area was extended to the north so as to evaluate the structure of the Carboniferous sequences and relate them to those seen elsewhere in the region. To establish the tectonic style of the area, it was necessary to construct cross sections through the intervening ground around Plymouth which contains Middle to Upper Devonian sequences. Therefore the stratigraphy of the Plymouth area had to be confirmed. A review of the Devonian lithostratigraphy and detailed sedimentology of the Lower Devonian rocks in the south of the area was also necessary as an essential pre-requisite to understanding the structure. This integration of structure, stratigraphy and sedimentology is an important feature of the work carried out during this project.

Detailed structural mapping has enabled the construction of accurate cross sections

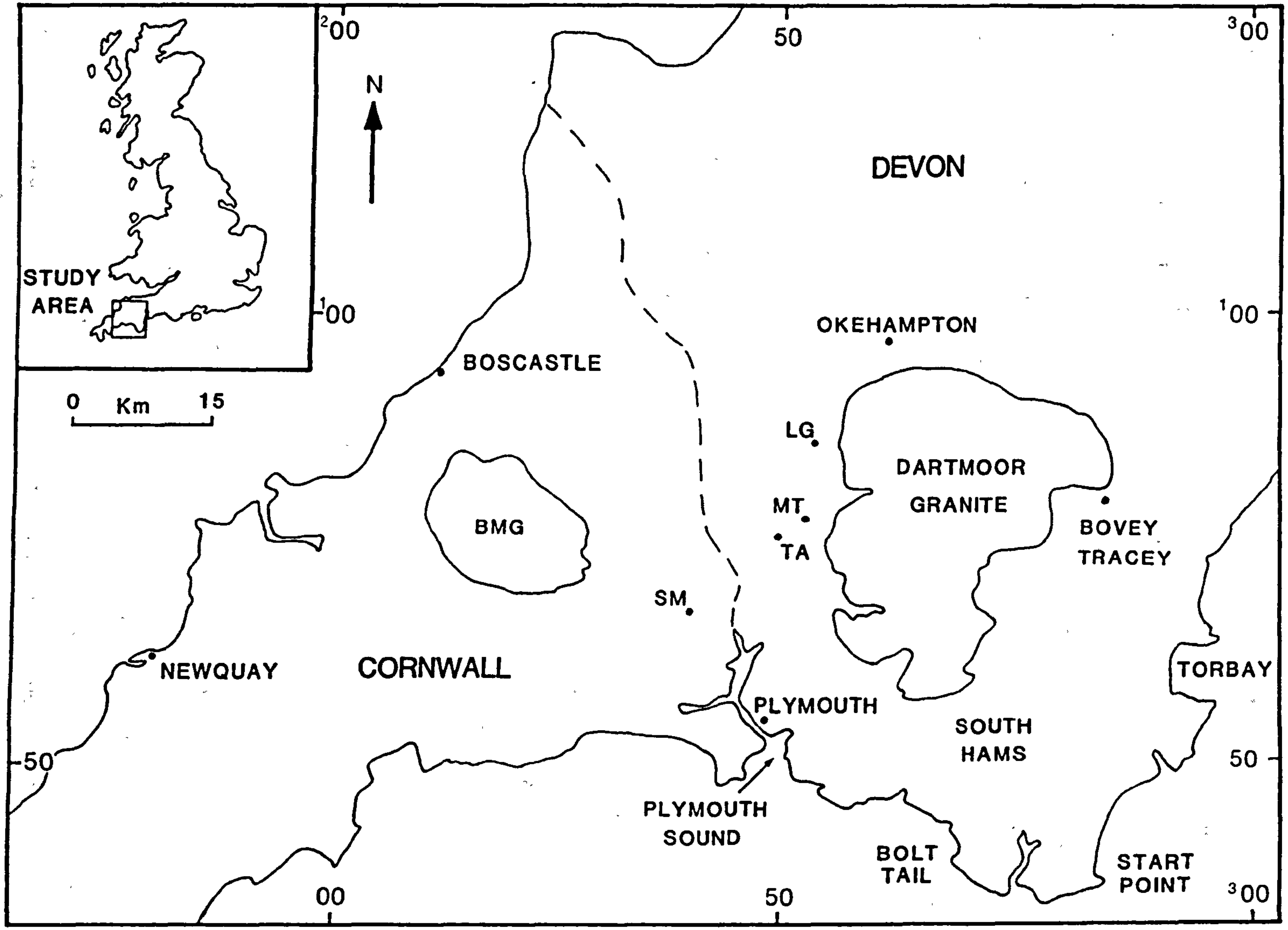

Fig. 1.1 Location map of the study area in Devon and Cornwall, SW England. BMG, Bodmin Moor Granite; LG, Lydford Gorge; MT, Mary Tavy; SM, St. Mellion; TA, Tavistock.

through the Palaeozoic sequences. These have been balanced and restored, where possible,in order to estimate the extent of the depositional basins and the total amount of crustal shortening. The first of the two sections examined is a SE-NW traverse from Bolt Tail, through Plymouth, and along the River Tamar into the area between Dartmoor and Bodmin Moor. The second cross section traverses the coast from Start Point, in the south, to the Torbay area in the north (Fig. 1.2). This section is continued north of Torbay into the Bovey Tracey area, east of the Dartmoor Granite, in order to relate the data to that observed to the west of Dartmoor.

Due to the complex deformation in the area it is not possible to construct a continuous detailed sedimentary log for the Lower Devonian formations. However, small scale representative logs have been constructed in order to deduce the sedimentary depositional environments. Petrographic and palaeocurrent analyses have been carried out in order to ascertain the provenance for the Lower Devonian sediments. Following the detailed mapping of the South Hams coastline, and by referring to the available offshore seismic data and BGS maps, it has been possible to relate the structures produced during the Variscan contractional phase of deformation to subsequent Permo-Triassic extension.

The stratigraphy of the region is presented first (Chapter 2), much of which is a review of accepted stratigraphic nomenclature. However, important revisions have been made to the stratigraphy of the Lower and Upper Devonian units. Chapter 3 contains the detailed sedimentology of the Lower Devonian sequences. Sedimentological examination of units higher in the sequence is beyond the scope of the project. Chapter 4 deals with the main structure of the region and Chapter 5 reviews the structure of the Start Schist Complex which occurs immediately to the south of the study area.

As a result of this integrated study, it has been possible to determine the geological evolution for SW Devon and SW England, from sedimentation and related Devonian palaeogeography through to orogenic deformation of the basin fill. This has been related to the tectonic evolution of the NW margin of the Variscan orogenic belt.

It should be noted by the reader that summary maps (Appendix 2) showing localities used in the text, sedimentary log locations, cross section locations and an index to the field slips (Appendix 3) are contained in the back pocket of Volume 2 of this thesis. Regarding photographs, a number of objects have been used to indicate the scale of each image. The objects correspond to the following sizes: rucksack 40cm long; lens cap 6cm diameter; umbrella 1m high; pencil 13cm long; compass 10cm x 6cm; hammer 40cm long; camera 14cm wide; penny 2cm diameter.

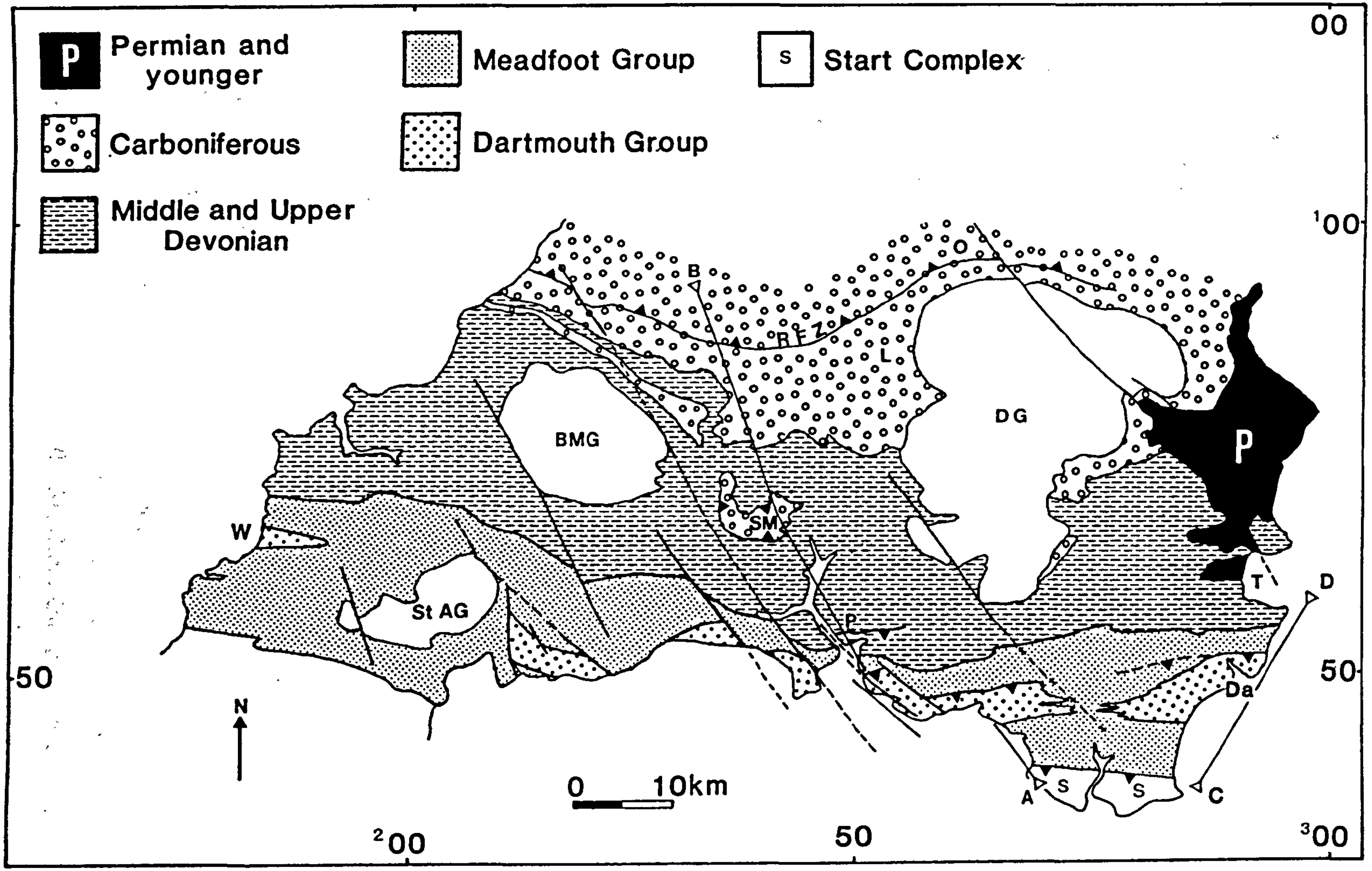

Fig. 1.2 Simplified regional geology of SW England. A-B and C-D are transects from which observations are used to construct the regional cross sections. BMG, Bodmin Moor Granite; Da, Dartmouth; DG, Dartmoor Granite; L, Lydford Gorge; P, Plymouth; RFZ, Rusey Fault Zone; St AG, St. Austell Granite; SM, St. Mellion; T, Torbay; W, Watergate Bay.

1.3 HISTORY OF RESEARCH

This section is divided into two parts; work prior to 1976 and work which post-dates 1976.

1.3.1 Pre-1976

Early research on the geology of SW England was carried out as part of an extensive regional survey by Sedgwick and Murchison (1837) and De la Beche (1839). This was followed by a seventy year period of very few significant contributions. It was not until the turn of the nineteenth century that the first detailed study was undertaken leading to a series of publications (Ussher, 1890, 1891, 1903, 1904, 1907, 1912 and 1913). During this period Ussher produced a series of maps and memoirs covering the geology of the counties of Devon and Cornwall. This has remained the most comprehensive piece of work in the area and access to his unpublished 6" to 1 mile maps as well as the published 1:50 000 maps have greatly supplemented the studies undertaken here. Ussher solved many of the problems encountered by the early workers and erected a comprehensive stratigraphy based on lithological and palaeontological data. It was the understanding of structural relations and detailed faunal study which helped him realise that the succession between Plymouth and Bigbury Bay became younger from south to north, even though the prominent dip of the rocks at outcrop along this section is to the south. Prior to this finding, it was thought that the section had an overall younging direction to the south in the same direction as the stratal dip (see Sedgwick and Murchison, 1837).

The early reports relevant to the present project are the Memoirs of Ussher (1904, 1907 and 1912). These describe the geology of Kingsbridge and Salcombe; Plymouth and Liskeard; Ivybridge and Modbury respectively. The resulting data are published on the 1:50,000 maps (sheet nos. 355, 356, 348 and 349). Within these areas Ussher recognised Palaeozoic strata ranging in age from Early Devonian (Gedinnian) to Permian.

The three-fold stratigraphical division of the Lower Devonian was based on lithology. These lithostratigraphic divisions were supported by palaeontological data allowing stage names to be applied. Using fish remains, Ussher assigned the oldest rocks of the area to the Lower Devonian and called this division, the Dartmouth Slates. Overlying this group he described the rocks as those belonging to the Meadfoot Group which are in turn overlain by the Staddon Grits. The Dartmouth Slates were assigned to the Gedinnian stage, being described essentially as green and purple slates with some hard grit and quartzite. Ussher (1907) produced a general correlation with the German/Belgian Devonian stages, and thus the overlying Meadfoot Group, was shown to have an age range from Taunusian to Early Coblenzian (Fig. 1.3). These stages are equivalent to the Siegenian stage which is used today (see House *et al.*, 1977) (Fig. 1.3). The Staddon Grits were placed in the Upper Coblenzian which corresponds to the Emsian stage. The Middle Devonian was also described by Ussher (1907) in the Plymouth area. Here it was divided into slates of Eifelian age and an overlying Plymouth Limestone, with associated volcanics, corresponding to the Givetian stage. The Upper Devonian was assigned to one lithostratigraphical unit of Frasnian to Famennian age.

Carboniferous aged rocks were described from the Pillaton [SX 3650 6430], Halton Quay [SX 4140 6560] and St. Mellion [SX 3890 6500] areas (Ussher, 1907). At Pillaton chert beds were recorded and at Halton Quay the *Posidonomya* Beds were recorded (see Fig. 1.4), both of which correspond to the Lower Culm Measures. In the St. Mellion area exposures of the Middle Culm Measures were described. The remaining Palaeozoic strata, those of the New Red Sandstone Series, were described from the coastal exposures of Crownhill Bay [SX 4925 4980].

Hendriks (1951) followed this work by producing a comprehensive study of the geology to the south of Plymouth, along the east side of Plymouth Sound, and re-examined the marine fauna within the rocks of the Meadfoot Group. She sub-divided the Dartmouth Slates on lithological grounds and assigned them an age range from Upper Gedinnian to Taunusian, the latter being equivalent to the Siegenian (see Fig. 1.3). Her sub-division of the Dartmouth Slates is threefold (zones 1a, b and c); massive quartzites and grits overlain by conglomerates which are in turn overlain by purple and green slates. The latter two contain the fish fossil *Pteraspis cornubica*. The oldest, and structurally the lowest, sub-division occurs between Andurn Point [SX 4900 4980] and Wembury Point [SX 5015 4800], with the younger slate sub-division occurring to the south, therefore establishing southward younging within the Dartmouth Slates. Hendriks also worked on the remainder of the Lower Devonian succession in SW Devon and for the strata overlying the Dartmouth Slates she erected a further seven sub-divisions (zones 2-8). Zones 2-6 (Lower Hunsruckian to Emsian) correlate with the Meadfoot Group (of Ussher, 1907) and zones 7 and 8 (Upper Emsian to Eifelian) correlate with the Staddon Grits (Ussher, *op. cit.*).

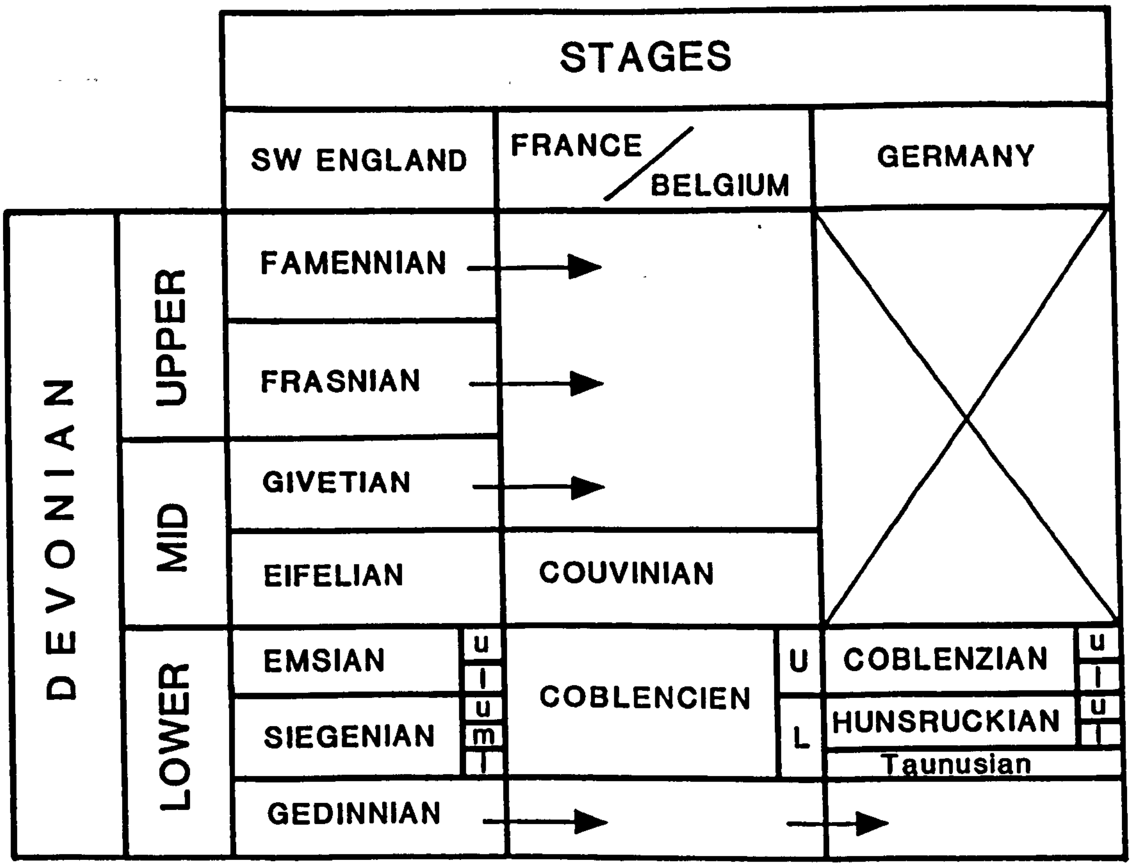

Fig. 1.3 Stratigraphic correlation diagram for the Devonian stages of western Europe.

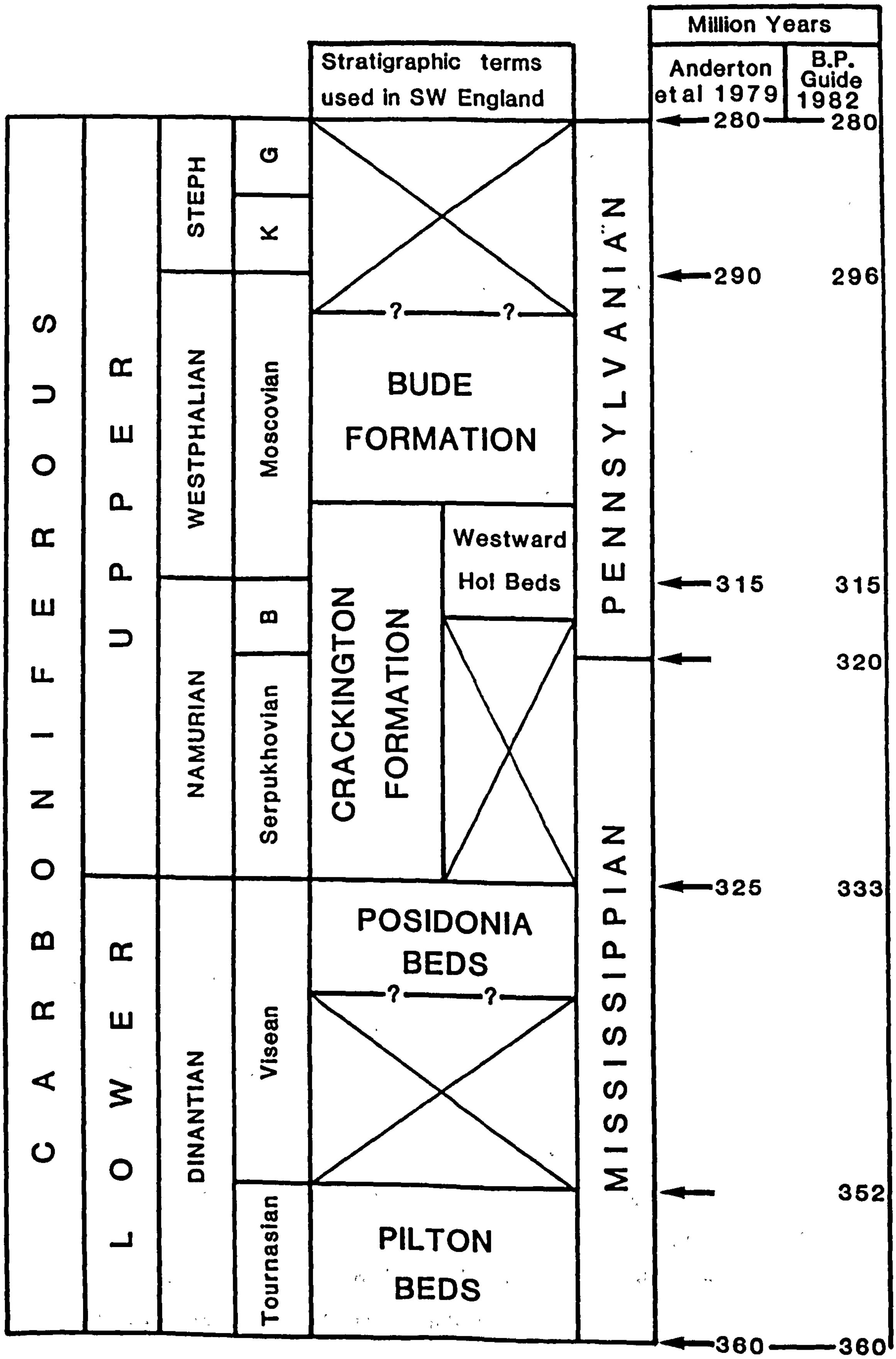

Fig. 1.4 Stratigraphic terms used in describing the rock units present in the Carboniferous of SW England.

Dineley (1966) described a section through the Lower Devonian of the South Hams area in which he defines a stratigraphy for the newly named Dartmouth Beds. Although making a very detailed and useful description of these rocks, he failed to realise the potential in Hendricks' work (1951). Dineley proposed a four-fold division for the Dartmouth Beds which he suggested youngs from south to north. However, Hobson (1976a) shows that the succession youngs from north to south just as Hendriks had done in 1951. Dineley (1966) considered the Warren Sandstones to be the oldest and the Wembury Siltstones to be the youngest but Hobson's work (1976a) indicated that the opposite is true i.e. the Wembury Siltstones are the oldest and the Warren Sandstones are the youngest within the Dartmouth Beds. Dineley (1966), thus proposes a stratigraphy which is upside down. However, this does not invalidate his lithostratigraphical sub-divisions. The modifications made by Hobson (1976a) were a product of detailed structural observations obtained from coastal exposures between Plymouth and Bolt Tail. The changes were in keeping with the detailed sedimentological, lithological and palaeontological work of Dineley (1966), whilst retaining the order of age described by Hendriks (1951).

Dineley (1966) also described the pteraspids of South Devon and equated them with *Pteraspis cornubica* from the Newquay area on the North Cornwall coast. He described two kinds of Pteraspid: some were of the *Crouchi-rostra* group which gives a Middle to Late Dittonian age (Middle to Late Siegenian) and others were of the *Leachi-dunensis* group, which indicates Late Dittonian (Breconian or Siegenian to Emsian) age. Dineley (1966) thus correlated the Dartmouth Beds of South Devon with the Dittonian and Breconian stages of Wales and the Welsh Borderland. He describes an initial phase of continental deposition consisting mainly of distal floodplain alluvium analogous to the Lower Devonian of western Europe. This interpretation is based on the occurrence of plants, fish, ostracods and similarities in the sedimentological character of a series of logged sections to the fluvial sequences of the Welsh Borders. He also suggests possible tidal and deltaic incursions but quotes no evidence for this.

Fyson (1962) studied the coast to the south of Plymouth and discussed the significance of the change in attitude and form of the small scale structures and their association with faulting. He suggested that the uniform dextral displacements across NW-SE trending strike-slip faults indicates a change in the direction of compression from being initially NW-SE to N-S. Fyson described small-scale thrusts but failed to appreciate the effects of larger thrusts in controlling the present disposition of the strata.

1.3.2 Post-1976

Hobson published two pieces of work in 1976 which contain the most detailed cross sections produced to date through the Devonian rocks south of Plymouth, and this led to the revision of both the structure and stratigraphy of the Dartmouth Beds (see above). In the first paper (1976a), he discussed a NW-SE structural section extending from Bolt Tail to Plymouth and along which he discovered four phases of deformation. In this paper he also re-evaluated the lithostratigraphy of the Dartmouth Beds and modified the existing maps of Bigbury Bay (cf. Dineley, 1966).

Hobson (1976b) discusses the relevance of a structural cross section south of Plymouth in terms of its regional context. The work was extended westwards to Newquay, on the north Cornish coast, along the outcrop of the Dartmouth Beds. These rocks were found to lie within a structure which he named the Dartmouth Antiform. This was described as a major D1 fold modified by subsequent D2 deformation. He describes the northern margin of the antiform in the Plymouth section (at Andurn Point) as a steep, late, normal fault which has a vertical displacement of ca. 3km down to the north (Hobson 1976a).

Harwood (1976) worked on the Meadfoot Group rocks on the east side of Plymouth Sound and discussed the dilemma: Staddon Grits - or Meadfoot Beds? She concluded that the criteria used for describing the Staddon Facies here, matched the descriptions for the Meadfoot Beds elsewhere eg. at the type section at Meadfoot Beach (Richter, 1967). Harwood (1976) describes the Meadfoot Facies, on the east side of Plymouth Sound as consisting of black to grey slates, lithologies which are incompatible with its type locality at Meadfoot Beach.

Detailed palaeontological investigations of the Meadfoot Group rocks have been carried out by Evans (1981, 1983 and 1985). He made a comprehensive study of the Lower Devonian brachiopods of Britain (Evans, 1980), one particular sampling ground being Crownhill Bay on the east side of Plymouth Sound. Other areas of his research relevant to this project cover sections around Torbay. He published a number of papers discussing the age range of the Meadfoot Group rocks based on the brachiopods. He refers to the rock units within the Meadfoot Group as the Meadfoot Facies (dominantly pelitic) and Staddon Facies (dominantly sandy), with the latter being laterally impersistent. The brachiopods described from the Meadfoot Group rocks in the Plymouth area indicate a Siegenian to Emsian age. The contact between the Meadfoot Facies and the Staddon Facies corresponds to the Siegenian/Emsian boundary (Evans, 1983). However Evans (1981) concluded that the

Meadfoot Group ranges from Late Siegenian to Late Emsian. Relationships are not as clear in the Torbay region (Evans, 1985) where the fauna from the Meadfoot Facies indicates a Early to Late Emsian age, whilst that from the Staddon Facies gives a Late Emsian age. Evans (1985) also discusses the depositional environments for the Meadfoot Group based on sedimentology, lithology and fauna. In the Torbay region he concluded that the Staddon Facies represents inner shelf conditions whilst the Meadfoot Facies represents an outer shelf environment. Similar results were obtained from the Meadfoot Group rocks of the Plymouth area by examining the benthic assemblages of the brachiopod fauna (Evans, 1985).

Pound (1984) suggests that the Staddon Grits developed in a deltaic environment and prograded southwards over the dominantly pelitic Meadfoot Beds. This is in contrast to the previous views that the Staddon Grits formed as offshore bars (Selwood and Durrance, 1982). Burton and Tanner (1986) favour its development in an offshore bar setting based on the presence of a rich brachiopod fauna.

Recent studies of the geology of SW Devon, particularly the South Hams region have been along structural lines (Chapman, 1983; Chapman *et al.*, 1984; Coward & McClay, 1983; Chandler & McCall, 1985), and on a more regional scale the work of Shackleton *et al.* (1982) and Coward & Smallwood (1984) are particularly significant. Chandler and McCall (1985) recognise thrusts in the Plymouth area and have redefined the stratigraphy of part of the Middle and Upper Devonian sequence. Thrusts had previously been recognised (Ussher, 1904; Hendriks, 1951; Fyson, 1962; Dineley, 1966) but their regional significance was not appreciated. However, accelerated development of thrust tectonics (Dahlstrom, 1969; Elliot & Johnson, 1980; Boyer & Elliot, 1982; Butler, 1982) has led to a better understanding of thrust-dominated orogenic zones. Thrust models have been applied to SW England and the regional tectonics can be explained in terms of thin skinned tectonics (Day, 1983; Chapman *et al.*, 1984; Coward and McClay, 1984; Shackleton *et al.*, 1982; Seago and Chapman, 1988) although some workers do refer to a thick skinned model in order to explain the present disposition of the strata (Sanderson, 1984; Turner, 1986; Holdsworth, 1989). It was the recognition of thrusts in the Plymouth area (Chapman, 1983; Chapman *et al.*, 1984), following their identification around the Torbay area, further east (Coward & McClay, 1983), that stimulated in part the present research into the structure and lithostratigraphy of the Lower Devonian rocks south of Plymouth.

Another important feature of Variscan deformation in SW England is whether or not a facing confrontation of first phase folds exists. For a number of years it was accepted that a facing confrontation of first phase Variscan folds did exist. It was described on the north

Cornwall coast where it is known as the Padstow or Polzeath facing confrontation (Gauss, 1967, 1973; Dearman, 1970, 1971; Roberts & Sanderson, 1971; Freshney *et al.*, 1972; Sanderson & Dearman, 1973; Hobson & Sanderson, 1975, 1983; Sanderson, 1979; Shackleton *et al.*, 1982), and has since been projected eastwards to the area north of Plymouth (Sanderson & Dearman, 1973; Hobson & Sanderson, 1983). Furthermore, Shackleton *et al.*, (1982) and Coward and Smallwood (1984) explained the confrontation in terms of southerly directed back-thrusting.

Subsequent to the work by the above authors, a geological programme carried out by the workers from Exeter University in collaboration with the BGS was undertaken in SW England. This involved mapping and associated structural, sedimentological and biostratigraphic work in the areas between Dartmoor and Bodmin Moor and farther west on the north Cornish coast. This work has gone a long way towards unravelling the complex stratigraphical and structural relationships in central SW England: in particular the recognition of major nappe structures has helped to explain the existence of large areas of flat-lying, often inverted, Upper Devonian and Carboniferous strata (Stewart, 1981; Isaac *et al.*, 1982; Selwood *et al.*, 1985; Selwood & Thomas, 1984, 1985, 1986a, 1986b; Whiteley, 1984; Isaac, 1985; Turner, 1985). These authors also recognize the importance of northwards prograding flysch sedimentation. Another important view of these workers is the rejection of the existence of the zone of south-facing first phase folds, the facing confrontation and the idea of southwards transport for the nappes (Isaac *et al.*, 1982; Selwood & Thomas, 1984, 1985, 1986a; Selwood *et al.*, 1985). Contrary to earlier views, these workers have argued that all the first phase folds face northwards and that the nappes of Upper Devonian and Carboniferous rocks (of central SW England) are derived from the south by gravity sliding (Stewart, 1981; Isaac *et al.*, 1982; Selwood & Thomas, 1984, 1985, 1986b, 1988; Selwood *et al.*, 1985; Isaac, 1985; Turner, 1985). There has been much controversy over this aspect of the structure. The present study will show that the facing confrontation is a reality and an important part of the structure of the Variscan of SW England.

Andrews *et al.* (1988), Pamplin and Andrews (1988), Selwood and Thomas (1988) and Durning (1989) contribute further to the tectonics of the region by discussing the evolution of the facing confrontation on the north Cornish coast. Studies over the last ten years have allowed a much greater emphasis to be placed on the regional significance of the Variscan Fold Belt of the NW Atlantic Region and its platetectonic setting (Hutton & Sanderson, 1984 - and references therein, Chapman, 1986 - and references therein) and this has stimulated new ideas which are presented in this work.

CHAPTER 2
STRATIGRAPHY

2.1 INTRODUCTION

This chapter describes the stratigraphy of the Palaeozoic sequence of SW Devon. Section 2.2 contains an account of the Lower Devonian succession in the area south of Plymouth and Section 2.3 describes the Middle and Upper Devonian rocks in the Plymouth area. Section 2.4 contains a brief description of the Carboniferous rocks which are involved in the large scale structures north of Plymouth and Section 2.5 gives an account of the New Red Sandstone rocks present in SW Devon. Depositional models for these stratigraphic units are described in the appropriate sections. A list of key points (Section 2.6) concludes the chapter.

The stratigraphic units described in the following sections are defined on lithostratigraphic grounds only (see Holland *et al.*, 1978) due to the lack of comprehensive palaeontological control. For the most part, stratigraphic thicknesses are measured directly from the cross sections presented in the structural part of the thesis (see Chapter 4).

2.2 LOWER DEVONIAN

The Lower Devonian (Dartmouth Group and Meadfoot Group) forms an E-W belt of rocks between Dartmouth [SX 8800 5100], in south Devon, and Watergate Bay [SW 8400 6500], in west Cornwall (Fig. 1.2), and has an age range of Siegenian to Emsian (Fig. 2.1). In this study data collection for the detailed stratigraphical analysis has been confined to SW Devon.

2.2.1 Dartmouth Group

The Dartmouth Group is divisible into four lithostratigraphic units: the Renney Rocks Formation (oldest), the Wembury Formation, the Yealm Formation and the Warren Formation (youngest) (Fig. 2.2). These formations are contained within the Dartmouth Group, the outcrop of which extends south westwards along the coast from Andurn Point [SX 4900 4980] to Wadham Rocks [SX 5800 4680] (Fig. 2.3). Faulting has repeated the sequence between Wadham Rocks and Westcombe Beach [SX 6350 4575] (Fig. 2.3) resulting in

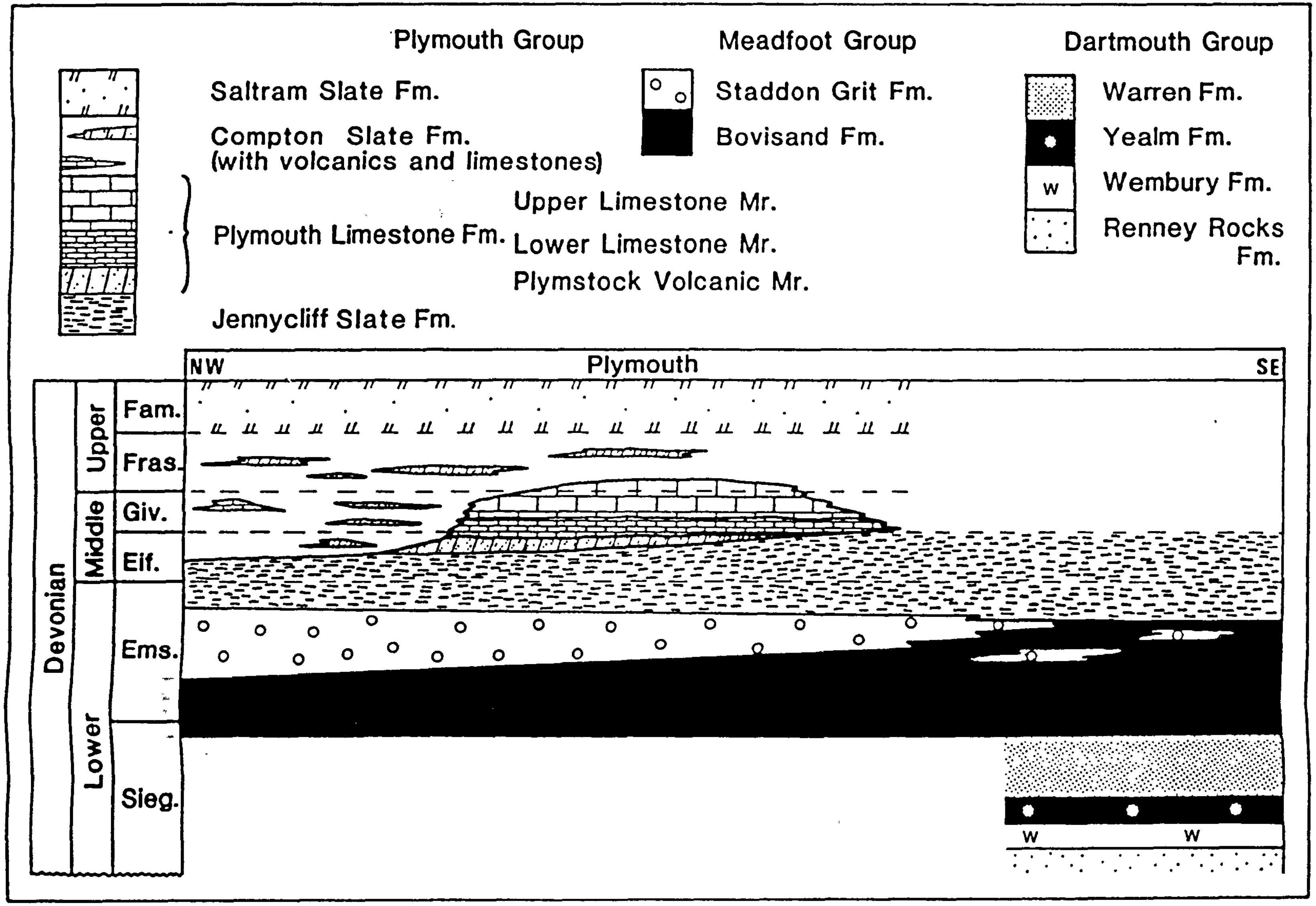

Fig. 2.1 Schematic representation of the Devonian stratigraphy along a NW-SE transect through Plymouth (not to scale). Base of the Dartmouth Group not seen. Sieg., Siegenian; Ems.,Emsian; Eif., Eifelian; Giv., Givetian; Fras., Frasnian; Fam., Famennian.

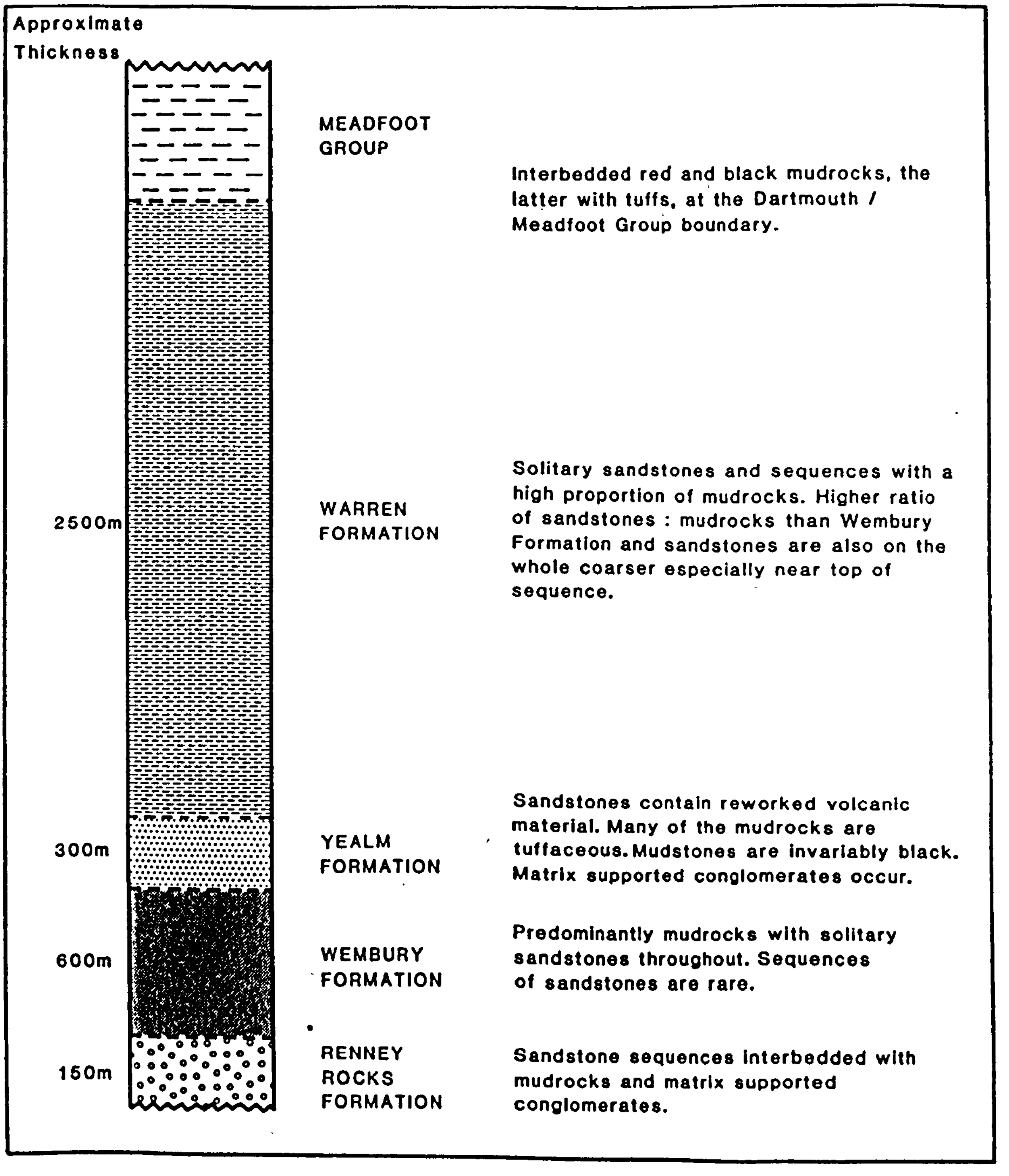

Fig. 2.2 The stratigraphy of the Dartmouth Group rocks in the region to the south east of Plymouth as defined by this study.

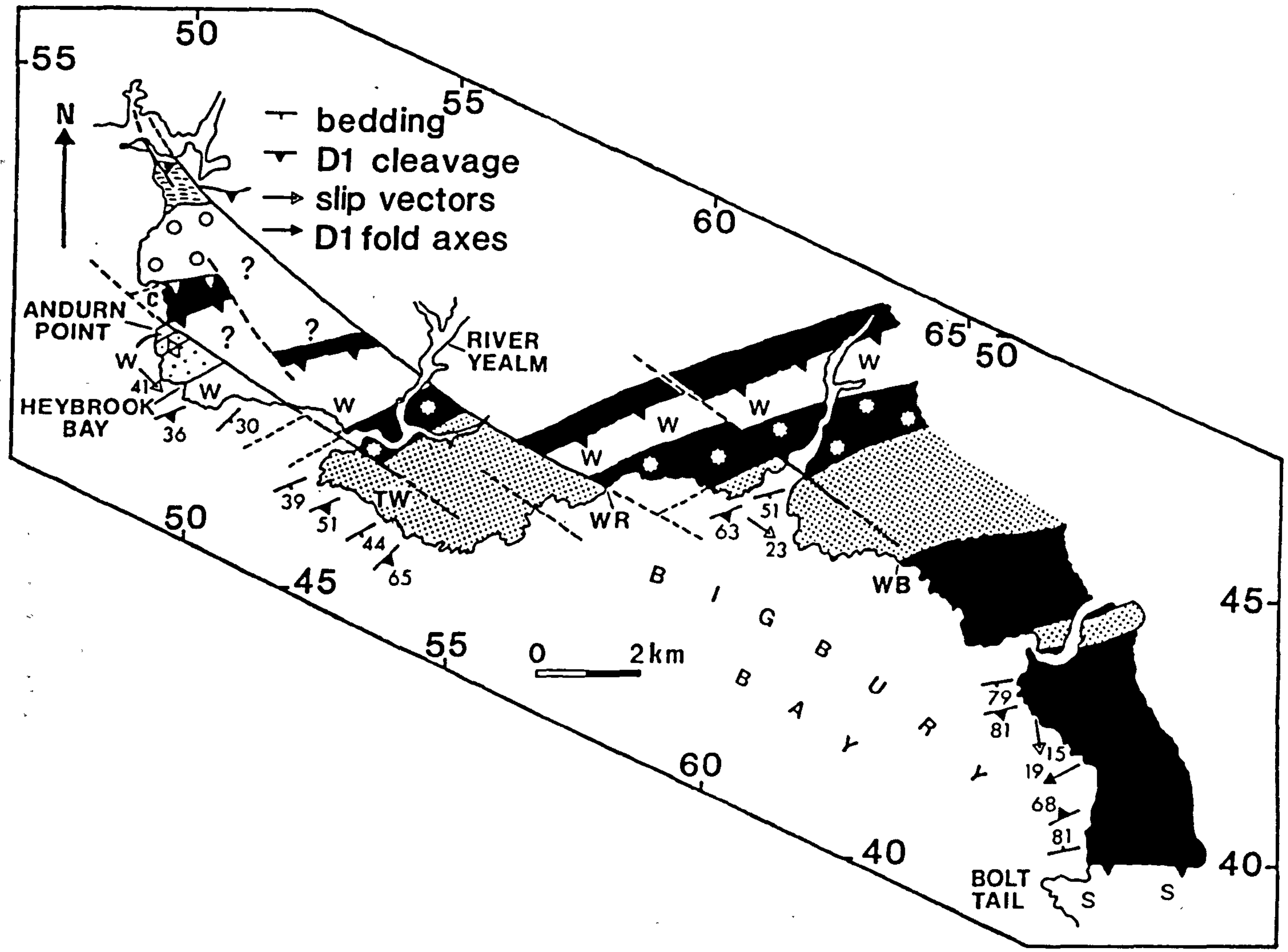

Fig. 2.3 Geological map of the western coast of the South Hams region showing the distribution of the Lower Devonian strata. Ornament to the stratigraphy as shown in Fig. 2.2. C, Crownhill Bay; TW, The Warren; WB, Westcombe Beach; WR, Wadham Rocks.

repetition of the sequence. The Dartmouth Group succession is described from north to south in the general direction of younging.

Renney Rocks Formation

This formation has been described in the coastal exposures between Andurn Point, in the north, to just south of Heybrook Bay [SX 4970 4875], in the south (Fig. 2.4) and contains the oldest rocks in SW Devon excluding the Start Schist Complex (see Chapter 5). The dominant lithology is red, pink or grey/green sandstone with subordinate purple, red and green slate (Pl. 2.1) and paraconglomerates. The formation's northern boundary occurs just south of Andurn Point where the Renney Rocks Formation is faulted against the Wembury Formation (Fig. 2.4). Although the base of this formation is not exposed, its thickness probably exceeds 150m although only 80m of the sequence is exposed (see Fig 4.29). The Renney Rocks Formation occurs in the core of a hangingwall anticline, previously referred to as the Dartmouth Anticline (Hobson 1976a, 1976b) and is associated with the Crownhill Thrust (see Chapter 4). Along this part of the coast the overlying Wembury Formation is also exposed as a result of minor folding of the boundary between the two formations close to the present erosion level (Fig. 2.4). The boundary of the Renney Rocks Formation and the overlying Wembury Formation is gradational and is taken to occur where the percentage of sandstones is considerably reduced and mudrocks become more dominant. This boundary occurs further south in the region of Heybrook Bay.

Wembury Formation

The Wembury Formation crops out in Wembury Bay and extends from Heybrook Bay in the west to the mouth of the River Yealm [SX 5275 4810] in the east. It is dominated by purple, red, brown and green slate (altered mudrocks) (Pl. 2.2) with occasional sandstone beds, which are generally less than a metre in thickness. From the structural cross sections in Chapter 4, it is determined that the thickness of this unit is ca. 600m. Volcaniclastics are present in the upper part of the formation just below the boundary with the overlying Yealm Formation. When the content of volcanic ash becomes extreme the rocks display more varied colours and as well as the greens and reds, seen in the major part of the Wembury Formation, there are also yellows and blacks. With this change in colour a new lithostratigraphic unit can be defined. The boundary is therefore interpreted as occurring where volcanic deposits are

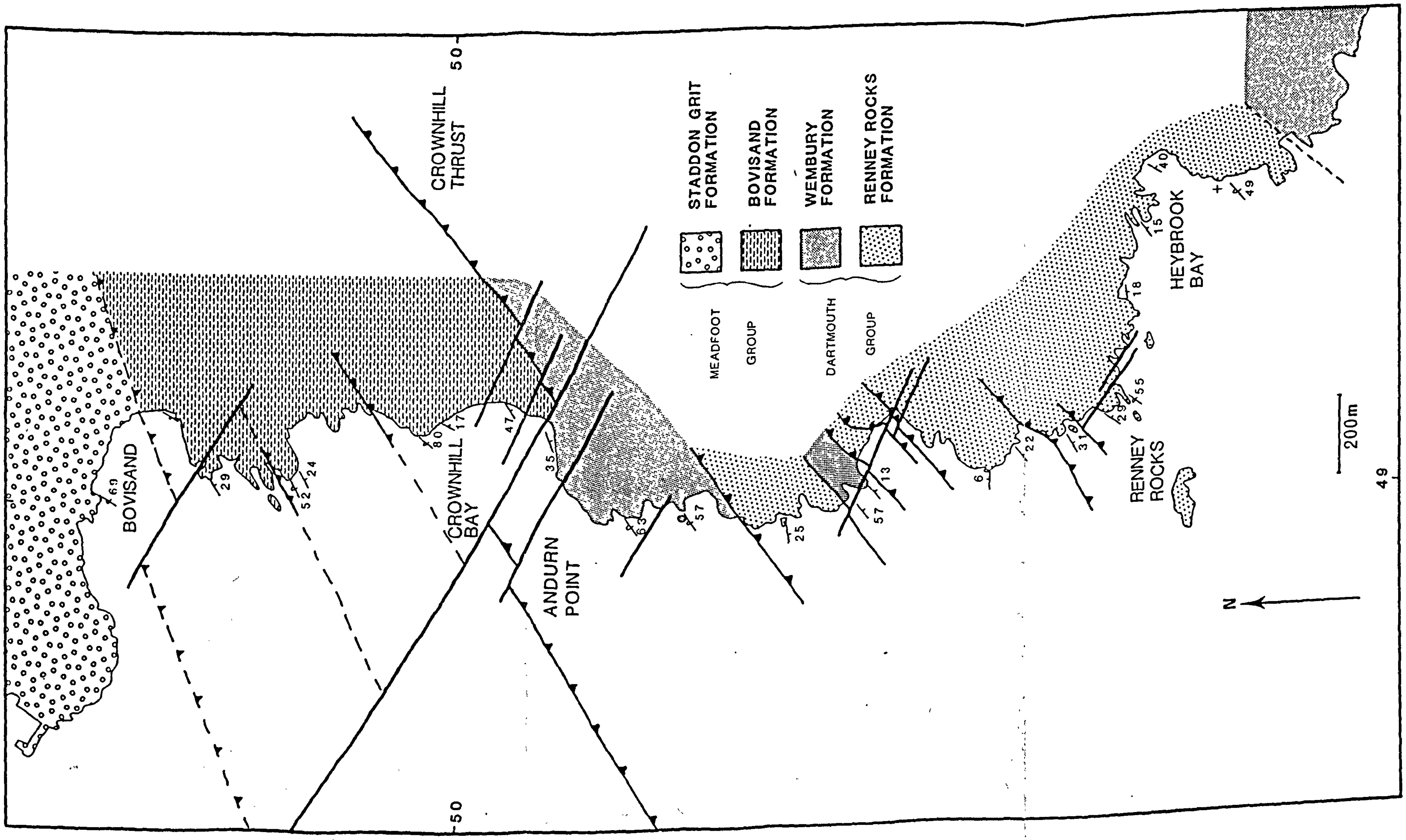

Fig. 2.4 Detailed geological map of the coastal section between Bovisand and Heybrook Bay.

Plate 2.1 A typical clastic sequence within the Renney Rocks Formation characterised by red mudrocks and pink to grey sandstones; Renney Rocks [SX 4925 4875].

Plate 2.2 Red to brown mudrock sequence within the Wembury Formation; Wembury Beach [SX 5170 4840].

a common occurrence. The Wembury Formation occurs within the Crownhill Thrust sheet in the hangingwall anticline to the Crownhill Thrust (see Figs 2.3 and 2.4) and cross sections in Chapter 4, Figs 4.29 and 4.31).

Yealm Formation

Along with sandstone (very fine to medium grained) and slate, this formation also contains a significant amount of volcanic material. It crops out in the vicinity of the River Yealm (see Fig. 2.3) which has clearly followed the outcrop of the easily weathered tuffs and volcaniclastics. Dineley (1966) estimates that the ratio of volcanics to slate and sandstone is 20:80. However, the fact that the sandstones and siltstones contain ash reworked by water as volcaniclastics makes an estimate on the percentage of volcanic material present extremely difficult. It is likely to be much greater than 20%. The presence of volcanic material causes this formation to weather to a mainly yellowish colour (Pl. 2.3). Black slates are present in this formation but have not been observed anywhere else in the Dartmouth Group. The thickness of the formation is ca. 300m and stratal dips are uniform to the south-east. However, mesoscopic folds and thrusts disrupt and cause repetition of the sequence.

Warren Formation

This formation occurs along the coast of the Warren between the River Yealm [SX 5300 4750] in the west, and Wadham Rocks [SX 5800 4680] in the east (see Fig. 2.3). The base of the Warren Formation is placed where the volcanics and volcaniclastics of the underlying Yealm Formation become rare or absent. Lithologically the Warren Formation is very similar to the Wembury Formation but the sandstones present are generally more coarse-grained (fine to coarse). The ratio of sandstones to mudrocks is difficult to estimate, however, a greater number of sandstone bodies occur in the Warren Formation compared to the Wembury Formation. In the Warren Formation sandstones not only occur as solitary beds (up to 1m thick) but also as sequences, the thickest of which has previously been mapped as a separate unit (Dineley, 1966), at Beacon Point [SX 6155 4600]. He referred to this sequence as the Scobbiscombe Sandstones which is ca. 120m thick. Due to the fact that the Warren Formation contains many sequences of sandstones, commonly no thicker than 10-20m, and also due to their limited lateral extent, it is not considered necessary to include them as distinct lithostratigraphic members. The Warren Formation which is ca. 2,500m thick, forms

Plate 2.3 Sandstone/mudrock sequence within the Yealm Formation. Mudstones (lower left) are black to grey and the siltstones and sandstones are grey to yellow; Wonwell Beach, Erme Estuary [SX 6180 4740].

Plate 2.4 Grey to black slates of the Bovisand Formation; Crownhill Bay [SX 4925 4980].

the top of the Dartmouth Group and passes upwards into the rocks of the Meadfoot Group. The boundary may be regarded as a transition zone as red mudrocks of the Dartmouth Group are interbedded with black mudrocks of the Meadfoot Group. The boundary relationships can be examined at Westcombe Beach [SX 6350 4575]. The attitude of cleavage with respect to bedding and the lack of thrust faults indicate that the repetition of red and black units is not tectonic in origin. They are simply interbedded with each other resulting in a continuous stratigraphic sequence.

2.2.2 Meadfoot Group

The Meadfoot Group rocks are divided into the Bovisand Formation (lower) (Bovisand Beds of Harwood, 1976) and the Staddon Grit Formation (cf. Chandler & McCall, 1985) and has been dated most recently on brachiopods which indicate a Siegenian to Emsian age (Evans, 1981, 1983, 1985). The overall sedimentological character of this group of rocks is essentially one of an overall coarsening upwards/thickening upwards sequence. Due to the complex facies relationships within the Meadfoot Group it is often difficult to differentiate the two formations especially in areas of poor exposure and where facies interdigitate. The latter case applies to the easternmost outcrops of the Staddon Grit in the Torbay region.

The descriptions contained in this chapter apply to the rocks on the east side of Plymouth Sound between Jennycliff Bay [SX 4915 5185], in the north, and Andurn Point, in the south. Outcrops of the Meadfoot Group also occur at the southern end of the area, in the coastal outcrops of Bigbury Bay (Fig. 2.3).

The problems that have evolved regarding terminology for this part of the Lower Devonian sequence are discussed and a working description (especially for differentiation of lithological associations in the field) is suggested.

Bovisand Formation

This formation is dominated by argillaceous lithologies with sub-ordinate grey sandstones and thinly bedded limestones. The mudrocks, now in the form of grey/black slates (Pl. 2.4), are interpreted as being shallow marine in origin (Evans, 1985). They contain thin fossiliferous bands which define a bedding lamination. Towards the top of this pelitic facies, sandstones which are yellow in colour become more common and occur within 4-5m thick coarsening upwards/thickening upwards sequences (Fig. 2.5). These sequences occur at the

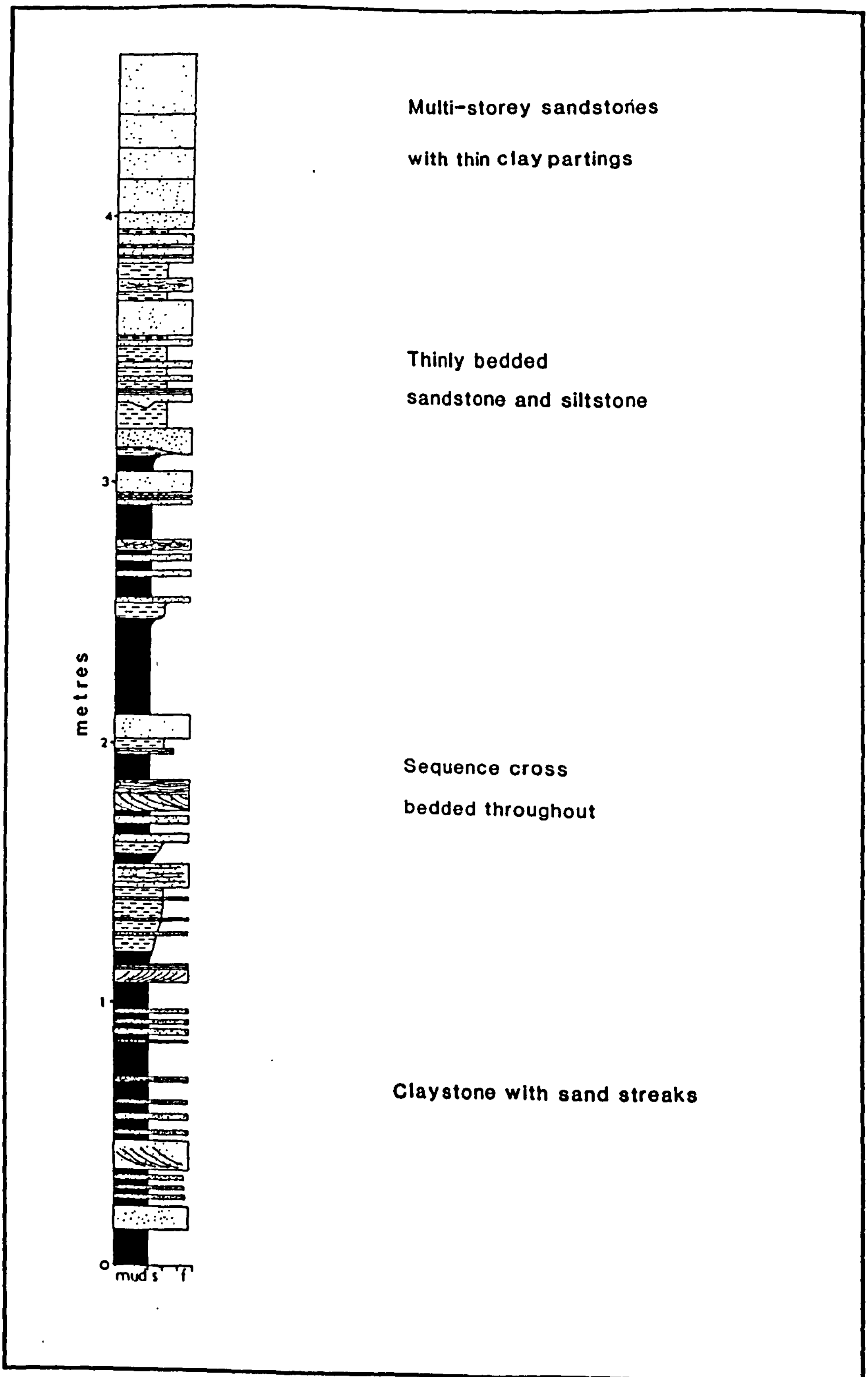

Fig. 2.5 Logged sequence near the top of the Bovisand Formation in Crownhill Bay [SX 4925 4980].

top of the Bovisand Formation just below the boundary with the overlying Staddon Grit Formation which is in turn dominated by coarser grained rock types. The rocks of the Bovisand Formation also occur further south, in Bigbury Bay [SX 6700 4200] where the lithology is predominantly black slate. However, coarser deposits are present (Beeson Grits of Ussher 1907) which probably represent lateral equivalents to the Staddon Grit Formation further north. The Bovisand Formation is thicker in the south (ca. 1500m) relative to the north (ca. 600m) (see structural sections in Chapter 4) and this is attributed to the proximity of the prevailing Early Devonian shoreline. In contrast, the overlying Staddon Grit Formation thins southwards from its coastal proximity onto the shelfal area.

Staddon Grit Formation

The Staddon Grit Formation (Chandler and McCall, 1985) is composed of somewhat coarser lithologies than the underlying Bovisand Formation. Another characteristic difference is the reddish colour of all lithologies present in the formation (see Pl. 2.5). The Staddon Grit Formation is ca. 400m thick (restored thickness) near Plymouth but thins rapidly in a southward direction. The thickness and lithological character of the Staddon Grit Formation also varies from west to east across Cornwall and Devon. The formation is well developed in the west and always overlies and is younger than the black pelitic Bovisand Formation. From the north Cornwall coast to as far east as Staddon Heights, south of Plymouth, the above relationships and well developed nature of the formation applies. Further east in the Torbay area, however, the thickness of the formation is substantially reduced and it becomes interbedded with the underlying black argillaceous rock types. These relationships are further complicated by subsequent folding and faulting. Thus the Staddon Grit and Bovisand Formations, when traced eastwards from Plymouth, become less distinct separate stratigraphic units. This is thought to be primarily due to lateral variations at the time of deposition. The interbedded nature, rapid facies changes and reduction in stratigraphic thickness of the coarse grained facies from west to east, over the area, is thought be represent deposition in more proximal (west) and more distal (east) environments.

From palaeocurrent analysis and the presence of coarsening up and thickening upwards sequences (Pound, 1984), it is shown that this formation is sourced from the north and represents the southwards progradation of a delta or shoreline (see also Selwood & Durrance, 1982). The area in the east (Torbay) may represent the easterly limit of this sedimentary facies, possibly the edge of the delta.

Plate 2.5 A typical sequence within the Staddon Grit Formation; Sandy Cove, Crownhill Bay [SX 4925 4980].

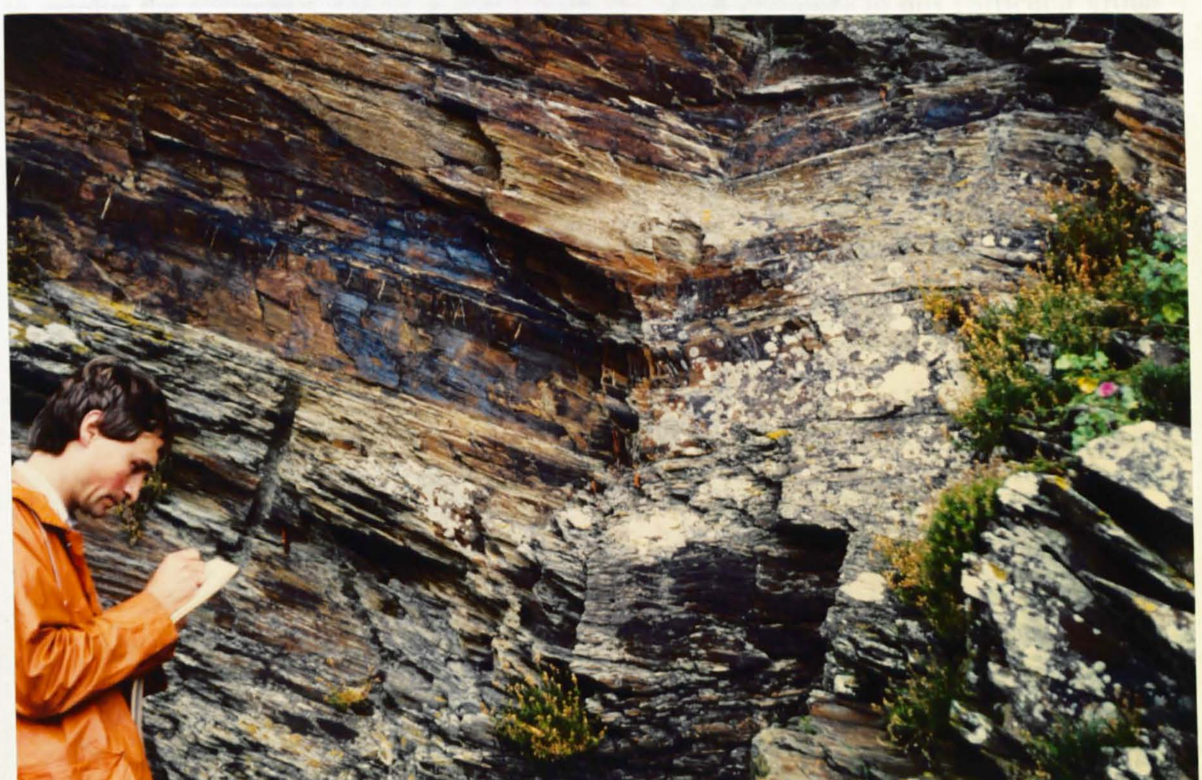

Plate 2.6 Grey slates and sandstones of the Upper Devonian/Lower Carboniferous rocks north of Plymouth at Hole's Hole; River Tamar [SX 4320].

The coastal section to the south of Plymouth, between Jennycliff Bay and Bovisand Beach, reveals a structural thickness of ca. 1km for the Staddon Grit Formation. This thickness decreases from north to south as a result of more proximal sedimentation in the north. Further south, equivalents of this formation occur in the form of coarse facies interbedded with the Bovisand Formation (formerly referred to as the Beeson Grits by Ussher, 1907). Like the deposits at the base of the Staddon Grit Formation, at Crownhill Bay, they represent offshore sand bars (see Chapter 3) which probably migrated across the shelf area, and may develop in front of either a linear clastic shoreline or in a prodelta environment. A deltaic interpretation is preferred as palaeocurrent patterns are analogous to mouth bar forms.

Discussion

During the research into the geology of SW Devon, there have been many suggestions as to how to classify the sequence of rocks which lie between the Lower Devonian Dartmouth Group and the Lower to Middle Devonian Jennycliff Slate Formation. This section of the thesis summarises the detailed previous work concerning this part of the Devonian stratigraphy and compares it with the data collected during this project. An attempt is made to resolve the difficulties that have arisen from the casual reference to this particular group of rocks by previous workers.

Ussher (1890, 1903) refers to two rock units at this particular stratigraphic interval in the Torquay area. He described an upper unit (Lincombe and Warbury Beds) of red sandstone, grits and shales, and a lower unit (Meadfoot Beds) of bluish grey slates and hard grits. He further pointed out that it is not always possible to determine the stratigraphic relations between these two units due to the presence of many faults. He also noted that problems in classification occur when the black slates are reddened by the overlying Permian (New Red Sandstone) sediments. Research in the Plymouth area (Ussher, 1907) revealed a more straightforward relationship between the two stratigraphic divisions. Just south of Plymouth, Ussher (1907) discovered a lower unit of black slates which are overlain by a series of sandstones, shales, grits and conglomerates. He refers to these two units as the Meadfoot Group and Staddon Grits respectively. The term Meadfoot Beds (Ussher, 1890) is used synonymously with the Meadfoot Group (Ussher, 1907). Further south is a sequence of similar aged rocks consisting of predominantly black slates with locally developed and occasionally reddened sandstones. Ussher (1904) has described these on the west side of the South Hams peninsula and refers to them as the Meadfoot Beds, dividing them into the Tinsey

Head Slate Series (youngest), the Beeson Grits (grey grits which are in fact sandstones), the Torcross Type and the Ringmore Type. Even at this early stage of research into the geology of SW Devon, there are many local names for the same rock units.

Asselberghs (1921) correlated the Lower Devonian of Devon with that of the Ardennes. The inference from this work is that the Staddon Grits are relatively younger (Emsian) than the Meadfoot Beds which give an age range of Taunusian - Hunsruckian (see Fig. 1.3). Lithologically he correlated the Staddon Grits with the very fossiliferous, often calcareous, sandstone and shales of the Ardennes. He correlated the Meadfoot Beds with a sequence of dark blue slates and shales interbedded with quartzite. In his work Asselburghs (1921) refers to both the Meadfoot Beds and the Meadfoot Group.

Lloyd (1933) recognised that the Meadfoot and Staddon Beds, comprising shallow water shales, sandstones and grits (Emsian in age), could not be separated in the Torquay area. However, Lloyd (1933) notes that further west the Staddon Grits are strongly developed and diminish towards the eastern end of their outcrop. Hendriks (1959) explained the variation and disposition of the facies as a function of the presence of the Staddon Rise. Dineley (1961) preferred the idea that the Staddon Grits are a lateral equivalent to the Meadfoot Beds with the latter giving way to the thickening Staddon Grits.

Dineley (1961) interpreted the Meadfoot Beds and Staddon Grits as two separate rock units with the Meadfoot Beds comprising bright red, grey-green and black claystones and siltstones with volcanic bands and lenticles. He described the top of the Meadfoot Beds as being marked by massive pale red quartzites (regarded as the base of the Staddon Grits). The Staddon Grits are thickly bedded to massive, pale and purplish quartzose and quartzitic sandstones, interbedded with thinner shales or slates and conglomeratic beds above erosion surfaces. He described the strong development of the sandy facies in the west, and its more interbedded nature to the east, as being a function of tectonic disturbance. A model involving the interfingering of facies is suggested (Dineley, 1961) and is probably indeed the case in the eastern part of the area around Torbay. However, in the west around Plymouth and into Cornwall the Staddon Grits undoubtedly form a separate stratigraphic entity, representing a distinct change in facies.

Describing the separate formations in the area around Torbay is difficult due to the above mentioned rapid lateral facies changes. Richter (1967) described the detailed sedimentology of the Meadfoot Beds in this area but doubted that the Staddon Grits form a separate unit.

In the West Hams area Harwood (1976) recognised the problem of distinguishing the

Staddon Beds (as she called them) from the Meadfoot Beds, and the possible erroneous correlation of boundaries due to the thick sandstone bodies occurring in both rock units. She realised that the criteria used to describe the Staddon Beds at Bovisand are elsewhere used for the Meadfoot Beds and that the occurrence of black pelites, similar to those at Bovisand, which she terms the Bovisand Beds, are relatively rare north of the Dartmouth Antiform (qv. Hobson, 1976b). It was also noted that lithologies on the southern flank of the Dartmouth Antiform, and forming part of the Meadfoot Group are invariably black pelites with localised development of coarser facies. House *et al.* (1977) infers that the term Meadfoot Beds is used to describe both Staddon and Meadfoot type.

Working south of Plymouth at Bovisand, Evans (1983), renamed the Meadfoot Beds and Staddon Grits as the Meadfoot Facies and Staddon Facies respectively. Dating them on brachiopods, he arrived at a Late Siegenian age for the Meadfoot Facies and an Emsian age for the Staddon Facies. He suggested that the two rock units are not entirely co-eval except near the base of the Staddon Facies. This, he said, is a function of a diachronous boundary between the two facies. Evans concluded that the terms Meadfoot Facies and Staddon Facies should be used as field descriptions with both rock units forming the Meadfoot Group. This is good practice in the region around Torbay where exposure is poor, but further west, in Plymouth and beyond, separation of the two units is possible and it is felt that formation status should be applied.

The confusion over this particular part of the Lower Devonian succession seems to have arisen from the fact that the two rock units in question are in part co-eval and subject to rapid lateral facies changes (particularly around Torbay). This relationship is further complicated by subsequent deformation. Evans (1983) is quite correct to refer to all rock types of this age in the area as the Meadfoot Group. However, this should only be practised around the Torbay area where relationships are complex. Further west the Staddon Grits become more pronounced as one unit and form a distinct belt of coarse clastics and separation into a distinct formation is possible. Those rock types which are black/grey in colour, essentially argillaceous with thin limestone laminations and only localised developments of grey or red sandstone, should be referred to as the Bovisand Formation. The rocks which are predominantly arenaceous and red in colour, locally possessing prolific fossil faunas, grey sandstones and slates, formerly described as the Staddon Grits, should be referred to as the Staddon Grit Formation (Chandler & McCall, 1985). The term, Meadfoot, in the form of the encompassing Meadfoot Group, is retained in order to comply with existing stratigraphic nomenclature. On the east side of Plymouth Sound there has been no difficulty in distinguishing the two rock units. The Staddon Grit Formation is dominantly sandy with red muds whilst the Bovisand Formation is black, argillaceous with yellow sands which increase towards the top, near the contact with the Staddon Grit Formation. In the Torbay area the term Staddon Grit Formation should be used where red sandy lithologies prevail and the term Bovisand Formation should be used where black pelitic lithologies prevail. A problem therefore arises from describing the red muds and sands, which are very fossiliferous, at Meadfoot Beach as the Meadfoot Beds. If descriptions of type sections were made in the west and then applied to the sections in the east, the problem could have been avoided.

2.3 MIDDLE AND UPPER DEVONIAN

The Lower/Middle (Emsian/Eifelian) Devonian boundary occurs within the Jennycliff Slate Formation (Chandler & McCall, 1985) which conformably overlies the Staddon Grit Formation (Fig. 2.2). The transition between the Staddon Grit Formation and the Jennycliff Slate Formation, which also marks the boundary between the Meadfoot Group and the Plymouth Group, marks the return to marine shelf conditions (Evans, 1985), similar to those observed in the Bovisand Formation. Localised shallowing during the Middle Devonian allowed the formation of reef like bodies and these are preserved in the form of limestones in both the Plymouth and Torquay areas. The limestones are localised and are surrounded by deeper water lithologies consisting of thick sequences of mud. These areas also experienced volcanicity during the period of limestone deposition.

2.3.1 The Plymouth Group

The Plymouth Group spans the Middle-Upper Devonian, ranging in age from Late Emsian to Famennian. It is exposed around the city of Plymouth and is divided into a number of diachronous lithostratigraphic formations (Fig. 2.2). It can be examined between Jennycliff Bay [SX 4915 5185] in the south and Warleigh House [SX 4560 6170] in the north, along river and coastal sections. Inland outcrops are limited but there are some particularly good exposures within the city of Plymouth. The elucidation of the stratigraphy of the Devonian slates in and around Plymouth has been made possible by combining the biostratigraphic information of Gooday (1975) and Orchard (1978) with structural and lithostratigraphical observations. Useful correlations have also been made with the Upper Devonian stratigraphy of the Liskeard area (Burton & Tanner, 1986), where a comparable section is more constrained biostratigraphically.

In South Devon the Middle Devonian limestones are succeeded by deeper water cephalopod limestones and ostracod shales (Gooday, 1975). Sandstones within the marine shales eg. the Wearde Grit of Ussher (1904), and renamed the Efford Sandstone Member by Chandler and McCall (1985), may indicate a turbiditic mode of deposition. These Upper Devonian deposits have been previously referred to as the Saltash Unit by Turner (1986) and the Plympton Slate Formation by Chandler & McCall (1985). However, this unit is separable into two distinct mappable units which should carry formation status. They are referred to here as the Compton Slate Formation, which ranges in age from Eifelian to Frasnian, and the Saltram Slate Formation which is Famennian in age.

North of Plymouth the rocks overlying the Saltram Slate Formation are grey slates with occasional sandstone bodies (Pl. 2.6). It appears that these are equivalent to the Kate Brook Unit (Upper Devonian to Lower Carboniferous) (Waters, 1970; Isaac *et al.*, 1982; Turner, 1986) later re-named as the Cann Wood Formation (Chandler & McCall, 1985).

The Plymouth Group is divided in this study into five lithological formations (cf. Chandler & McCall, 1985). The guide to lithological stratigraphy introduced by Holland *et al.* (1978) is used throughout.

Jennycliff Slate Formation

Exposed in Jennycliff Bay [SX 4915 5185], this formation, commonly referred to as the Jennycliff Slates, has been renamed as the Jennycliff Slate Formation (Chandler & McCall, 1985). The lithologies are predominantly black-grey slates with occasional sandstones and thin limestones (Pl. 2.7) which are between a few centimetres and a few metres thick and are thought to represent deposition on a storm dominated shelf (Pound 1984). Towards the top of the Jennycliff Slate Formation (predominantly Eifelian in age) limestones become well developed and more numerous before the transition to the Plymouth Limestone Formation. The structural thickness of the Jennycliff Slate Formation is ca. 1,000m and is measured directly off the deformed cross sections in Chapter 4.

Plate 2.7 Black to grey slates with thin limestone horizons (weathered brown) of the Jennycliff Slate Formation; Jennycliff Bay [SX4915 5225]

Plate 2.8 Black to grey calcareous slate of the Plymouth Limestone Formation (Lower Limestone Member); River Plym, Plymouth [SX 5010 5425]. Height of exposed rock face ca. 5m.

Plymouth Limestone Formation

This formation can be examined in many quarries around Plymouth and also on the sea front at Plymouth Hoe. It has previously been defined as the Plymouth Limestone (Ussher 1907) but has been further subdivided by Chandler & McCall (1985). The three-fold stratigraphy previously used is retained. Hence the Plymouth Limestone Formation consists of the Plymstock Volcanic Member (oldest), the Lower Limestone Member and the Upper Limestone Member (youngest). The age of this formation is Eifelian to Frasnian and is approximately 300-400m thick.

Plymstock Volcanic Member

This is developed at the base of the Plymouth limestone Formation and crops out along the coast to the south of Mt. Batten [SX 4850 5320]. The outcrop extends eastwards through the village of Plymstock. The orientation of the strata is vertical and forms the steep limb of a footwall syncline having been overthrust by the Jennycliff Slate Formation.

Lower Limestone Member

This is composed of a sequence of black-grey calcareous slates (Pl. 2.8) with minor bodies of more massive grey fossiliferous limestone. Its outcrop pattern indicates that it lies stratigraphically beneath the main body of limestone referred to as the Upper Limestone Member (see Fig 2.6).

Upper Limestone Member

This unit is composed of massive, but occasionally bedded, grey limestone (Pl. 2.9) which contains a rich fossil fauna (Pl. 2.10). Where unbedded the sequence shows evidence of sedimentary or contemporaneous disruption and redeposition. This member crosses the Givetian/Frasnian boundary and passes laterally and upwards into a sequence of slates.

Compton Slate Formation

The rock units of the Plymouth Limestone Formation pass upwards and laterally into

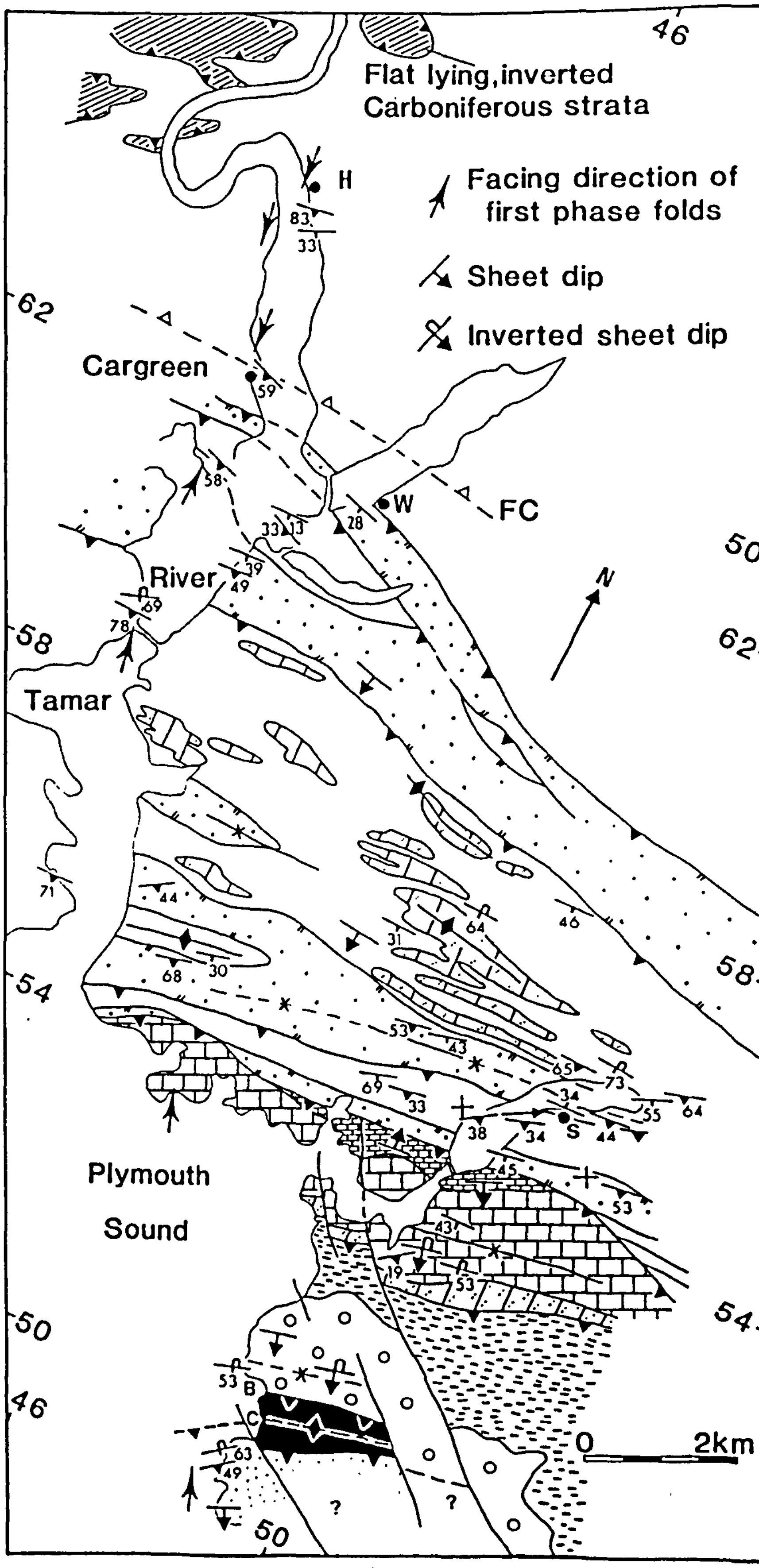

Fig. 2.6 Geological map of the Plymouth area. Ornament to the stratigraphy as in Fig. 2.2. B, Bovisand Bay; C, Crownhill Bay; H, Hole's Hole; W, Warleigh House.

Plate 2.9 Thickly bedded limestone of the Plymouth Limestone Formation (Upper Limestone Member); Plymouth [SX 4640 5355]. Height of exposed rock face ca. 4m.

Plate 2.10 Fossils of the Plymouth Limestone Formation (Upper Limestone Member); Plymouth Hoe [SX 4755 5375].

a sequence of deeper water deposits, composed predominantly of mudrocks which are black-grey in colour and are known here as the Compton Slate Formation. Also present are a number of impersistent limestones and both sheet-like and laterally discontinuous volcanics consisting of tuffs and vesicular pillow lavas (see Pl. 2.11). They generally occupy fold cores to the north of Plymouth (Fig. 2.6). This formation is exposed to the north and south of the Plymouth by-pass [SX 4900 5730] as well as in cuttings along the roadside. Volcanics are common to the south of the by-pass in the Compton area of Plymouth [SX 4950 5650].

Saltram Slate Formation

Above the Compton Slate Formation is a distinct sequence of purple and green slates which is devoid of volcanics. A well exposed section occurs along the east shore of the River Plym, to the west of Saltram House [SX 5195 5565]. Thin sandstone and limestone bands occur and pick out the bedding which is also defined by green laminations within the purple slate (Pl. 2.12). The Saltram Slate Formation and Compton Slate Formation were not separated by Chandler & McCall (1985). However, they are obviously two distinct stratigraphical units which are also recognised in the Liskeard area by Burton & Tanner (1986).

2.3.2 Middle and Upper Devonian Palaeogeography

Deposition of the Jennycliff Slate Formation indicates a return to open marine conditions following a period of regression, in which the Staddon Grit Formation was deposited. Marine conditions persist throughout the rest of the Devonian sequence with only local shallowing on localised highs, where thicker sequences of limestones accumulated. These highs were probably fault-controlled.

The presence of sandier horizons within the slates of the uppermost Devonian north of Plymouth probably represent shallowing, after long lived deeper marine conditions which gave rise to the deposition of the Upper Devonian mudstone dominated sediments further south.

Late Frasnian times record the onset of the Late Devonian-Early Carboniferous marine transgression northwards towards Wales and central England. The uprising Bretonic land masses to the south of Devon (Anderton *et al.*, 1979) provided the clastic sediment input for the marine Upper Devonian and 'later' the Lower Carboniferous foreland basins of central

Plate 2.11 Vesicular pillow lavas within the Compton Slate Formation exposed in a temporary road cutting; Plymouth [SX 4840 5800]. Pillow ca. 70cm long.

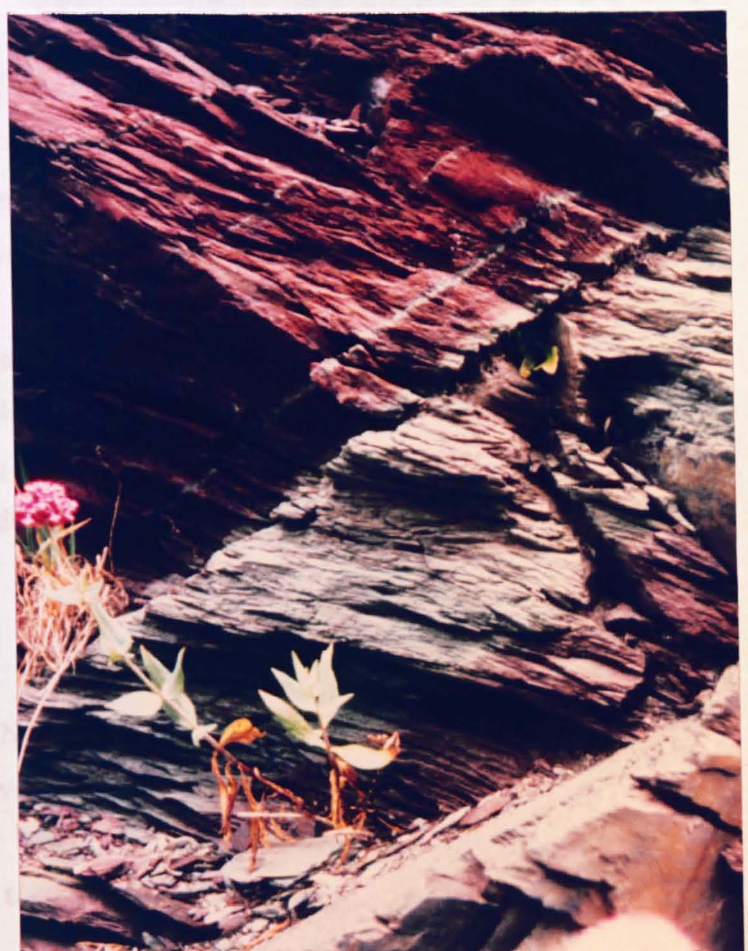

Plate 2.12 Purple and green slates of the Saltram Slate Formation, Plymouth [SX 5260 5400]. Height of photograph ca. 1m.

SW England.

2.4 CARBONIFEROUS

Structurally and stratigraphically overlying the Upper Devonian rocks are Lower Carboniferous deposits. These occur in South Devon at the southern margin of the Culm Synclinorium (Fig. 2.7). Two main areas of interest are within the scope of this project; the area around St. Mellion [SX 3880 6600] and the Mary Tavy, Lydford and Okehampton area (see Fig. 1.1). At Wheal Betsy, near Mary Tavy, the Carboniferous strata are Namurian in age and are assigned to the Crackington Formation (Isaac *et al.*, 1983) (see Fig. 1.4). In the St. Mellion area, ages range from Tournasian to Namurian (Ussher, 1907) and the rocks occur within structural outliers (Heathfield Nappe of Isaac *et al.*, 1982; Whiteley, 1984; Blackdown Nappe of Turner, 1986). Stratigraphic relations are complex due to large scale overturning of strata, thrusting (see Fig. 2.8) and 'late' extensional faulting (Pl. 2.13). Hence, care must be taken when deciphering the detailed stratigraphy. At outcrop, Carboniferous aged rocks cap many hilltops structurally overlying Upper Devonian strata. However, close examination reveals that the Carboniferous deposits are inverted (Pl. 2.14) and occur on the inverted limbs of large scale fold nappes (see Chapter 4).

The Lower Carboniferous of this area accumulated in shallow water, possibly deltaic conditions (Whiteley, 1984) although the cyclic nature of the sandstones and shales at Mary Tavy suggests the action of turbidites (Isaac *et al.*, 1983). Deposition took place within a fore-deep ahead of the northwards migrating Variscan Deformation Front and the depocentre is regarded as a foreland basin.

Igneous activity was widespread during Early Carboniferous times. In the Brent Tor area there is a thick sequence of spilitic volcanics (Edmonds *et al.*, 1975). This was used as building stone in the Tavistock area where many of the buildings weather a chloritic green colour characteristic of the low grade, metamorphosed volcanics.

2.5 NEW RED SANDSTONE

The New Red Sandstone (NRS) rocks of SW Devon are well exposed in coastal outcrops in SW Hams (Fig. 2.9). Investigations are confined to these localities although more extensive exposures occur further to the east in the Torbay area. The significance of extensive, offshore deposits is also taken into account in order to evaluate Late Palaeozoic

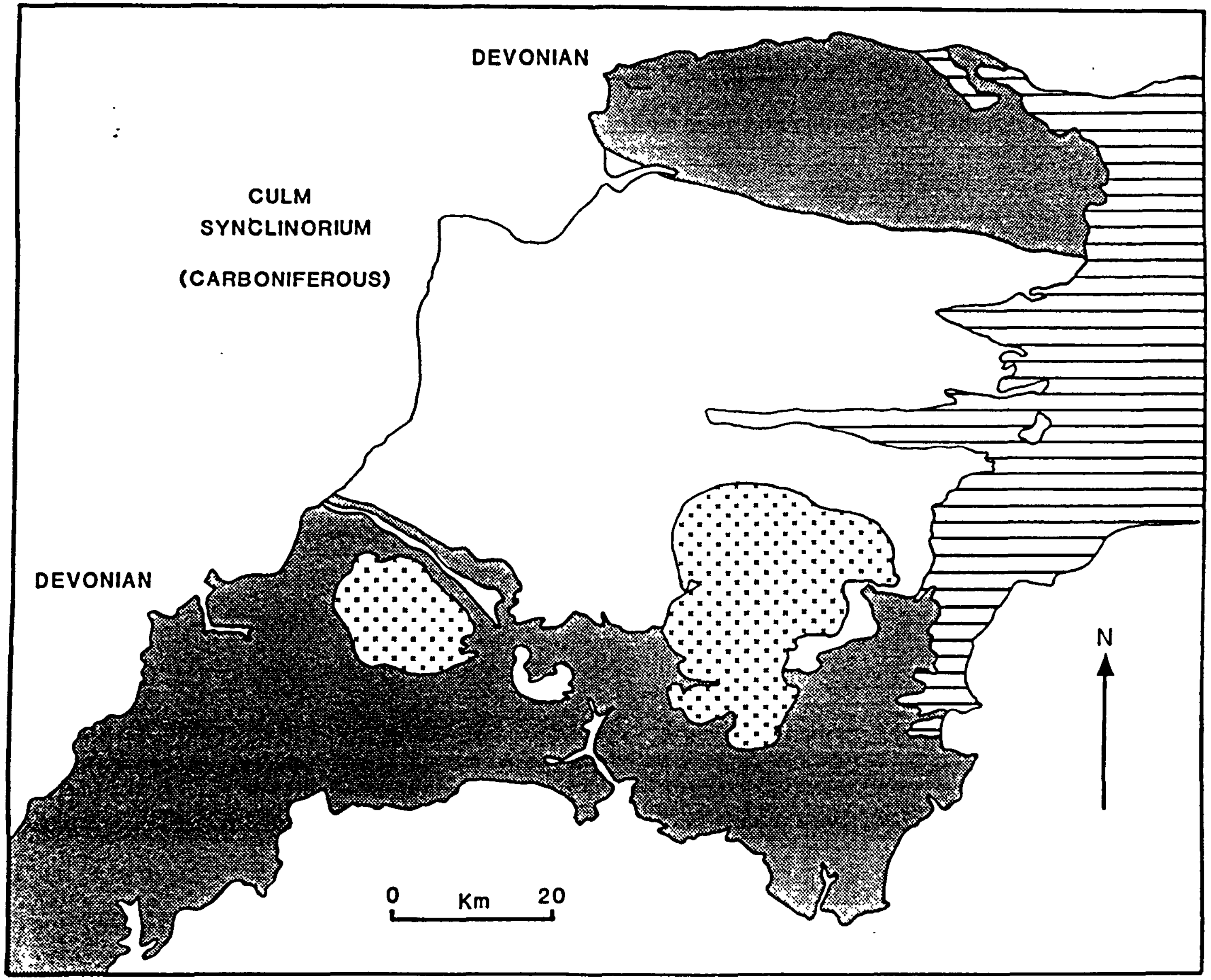

Fig. 2.7 Distribution of the Devonian, Carboniferous and younger deposits of SW England. Crosses represent granite bodies and horizontal lines represent Permian and younger rock units.

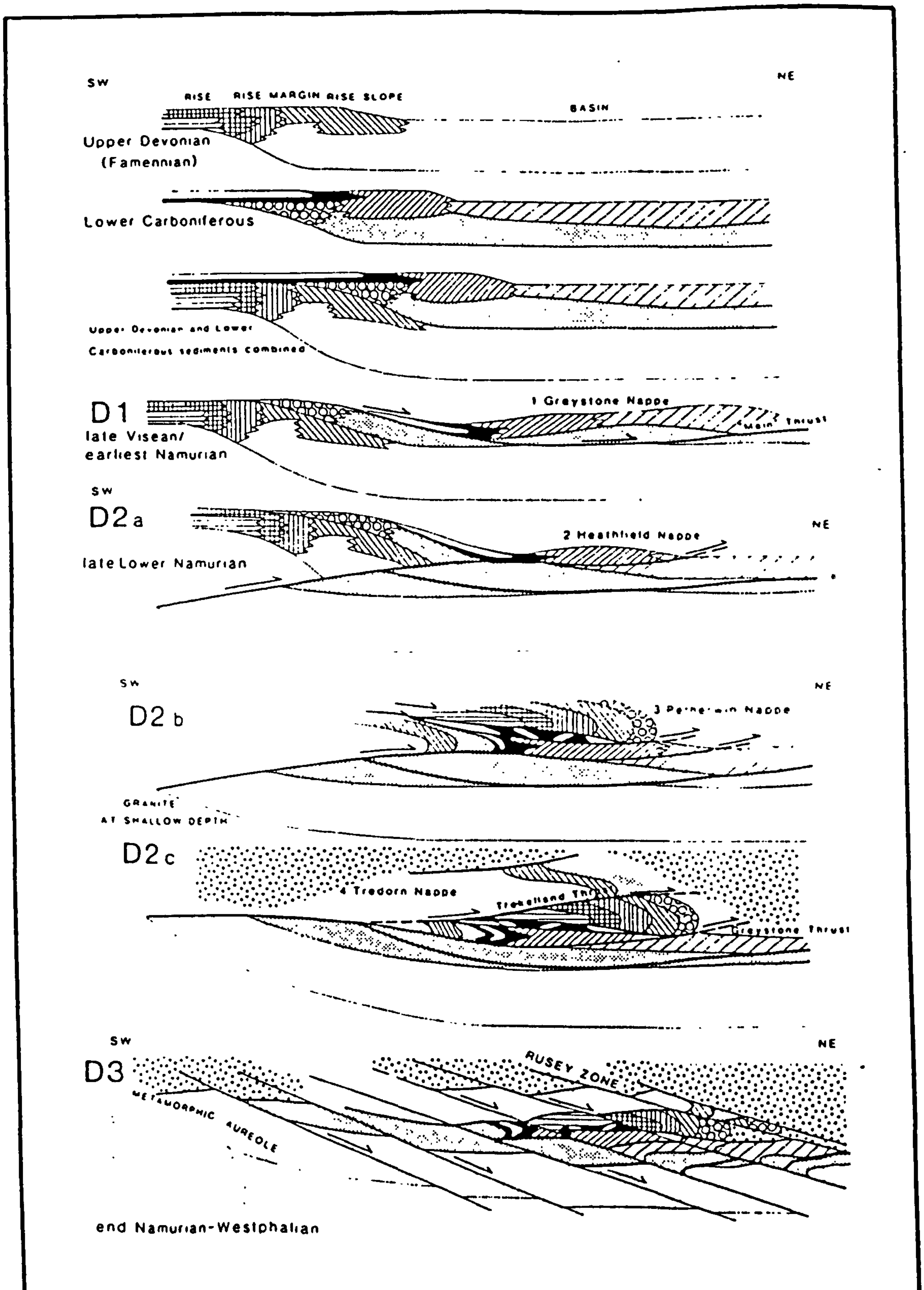

Fig. 2.8 Famennian to Westphalian basin evolution for the area to the west of the Dartmoor Granite (after Isaac *et al.*, 1982).

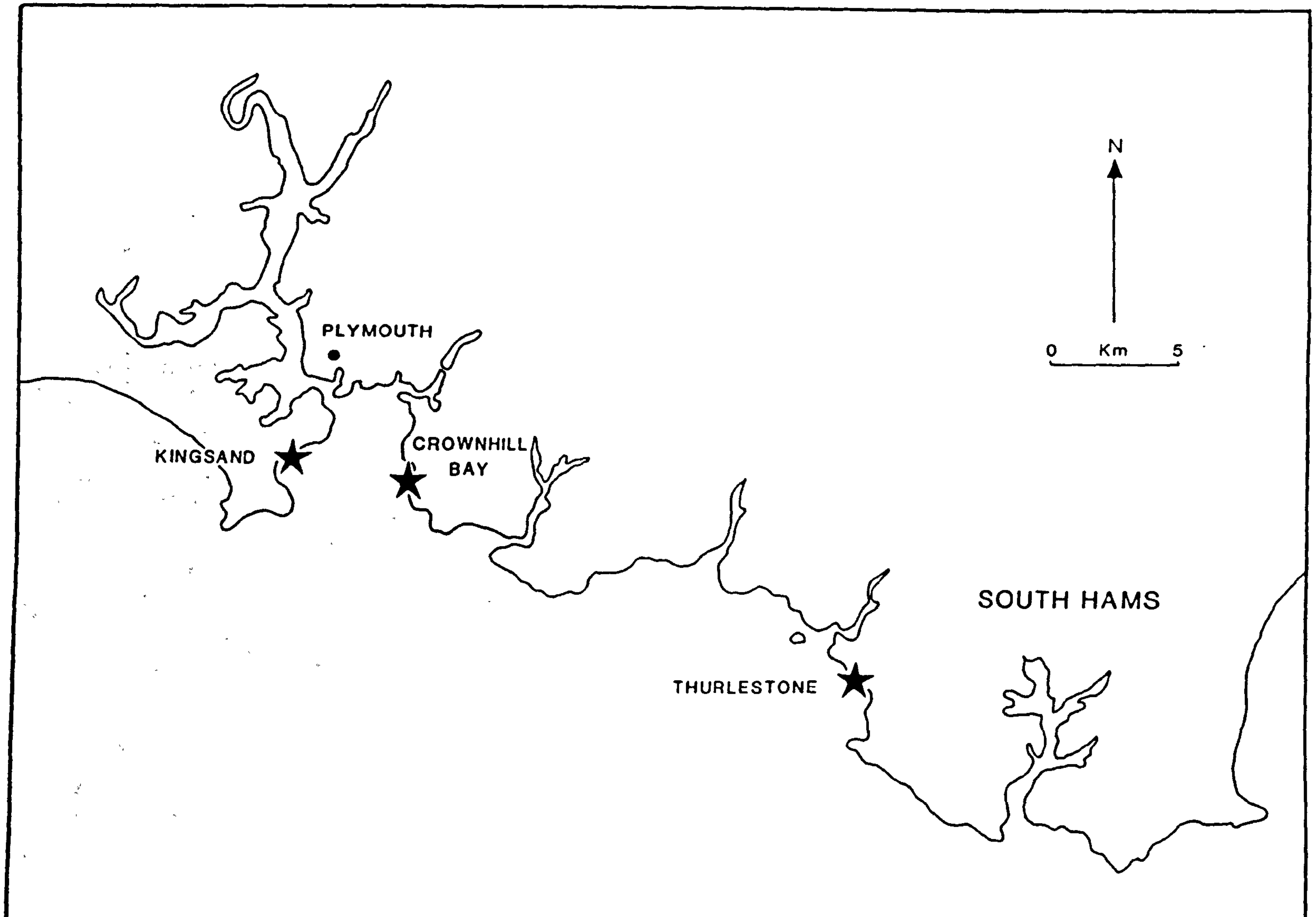

Fig. 2.9 Outcrop locations of the New Red Sandstone (Permian) rocks studied.

Plate 2.13 Low angle normal fault within the Carboniferous rocks to the north of Plymouth; St. Mellion area [SX 3890 6550]. Height of rock face 1.5m.

Plate 2.14 Inverted cross stratification in the Carboniferous sandstones of the St. Mellion outlier,near St. Mellion [SX 3890 6550].

basin evolution. The outcrops in SW Hams occur to the south of Plymouth and are probably Permian in age, eg. at Crownhill Bay (Pl. 2.15), Kingsand and Thurlestone (Pl. 2.16, see also Fig. 2.9). Associated with these deposits in space and time are acid (felsite) lava flows. One of these flows is exposed on the west side of Plymouth Sound at Kingsand [SX 4380 5070] (see Section 4.2.2).

2.5.1 New Red Sandstone of Crownhill Bay

Red bed conglomerates crop out on the foreshore and at the back of the beach in Crownhill Bay. The foreshore outcrops can be examined at low water and probably extend below sea level onto the floor of Plymouth Sound. Exposures at the back of the beach are periodically covered by landslips. The deposits are crudely bedded (sub-horizontal) and are composed of breccia/conglomerate (Pl. 2.17). The clasts are angular to rounded and consist of slate, limestone and sandstone derived from the underlying Devonian succession. The sequence occurs along what is regarded as a NW-SE Variscan compartmental fault but the deposits have a sedimentary origin and are not fault derived. Later, minor faulting has affected the contact between this NRS sequence and the Lower Devonian clastics (see Pl. 2.15).

2.5.2 New Red Sandstone of Thurlestone

The outcrop at Thurlestone [SX 6760 4190] is the most extensive (ca. 2-3 km^2) on the west side of the South Hams promontory (Fig. 2.9). The thickness of the sequence here is ca. 20m and it lies with an angular unconformity on top of Devonian slates (Pls 2.18 and 2.19). The dip of the unconformity is gentle to the SW and the presence of a clay gouge, and the direction of drag on the underlying cleavage, indicates that slip has occurred along it.

The sequence at Thurlestone is cut by a sub-vertical fault trending 081° with a throw greater than 20m down to the south. This is indicated by elongate clasts within the conglomerates on either side of the fault which are deflected by movement along the fault. In the northern block the NRS sequence is in part well bedded (098°/22°S) but on the whole it is only crudely bedded. Lithologies range from muds to conglomerates although ortho-conglomerates dominate and these are generally grain supported (Fig. 2.10 and Pl. 2.20). The most common clasts within the ortho-conglomerates are between 5 and 10cm in diameter, although boulders up to 30cm in diameter also occur. The clasts are composed of vein quartz,

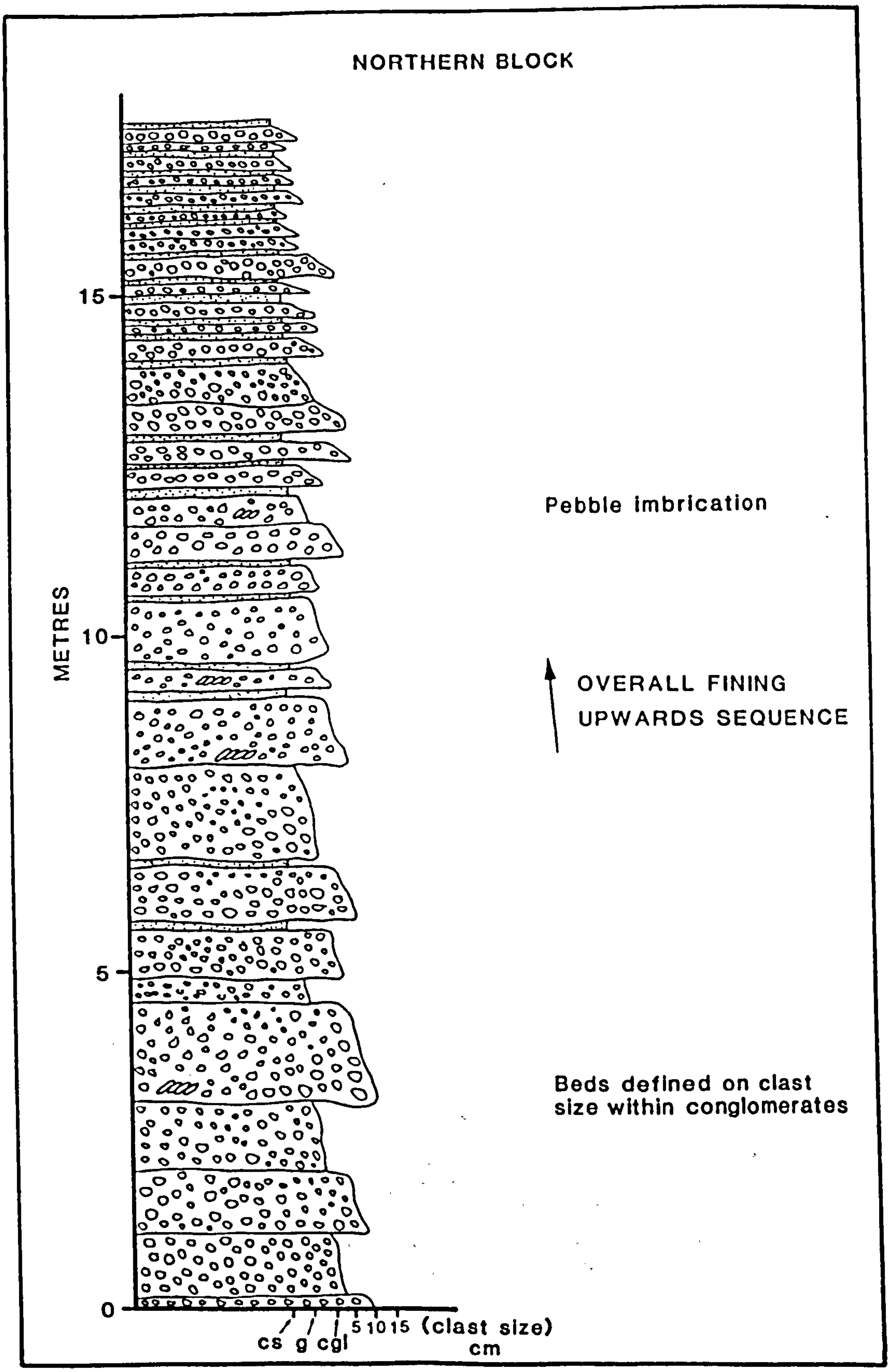

Fig. 2.10 Logged section through the northern block of New Red Sandstone exposed on Thurlestone Beach [SX 6745 4195].

Plate 2.15 Permian (New Red Sandstone) conglomerates faulted against tilted Lower Devonian strata; Sandy Cove, Crownhill Bay. [SX 4925 4980].

Plate 2.16 Well bedded Permian (New Red Sandstone) conglomerates at Thurlestone [SX 6745 4195]. Looking east.

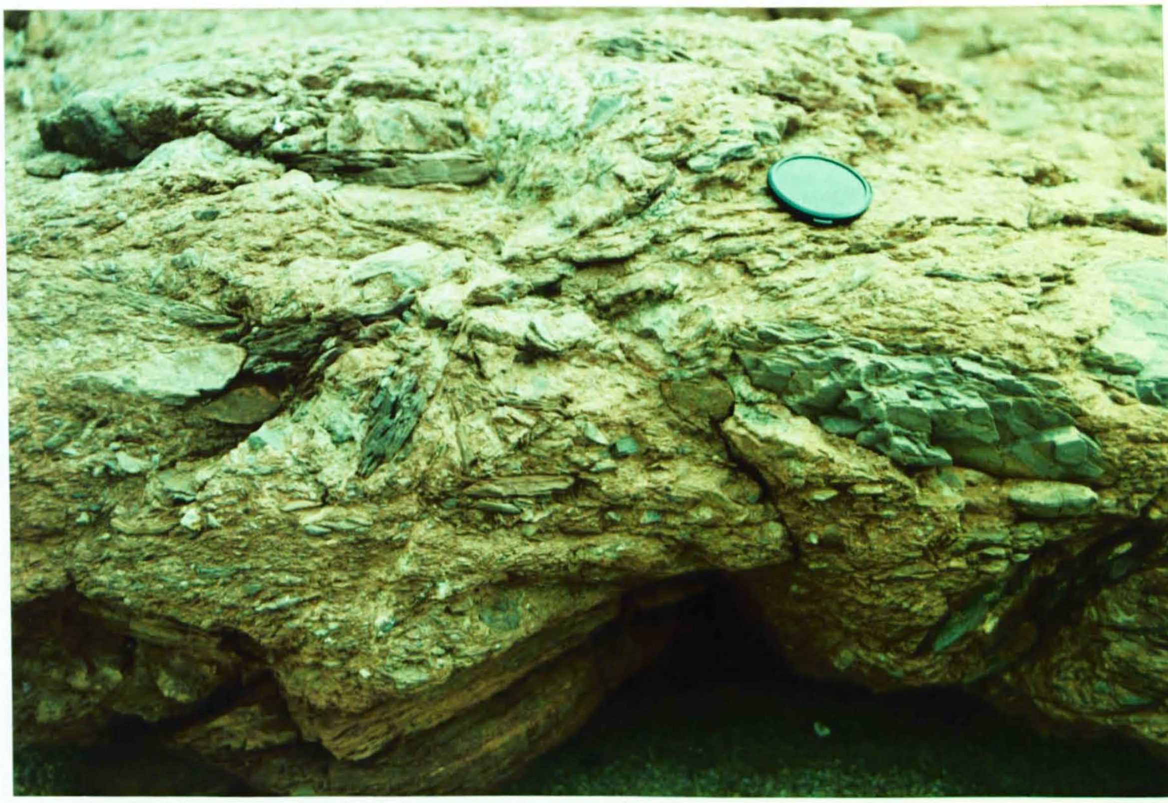

Plate 2.17 Poorly sorted breccia/conglomerate consisting of limestone, sandstone and slate clasts derived from the underlying Devonian succession; Sandy Cove, Crownhill Bay [SX 4925 4980].

Plate 2.18 Unconformable contact between New Red Sandstone deposits and Lower Devonian Slates; Thurlestone[SX 6745 4195]. Looking north east.

Plate 2.19 Close up of the unconformity shown in Pl. 2.18, note crude pebble imbrication in the conglomerates indicating a northerly flow. Looking east.

Plate 2.20 Grain supported ortho-conglomerate with clasts of slate, vein quartz, schist and sandstone; Thurlestone [SX 6745 4195].

slate and schist. The beds measure up to 75cm in thickness. Many of the rounded pebbles are imbricated (Pl. 2.21) suggesting a northerly directed palaeoflow (Fig. 2.11). The majority of the finer beds are fine grained conglomerates or gravels. In the southern block the sediments are on the whole more thinly bedded (10-15cm) and the beds are more well defined than on the northern side of the fault (Fig 2.12 and Pl. 2.22). Conglomerates and coarse sand are the common lithologies and are in general, finer than those on the northern side of the fault. The imbrication of the pebbles indicates palaeoflow to the north although very rarely it has an opposite polarity. The sedimentary features of the NRS in this area of South Hams are similar to those of the NRS in SE Devon where it is divided into the Watcombe Conglomerate and the Teignmouth Breccia (Edmonds *et al.*, 1975).

2.5.3 Depositional Setting

The Permian red beds of this area are limited in outcrop compared with the thick offshore sequences (Ziegler, 1987). This is a function of the relative positions of the Cornubian High and the Western Approaches Basin (Fig. 2.13). The structural cross sections in this paper show SW Devon as a regional high from the Jurassic onwards, and probably since the Permian. It is likely that such coarse sediments were deposited in highland areas and were locally, topographically controlled as opposed to the offshore deposits to the south which were fault controlled. Extensional faults cutting the onshore sequences are an effect of subsidence offshore and do not necessarily control deposition. The presence of schist clasts, resembling rock types present in the Start Complex, supports the palaeoflow data that there was a southern source for the sediments in addition to a northern source. This indicates flow to the north away from the main depocentre. A high area is therefore indicated in the region of the Start Complex which in turn shed sediment to the north and south sourcing the Western Approaches Basin (Fig. 2.13). The high area is a function of the basins developing to the north and south. It is probable that the northerly transported sediments were a local feature and they then turn to the NW and SW to join the main offshore basins in the south (Fig. 2.14).

The present onshore deposits reflect proximal deposition in an alluvial fan type environment and are sourced by the Start Schist Complex (palaeo-high) presently situated only 2km to the south of the Thurlestone outcrops.

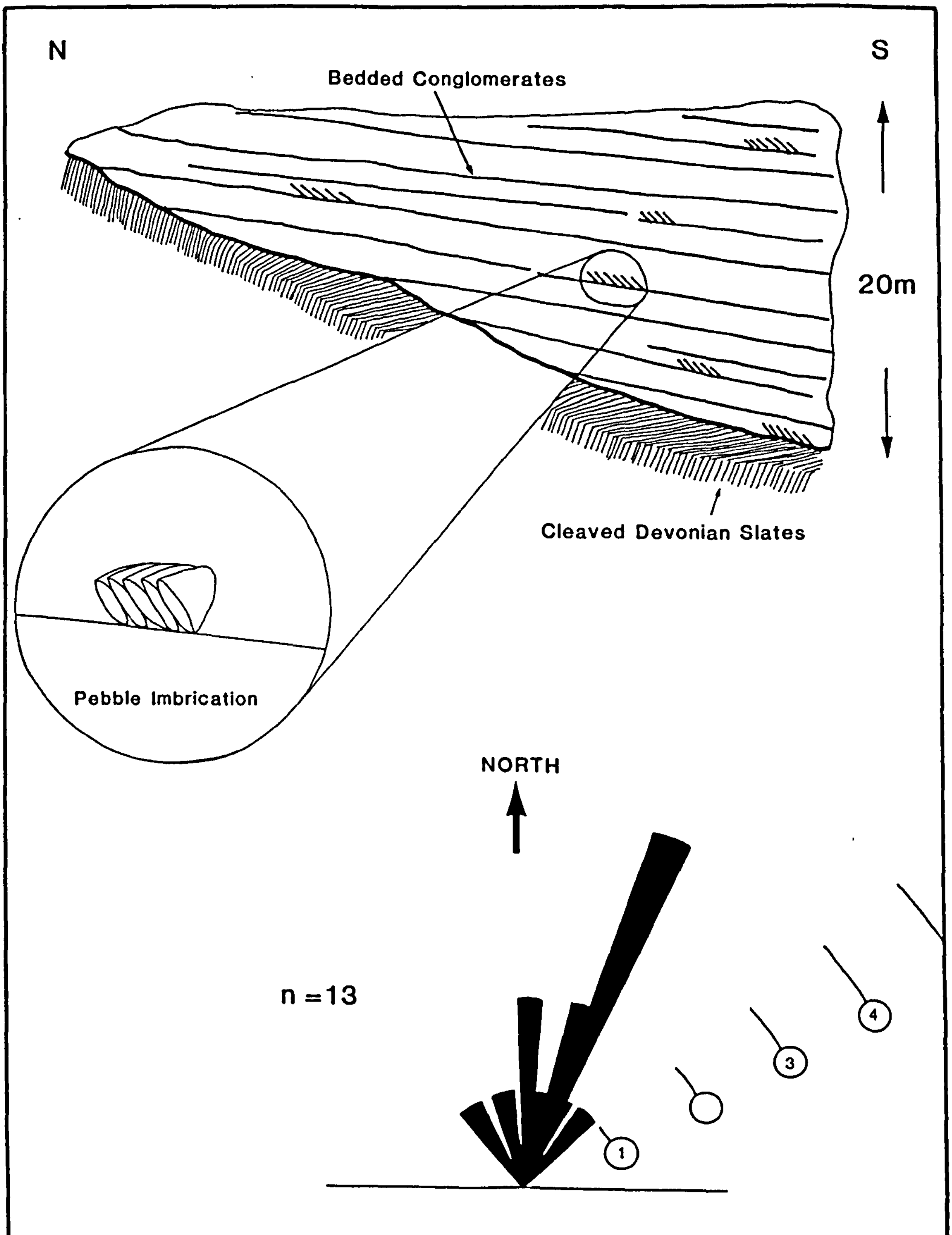

Fig. 2.11 Outcrop detail, pebble imbrication and palaeoflow data from the New Red Sandstone at Thurlestone [SX 6745 4195].

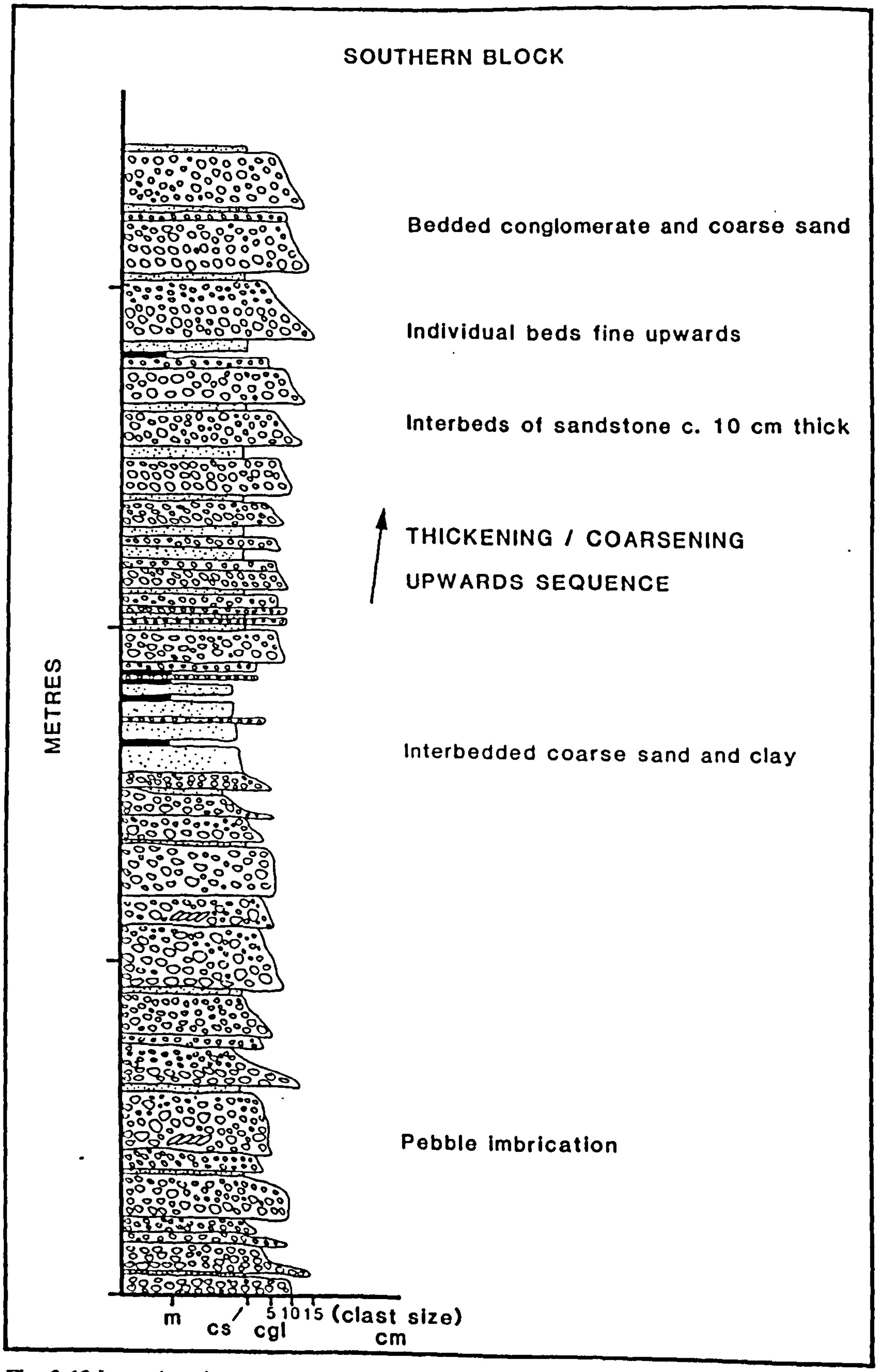

Fig. 2.12 Logged section through the southern block of New Red Sandstone exposed on Thurlestone Beach [SX 6745 4195].

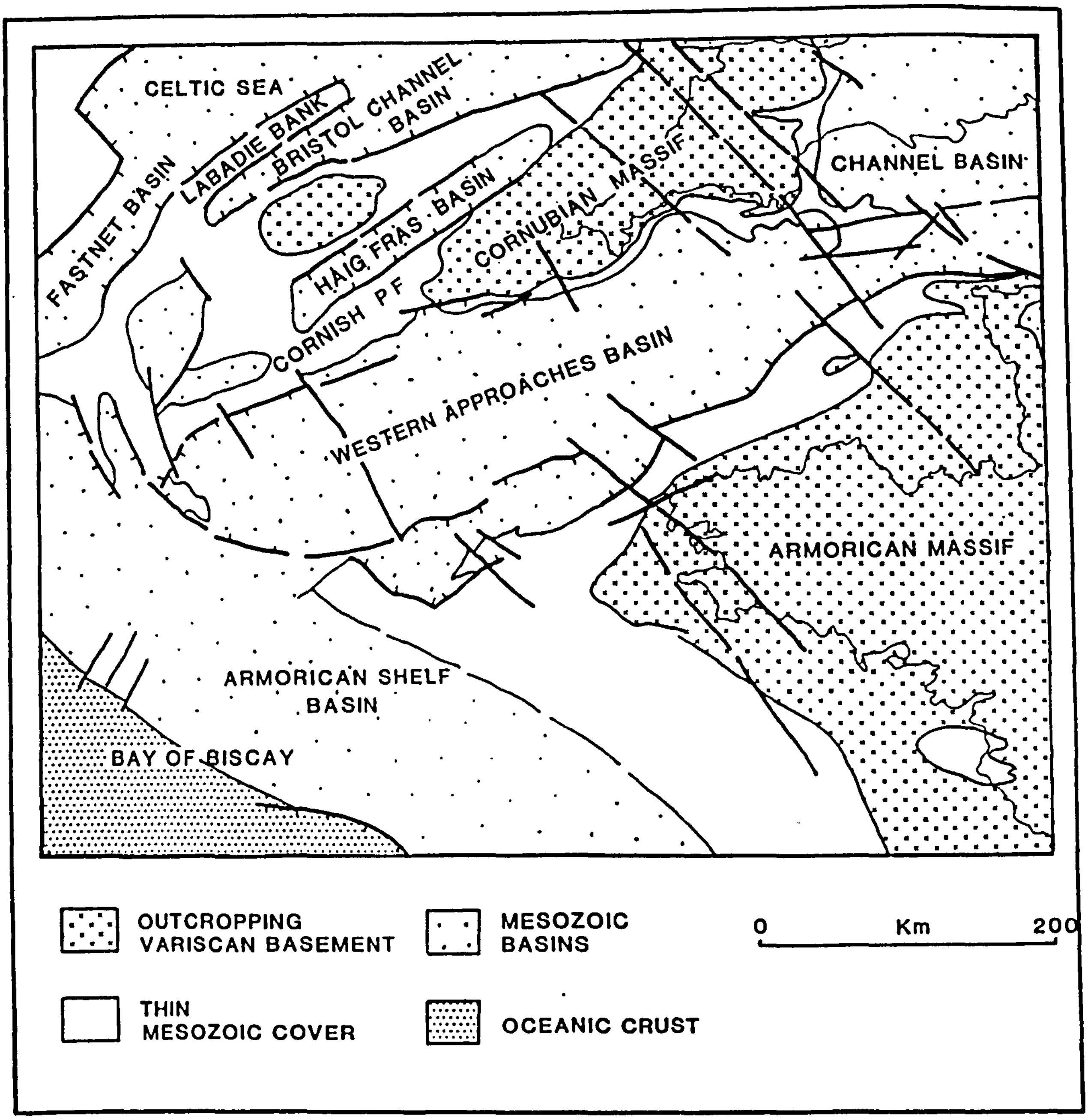

Fig. 2.13 Tectonic map of the Western Approaches (after Ziegler, 1986).

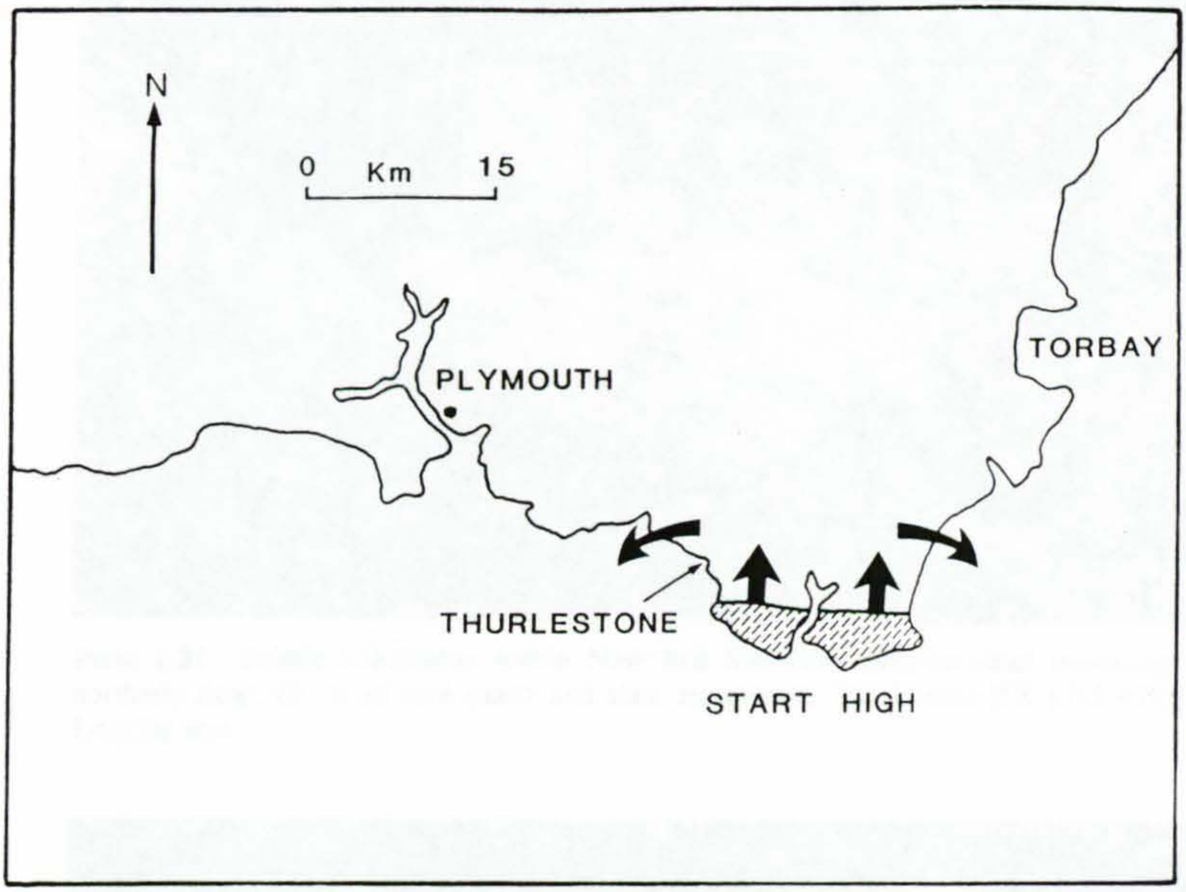

Fig. 2.14 Palaeoflow map for the New Red Sandstone rocks of SW Devon. Directions deduced from outcrop data and known positions of the main Permian basins offshore.

Plate 2.21 Pebble imbrication within New Red Sandstone conglomerates indicating a northerly flow. Clasts of vein quartz and slate are present; Thurlestone [SX 6745 4195]. Looking east.

Plate 2.22 Thinly bedded very coarse sand and conglomerate exposed on the south side of the fault within the New Red Sandstone sequence at Thurlestone [SX 6745 4195]. Looking east.

2.6 KEY POINTS

1. The stratigraphic terminology for the Devonian system of SW Devon has been standardized.
2. The Lower Devonian Dartmouth Group, previously referred to as the Dartmouth Beds/Slates, has been divided into four mappable lithostratigraphic formations. Conformable transitional contacts separate the Renney Rocks Formation (oldest), Wembury Formation, Yealm Formation and the Warren Formation (youngest).
3. The Meadfoot Group, which passes upwards by interdigitation from the Dartmouth Group, has been divided into two mappable lithostratigraphic formations. The Bovisand Formation usually underlies the Staddon Grit Formation but may be laterally equivalent.
4. The Middle and Upper Devonian sequence of rocks in the Plymouth area has been incorporated into the Plymouth Group. The Jennycliff Slate Formation is overlain by the Plymouth Limestone Formation which is in turn overlain by the Compton Slate Formation and the Saltram Slate Formation respectively.
5. The Compton and Saltram Slate Formations comprise the previously described Plympton Slate Formation and this further division enables more accurate structural mapping.
6. The Carboniferous deposits to the north of Plymouth are thought to have been deposited in a foreland basin setting.
7. Analysis of the New Red Sandstone indicates an alluvial setting with northerly directed palaeoflow. In conjunction with offshore Permian deposits it is possible to infer a Permian palaeogeographic setting.

CHAPTER 3
SEDIMENTOLOGY

3.1 INTRODUCTION

This chapter describes the sedimentological features of the Lower Devonian rocks south of Plymouth. Sub-sections in Section 3.2 deal with the lithologies, sedimentary structures and litho-facies association of the rocks of the Dartmouth Group. Section 3.3 describes the sedimentology of the Meadfoot Group rocks and pays particular attention to the boundary conditions between the Bovisand and Staddon Grit Formations. Depositional models and palaeogeographical settings are presented for both units. The key points of the chapter are contained in Section 3.4.

Symbols used in the sedimentary logs are shown in Fig. 3.1.

3.2 SEDIMENTOLOGY OF THE DARTMOUTH GROUP

The Dartmouth Group rocks (cf. Seago & Chapman, 1988) are a thick (ca. 3.5km) sequence of cleaved, silty claystones with sub-ordinate sandstones. These Lower Devonian sediments are the oldest seen in South Devon and can be examined at numerous localities in both Devon and Cornwall (Fig. 1.2). However, sedimentological studies are confined to the coastal exposures in south Devon, chiefly between Andurn Point and Westcombe Beach, to the south of Plymouth, in the Bigbury Bay area (Fig. 2.3). Division of this group is based on lithological character due to the lack of palaeontological material. Dineley (1966) determined a Siegenian age for the Group, and subsequent work (Evans, 1981) has shown that the overlying Meadfoot Group also yields a Siegenian fauna, at its base, implying that the whole of the Dartmouth Group occurs within the Siegenian stage of the Lower Devonian. Thus, the thickness of ca. 3.5km determined for the Dartmouth Group accumulated over a relatively short period of time (see Section 3.3).

The rocks of the Dartmouth Group are dominated by argillaceous sediments, with minor, variable proportions of arenaceous and rudaceous sediments (see Fig. 3.2). The mudrocks have been converted to slates and the sandstones to quartzites during Variscan deformation. The sediments vary in colour from purple-red-green-yellow-grey-black with the reddish colours dominating. Volcanics (often reworked as volcaniclastics) are also present in the Dartmouth Group. Green banding, spotting and bedding usually described as being

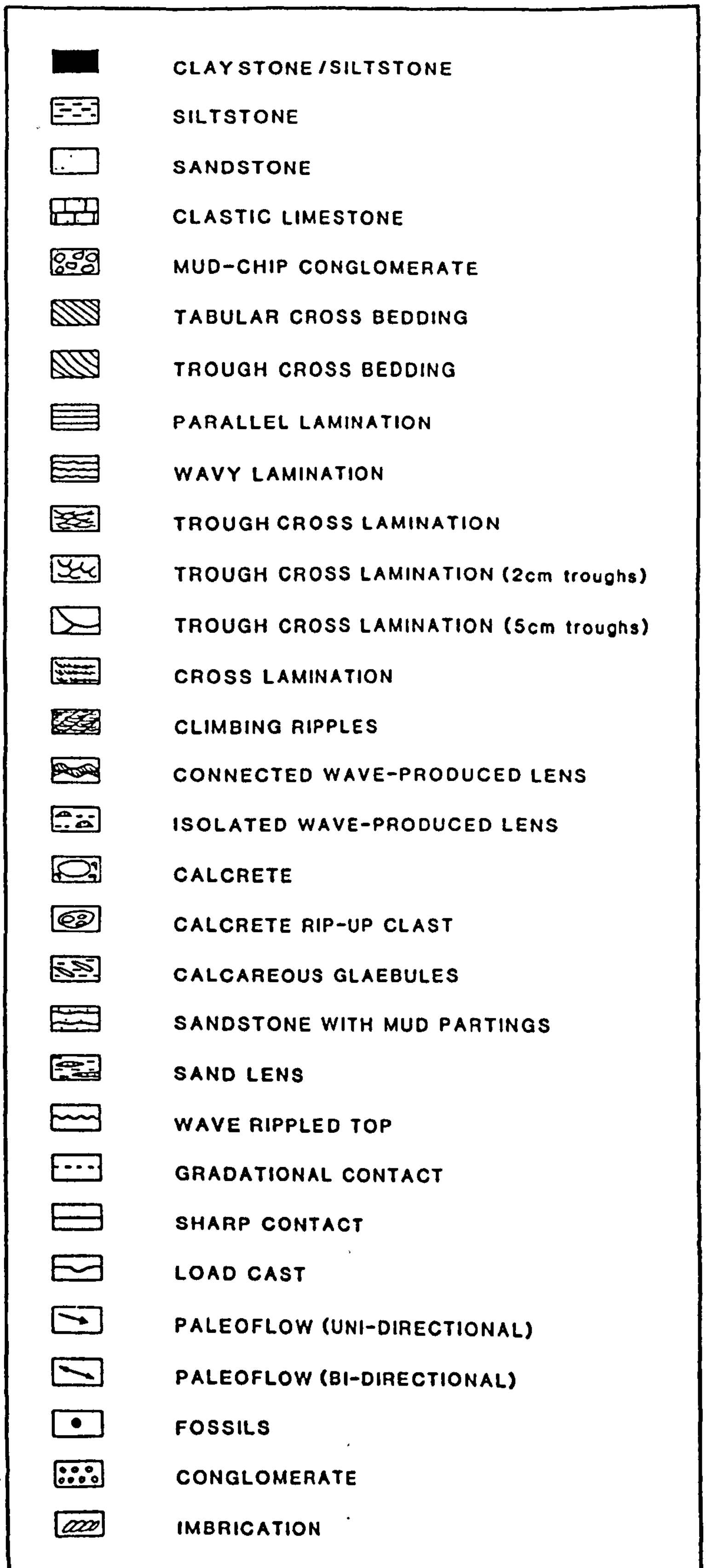

Fig. 3.1 Symbols used in the sedimentary logs of this chapter.

		DESCRIPTION	THICKNESS
DARTMOUTH GROUP	WARREN FORMATION	Sandstones, mudrocks and conglomerates Sandstones are fine to medium grained (rarely coarse). Purple, red, green and grey.	ca.2500 m
	YEALM FORMATION	Sandstones, mudrocks and conglomerates. (intraformational and paraconglomerates). Sandstones are fine-medium grained. Tuffs, lapillistone and agglomerate reworked as volcaniclastics. Yellow, grey, green and black.	ca.300 m
	WEMBURY FORMATION	Mudrocks and sandstones. Sandstones are fine grained, usually solitary beds and uncommon. Clay dominated. Purple, red and green.	ca.600 m
	RENNEY ROCKS FORMATION	Sandstones, mudrocks and conglomerates (intraformational and paraconglomerates). Sand dominated. Pink, purple, red and green.	ca.150 m+ (base not seen)

Fig. 3.2 The Dartmouth Group, its formations and lithological descriptions as defined by this study.

diagenetic in origin (Turner, 1986) is of common ocurrence.

The lowest unit of the Dartmouth Group is represented by a succession of sandstones and siltstones and a relatively low percentage of claystones, compared to the overlying formations. This unit is referred to as the Renney Rocks Formation. Above this is a sequence consisting mainly of claystones with occasional sandstones (Wembury Formation). In the upper part of this formation volcanic air fall deposits occur and mark the onset of volcanicity, and also the base of the Yealm Formation. In terms of colour the Yealm Formation can be easily recognised by the presence of yellow and black sediments (not seen elsewhere in the Dartmouth Group). The uppermost unit of the Dartmouth Group, conformably overlying the Yealm Formation, is the Warren Formation which is lithologically very similar to the Wembury Formation although it contains a higher proportion of sandstones, some of which are coarse grained. This formation is the thickest within the Dartmouth Group (see Fig. 3.2).

3.2.1 Lithologies

The most common lithologies in Dartmouth Group are the mudrocks (claystone, siltstone and silty claystone). Occurring throughout the succession, but to a much less degree, are sandstones which are predominantly fine grained but locally medium or coarse grained. Also locally common are conglomerates, of various type and origin, and reworked volcanics. Four lithological categories (mudrocks, sandstones, conglomerates and volcanic rocks) are described (see Table 3.1).

LITHOLOGY		GRAIN SIZE
clay)	mudrocks	<0.0156 mm
silt)		0.0156 - 0.0625 mm
fine sand		0.0625 - 0.25 mm
medium sand		0.25 - 0.5 mm
coarse sand		0.5 - 1.0 mm
v. coarse sand		1.0 - 2.0 mm
conglomerates		>2.0 mm

Table 3.1 Grain sizes used in this study (see Tucker, 1981)

Mudrocks (claystone/siltstone)

Metamorphism has greatly altered these rocks and the original detrital grains of quartz are strained and clays are altered to sericite, muscovite and chlorite. Some of the muscovite, however, may be primary. Calcareous material occurs within some of the mudrock units as a cementing agent. If it is a primary constituent it may have been derived from local calcrete horizons rather than limestones which are absent from the Dartmouth Group. In some of the silty clays the silt and clay alternate on a microscopic scale as well as at outcrop scale. Sorting is poor in the silty clays and the clay matrix is the predominant constituent. However, some thin sections show that silt comprises 65% of the total rock volume.

The Wembury Formation contains a high proportion of claystones. They are usually mottled, glossy and purple and green in colour (Pl. 3.1). The Wembury Formation also contains much silty claystone as does the Yealm Formation and in the latter it tends to be dull to glossy and grey/black in colour (Pl. 3.2). In terms of distribution the mudrocks are generally rare in the Renney Rocks and Warren Formations where the fine fraction is usually composed of silty claystones. Pyrite, haematite, epidote, tourmaline and zircon are the heavy minerals present, although pyrite is confined to the Yealm and Warren Formations.

Sandstones

The majority of the sandstones are very fine to fine grained (Pl. 3.3) (especially in the Renney Rocks and Wembury Formations) although some are medium to coarse grained. Gravel conglomerates are present but rare (Pl. 3.4). The primary sedimentary mineral constituents are quartz, feldspar and muscovite mica. The quartz grains tend to be subrounded to rounded although later deformation has significantly altered their primary sphericity. However, it is relatively higher than the low sphericity of the detrital mica fraction. Quartz grains (mainly monocrystalline) are strained and display overgrowth cementation, evidence of pressure solution processes.

Both potassium and plagioclase feldspars occur as minor constituents in the sandstones of the lower part of the Dartmouth Group (Renney Rocks and the Wembury Formations). However, in the upper part of the Dartmouth Group (Yealm and Warren Formations) the percentage of feldspar, particularly plagioclase, is much greater (Pl. 3.5). This is a direct result of the onset of volcanicity during deposition of the Yealm Formation. The feldspars of

Plate 3.1 Purple and green mottled mudrocks within the Wembury Formation; Andurn Point [SX 4920 4975].

Plate 3.2 Black to grey mudstones within the Yealm Formation; Erme Estuary [SX 6180 4740].

Plate 3.3 Fine grained, cross bedded sandstone within the Renney Rocks Formation; Renney Rocks [SX 4925 4875].

Plate 3.4 Gravel conglomerate overlying medium grained sandstone within the Warren Formation; Stoke Beach [SX 5650 4640].

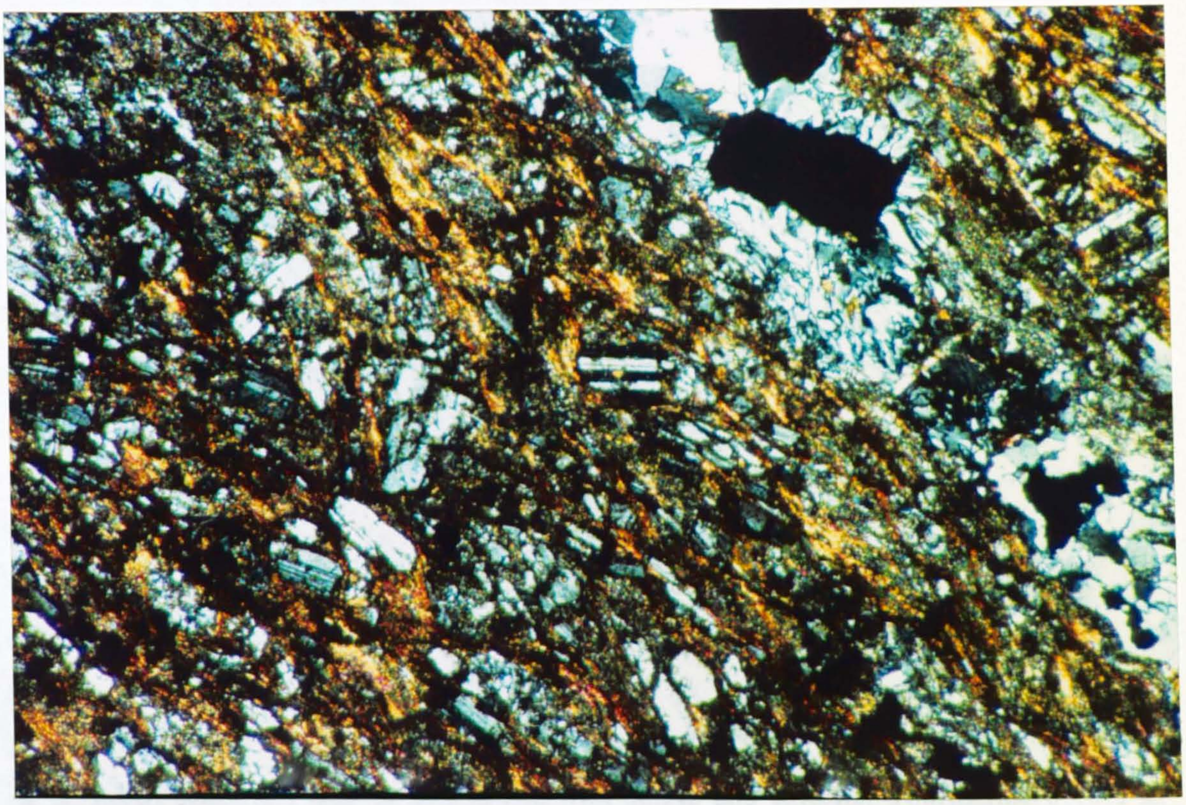

Plate 3.5 Photomicrograph (x64) of reworked tuff containing sub-rounded to angular grains of quartz and plagioclase feldspar; crossed polars. Yealm Formation, Wonwell Beach [SX 6180 4740].

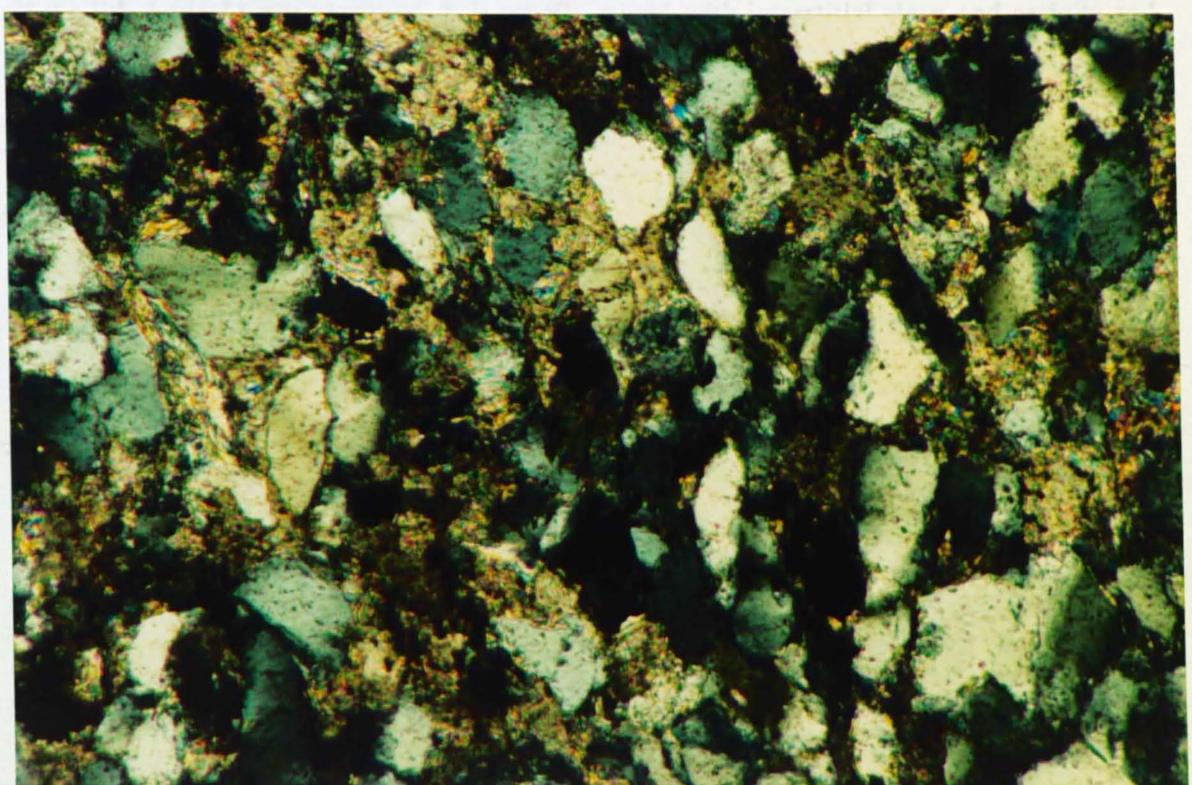

Plate 3.6 Photomicrograph (x160) showing quartz grains cemented by calcite within a sandstone clast of paraconglomerate from the Renney Rocks Formation; crossed polars. Heybrook Bay [SX 4965 4870].

the Renney Rocks and the Wembury Formations are subrounded to sub-angular with generally high sphericity, whereas in the Yealm Formation the volcanic feldspars tend to be elongate (not a function of cleavage alignment) and therefore show low sphericity. Many feldspars and micas in the volcanic rocks are altered to sericite and are products of retrograde metamorphism or recent weathering. The fine sandstones of the Renney Rocks and the Wembury Formations may be classed as quartz arenites due to their maturity, low feldspar content and low lithic fragments (both below 5%) whilst those of the Yealm and Warren Formations may be referred to as feldspathic sandstones.

Detrital, muscovite mica grains are sometimes kinked (axes are parallel to first phase cleavage), have a grain size of the same order as the quartz fraction, low sphericity, are 'clean' in crossed polars, have altered rims, strained extinction and are oblique to the cleavage direction. Metamorphic micas tend to be oriented in the cleavage, heavily sericitized and hence, appear 'dirty'. Heavy minerals include pyrite, zircon, tourmaline, haematite, garnet (well rounded) and epidote. Pyrite occurs in places in appreciable quantity as single or clustered cubes and may be intergrown with quartz and chlorite. Tourmaline occurs as green to brown pleochroic grains. Haematite occurs in vast quantities in the form of tiny crystals, grains or as an interstitial mass. It is the prime colouring agent of the red beds of all the lithological types observed. It is usually mixed with interstitial clays and sericite and in some cases it is concentrated along cleavage planes suggesting its mobility during pressure solution and cleavage formation.

The sandstones occasionally possess a high proportion of clay matrix which may be both primary (formed during deposition) and secondary (metamorphic). Sorting tends to be good to poor but those that are well sorted, relatively clean and devoid of matrix are most common in the Renney Rocks Formation. These factors facilitate pressure solution, silica cementation and quartzite formation during metamorphism. However, calcite is also present as a cementing agent (Pl. 3.6). The sandstones that contain relatively high proportions of matrix may be classed as quartzwackes.

Conglomerates

Six types of conglomerate are described from the rocks of the Dartmouth Group:

(i) Polymict conglomerates occurring above erosion surfaces.

(ii) Oligomict, intraformational conglomerates with a fine sandstone matrix.

(iii) 'Conglomeratic' calcrete.

(iv) Paraconglomerate containing sandstone, siltstone and claystone intraclasts.

(v) Paraconglomerate containing sedimentary and volcanic intraclasts (agglomerate).

(vi) Intraformational, volcaniclastic orthoconglomerate (lapillistone).

Polymict orthoconglomerates occurring above erosion surfaces

Clasts within this type of conglomerate consist of claystone, siltstone, sandstone, carbonate and quartz grains. The diverse components constitute a polymict conglomerate which is also polymodal with clasts ranging in size from <2mm-20cm. However, subsequent deformation may have increased the dimensions of some clasts. The clasts support themselves although a matrix of clay to fine sand is also present. Overall the conglomerate is poorly sorted but the framework and the grain supported nature produces an orthoconglomerate. The coarser clasts are invariably rounded, although angular clasts do occur. The clasts consisting of the finer grained material tend to be tabular.

The conglomerates are generally thinly bedded (10-15 cm thick) and lie above scoured surfaces, which tend to have very low relief, but cut into the underlying finer sediment (Pl. 3.7). The bases are gently undulatory in profile resulting in lateral bed thinning to only a few cms. The tops of the beds usually grade into the overlying fine sandstones. Inclined cross bedding traverses some conglomerate beds and tabular clasts lie on the cross strata. This stratification is also defined by differences in grain size. The beds are usually up to 15m in lateral extent although this must be regarded as a minimum due to the restricted coastal exposure. The conglomerates mark the base of fining upwards cycles and are most common in the Renney Rocks Formation.

Provenance

Due to the maturity and composition of the deposits it is of little doubt that the claystone clasts are derived from within the depositional basin and can be referred to as an intraformational component of the conglomerate (qv. Allen, 1962). However, the origin of the sandstones is not so clear. It may be possible that fine sandstones became partially cemented or consolidated at an early stage before re-working (intraformational). Alternatively, they may be derived from a source outside the depositional basin (extraformational) or from basement rocks (Devonian rocks of a similar age) within the depositional area. The large

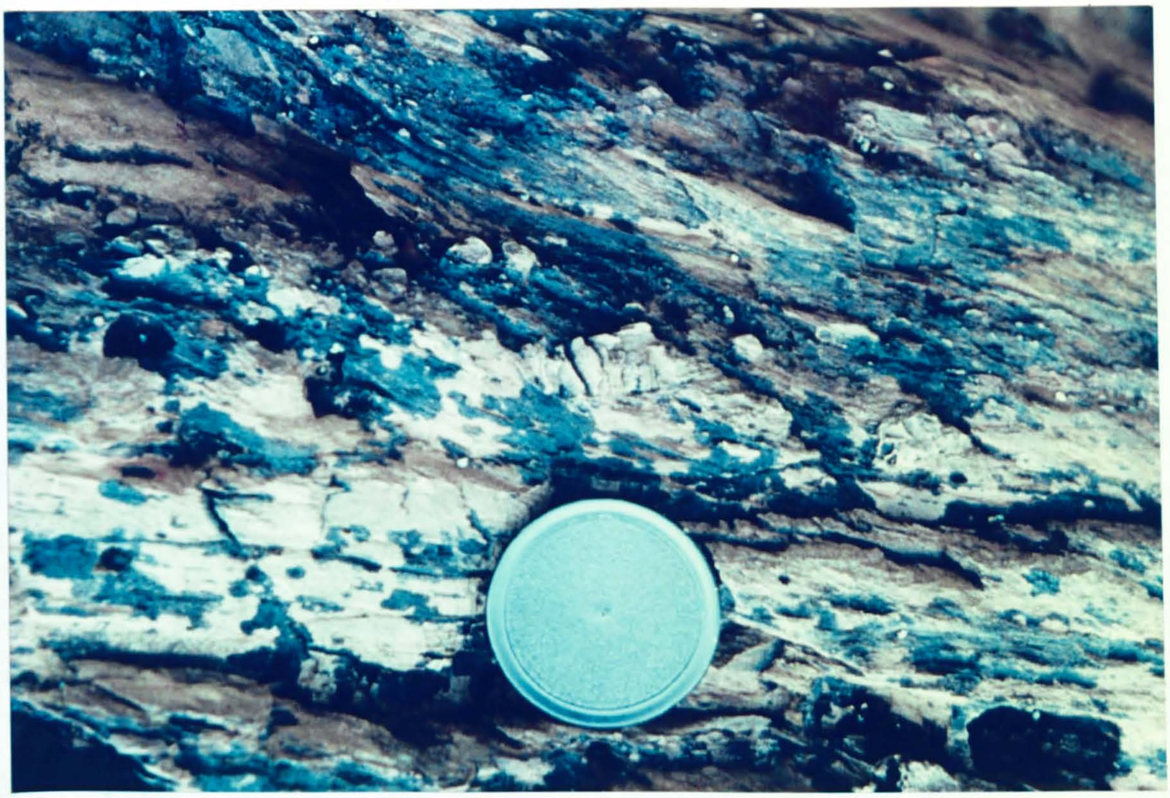

Plate 3.7 Low relief, scoured base to an orthoconglomerate within the Renney Rocks Formation. Clasts consist of claystone, siltstone and sandstone; Heybrook Bay [SX 4965 4870].

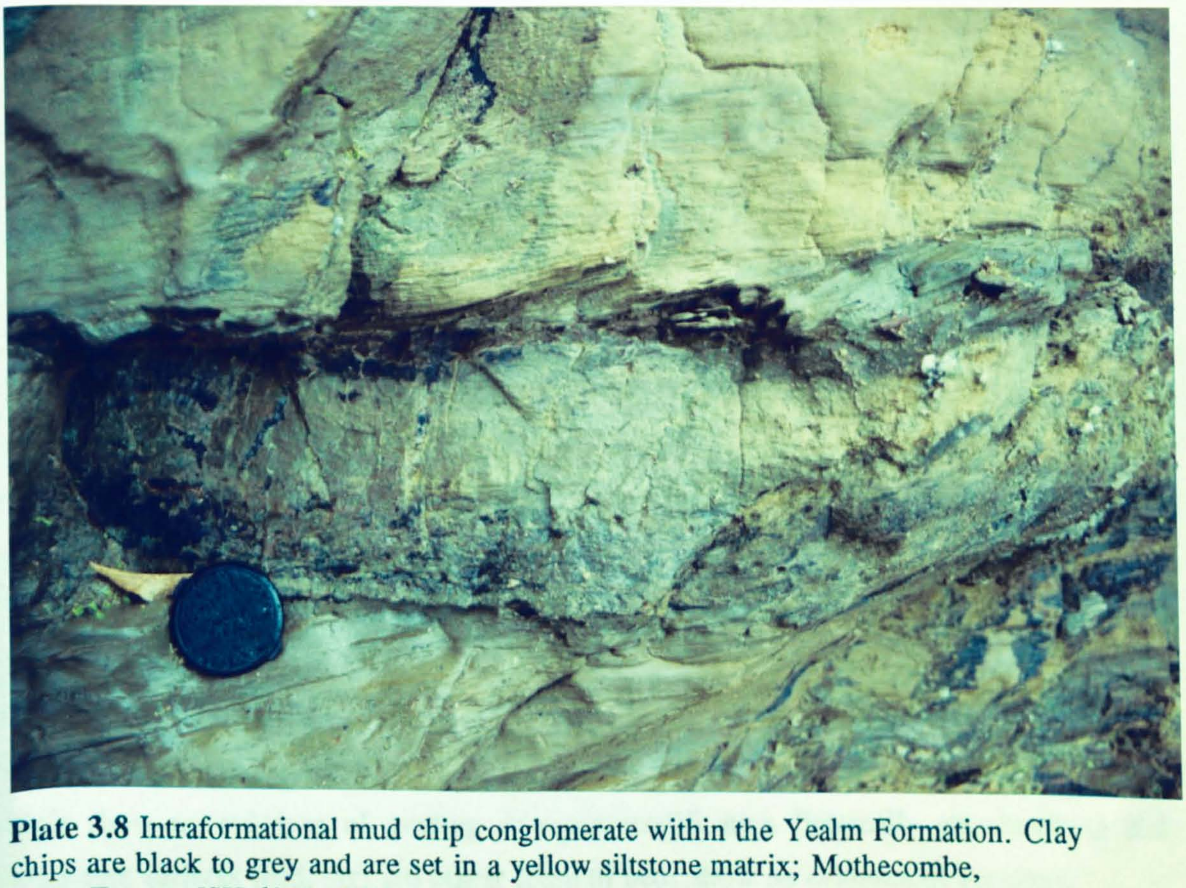

Plate 3.8 Intraformational mud chip conglomerate within the Yealm Formation. Clay chips are black to grey and are set in a yellow siltstone matrix; Mothecombe, Erme Estuary [SX 6145 4760].

carbonate clasts present in the conglomerates appear to be locally derived.

Oligomict, intraformational conglomerates with a fine sandstone matrix

These consist of a background of well sorted fine sandstone, acting as a matrix to disconnected, well spaced clay chips. The tabular clay chips measure ca. 5cm x 0.5cm and they decrease in quantity upwards within any one bed. The clasts are often referred to as rip-up clasts due to their mode of origin.

This type of conglomerate occurs throughout the Dartmouth Group although it is not particularly common. In the rocks around Andurn Point [SX 4900 4980], within the lower reaches of the Wembury Formation, the host sandstone (matrix) is pink/grey and the clay chips along with the underlying claystones are deep purple. However, in the rocks of the Yealm Formation, near Mothecombe [SX 6175 4725], the host sandstones and siltstones are yellow/grey and the muddy fraction (chips and substrate) is black to grey (Pl. 3.8).

Provenance

These conglomerates are thought to be solely intraformational in origin, involving erosion of a muddy substrate and subsequent incorporation of rip up clasts into a sand body during water body movement.

'Conglomeratic' calcrete

An example of this 'conglomerate' occurs on the coast at Heybrook Bay [SX 4970 4875] at the top of the Renney Rocks Formation, the lateral extent of which cannot be established due to local folding, thrusting and the limited extent of outcrop. This 'conglomerate' is clast supported (orthoconglomerate), unimodal and oligomict. The clasts are well rounded and consist entirely of carbonate concretions which produce a well sorted framework (Pls 3.9 and 3.10). Angular to rounded, detrital quartz grains are often present in the cores of the concretions (Pl. 3.11). The clasts, which measure up to 4 cm in diameter, are well rounded with high sphericity and are cemented by calcite. The 'conglomerates' are bedded in a 2.5m sequence and individual beds measure up to 40cm in thickness. Individual beds show no evidence of grading or cross stratification (internally structureless) and bounding surfaces (bedding) are planar (base of beds show no evidence of erosion).

Plate 3.9 Bedded conglomeratic calcrete within the upper part of the Renney Rocks Formation; Heybrook Bay [SX 4965 4870].

Plate 3.10 Close up of Pl. 3.9.

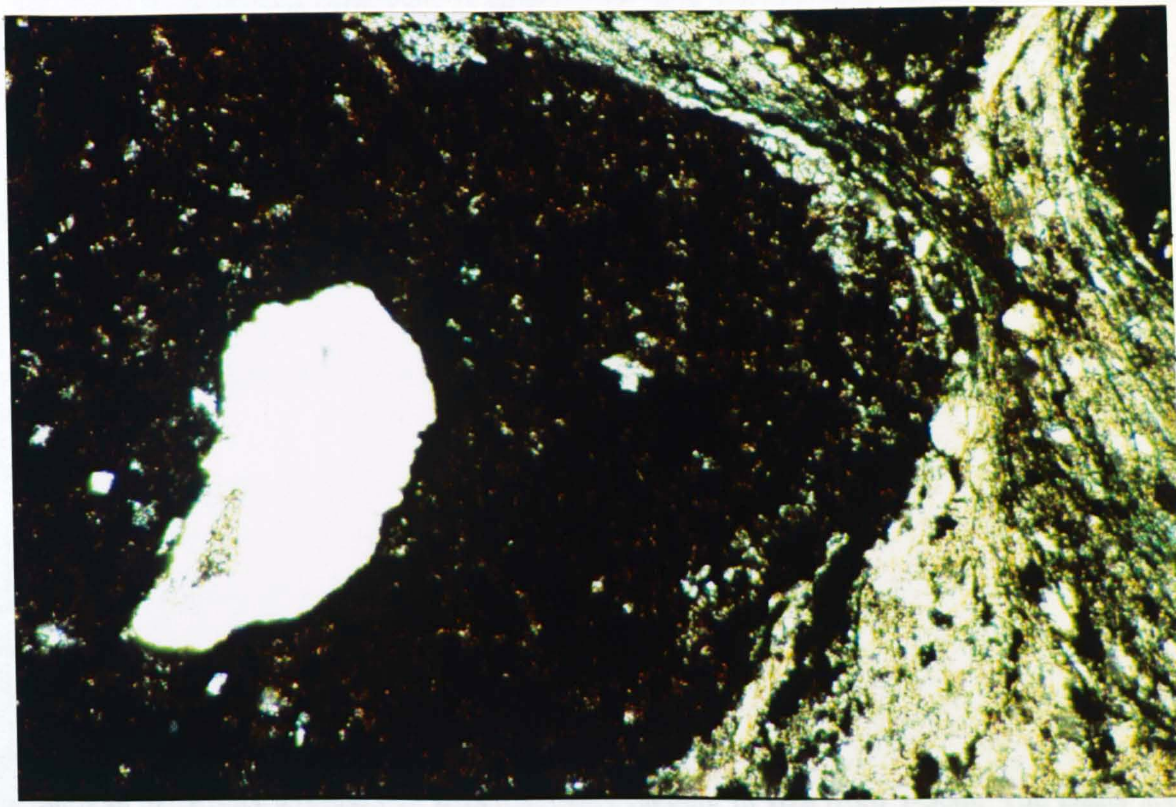

Plate 3.11 Photomicrograph (x64) of conglomeratic calcrete showing a quartz grain in the centre of a calcareous clast; plane polarised light. Renney Rocks Formation, Heybrook Bay [SX 4965 4870].

Plate 3.12 Paraconglomerate containing sandstone, siltstone and claystone clasts within the Renney Rocks Formation; Heybrook Bay [SX 4965 4870].

Provenance

Although 'conglomeratic' calcretes may originate from reworking of a calcrete profile the lack of grading and erosional/transport features makes an *in situ* origin more likely (see section on calcretes for a more detailed explanation).

Paraconglomerate containing sandstone, siltstone and claystone intraclasts

These conglomerates are relatively rare and are restricted to the Renney Rocks Formation. They are polymodal and polymict (diamictite), matrix supported and lack a framework. The matrix is predominantly claystone or silty claystone but coarsens to fine sandstone (ca. 0.2mm) and suspended within it are clasts of claystone, siltstone, sandstone and carbonate varying in size from a few mm to ca. 30cm (Pl. 3.12). This suite of clasts is similar to that observed within the polymict conglomerates described above. The most common clast type is sandstone with diameters ranging in size from 1-3cm. The clasts are rounded to sub-angular and show low to high sphericity. The matrix is two-fold with a sandstone fraction supported by a silty claystone fraction, the latter consisisting of ca. 90% of the total rock fraction. A 25m thick sequence of the paraconglomerates, in which the frequency of clasts decreases upwards and the base of which is non-erosive, occurs at the rear of the beach at Heybrook Bay [SX 4970 4875]. The sequence appears to be unbedded but subsequent deformation may have obliterated bedding interfaces within the sequence. The thick conglomerate sequence lies above a series of fine sandstones and at its top it passes upwards into a sequence of unbedded siltstone (the matrix lithology to the conglomerate) with no sedimentary break. Overlying and cutting into these siltstones is a thickly bedded unit of trough cross bedded sandstone. Within the conglomerate sequence is a laterally discontinous (<2m), sharp based, sandstone bed the top of which grades into the overlying matrix lithology of the conglomerates. Clasts (up to a few centimetres in diameter) of sandstone lie immediately above and are likely to be derived from the bed itself. Although the distribution along the coast to the west and east of Heybrook Bay implies that these conglomerates are of frequent occurrence in the Renney Rocks Formation accurate mapping and cross section construction shows that they largely belong to one stratigraphic horizon sandwiched between a series of interbedded sandstones and mudrocks.

Provenance

The similarity in clast composition to those of the polymict conglomerates described above implies that they have a similar origin in terms of their sedimentary source (predominantly locally derived). However, the overall character of the deposits indicates the action of different sedimentary processes. The matrix supported nature and variation in clast size indicates that the paraconglomerates were deposited rapidly by debris flow motion.

Paraconglomerate containing sedimentary and volcanic intraclasts (agglomerate)

This type of conglomerate is confined to the Yealm Formation and is well exposed at Wonwell Beach [SX 6175 4725]. The lithologies are buff/yellow when weathered and grey when fresh. The conglomerates contain < 10% clasts and are composed of a suite of lithic and volcanic clasts, supported by a matrix of clay and silt size grains. They are therefore referred to as diamictites (Pls 3.13 and 3.14). The clasts are composed of quartzite, polycrystalline quartz, slate, muscovite mica and microcline. The quartzite clasts consist of welded quartz grains (point contacts and overgrowths) and have a grain size in the order of 0.15mm (fine sand) and no matrix. These features are similar to the texture of adjacent sandstone beds (Pls 3.15 and 3.16). Volcanic (doleritic) rock fragments are also present and so the conglomerate may be classed as polymict. Other grains of igneous origin occur and these are dominated by feldspar and pyroxene. The conglomerate is polymodal with clasts varying in size from ca. 3mm to ca. 25cm although the dominant clast size is ca. 1-5cm. They are rounded to angular and have variable sphericity. However, this is complicated by the fact that they are oriented in the cleavage and grains/clasts less than 2cm in diameter are sometimes sheared. The composition of the matrix resembles that of the tuffaceous sandstones (fine grained quartz and igneous grains in an altered ash/clay matrix - see section on volcanic rocks).

Some of the conglomerates are well bedded at their upper and lower surfaces but contain no internal stratification. Others have no upper or lower bounding surfaces and grade upwards and downwards into silty claystones. The bases to some beds disrupt underlying sandstone beds and therefore may be regarded as erosive. Internally the conglomerate beds are generally ungraded (cf. Smith & Humphreys, 1991 - who recognise inverse grading in a pebbly mudstone), however, an upwards reduction in clast size has been recognised within a 30m logged sequence (Fig. 3.3). At the base of this sequence individual conglomerate units

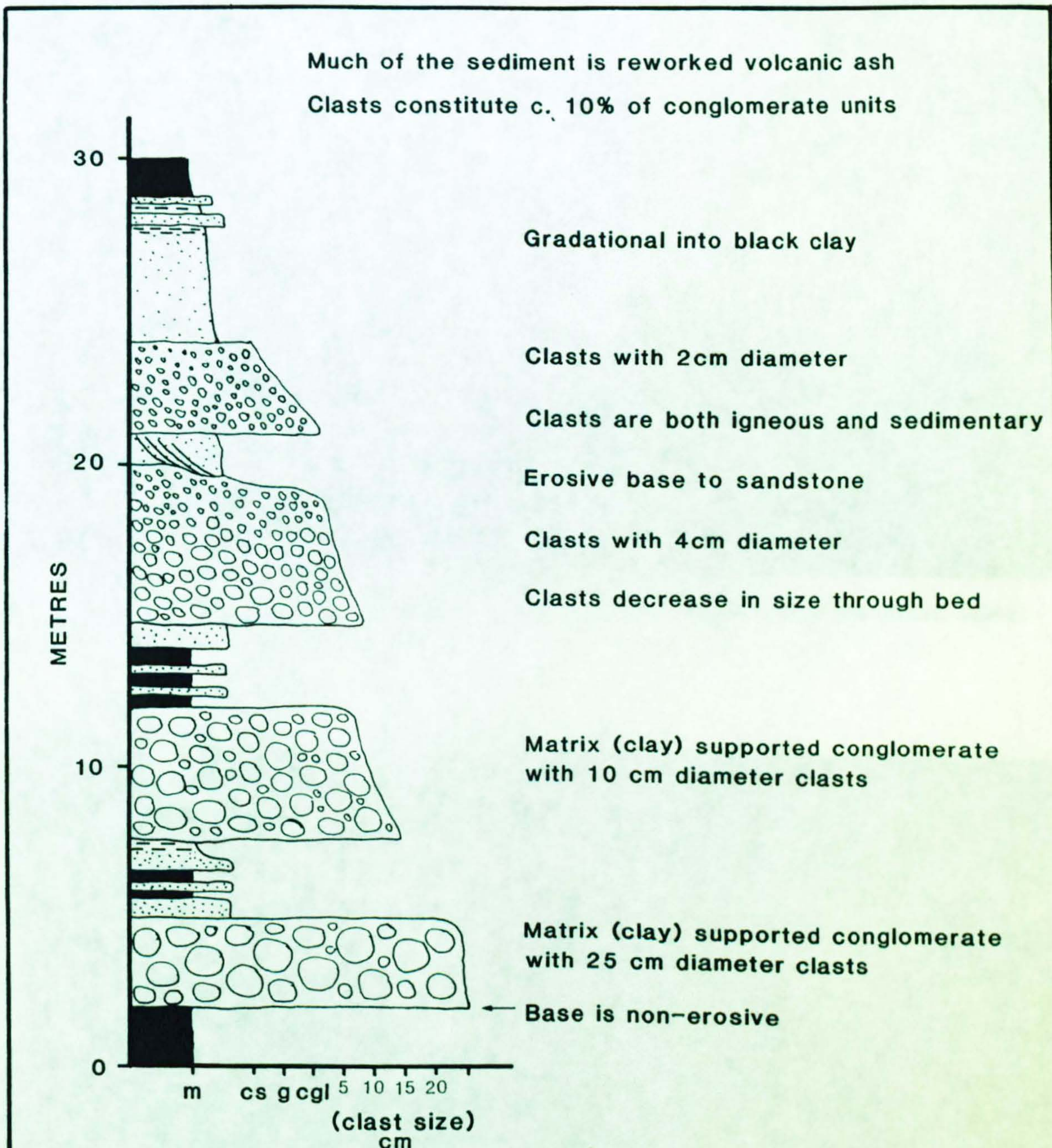

Fig. 3.3 Logged section through the Yealm Formation (Erme Estuary - SX 6180 4740) which fines upwards withrespect to the clast size within the conglomerate horizons.

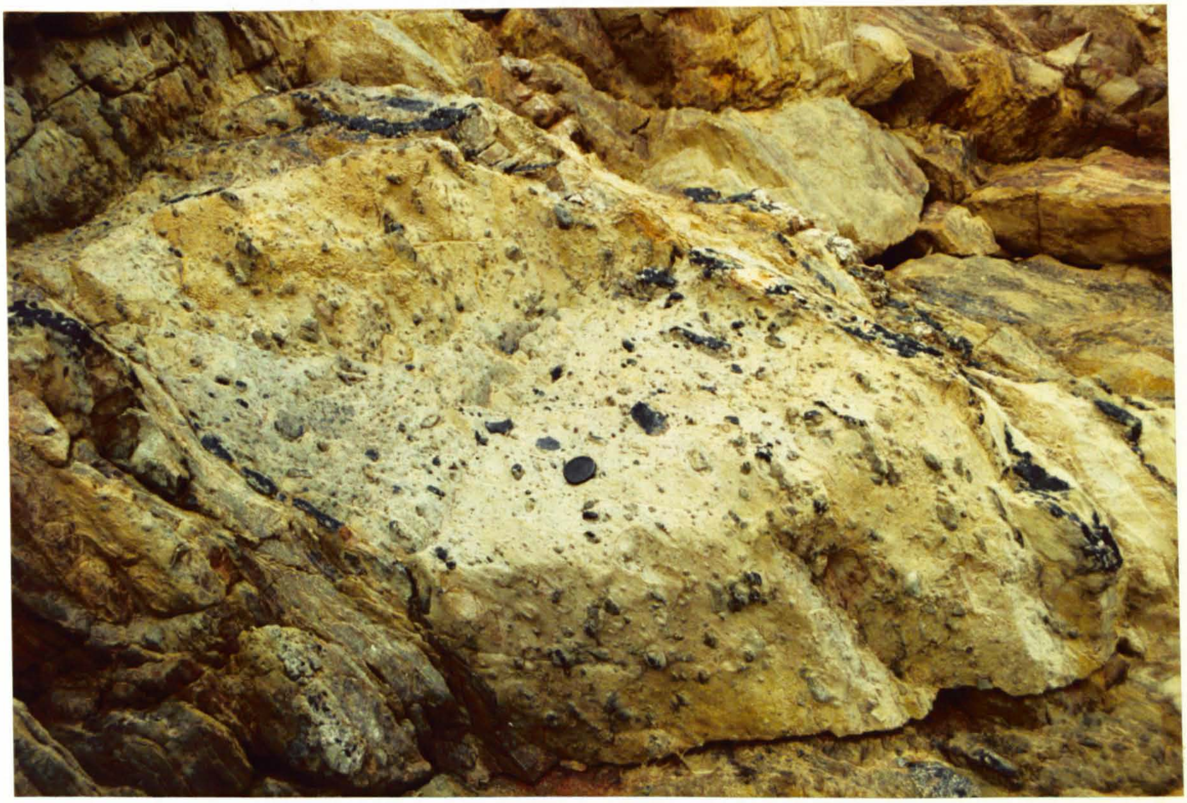

Plate 3.13 Paraconglomerate containing sedimentary and volcanic clasts within the Yealm Formation; Erme Estuary [SX 6180 4740].

Plate 3.14 Paraconglomerate containing sedimentary and volcanic clasts within the Yealm Formation; Erme Estuary [SX 6180 4740].

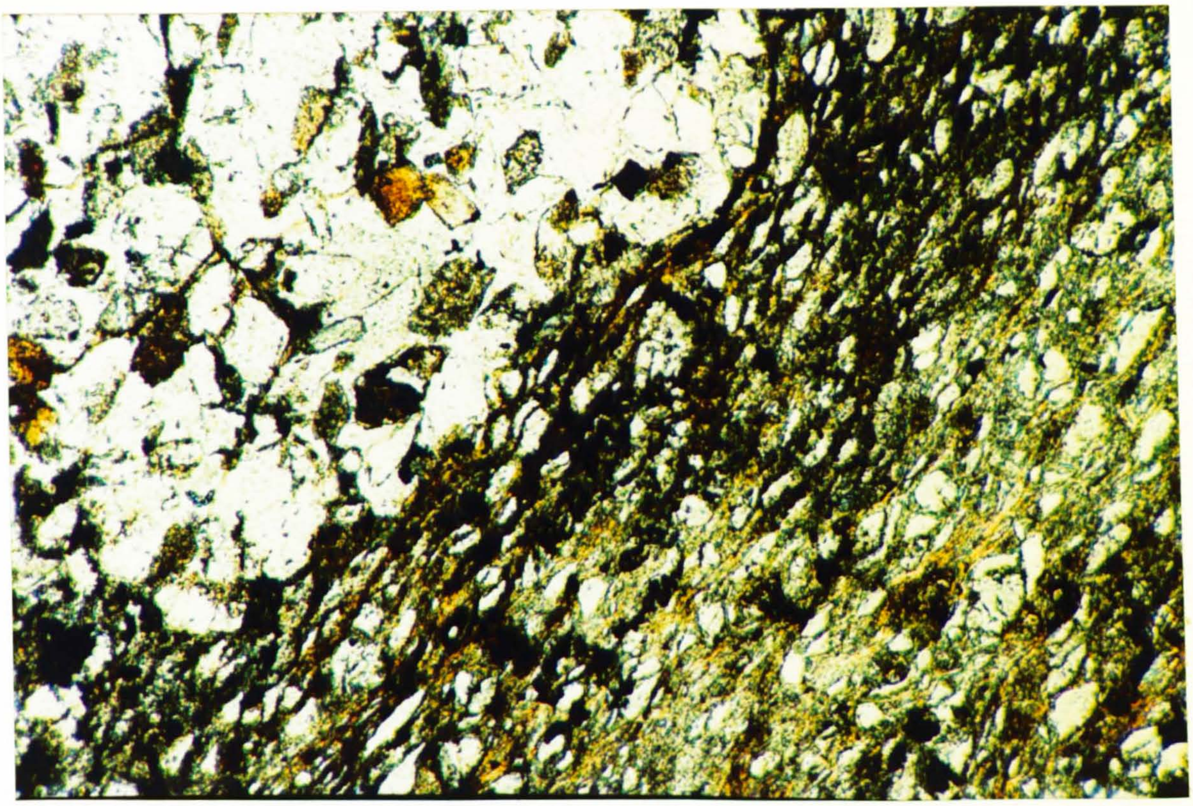

Plate 3.15 Photomicrograph (x64) of a sandstone clast and surrounding matrix from the paraconglomerate of the Yealm Formation; plane polarised light. Wonwell Beach [SX 6180 4740].

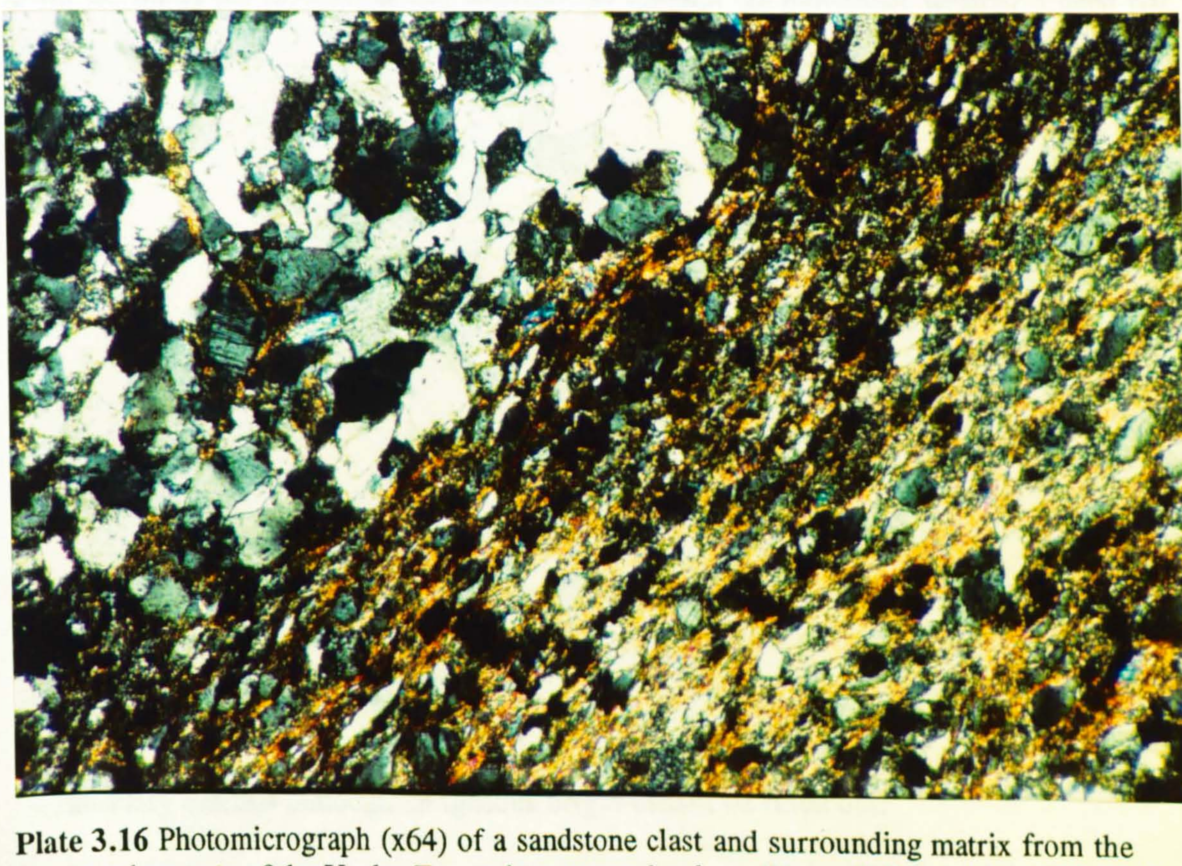

Plate 3.16 Photomicrograph (x64) of a sandstone clast and surrounding matrix from the paraconglomerate of the Yealm Formation; crossed polars. Wonwell Beach [SX 6180 4740].

contain clasts with a diameter of ca. 25cm and these fine to clast sizes of 10cm, 4cm and 2cm progressively up the sequence.

Provenance

The presence of clastic material, which resembles rock types immediately below the conglomerate horizons, indicates that the detritus has an intraformational source. However, an extraformational source is indicated by the presence of volcanic material. The fact that the conglomerate beds rarely exceed 5m in thickness indicates that they have formed in water filled depressions of at least this depth.

Intraformational, volcaniclastic orthoconglomerate (lapillistone)

These conglomerates are grain supported, poorly sorted and polymictic containing clasts of clay, detrital quartz and volcanic debris less than 64mm in diameter (Pls 3.17 and 3.18). The clay fraction consists of green rip-up clay chips which measure up to 15cm long and 5cm wide. Feldspar, pyroxene, clinozoisite, epidote and angular quartz (see Pls 3.19 and 3.20) constitute the volcanic debris fraction. At outcrop the pyroxenes weather a deep red colour, measure up to a few mm in diameter and produce a rubbly texture to weathered surfaces. The epidotes are often very rounded, show pale green colours in plane polarized light and high birefringence. The clinozoisite crystals are larger (up to 2mm in diameter), more angular and elongate. They have straight extinction and weak birefringence (blue-grey). This lithological division has been observed at Wonwell Beach [SX 6175 4725] in the upper part of the Yealm Formation.

Provenance

These conglomerates are thought to form by reworking of a muddy substrate with bedloads consisting of volcanic debris. The epidote group minerals are igneous in origin and must be derived either from volcanic ejecta or from surrounding volcanic rocks, before being reworked in a sedimentary environment. The clay chips are thought to be sedimentary and derived from a local source (intraformational) in origin. The quartz is probably part of the sedimentary detritus although an igneous origin cannot be ruled out.

Plate 3.17 Lapillistone containing volcanic clasts and intraformational clay chips from the Yealm Formation; Wonwell Beach, Erme Estuary [SX 6180 4740].

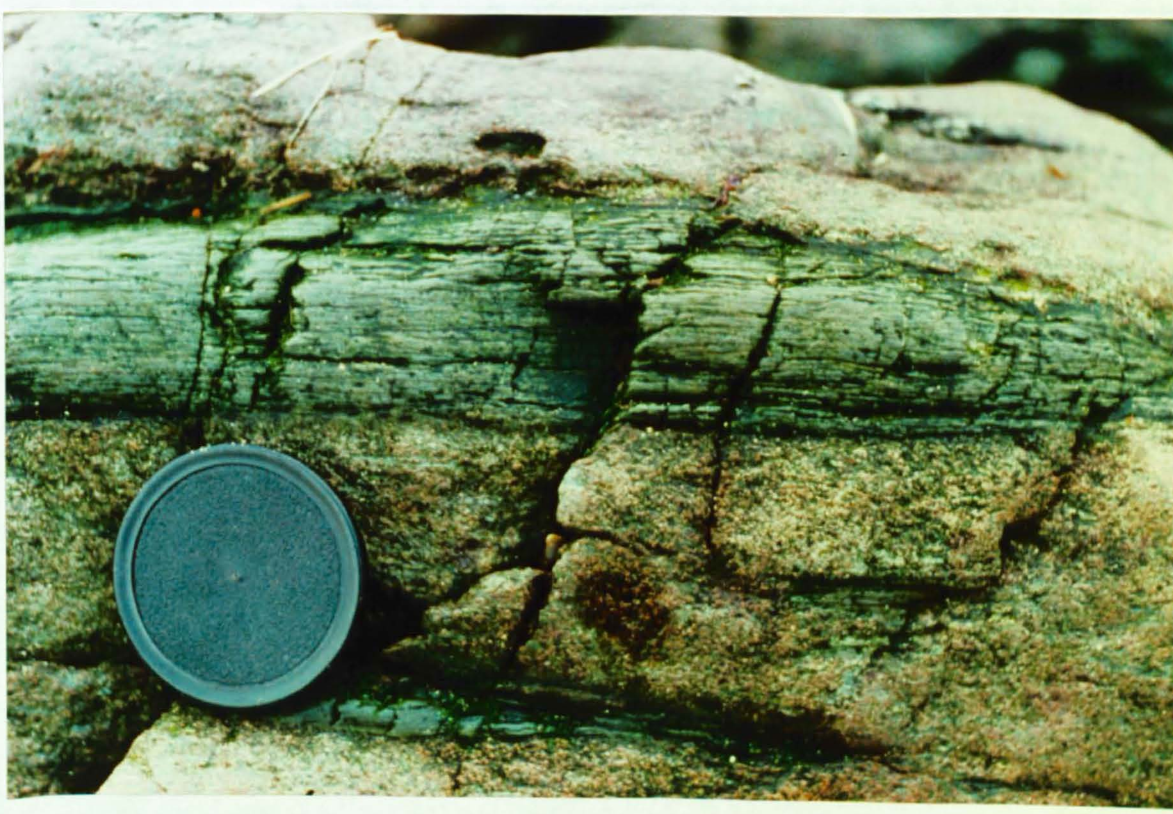

Plate 3.18 Close up of Pl. 3.17.

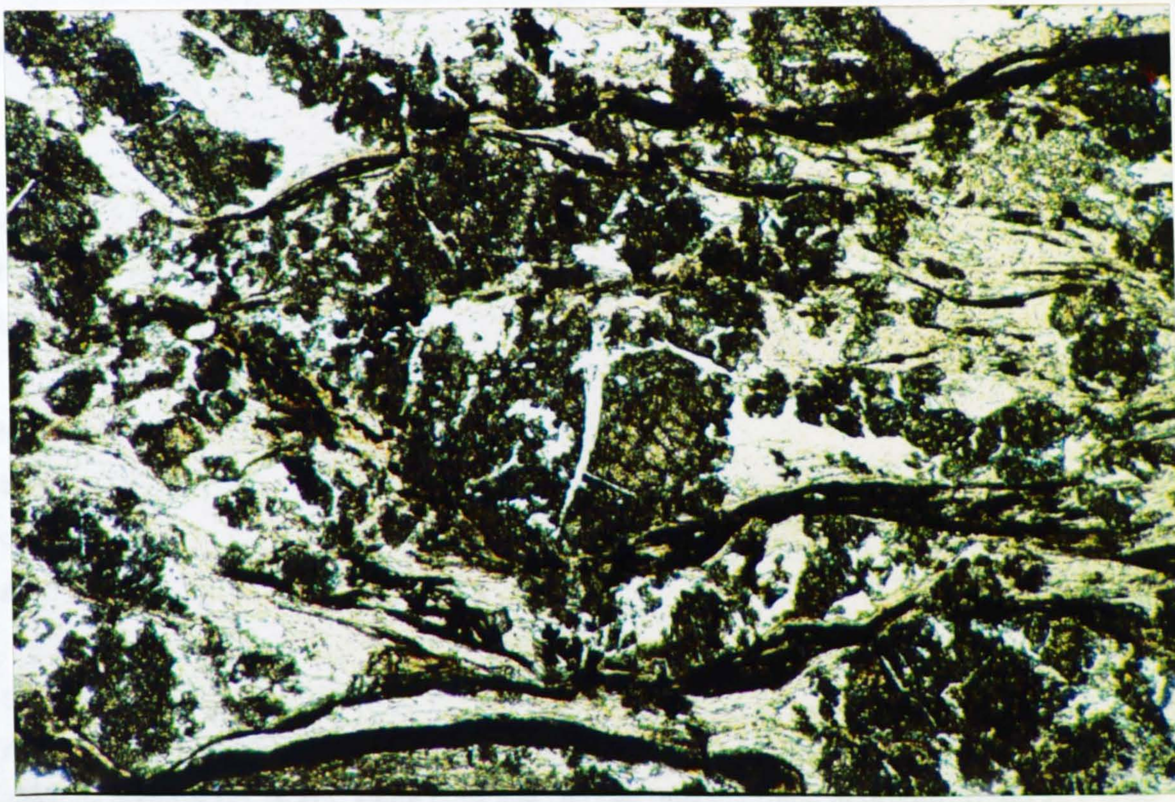

Plate 3.19 Photomicrograph (x64) of lapillistone showing rounded volcanic clasts (pyroxene); plane polarised light. Wonwell Beach [SX 6180 4740].

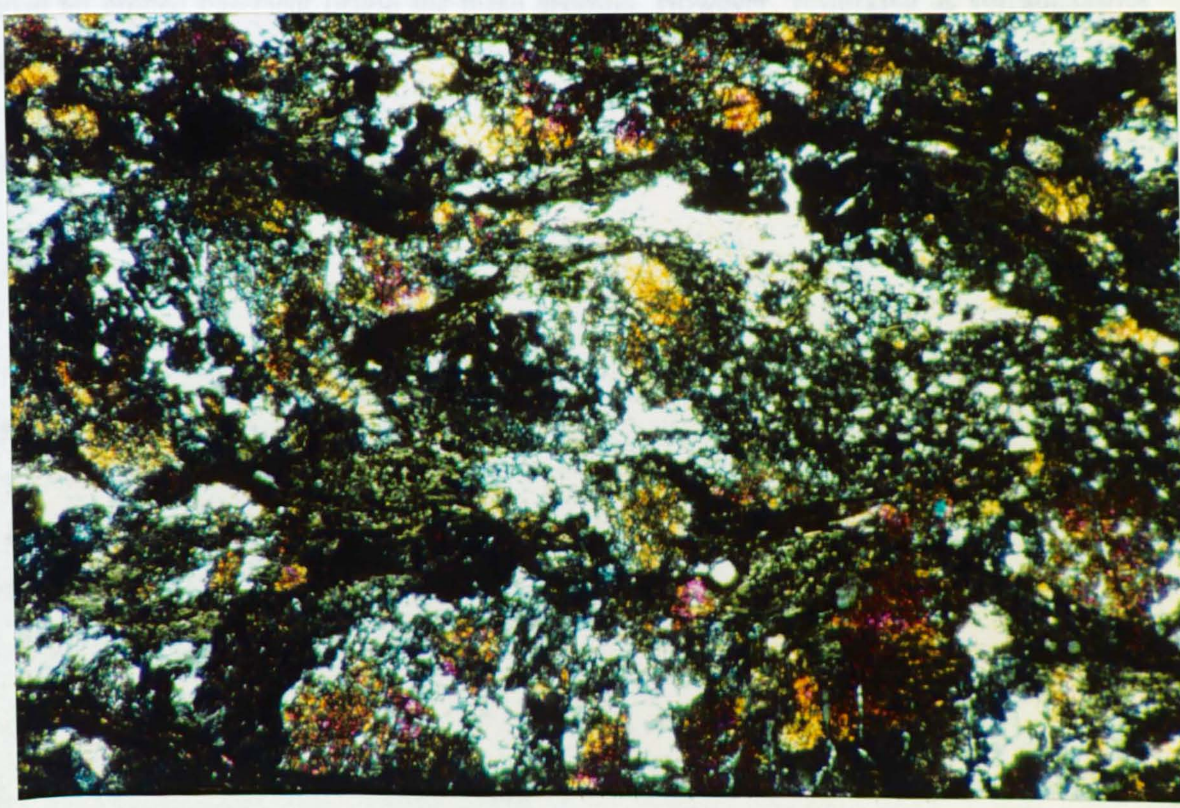

Plate 3.20 Photomicrograph (x64) of lapillistone in crossed polars. Wonwell Beach [SX 6180 4740].

Volcanics Rocks

To the south of Plymouth the present day river courses (Yealm and Erme) follow the outcrop of the Yealm Formation. This formation contains a large proportion of volcanic rocks interbedded with mudrocks and sandstones which are prone to severe weathering and river incision compared to the clastic lithologies of adjacent formations.

The volcanic rocks are mainly reworked tuffs (originally ash), volcaniclastic sandstones and volcanic conglomerates (lapillistone and agglomerate). They are grey/green in colour and generally weather to yellow or rusty orange colours. The volcanic conglomerates have been described in the above section thus only the sandstones and tuffs are described here.

The overall mineralogy of the sandstones, tuffs and matrix of the conglomerates consists of quartz (detrital and sedimentary in origin), feldspar (mainly plagioclase grains many of which are broken and altered and are of a volcanic source), rock fragments showing igneous textures (Pl. 3.21), white mica and chlorite (metamorphic in origin). Grain size is up to fine sandstone with the larger grains measuring ca. 0.13mm. The euhedral nature of some quartz grains and the presence of feldspar and pyroxenes indicates a volcanic origin rather than an eroded basement origin for these deposits. However, reworking as volcaniclastics generally destroys the angularity of many of the grains.

The tuffs are by definition much finer grained and are almost entirely composed of lathe shaped, angular, plagioclase feldspar and sub-ordinate, rounded quartz grains.

Interpretation

The deeply weathered nature of the rocks within the Yealm Formation results from the presence of easily eroded volcanic material. The volcanic rocks are likely to be derived from explosive volcanic activity with the ejected material, principally ash, probably originating from distances in the order of 10's of km from the site of deposition. Volcanic flow deposits are not observed.

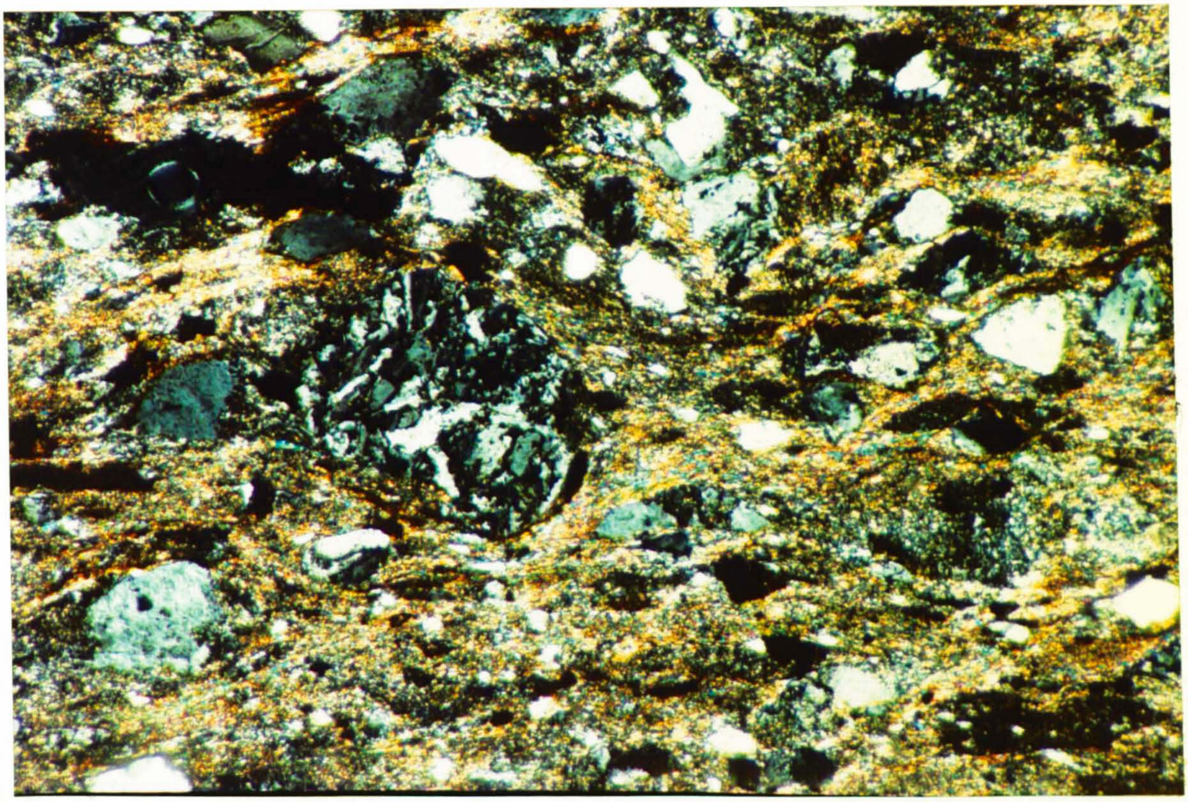

Plate 3.21 Photomicrograph (x64) of volcaniclastic sandstone containing grains of quartz and igneous rock fragments set in a clay grade matrix; crossed polars. Wonwell Beach [SX 6180 4740].

Plate 3.22 Calcareous concretion within the fine member units of the Renney Rocks Formation; Heybrook Bay [SX 4965 4870]. Hand lens (2.5cm wide) for scale.

Calcretes

Concretionary, carbonate deposits (calcretes) similar to those described as calcretes elsewhere in red bed sequences (Allen, 1960, 1974; Leeder, 1975), have been observed in this study area. They can be examined on the foreshore in the Heybrook Bay area where they occur at the top of the Renney Rocks Formation. On the whole the calcretes are poorly preserved/developed and massive limestone tops and pseudo-anticlines, observed in well developed pedogenic profiles, are not present. The calcretes mainly occur towards the top of fine member units (mudrocks) (Pl. 3.22) but are occasionally found in fine sandstones (Pl. 3.23). They occur in the form of scattered carbonate glaebules, nodular masses and as bedded 'conglomeratic' units.

The glaebular calcretes consist of red calcareous claystone, angular quartz grains and calcite veins. The glaebules tend to be ellipsoidal in shape and their long axes which measure up to 15cm are oriented parallel to the cleavage. The mudrock units which contain these scattered glaebules are similar to the glaebular soils described by Blockhuis *et al.* (1969) and Singh & Singh (1972). The fine member units containing the glaebular calcretes are usually overlain and cut by sandstone bodies.

Calcretes that are developed in sandstones appear as large nodular masses surrounded by tubiform calcrete (Pl. 3.24). These tubes are up to several mm in diameter and are often branching.

Another form of calcrete exists and resembles a fine conglomerate. In these 'conglomeratic' calcretes the texture is pseudo-pisolitic, composed of rounded grains of red, aggregated, calcareous clay with occasional angular quartz grain nuclei or a mass of quartz grains at their centres (see section on 'conglomeratic' calcretes). These micritic clasts (ca. 2mm diameter) are separated by interstitial calcite which has eroded and replaced the quartz grains (Pl. 3.25). These are corroded to such an extent that they have serrated edges. The calcrete occurs in a bedded sequence ca. 2.5m thick, with individual beds measuring ca. 20-40cm. The beds have sharp, flat bounding surfaces and are not typical of high energy erosive conditions.

Occasionally calcretes occur within thin basal conglomerate units implying that erosion of the calcrete profile and redeposition has occurred (see section on conglomerates).

Plate 3.23 Calcretes in fine sandstones of the Renney Rocks Formation, Heybrook Bay [SX 4965 4870]. Height of photograph ca. 2m.

Plate 3.24 Tubiform calcrete in siltstones of the Renney Rocks Formation; Heybrook Bay [SX 4965 4870].

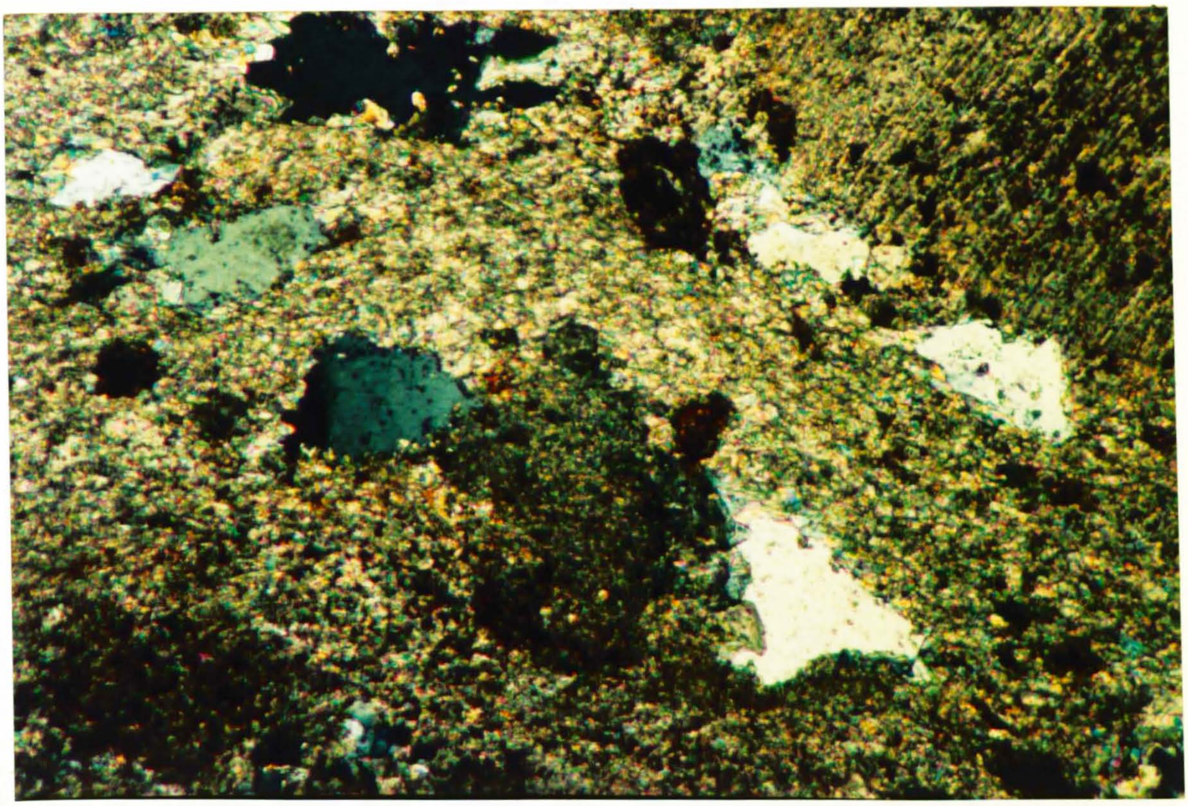

Plate 3.25 Photomicrograph (x64) of quartz grains corroded and replaced by calcite within calcretes of the Dartmouth Group; Scabbacombe Head [SX 9230 5170].

Plate 3.26 Ferruginous concretions within the mudrocks of the Renney Rocks Formation; Heybrook Bay [SX 4965 4870].

Interpretation

The characteristics of the 'conglomeratic' calcretes resemble those of calcite spherulites which form the upper zones of some calcrete profiles (Nagtegaal, 1969). Spherulites have a size range from 20 microns to 3mm and generally contain a nucleus of a single quartz grain, a rock fragment or an aggregate of fine grained calcite or clastic sediment. Microcrystalline quartz and ferric oxides are present as a light brown stain and also characterize the spherulites (Nagtegaal, 1969). These similarities and the low energy conditions implied by the form of the sequence indicate that the bedded calcretes, observed near Heybrook Bay, are formed *in situ* rather than eroded from a calcrete profile and redeposited.

Calcretes are known to form in arid to semi-arid climates with markedly seasonal rainfall and a relatively high mean annual temperature (Goudie, 1973). They are of pedogenic origin and indicate periods of sub-aerial exposure and soil formation. Thus together with other sedimentary features described in this chapter the presence of calcretes indicate that parts of the Lower Devonian, Dartmouth Group rocks were deposited under continental conditions. The lack of well developed calcretes may reflect that the area of deposition was rather wet.

Other Concretions

Non-calcareous concretionary or nodular bodies are locally common in the slates and sandstones of the Renney Rocks and Wembury Formations. They are mainly ferruginous and siliceous, composed of quartz and iron, and are preferentially weathered to a brown powdery, very friable material (Pl. 3.26). Some of these concretions contain traces of calcium carbonate which may suggest that they were originally some form of calcareous nodule not unlike the glaebules described above. Nodular concretions (francolite) unlike any of those described here have also been observed by Humphreys & Smith (1989). These are thought to indicate marine incursions (Humphreys & Smith, 1989) or deposition within substantial lakes (Smith & Humphreys, 1991).

3.2.2 Sand body geometry

The following descriptions on the geometry of sandstone bodies in the Dartmouth Group rocks mainly apply to the general form of the bounding surfaces to the sandstones and not to their internal structure. Two forms are described; those with a sheet like geometry and those which display a more channelised form. Differentiation of these forms however, is often difficult due to the limited coastal exposure, folding and faulting. This hampers three dimensional analysis and thus restricts accurate interpretation. Sandstone beds range in thickness from a mm scale up to ca. 2m. However, the most common thickness range is between 3 and 30cm. Sandstone beds often die out laterally by grading into finer grained lithologies and this is usually related to thickness. Thus the thicker beds have a greater lateral extent. The sandstone beds are usually defined by sharp, lower surfaces and gradational, upper surfaces which pass upwards into finer sediment.

Sheet like sand bodies

Usually measuring over 50cm in thickness these units are generally laterally continuous over the width of outcrop (a distance of ca. 25m) with no appreciable thinning and tend to be parallel laminated (Fig. 3.4). In the dimension perpendicular to flow they are laterally continuous for ca. 20-25m, whilst in a direction parallel to flow they are continuous for distances of at least 75m. It is therefore difficult to be certain of the sand body's true geometry ie. they may be very broad, low gradient 'channels' (semi-confined sheets). The lower surfaces of the sandstones of this type are parallel to the underlying strata. Within the sandstone beds there is occasional trough cross lamination which alternates with the parallel laminations.

Channelised sand bodies

Channeling on the underside of some sandstone beds is irregular in profile and cuts down into underlying finer sediment. This scouring is of relatively low relief and can be described as undulatory. Thin conglomerates are occasionally present above these surfaces (Pl. 3.7). Channels are also present which have much greater relief and steep margins (Pl. 3.27). Trough cross lamination on a 2cm scale is preserved in this channel type, however, so few are observed that they cannot be regarded as definitive sedimentary features of the depositional environment.

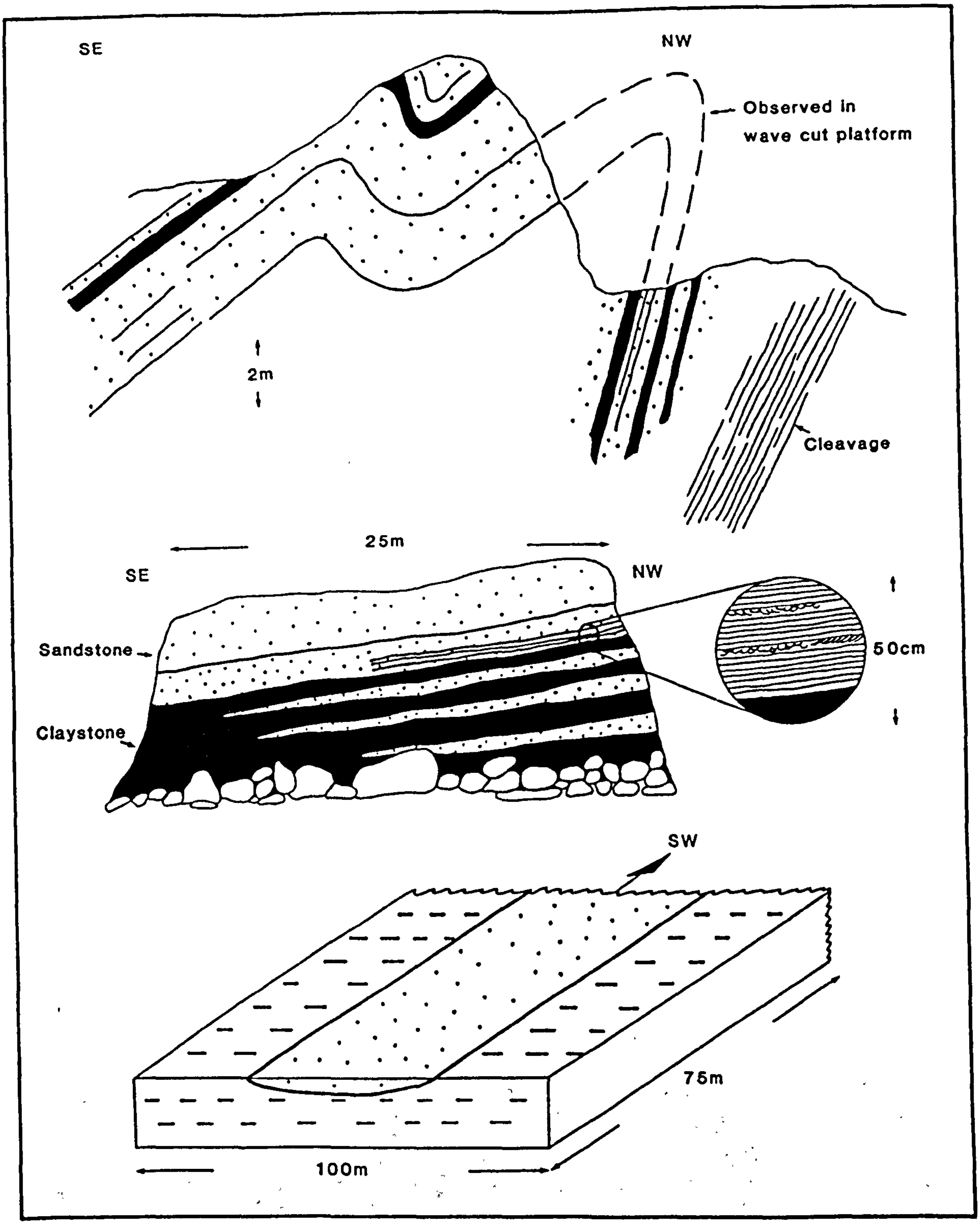

Fig. 3.4 Lateral and vertical extent of sand bodies observed in the Warren Formation; The Warren [SX 5320 4660].

Plate 3.27 Channelised sandstone with a steep margin within the Renney Rocks Formation; Heybrook Bay [SX 4965 4870]. Height of can ca. 15cm.

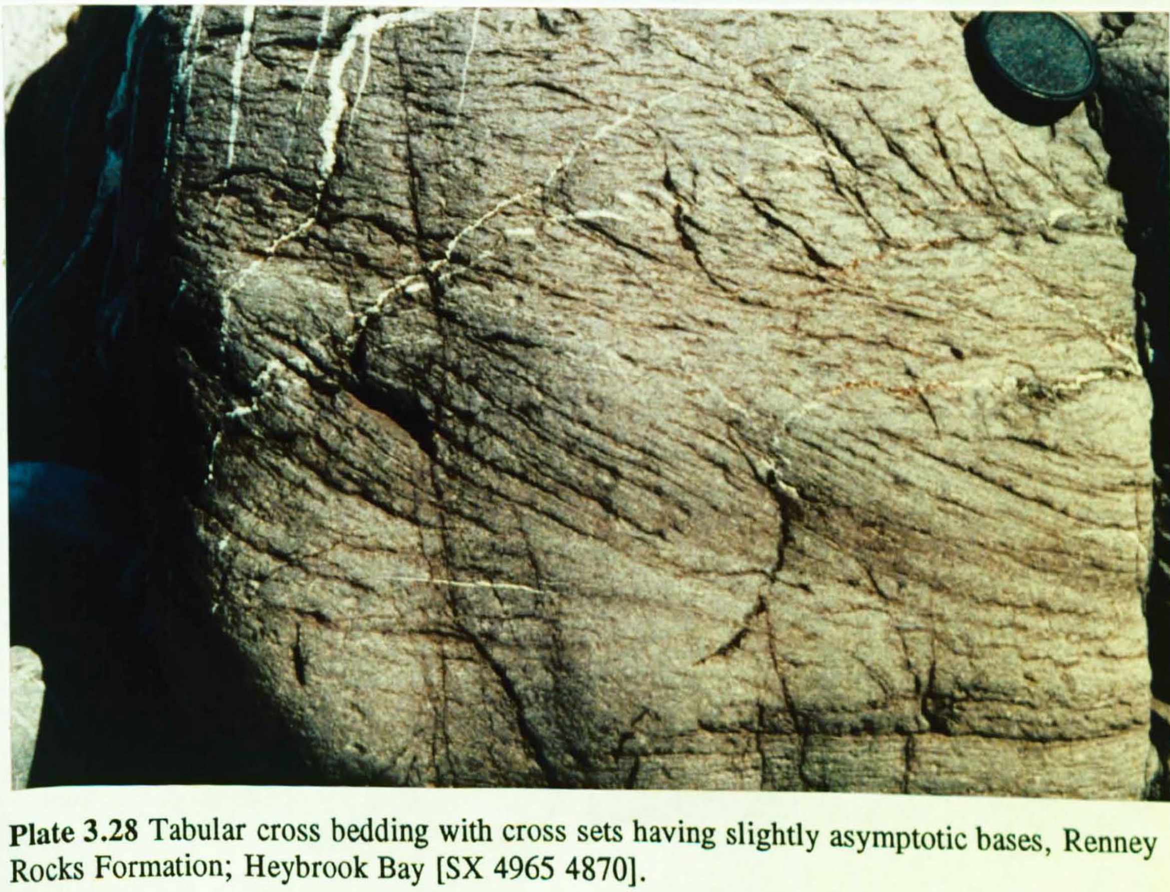

Plate 3.28 Tabular cross bedding with cross sets having slightly asymptotic bases, Renney Rocks Formation; Heybrook Bay [SX 4965 4870].

Interpretation

Undulatory, erosive bases and steep margins appear to be a local phenomenon and are relatively rare. The general form of the sand bodies is therefore probably sheet like having been deposited by unconfined or semi confined (broad channels) water bodies. These broad shallow water bodies vary in scale from metres to tens of metres and even hundreds of metres.

3.2.3 Sedimentary Structures

Tabular cross bedding

Tabular cross bedding is not a common internal feature of the sandstones. It is only occasionally preserved in the fine sandstones of the Renney Rocks and Warren Formations where cross sets of up to 30cm occur. However, in the Yealm Formation sandstones 1m thick have cross strata which traverse the bed. The bases of the cross strata are slightly curved but the sets tend to be tabular in form (Pl. 3.28). These beds were probably deposited by migrating sand waves and are not as common as the parallel laminated and trough cross laminated units observed in the Renney Rocks Formation.

Parallel lamination

This particular type of sedimentary structure is preserved in siltstones as well as fine grained sandstones (Pl. 3.29). In some units, the silt and clay alternate on a microscopic scale. The individual laminae are defined by variations in grain size and in some cases grading occurs. The size of the quartz and feldspar grains in the coarser fraction range from coarse silt to very fine sand (0.05-0.1mm). Where the deposits are fine sand the process of formation is probably by high velocity in low water depths (upper flow regime flat bed). However, in the case of the finer grained units the parallel lamination may reflect lower flow regime or deposition from suspension.

Plate 3.29 Parallel laminated siltstones in the Renney Rocks Formation; Heybrook Bay [SX 4965 4870].

Plate 3.30 Trough cross lamination in fine grained sandstones of the Renney Rocks Formation, Heybrook Bay [SX 4965 4870].

Low angle lamination

Low angle lamination rarely occurs but is present in a few thick (ca. 1.0 to 1.5m) sandstones of the Yealm Formation. Laminations are parallel to each other and traverse the bed at a very low angle (10° to 15°) producing laminae of considerable length. They may reflect bar form deposition.

Trough cross lamination

Trough cross lamination occurs in the very fine to medium grained sandstones and is by far the most common sedimentary structure observed (Pl. 3.30). In sections perpendicular to the flow direction cross laminae with both concordant and discordant base relations are observed. In sections parallel to the flow direction the cross strata are concave with asymptotic bases, tabular with asymptotic bases and occasionally climbing. The set thicknesses (trough depths) are generally ca. 2cm but ones of ca. 5cm also occur. The sets are similar in size, shape, attitude and lithology and are grouped into cosets. The sets or cosets are stacked into beds up to 1.5m thick of fine sandstone throughout. The beds containing this type of stratification occur in fining up cycles of sandstone, are interbedded with siltstones and claystones and are most common within the Renney Rocks Formation. They also occur less frequently throughout the Dartmouth Group.

It is likely that trough cross lamination is generated by the migration of linguoid ripples, within a moving body of water. When combined with sedimentary features of the sandstone beds containing them it is likely that they are produced in some sort of semi-confined channel of very shallow depth. The term semi-confined is used as it is likely that switching from confined to unconfined flow, within shallow channels, occurred periodically depending on the availability of water. The palaeocurrent direction derived from these structures indicates a general flow to the south west (Fig. 3.5).

Climbing-ripple cross lamination (ripple drift)

These structures are relatively rare, when compared to the occurrence of trough cross lamination or parallel lamination, but are present in some fine sandstones of the Renney Rocks and Wembury Formations. It must be stressed that any percentage estimation of relative occurrence would be inaccurate due to the majority of sandstones displaying no

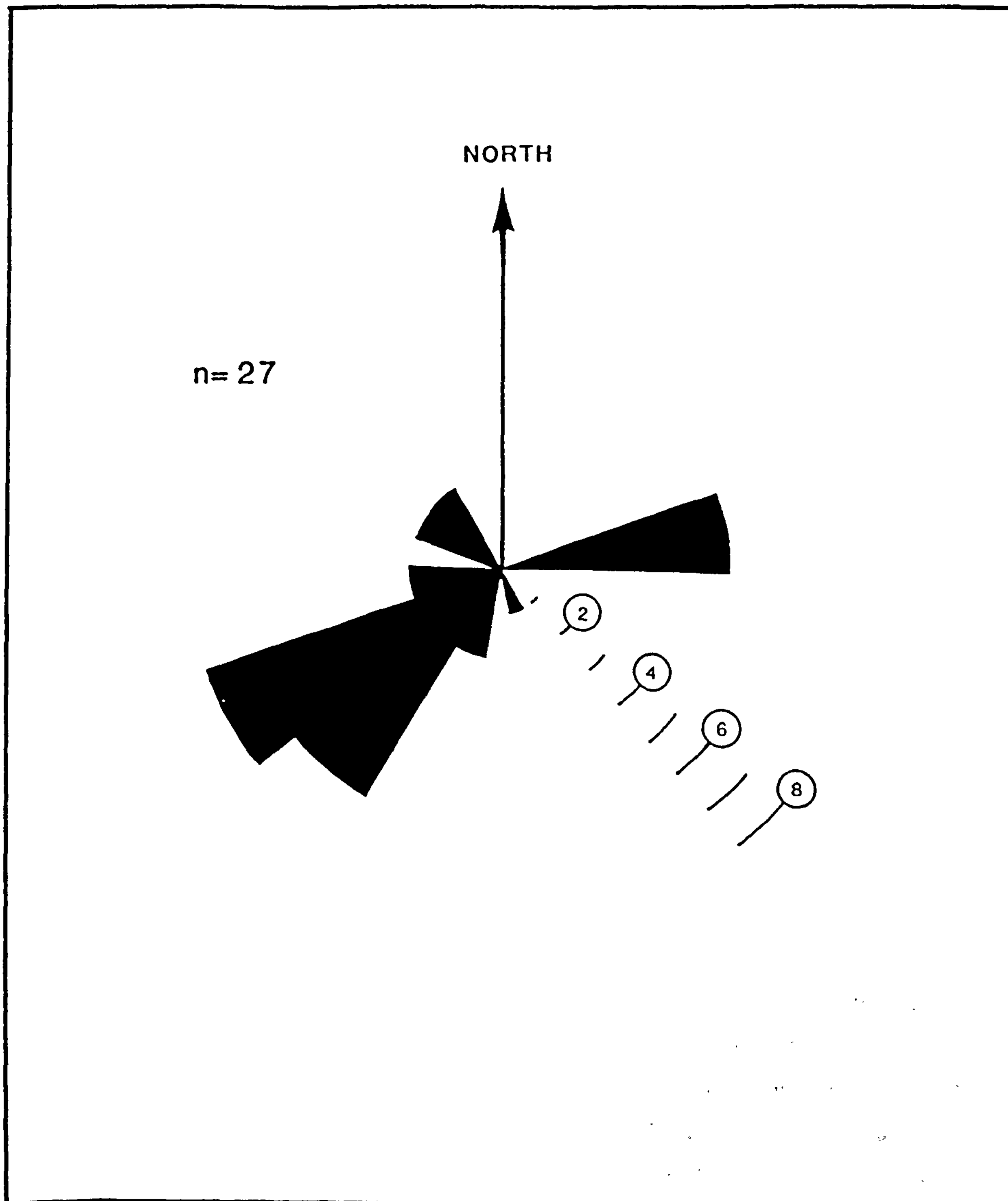

Fig. 3.5 Palaeoflow analysis of trough cross lamination from the Renney Rocks Formation between Andurn Point [SX 4920 4975] and Renney Rocks [SX 4925 4875].

internal structure. This latter point may be a function of subsequent deformation but may also be a primary sedimentary feature. The ripples of this category display their climbing form in sections parallel to flow but are trough shaped in sections perpendicular to flow. The contacts between adjacent sets are sharp, inclined and erosive dipping in an upstream direction and opposite to the dip of the laminae. The grain size is constant throughout each set which are ca. 2-3cm thick and are contained within beds of ca. 1.5m thickness. The sandstones containing the climbing ripples have sharp bases and tops and occur within a sequence of mudrocks. Occasionally ripple drift occurs as an individual coset, between sets of trough cross lamination. Palaeocurrents for this type indicate flow in a southerly direction but on occasions they describe no consistent palaeoflow direction.

Ripple drift will form when net deposition occurs with respect to erosion, allowing ripples to build upwards as well as forwards (Allen, 1973). This occurs during migration causing the ripples to climb up the stoss sides of those further downstream.

Graded bedding

In some sandstones grading occurs, the characteristics of which are sharp bases, gradational tops, and grain size reduction upwards through the bed (fining up). In some siltstones the parallel laminations are graded on a mm scale. These may be described as multiple graded units. Graded bedding reflects a change in flow conditions and may be generated during waning flow. However, deposition from suspension in areas of static water may also be responsible for this sedimentary structure.

Heterolithic bedding

Flaser type

This feature is observed within yellow, cross laminated sandstones of the Yealm Formation. The clay flasers (clay drapes) form within depressions (ripple troughs) and on the crests of ripples (Pl. 3.31). The sand is deposited during water body flow whilst the clay settles from suspension during quiescent periods. Although a common feature in tidal flat areas these structures are also found on delta fronts or in any other environment where there are fluctuations in sediment supply and flow strength. However, the shape of the cross sets and ripple crests (Pl. 3.31) show that they are wave produced.

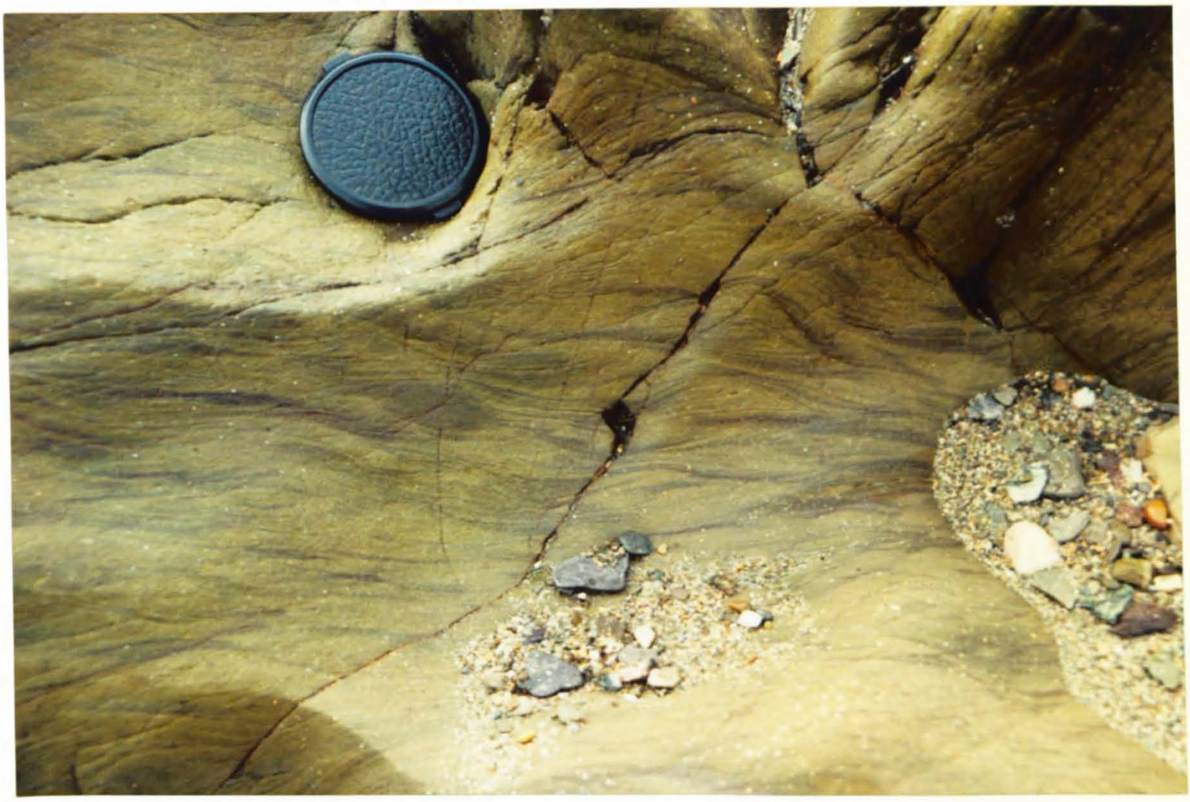

Plate 3.31 Flaser bedding within cross laminated sandstones of the Yealm Formation; Erme Estuary [SX 6180 4740].

Plate 3.32 Wave ripples within the Wembury Formation; Andurn Point [SX 4920 4975].

Sand streaked black clays

These are found in the Yealm Formation and are clay dominated lithologies with subordinate sand streaks. The sand lenses are rippled and also occur as elongate streaks. Their presence indicates that more sedentary water bodies exist receiving occasional influxes of sand, deposited as ripples, during gentle water movements.

Wave ripples

These are observed in thin sandstone beds at the base of the Wembury Formation to the south of Andurn Point. They show typical features of wave ripple formation (cf. Allen, 1981; Reading, 1986 p. 247). Bi-directional, bundled, intricately interwoven cross lamination and assemblages of differently structured lenses with curved boundaries are typical features (Pl. 3.32). The structures probably result from waves generated by wind action over the surface of shallow standing water bodies.

Soft sediment deformation

These take the form of sandstone balls, load casts, flame structures and slump folds. Ball and pillow structures occur, at Wembury Point, in the Wembury Formation and consist of isolated sandstone load balls or pseudo-nodules which 'float' in the host fines. In this case there is total bed disruption. The load casts and flame structures occur at the base of sandstone units and can be taken as partial development of these load balls. The flame consists of the underlying fine sediment whilst the load cast is the disturbed base of the overlying bed. Slump folds are present in the heterolithic units of the Yealm Formation and may indicate some form of slope deposition.

Bioturbation

Burrows occur throughout the rocks of the Dartmouth Group. However, they are often difficult to categorise due to subsequent deformation. Those that occur in the claystones of the Wembury Formation produce an intense mottling and are not taxonomically identifiable. When present in siltstones they form dark purple pipes in the lighter purple/green silt (Pl. 3.33). The pipes are of slightly coarser silt than their host. They are subject to a

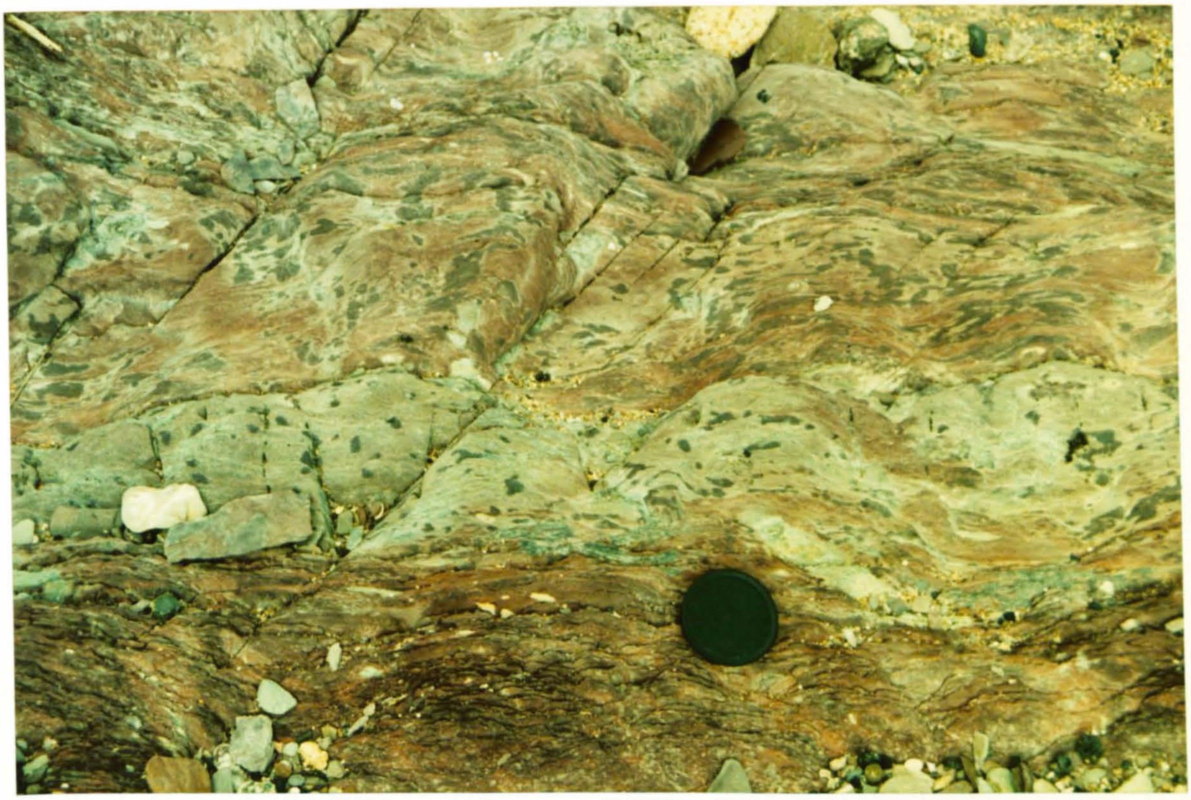

Plate 3.33 Burrowed siltstone in the Wembury Formation; Andurn Point [SX 4920 4975].

Plate 3.34 Scour structure with concordant infill of medium grained sandstone within the Renney Rocks Formation; Westlake Bay [SX 4925 4920].

change in their form after deformation and are aligned in a direction down the dip of the cleavage and their original attitude to bedding is difficult to discern.

Those that occur in the rocks of the Yealm Formation are better preserved and are both parallel and perpendicular to bedding (ie. tunnels and shafts). Lithologically they are sand filled pipes in clay. The pipes are uniform in diameter (up to a few mm), have a structureless infill and are unbranched. They are therefore thought to be of the *Skolithos* (perpendicular to bedding) and *Planolites* (parallel to bedding) type.

Scour and fill structures

These structures have been recognised in a sequence of siltstones which also contain cyclically graded units on a 2cm scale, and carbonate glaebules. They consist of shallow depressions which are symmetrical in shape and ca. 30cm wide and ca. 5cm deep. The scour bases, as their name suggests, are erosive and cut down into the underlying sediment. The tops are flat and non-gradational. The uppermost sediment layers of the fill are parallel laminated and the contact between the fill and the overlying sediment is sharp. The infill is of orange/red, medium grained sand and the laminations are concordant (Pl. 3.34) and are defined by thin clay layers. The layers of sand between the clay laminations reflect the shape of the scour, are concave upwards and thin laterally, towards the sides of the scour.

The scour structures have only been observed in 2D profiles and so their origin is not certain. However, the depressions and their fill may be regarded as small scale channel features if they are continuous along the axis of the depression (not seen). If this is the case, then the direction of elongation is parallel to the flow and they are several times longer than wide. Thus the profile observed applies to a section perpendicular to flow. This profile is oriented NW-SE and so would indicate a flow to the SW or NE. Alternatively the depressions could be asymmetric in the direction parallel to flow and so may be regarded as much smaller scale structures, with their lengths being marginally greater than the widths. This would not affect the palaeocurrent direction but would imply that a flute scour rather than an elongate groove scour existed.

Under favourable conditions water flowing over unconsolidated silts may scour out shallow depressions such as those described in the latter case above. With a decrease in current velocity (waning flow) the depressions would be back-filled with coarser sediments than the substratum.

3.2.4 Litho-facies and their association

The form and distribution of the lithologies and their sedimentary structures allows them to be incorporated within a series of litho-facies.

a) **Litho-facies A:** Sandstone units and sequences (with individual beds >30cm thick) and sub-ordinate mudrocks. Associated features are basal conglomerates, trough cross laminated sandstone, parallel laminated sandstone, flaser bedded sandstone, cross bedded sandstone, massive sandstone and siltstone.

b) **Litho-facies B:** Interbedded sandstone and mudrock with beds less than 30cm thick.

c) **Litho-facies C:** Claystone and silty claystone

d) **Litho-facies D:** Paraconglomerates

Litho-facies A (Pls 3.35 and 3.36)

In general this litho-facies consists of very fine to fine grained, moderate to well sorted sandstones and siltstones, which are pink to grey in colour. Medium to coarse grained sandstones are rare. Beds occasionally fine upwards and range from ca. 30cm to 2m thick but sandstones of ca. 0.75m thick are most common. Thin mudrock interbeds cause sequences of repeatedly bedded sandstones to have a multi-storey character. The dominant internal structure of the sandstones is trough cross lamination and parallel lamination, ripple drift, cross bedding, lateral accretion surfaces (see Pls 3.35 and 3.37), low angle lamination and flaser bedding are less common. The occurrence of internally massive sandstone may be due to the obliteration of internal sedimentary structures during subsequent deformation. However, a purely sedimentary origin for structureless beds cannot be ruled out. Thin, discontinuous, intraformational, clay-chip conglomerates and other forms of basal conglomerate, sometimes cross bedded, occur at the base or underlie these sandstones. Palaeocurrents are generally uni-directional for any one bed and indicate a southerly directed flow. Solitary bedded sandstones with mudrock sequences are also categorized within this litho-facies. The lithological units of litho-facies A usually grade upwards into rock types attributed to litho-facies B. The sandstones also cut into the fines of litho-facies' B, C and D.

In general the majority of sediments of litho-facies A are often laterally continuous over distances of at least 25m. Beds are relatively thin and uniform in thickness with very

Plate 3.35 Fine grained, multi-storey sandstones (litho-facies A), with lateral accretion surfaces, overlying mudrocks (parallel laminated at base), Renney Rocks Formation; Heybrook Bay [SX 4965 4870]. Looking north.

Plate 3.36 Parallel laminated, fine grained sandstones (litho-facies A) overlying mudrocks in the Renney Rocks Formation; Heybrook Bay [SX 4965 4870].

Plate 3.37 Minor scale lateral accretion surfaces within fine sandstones of the Renney Rocks Formation; Heybrook Bay [SX 4965 4870]. Height of photograph 40cm.

Plate 3.38 Interbedded sequence of sandstone, siltstone and claystone (litho-facies B) overlain by sandstone of litho-facies A, Renney Rocks Formation, Heybrook Bay [SX 4965 4870].

little evidence of channeling. The abundance of cross laminated sand, with only rare cross bedded units, suggests high stage flow with little low stage modification of bedforms. This indicates possible formation within unconfined (sheet) or semi-confined (shallow, broad channels often overflowing thus leading to sheet flow) water bodies. The sediments of litho-facies A are generally thought to represent transport and deposition by bed load in traction currents within an alluvial setting. This is deduced from the presence of calcretes in the mudrock sequences, the contained flora and fauna (Dineley, 1966) and the overall type and lithological variation of the sequences examined. However, sandstone units observed in the Yealm Formation, also belonging to litho-facies A, appear to have a different origin (see Section 3.2.5).

Litho-facies B (Pl. 3.38)

This litho-facies is composed of a complex interbedding (less than 30cm thick) of very fine grained, moderately to poorly sorted sandstones, siltstones and claystones. The sandstones are grey to red and the mudrocks are invariably red. The beds (centimetres to tens of centimetres thick) are arranged in cycles and both fine or coarsen upwards (Figs 3.6 and 3.7). Bases of the sandstone beds are sharp and erosional with low relief (up to 10cm). Lying above some of these contacts are thin conglomerates with clasts up to 20cm across. The clasts match the lithologies beneath and are predominantly intraformational. The bases of some beds are disrupted by soft sediment deformation. The conglomerates also contain plant fragments and fish remains (Dineley, 1966) and reworked calcretes. The tops of the beds may be sharp or gradational into finer units. The sandstones of this facies are trough cross laminated, parallel laminated, wave rippled or massive. The thickness, texture and internal structure of the sandstones changes laterally as they grade into fines by way of interfingering at their margins. The mudrocks are poorly bedded and rarely contain stratification indicative of bedform generation. Burrows occur in the finer fraction and are sand filled.

The more thickly bedded sandstone sequences of this facies may represent thin, laterally extensive sheets (tens of metres) or may fill very broad channels with very low relief. Palaeocurrents from cross lamination indicate uni-directional flow to the SW similar to that of litho-facies A. The components of litho-facies B overlie, and are also overlain by, those of litho-facies A. Litho-facies' A and B together form a facies sequence where litho-facies A grades up into litho-facies B producing a fining up cycle. The more thinly bedded sequences of this litho-facies (eg. the heterolithic sand streaked clays) may represent

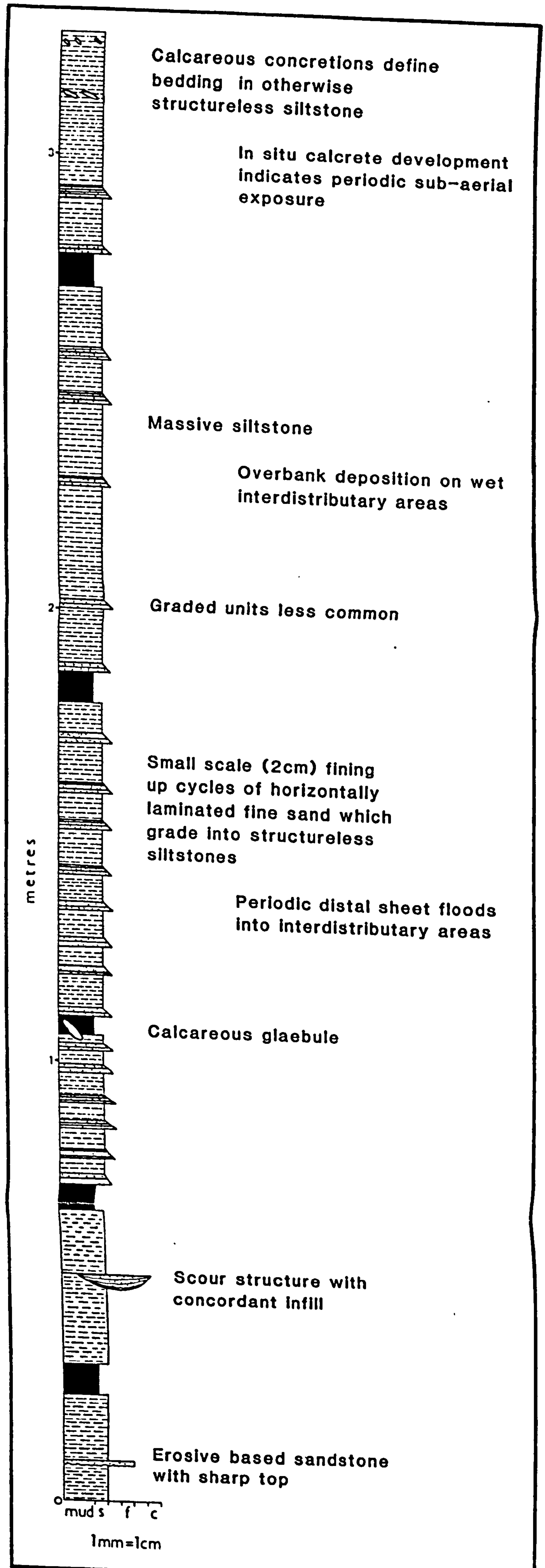

Fig. 3.6 Logged section through the Renney Rocks Formation at Westlake Bay [SX 4925 4920].

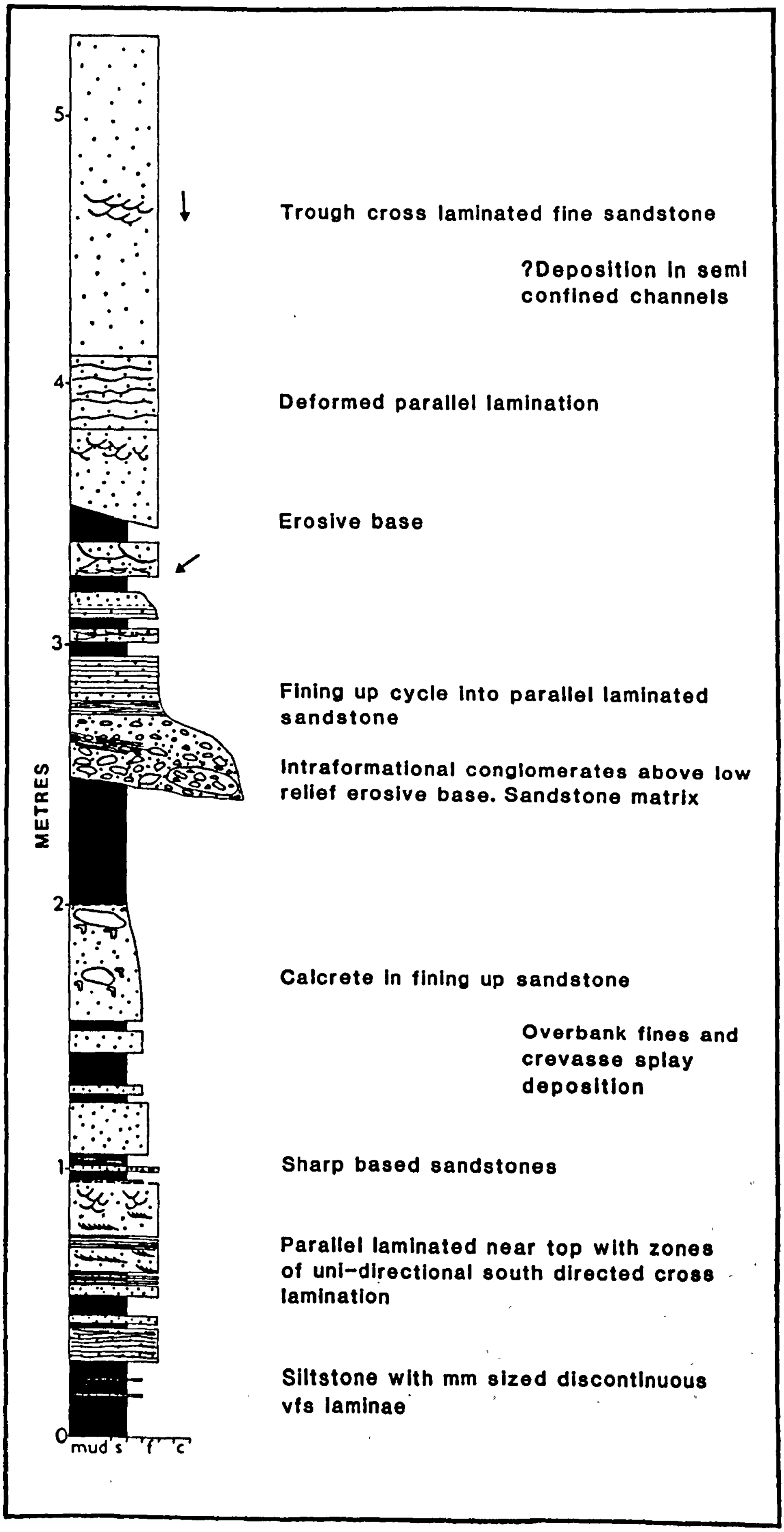

Fig. 3.7 Logged section through the Renney Rocks Formation at Heybrook Bay [SX 4965 4870]. (See Appendix 2 for location).

deposition in areas of standing water.

The presence of calcretes within mudrock sequences described above are indicative of development within a continental setting. Litho-facies B is thought to represent deposition on a floodbasin involving numerous, small scale, high stage flood events represented by the sandstones. The fines indicate a waning of this flow and are derived from suspended sediment. The presence of wave ripples in the sequences of this facies indicates reworking of the sediments in areas of shallower water. Small scale, upwards thickening cycles present in this litho-facies may represent infilling of the ponded areas.

The calcretes represent youthful developments of soil profiles in areas of least active sedimentation. Their lack of maturity reflects the continual relocation of the site of active deposition and water course avulsion. As youthful calcretes may only take hundreds of years to develop (Reeves, 1976) regions of the floodbasin floor were probably isolated from sedimentation for relatively brief periods.

Litho-facies C (Pl. 3.39)

This litho-facies is composed of thick sequences of claystone and silty claystone (described in Section 3.2.1). The sedimentary characteristics imply that formation is by deposition from suspension in areas away from active sedimentation. Solitary sandstones (ca. 1.5m thick) of litho-facies A are interbedded with the muddy sediments and possibly represent sheet flood deposits. Sandstones similar to those described for litho-facies B are also interbedded with this litho-facies. These may represent lateral equivalents to the high water stage conditions, indicated by litho-facies A.

Litho-facies D (Pl. 3.12)

This litho-facies is composed of paraconglomerates with sequences measuring up to 25m thick (see Section 3.2.1). The most likely sub-environment for litho-facies D is an area of ponded water with deposition occurring in the form of sub-aqueous debris flows. The lack of bedding within the deposits may not necessarily be a primary feature as such surfaces could have been obliterated by subsequent deformation. Hence water depths may not be as great as that indicated by a sequence 25m thick. The Yealm Formation contains bedded units of litho-facies D which are up to .5m thick. This gives a minimum value for the prevailing water depth during deposition of the debris flows. Litho-facies D is interbedded with litho-facies A,

Plate 3.39 Thick mudrock sequence comprising litho-facies C, Wembury Formation; Andurn Point, [SX 4920 4975].

B and C.

The sedimentary structures of the four litho-facies described above are similar to those which characterize the Markanda terminal fan in India (Parkash *et al.*, 1983). The relative occurrence of the structures indicate the depositional regime (see Table 3.2).

RARE	COMMON
Scours	Trough cross laminated sand
Flaser bedding	Horizontally bedded sand
Medium grained sand	Massive sand
Calcretes	Fine grained sand
Trough cross bedded sand	Clay or silty clay
Planar cross bedded sand	Paraconglomerates

Table 3.2 The relative occurrence of sedimentary structures observed within the Dartmouth Group rocks of SW Devon.

3.2.5 Facies sequences within the Dartmouth Group

All four litho-facies described in section 3.2.4 are present within the Renney Rocks Formation (Fig. 3.8) and their relationships indicate that they were deposited within intimately related sub-environments. Litho-facies A is dominant (Figs 3.9, 3.10 and 3.11) and is interbedded with litho-facies B, and to a lesser extent, litho-facies C and D. Repeated fining upwards cycles often occur (A-B and occasionally A-B-C) (cf. Allen, 1963b, 1964 and 1965). Sequences A-B and A-B-C represent filling of very broad channels, or sheetflow at high stage, followed by deposition of the overlying fines, from suspension, during waning flow. Towards the top of the Renney Rocks Formation the occurrence of litho-facies' D, and the coarsening up/wave rippled variety of litho-facies B, suggests the existence of areas of ponded water.

The Wembury Formation (Fig. 3.12) is generally characterized by litho-facies C with

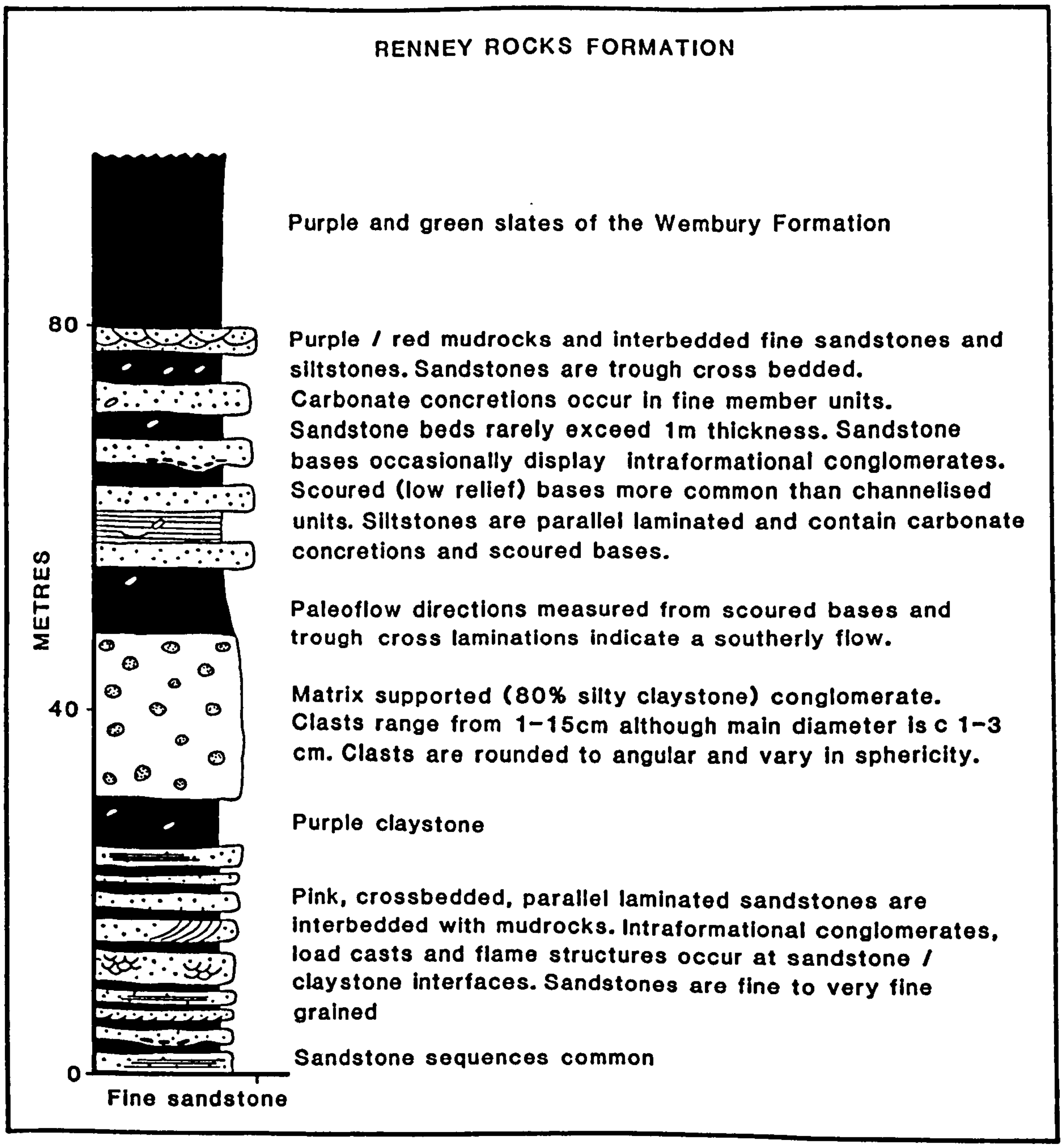

Fig. 3.8 Representative log through the Renney Rocks Formation.

Fig. 3.9 Logged section through the Renney Rocks Formation at Heybrook Bay [SX 4965 4870]. (See Appendix 2 for location).

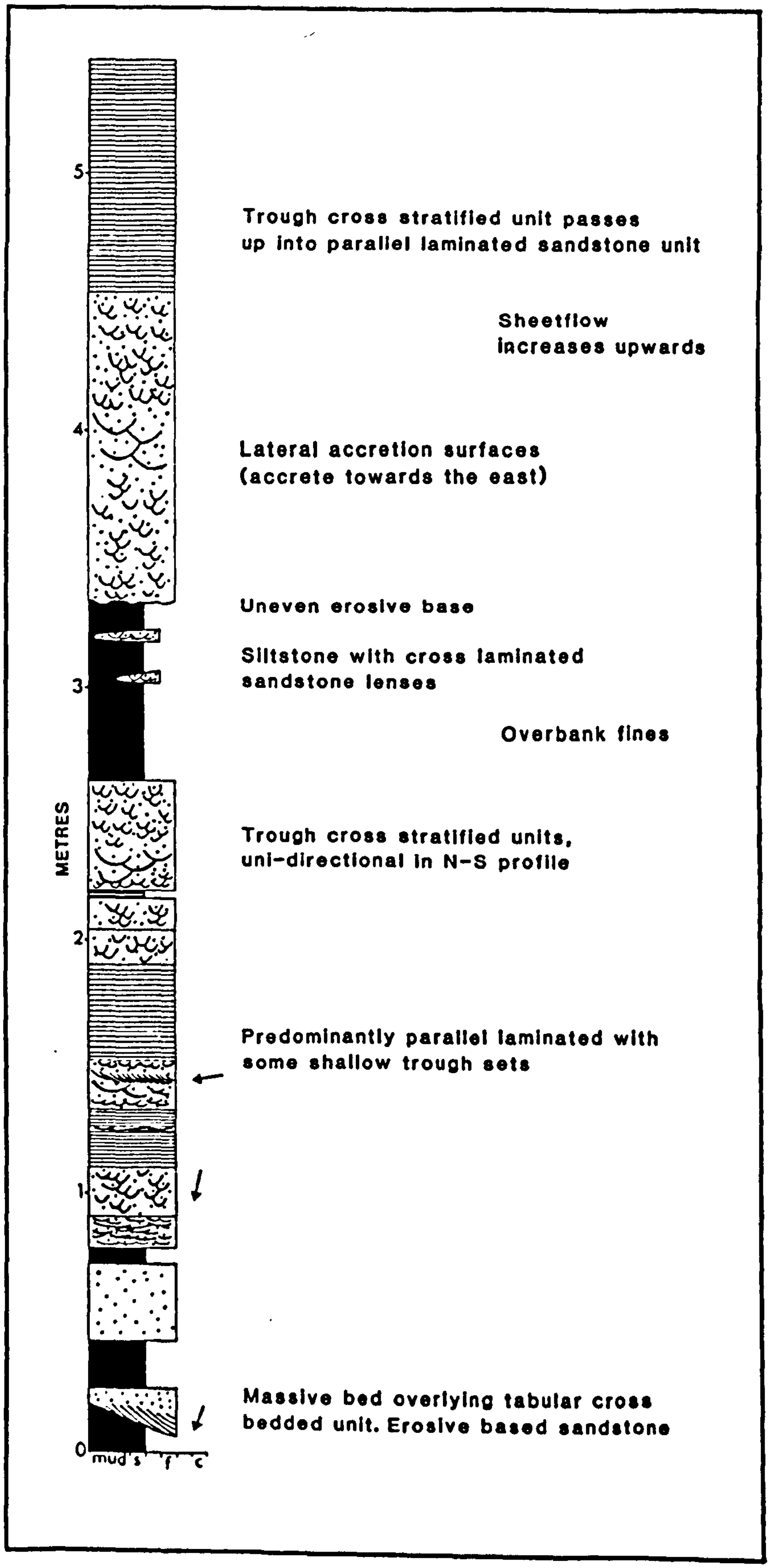

Fig. 3.10 Logged section through the Renney Rocks Formation at Heybrook Bay [SX 4965 4870] (See Appendix 2 for location).

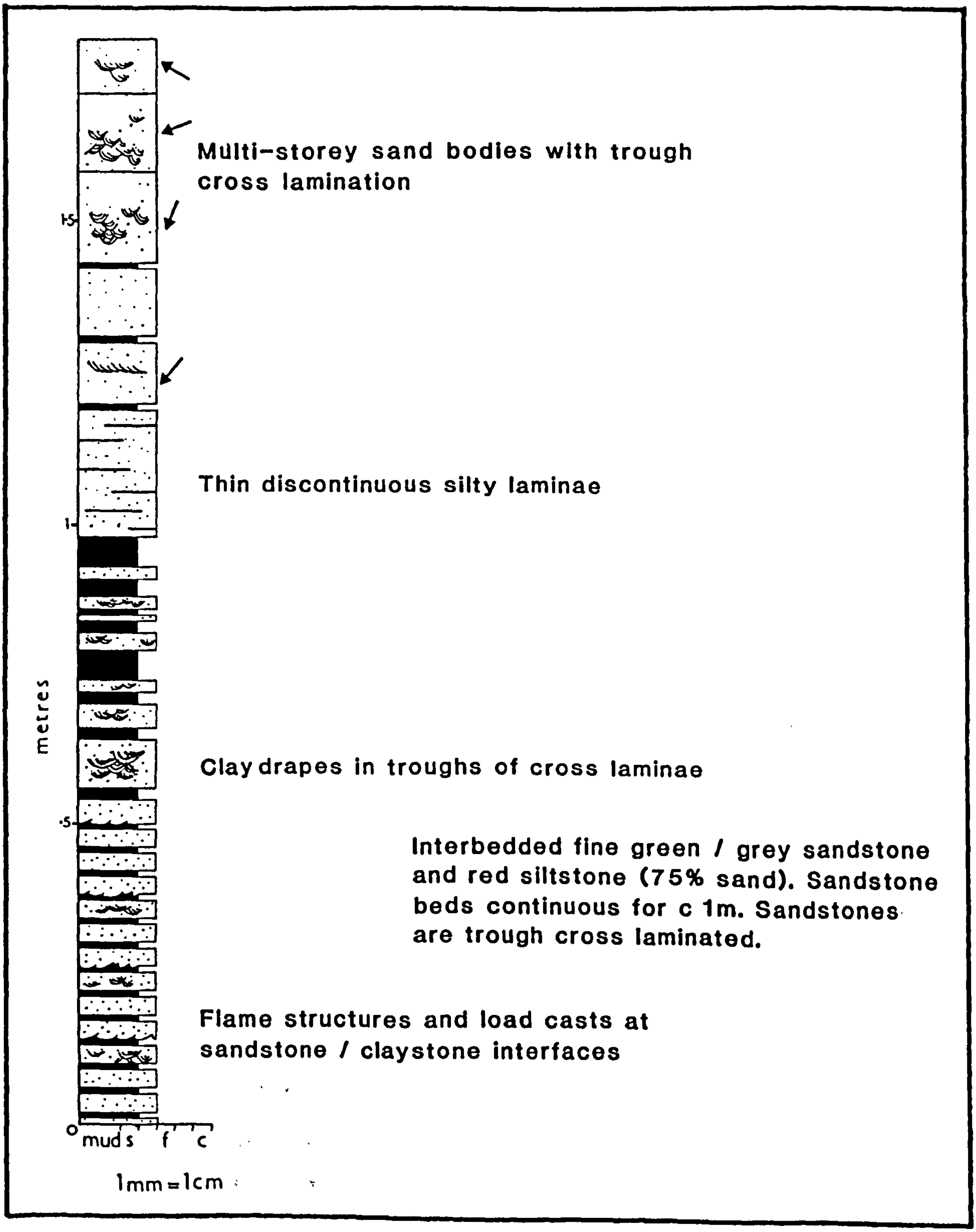

Fig. 3.11 Logged section through the Renney Rocks Formation between Heybrook Bay [SX 4965 4870] and Renney Rocks [SX 4925 4875].

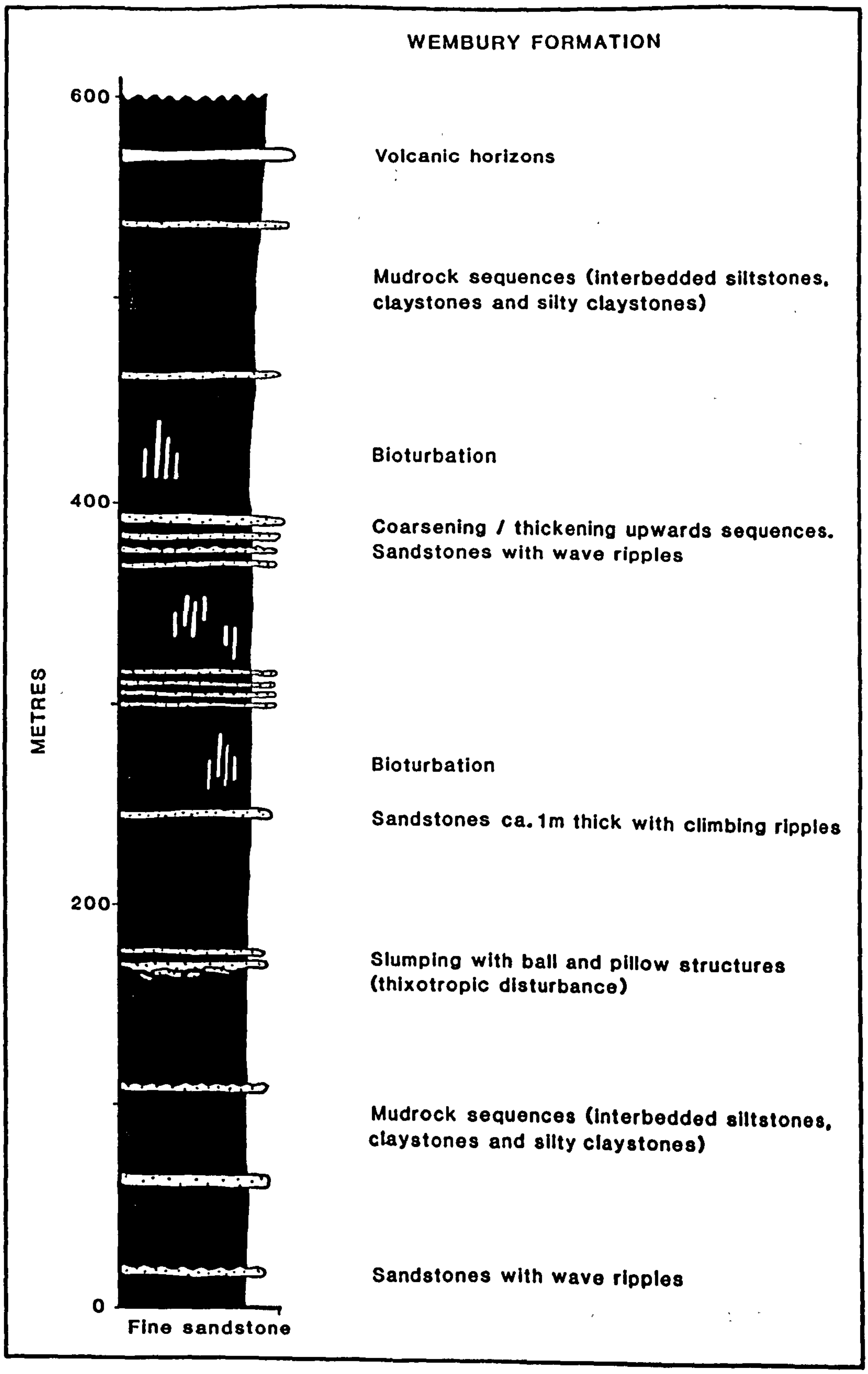

Fig. 3.12 Representative log through the Wembury Formation.

occasional interbedding of litho-facies A and B. Litho-facies A occurs as solitary sandstones (Pl. 3.40) which are up to 1.5m thick and contain ripple drift, cross lamination. The passage from the Renney Rocks Formation to the Wembury Formation is marked by a change from relatively coarse to fine lithologies. This is thought to indicate the transition from a sub-environment involving active sedimentation of sand bodies under, high stage and flow conditions, to a sub-environment dominated by deposition from suspension.

The Yealm Formation (Fig. 3.13) is dominated by litho-facies B, C and D and in addition to the clastic sediments seen elsewhere in the Dartmouth Group there is also a high proportion of volcaniclastics. These are incorporated into all types of litho-facies and changes at the site of deposition appear to be both lithological and environmental. Due to the presence of volcanic material the clays of litho-facies B and C are black and the sands of litho-facies A and B are yellow. The presence of a high proportion of coarsening up short cycles (B-A), slumping, heterolithic units, paraconglomerates of litho-facies D and the lack of calcretes, indicates that deposition may have taken place in standing bodies of water. It is therefore suggested that the Yealm Formation is dominated by sedimentation on a drowned floodplain possibly on the margins of a substantial lake.

The Warren Formation marks a return to active sedimentation on the floodplain within environments similar to those shown by the Wembury and Renney Rocks Formations. Sequences of litho-facies A occur and represent periods of deposition in broad channels in wide silt/fine sand dominated water courses. However, overall the Warren Formation is dominantly argillaceous (Fig. 3.14) with litho-facies B and C representing deposition away from the major sheet floods. Litho-facies D is absent from the Warren Formation.

3.2.6 Depositional model for the Dartmouth Group

The sediments of the Dartmouth Group are generally fine grained and represent both bedload and suspended load deposits. The clays and finest silts can be regarded as suspended load deposits whilst the sand and silt, which are generally deposited within sheetflows by traction currents, may be regarded as bedload. The described sedimentary sequences suggest that low relief bars and wide sheet floods dominate the depositional environment and they show little variation in sediment type. The coarse facies (mainly fine sandstone) forms in low sinuosity shallow, wide water courses. These sediment bodies are characterized by trough cross lamination, parallel lamination and massive, fine sandstone. It is assumed that although the sediment is very fine it is still deposited, to a large extent, by traction currents.

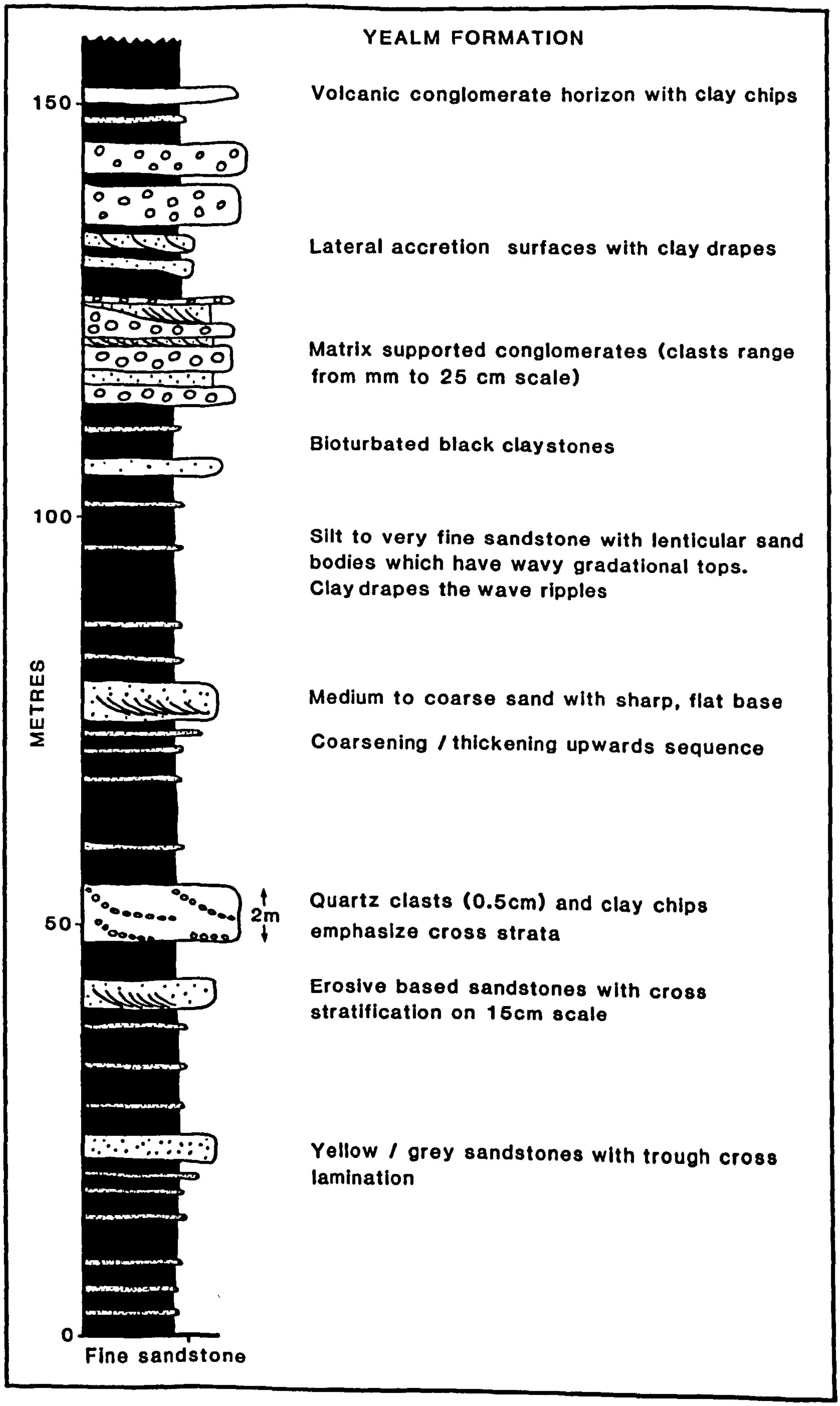

Fig. 3.13 Representative log through the Yealm Formation.

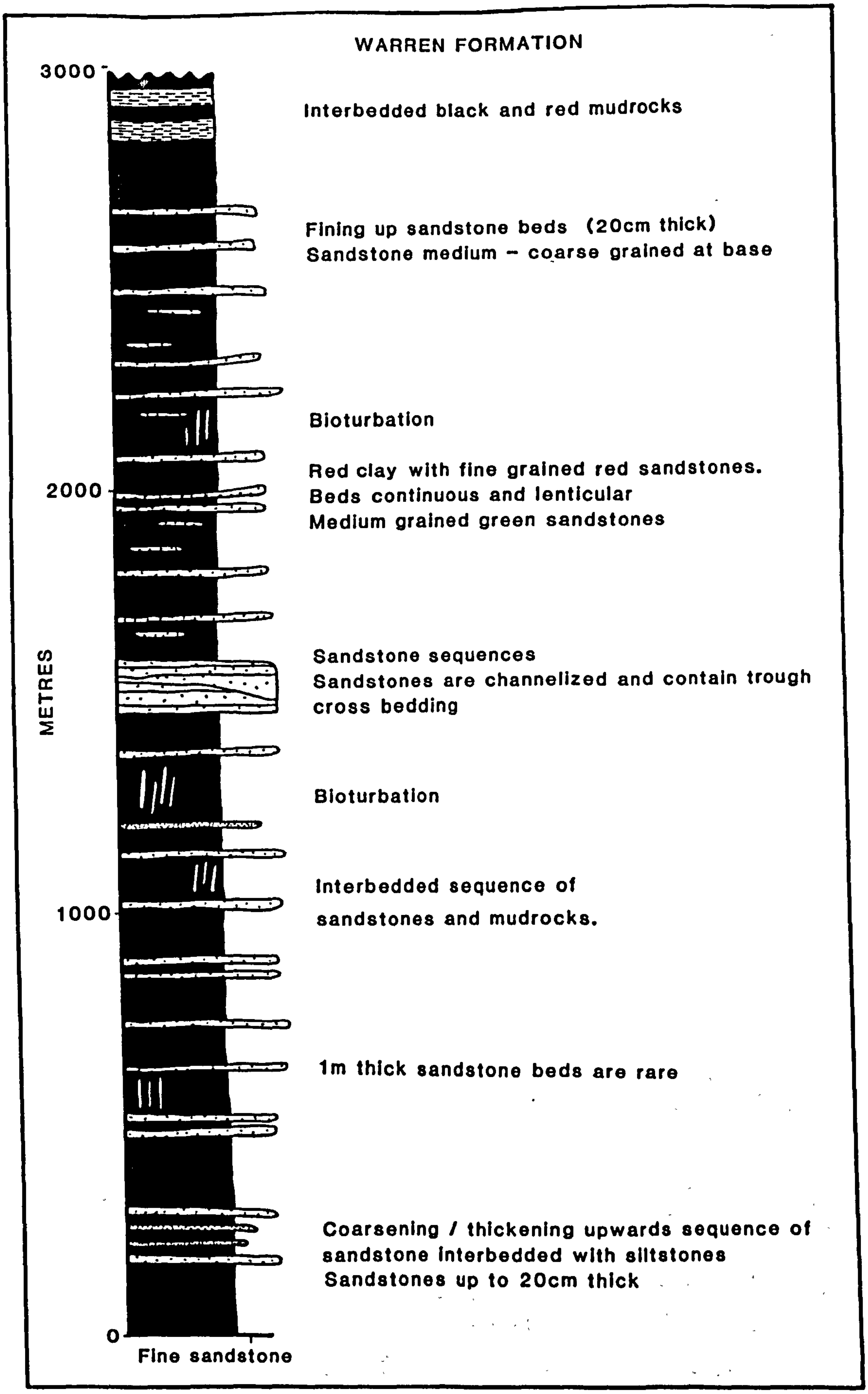

Fig. 3.14 Representative log through the Warren Formation.

Plate 3.40 Solitary sandstone bed within a claystone sequence of the Wembury Formation; Andurn Point [SX 4920 4965].

Plate 3.41 Black to grey claystones (slate) with thin sandstones of the Bovisand Formation; Thurlestone [SX 6745 4195]. Looking west. Hand held tape measure for scale (6cm wide).

Sedimentation seems to have taken place by vertical accretion on a floodplain rather than lateral accretion on point bars of a meandering stream system. This is indicated by the lack of epsilon, cross stratification and the rare occurrence of steep sided channels. Aeolian reworking, mud cracks and evaporites are not detected suggesting that much of the region was under water for considerable lengths of time. This is also indicated by the sparse occurrence of calcretes, the presence of thixotropic disturbance (soft sediment deformation), which occurs at times of water saturation, the presence of thick mudrock sequences and the presence of sub-aqueous, debris flows.

On the whole the features of the major part of the Dartmouth Group, described within this chapter, fit a silt/fine sand dominated, distal alluvial system (cf. Tunbridge, 1981, 1984 and 1986) set in an arid/semi-arid region. The fine grained nature of the sediments, to the exclusion of coarse, sheet flood sands, may be regarded as a distinctive character of distal, silty, floodplain systems (cf. Miall, 1977; Rust, 1978). The term floodplain is used here to encompass the sub-environments present in the mature reaches of river systems, occurring on extensive alluvial plains, in the distal part of an alluvial fan rather than overbank facies seen today in meandering river belts where vegetation is an important controlling factor. During deposition of the Dartmouth Group the lack of vegetation produced an unstable setting in which reworking of previously deposited sediment was not restricted. Without the presence of vegetation, flood events would have been much more frequent. Thus extensive plains could be constructed in contrast to the present day meandering systems. The presence of a high proportion of clay material would render any unconsolidated material very mobile when wet, a condition envisaged for much of the time (see also Hill, 1989). The presence of any break of slope, steep or gentle, short periods of rain or influx of flood water and lack of vegetation are all conditions which could lead to debris flow deposition. In the Dartmouth Group the debris flows are thought to form in areas of ponded water (cf. Smith & Humphreys, 1989, 1991) which may only exist for short periods of time before being infilled by subsequent sedimentation. However, the presence of sub-aqueous debris flow deposits within the Renney Rocks Formation, associated with sheet flood sands, is an anomalous feature which is not fully understood. The occurrence of the debris flows in the Yealm Formation, where they occur with other sub-aqueous deposits, is a more acceptable association.

The inferred distal fan region usually comprises the toe end of an alluvial fan complex and is characterized by gentle slopes, fine sediments and lack of well defined channels (Friend, 1978). In general they comprise the most extensive alluvial deposits, occupying large areas in the lower reaches of fluvial systems and produce extremely thick sequences, often attaining several 1000's of metres (Friend, *op. cit.*). In the type of environment proposed the sequences develop under very high subsidence rates and the 3.5km (approximate) sediment thickness of the Dartmouth Group has accummulated in less than 7my (see below).

The thickness and rate of accumulation of the sediments of the Dartmouth Group can be compared to those of terminal fan regions (see Friend, 1978, table 1 p. 534). The accumulation rate is an estimate as the total time span of the Dartmouth Group is not known. Sediment compaction and the use of structural, rather than stratigraphic thicknesses also cause inconsistencies. However, it is estimated that the Dartmouth Group sediments accummulated over 5 million years, within the Siegenian stage (401 to 394 Ma), of the Lower Devonian. Due to the base of the Dartmouth Group not being exposed the thickness is a minimum. Thus with a period of deposition lasting 5 million years and a sedimentary thickness of 3650m the accumulation rate is 0.73m/1000 years. This is consistent with the values obtained by Friend (1978).

The proposed distal, flood basin results from the drainage of an alluvial, flood basin present at the time to the north of the region (South Wales) (Bluck *et al.*, 1988). This is supported by a SSW directed palaeoflow in the Dartmouth Group. It is envisaged that this alluvial plain had a general palaeoslope direction to the south on the scale of $10^2 km^2$. The scale of alluvial fans may be small ($10^{-1} km^2$) (Parkash *et al.*, 1983) with high gradients or much larger ($10^4 km^2$) with low gradients (Friend, 1987). The alluvial plain in SW Devon may have been linked to a more proximal system in the unexposed ground between SW England and South Wales. Unfortunately Devonian rocks of an equivalent age are not exposed in the area between South Devon and South Wales and therefore an examination of the flood basin from the distal reaches to its source area is not possible. The distal fan described cannot be linked to the source area in terms of petrography as the sediments are essentially intraformational, mature and fine grained. Thus, provenance is deduced from palaeoflow measurements alone.

Rapidly subsiding tectonic basins (possibly extensional half graben systems) are necessary to initiate deposition of the Dartmouth Group as well as preserve the very thick distal fan body. However, the existence of structures of this nature have not been observed. This may be due to the subsequent Variscan deformation affecting the area. However, the presence of debris flows within the Renney Rocks Formation may indicate minor faulting in the distal alluvial setting. The lack of coarse sand deposits indicates that any fault generated depressions would have to be rapidly filled by the paraconglomerates before coarse sediments were able to be generated.

Distal fan deposits usually grade laterally into upper deltaic plains, coastal sands and tidal flat sediments, eventually arising in a shallow marine sequence. In the case of the Dartmouth Group the fluvial sequence passes up into shallow shelf muds with storm deposits of the Meadfoot Group, the transition of which occurs at the top of the Warren Formation.

3.3 SEDIMENTOLOGY OF THE MEADFOOT GROUP

Stratigraphically above the continental facies of the Dartmouth Group are the rocks of the Meadfoot Group. These are composed of the Bovisand and the Staddon Grit Formations. This section, although containing descriptions of the formations, pays particular attention to the sedimentology of the boundary conditions.

3.3.1 Bovisand Formation

In general the Bovisand Formation is dominated by black/grey claystones (Pls 3.41 and 3.42). However, throughout, and especially within the upper parts of the formation, there are a number of yellowish coloured sandstone bodies and sequences. Pale green/grey calcareous, tuff beds are also present (see Pl. 3.43).

A number of sandstone sequences crop out in the Bovisand/Crownhill Bay area (see Fig. 2.3) where the colour of the rocks is strikingly different to the adjacent red mudrocks and sandstones of the Staddon Grit Formation. The base of a 4.5m sequence (see Fig. 2.5), at the top of the Bovisand Formation, is characterized by claystones and sub-ordinate sandstones. The sandstones are commonly ca. 2cm thick although they may attain thicknesses of up to 10cm. They are both cross bedded and massive. Some cross bedded units are overlain by parallel laminated sand whilst units higher in the sequence grade upwards from silty clay to fine sand. The clay dominated part of the sequence is overlain by a series of fine sandstones, occasionally parted by clay, which are either cross bedded, parallel laminated or massive. Above this, claystones overlie the sandstones thus marking the end of a short coarsening up/thickening up cycle of ca. 2m in thickness. The cycle is then repeated and is capped by fine grained sandstones of ca. 1.5m thickness. The sandstones contain interbeds of silt and pass upwards into sandstones which are multi-storey in character with clay partings. These are mainly massive, although some are parallel or cross laminated. Scour features and low relief channeling occurs at the base of some of these sandstone units. The multi-storey sandstones pass upwards into clay dominated sediments at the top of the logged

Plate 3.42 Close up of Pl. 3.42. Tape measure (6cm wide) for scale.

Plate 3.43 Intercalated black claystone and tuffs of the Meadfoot Group (Bovisand Formation); Bigbury Bay [SX 6600 4330].

sequence. Palaeocurrent analysis of the sedimentary structures indicates a southward flow (towards 161°).

3.3.2 Staddon Grit Formation

The following descriptions apply to the sequences in the Crownhill/Bovisand Bay area, on the east side of Plymouth Sound (see Pls 3.44, 3.45 and 3.46). Here the transition between the Bovisand and Staddon Grit Formations is exposed and three logged sections show similar features. It is possible to evaluate the vertical stacking of these sequences, but their lateral extent is difficult to ascertain due to folding, faulting and the limited coastal exposure.

The deposits are cyclic and range from 4 to 6m in thickness (Figs 3.15 and 3.16). At the base of each cycle (see Table 3.3) red claystones overlie limestone beds of an underlying sedimentary cycle. The claystone (Pl. 3.47) grades upwards into silty claystone containing lensoid bodies of silt or very fine sand (Pl. 3.48). These usually measure ca. 3cm (wavelength) x 1cm (amplitude). They are flat based and wavy topped, having a symmetrical form, and their internal lamination is uni-directional, describing a palaeocurrent direction to the SW. Lenses become more laterally continuous up the sequence (Pl. 3.49) and eventually coalesce to form continuous thin beds (ca. 5-10cm thick) (Pl. 3.50). These beds display a bi-directional internal lamination which indicates reworking by oscillating currents. These symmetrical ripples trend NW-SE and indicate water body movement to the NE and SW. The sandstone beds thicken up sequence to ca. 10-20cm and become medium grained (Pl. 3.51). They are classed as quartz arenites and contain accessory tourmaline, feldspar (plagioclase and potassium), muscovite mica, zircon and muddy lithic fragments. Silts and occasional clastic limestones are interbedded with the sandstones at this level in the sequence. Intraformational clay-chip conglomerates (Pl. 3.52) occur at the bases of some of these beds. The clay chips are derived from thin clay horizons which occur between the thickly bedded units. The limestone beds are cross bedded (Pl. 3.53) unlike other thicker, coarser and more massive limestone units capping the sequence (Pl. 3.54). These uppermost limestones are characterized by an abundance of marine fossil debris including broken crinoids, brachiopods, bryozoans and corals.

UNIT	LITHO-FACIES	THICKNESS
7	Claystone	-
6	Interbedded fine-medium sandstone and clastic/bioclastic limestone which may be cross bedded or massive. Intraformational conglomerates are present. Cross bedding indicates flow to the SW (217°). Beds are up to 40cm thick.	>1m
5	Interbedded fine sandstone and siltstone (beds up to 20cm thick). Sand:silt ratio is 75:25. Beds contain ripple lamination indicating flow to the WSW (254°). Flaser bedding is sometimes present.	0.7m
4	Interbedded fine sandstone and siltstone (beds ca. 5cm thick). Sand:silt ratio is 50:50. Beds are ripple laminated.	0.6m
3	Ripple laminated, fine sandstone with silty claystone laminae. Sandstone bodies up to 2.5cm thick and become discontinuous upwards. Bed tops are wavy and bases are flat. Palaeocurrents are bi-directional (towards 024° and 204°) although the majority have a southward flow.	0.3m
2	Siltstone with ripple lenses of very fine sandstone (<30% sand). Many of the sand lenses have no visible internal stratification. However those that do, indicate uni-directional flow to the SW (200° to 205°), and the ripple crests trend (110° to 115°).	2m
1	Claystone (structureless)	>0.5m

Table 3.3 Lithological units present in the cyclic deposits at the base of the Staddon Grit Formation, Crownhill Bay. These distinctive units are gradational but in general a change in bedding and rock type occurs over several cms. Units may be absent or thicknesses may vary but the cycles do not exceed 6m. Some sequences are dominated by the upper units, whilst others are uniform in their distribution of units.

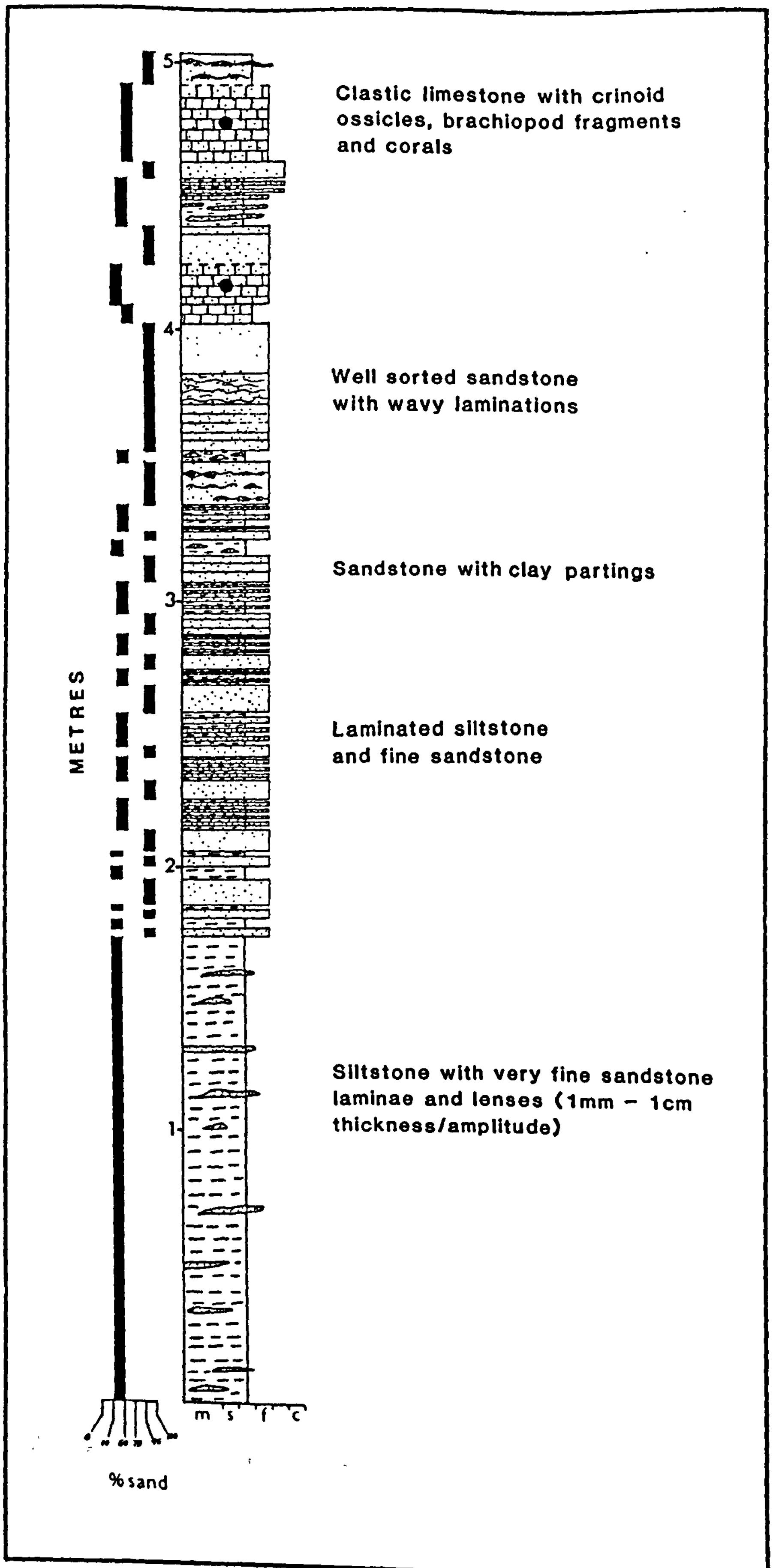

Fig. 3.15 Logged section through the Staddon Grit Formation at Crownhill Bay [SX 4925 4980].

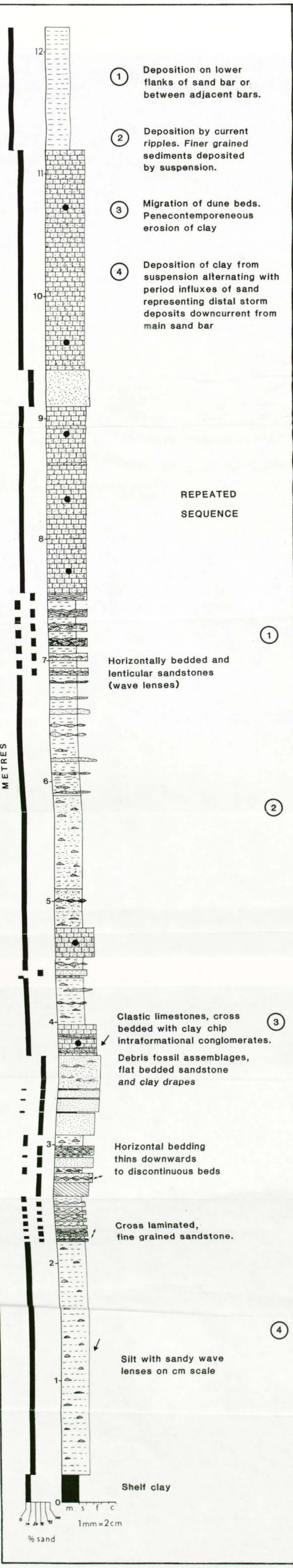

Fig. 3.16 Logged section through the Staddon Grit Formation at Crownhill Bay [SX 4925 4980]. (see Appendix 2 for location).

Plate 3.44 Lower part of the Staddon Grit Formation exposed at Crownhill Bay, [SX 4925 4980] Sandy Cove to right and Dartmouth Group rocks of Andurn Point in foreground. Looking north east.

Plate 3.45 Typical clastic sequence within the Staddon Grit Formation of Sandy Cove; Crownhill Bay [SX 4925 4980]. Younging direction to the left. Sequence coarsens and thickens upwards and is capped by clastic limestones.

Plate 3.46 A typical clastic sequence of the Staddon Grit Formation similar in character to that shown in Pl. 3.46; Crownhill Bay [SX 4925 4980].

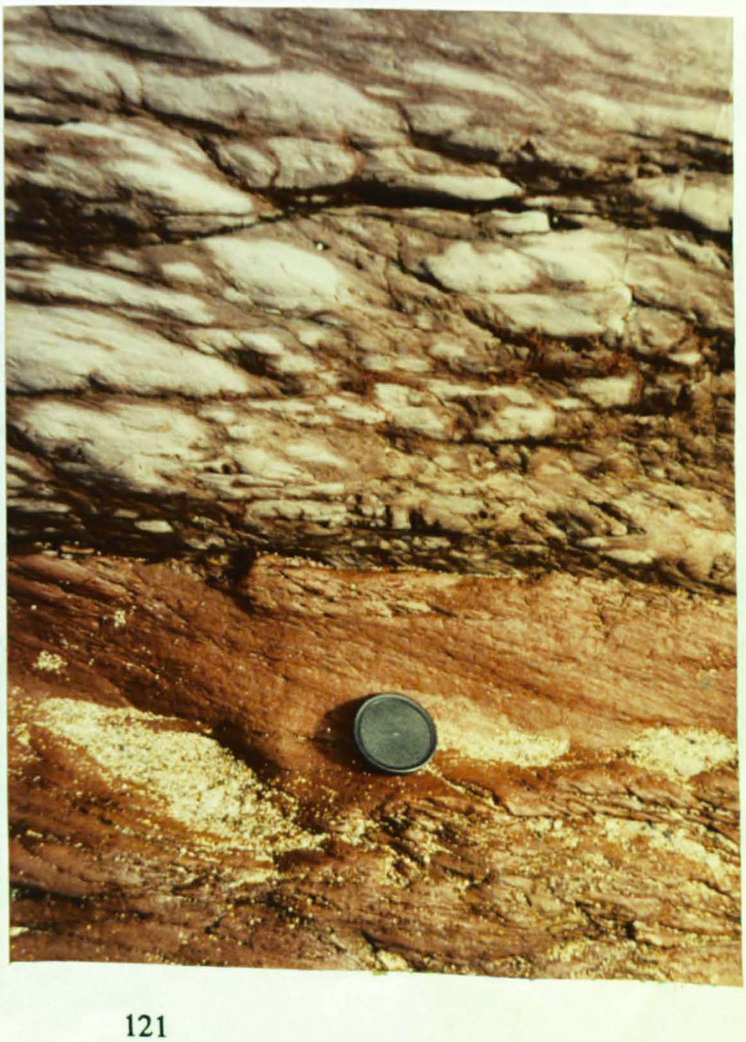

Plate 3.47 Claystones at the base of the sedimentary cycle shown in Pl. 3.47; Crownhill Bay [SX 4925 4980].

Plate 3.48 Silty claystone with lensoid bodies of silt and very fine sand.

Plate 3.49 Thinly bedded very fine sandstone with bi-directional internal stratification interbedded with silty claystone.

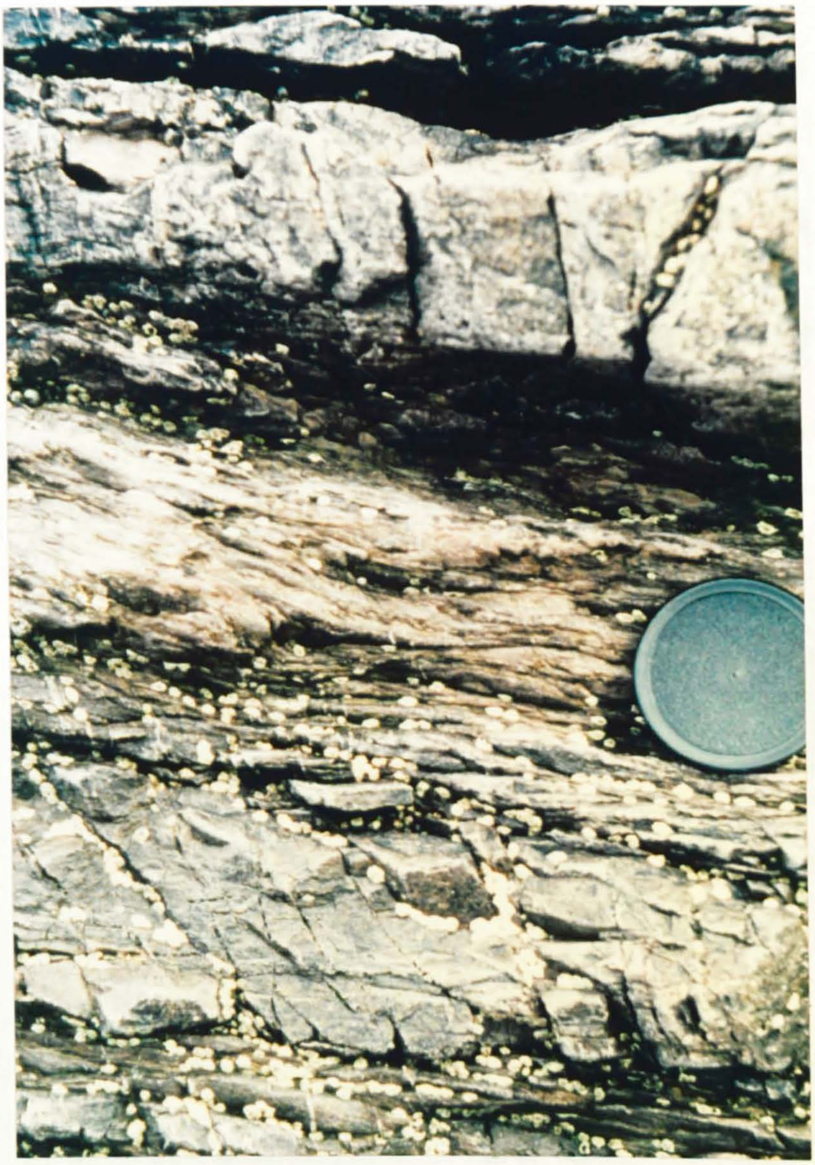

Plate 3.50 Sandstones, bedded on 5-10cm scale, interbedded with thinly bedded fine sandstone and silty claystone.

Plate 3.51 Thickly bedded (10-20cm) medium grained sandstone with silty claystone partings.

Plate 3.52 Clastic limestone containing intraformational rip up clasts of clay.

Plate 3.53 Cross bedded clastic limestones at the top of the sequence shown in Pl. 3.47.

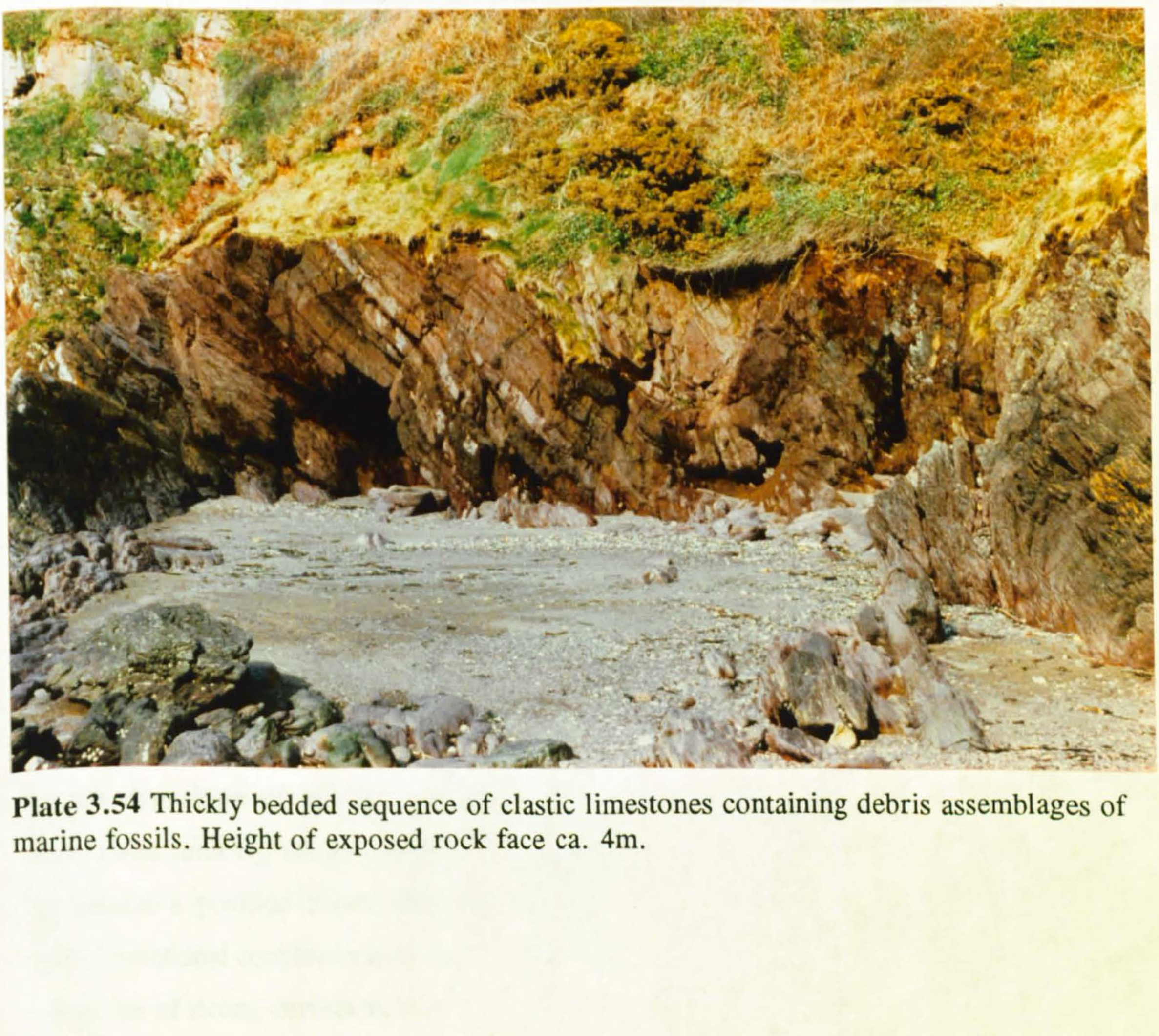

Plate 3.54 Thickly bedded sequence of clastic limestones containing debris assemblages of marine fossils. Height of exposed rock face ca. 4m.

3.3.3 Depositional model for the Meadfoot Group

The sediments and facies of the Meadfoot Group indicate that there is a marked increase in current activity from its base to its top over a thickness of ca. 1000m. Relatively quiet conditions, which led to deposition of mainly clay from suspension (Bovisand Formation), were superceded by a regime of highly agitated waters leading to the initiation of bedforms and transportation of fossil debris under shallower water conditions (Staddon Grit Formation). This is also reflected on a smaller scale within the sedimentary cycles exposed at Crownhill Bay at the boundary between the Bovisand and Staddon Grit Formations. The cycles thicken and coarsen upwards, from being unbedded at the base to thinly bedded, and thickly bedded at the top. Deposition during active movement of some form of sand body over undisturbed bottom sediments is inferred. These sequences are indicative of a prograding (or migrating) body (bar form) of coarser clastic sediment over a muddy substrate by currents of increasing competence and flow regime.

Deposition of each cycle began with the accumulation of muddy sediment from sediment clouds (units 1 & 7, in Table 3.3). These probably represent a much greater time span when compared with the time it takes for the coarser deposits of the top of the cycle to accumulate. Following clay deposition active sedimentation, by traction currents, began with the deposition of fine sand by intermittent, low flow regime currents forming ripple lenses on a silty substrate (unit 2). The uni-directional nature of the palaeocurrents, in this unit, reflect the position on the shelf and the sedimentological processes taking place. These principally involve offshore directed sedimentation and may be ascribed to distal storm events (cf. Spearing, 1976). Due to their uni-directional nature they are considered to form below mean fairweather wave base. Units 3 and 4 represent the deposition of larger amounts of sand, still under low flow regime currents, but later by stronger currents which deposit cross bedded sands (unit 5). Still stronger currents followed with decreasing water depth resulting in the deposition of bioclastic limestones (cross bedded or massive) and cross bedded sandstones (unit 6), on the bar top. This increased rate of sedimentation, and flow regime represents a position above mean fairweather wave base, and initiated the formation of intraformational conglomerates. The latter are erosive in nature and also occur in unit 6. The cessation of strong current activity is shown by the presence of the overlying claystone (unit 7) indicating the return to quiescent conditions (fairweather period). Pulses of more active sedimentation are shown by repetition of the cycle.

The overall nature of the sequence implies that shallowing, but not necessarily emergence, and accompanied migration (progradation), occurred before a return to a relatively deeper environment. On the basis of directional measurements, from cross laminae and ripple crests, the mean direction of transport appears to be to the SW. However, insufficient data make palaeoflow analysis unreliable. Deposition in an offshore bar setting, probably located in an offshore transition zone is inferred (cf. Reading, 1986 p. 157). The succession indicates progradation and deposition by increasing flow regime currents. The sand bars probably rework sediment derived from another source such as a delta or shoreline front. On a much larger scale the Staddon Grit Formation also coarsens upwards. This possibly indicates a much closer proximity to the prevailing shoreline.

The bar forms described here may reflect a southward progradation of the overlying deltaic sequence represented by the main body of the Staddon Grit Formation (Pound, 1984). In this case they would represent mouth bars deposited at the point of emergence of a deltaic distributary into the open marine environment. Alternatively, the base of the Staddon Grit Formation could represent an offshore bar setting with a river system reworking the alluvial plain deposits represented by the Dartmouth Group (Selwood & Durrance, 1982). Burton & Tanner (1986) describe a prolific fauna of filter feeders and therefore favour an offshore bar setting in preference to a deltaic environment for the Staddon Grit Formation. However, it is noted that there is an absence of an *in situ* fauna in the main body of the Staddon Grit Formation (Evans, 1980; Pound, 1984) but its presence at lower levels in muddier facies indicates a sub-tidal regime. In this study the filter feeders are invariably found in debris assemblages and do not occur in living position. Their presence therefore does not define environmental conditions, except one of an erosive nature, and thus does not negate the ideas of Pound (*op. cit.*). Palaeocurrents are uniform throughout the Staddon Grit Formation (Pound, *op. cit.*), a feature which is consistent with a sequence passing upwards from mouth bars into a prograding deltaic complex. The uni-directional measurements of flow suggest an orthogonal relationship with the coastline, which would therefore trend NW-SE. Offshore bars usually move parallel to the coast and thus palaeocurrents would also trend NW-SE. The fact that palaeocurrents throughout the Staddon Grit Formation are consistently directed to the south or south west therefore tends to support the argument for a deltaic environment. A model involving mouth bars or offshore bars on the seaward side of the delta is therefore preferred. The Beeson Grits (Ussher, 1907), occur within similar sequences in the south of the area, and probably represent offshore bar sequences which received their detrital material from the deltaic input further to the north.

The southwards regressive pulse, represented by the Staddon Grits Formation, which interrupts the major northwards transgression across the area, may be induced by local movements on extensional fault blocks. If such fault blocks are present they may also explain the development of localised carbonate build ups such as the Plymouth Limestone during the Middle and Upper Devonian. The initiation of the Bretonic contractional phase of deformation may be responsible for inversion (re-activation) of these suggested local fault blocks thus allowing 'rise facies' to form.

3.4 KEY POINTS

1. The most common lithologies of the Dartmouth Group are mudrocks. Less common are sandstones, which are predominantly fine grained, and conglomerates.
2. The general form of the sand bodies is one of limited thickness with low relief bases and variable lateral extent. Transport by semi or unconfined flow is envisaged.
3. The presence of calcretes indicate periodic drying within the sediments of the Renney Rocks Formation.
4. Debris flow conglomerates are deposited in temporary ponded areas within the Renney Rocks Formation whilst in the Yealm Formation they are deposited in more substantial lakes. Their presence may also reflect local fault movements.
5. Wave ripples, slump folds and CU/TU cycles in some sandstones of the Yealm Formation indicate the presence of ponded/standing water (lakes).
6. The palaeocurrent data, usually measured in trough cross laminated sandstones, indicates flow in a southerly direction throughout much of the Dartmouth Group.
7. The presence of air fall volcanics, reworked as volcaniclastics, and the lack of flow deposits indicates that the volcanic source was not local.
8. Deposition on a distal alluvial fan is envisaged for the sediments of the Dartmouth Group and this may be a southward extension of the alluvial flood basin conditions observed in the Old Red Sandstone of South Wales. The lack of aeolian reworking and limited calcrete development indicates that the fan area was often wet. The presence of debris flows etc. in the Yealm Formation indicates lateral migration of the lake deposits over the alluvial plain.
9. The Bovisand Formation comprising the lower part of the Meadfoot Group is represented by black mudrocks deposited on a marine shelf.
10. CU/TU sequences occur in the upper part of the Bovisand Formation and lower part of the Staddon Grit Formation and grade from claystone bases, through lensoid and

thinly bedded sandstones, to more thickly bedded sandstone and reworked limestone tops.

11. The CU/TU sequences represent deposition in mouth/offshore bars which are related to the southward deltaic progradation represented by the sediments of the Staddon Grit Formation.