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THE GEOMORPHOLOGICAL DEVELOPMENT OF EPHEMERAL AND RELICT RIVER VALLEY SYSTEMS IN THE NORTH PART OF THE IRAQI WESTERN DESERT

By

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Abstract

This research project provides a geomorphological and geological analysis of ephemeral and relict river valley systems in the north part of the Iraqi Western Desert. The area surveyed covers approximately 30 000 km^2 and is one of the remotest and least studied parts of the Arabian Peninsula. Part of the reason for the lack of research in this area in recent years has been the ongoing security problems and all fieldwork undertaken for this thesis was carried out with the support of armed guards and police. In addition much of the work on the geology and geomorphology of the region is in confidential files commissioned by oil companies, and in MSc and PhD theses held in Iraqi Universities. A significant part of this work and indeed many scientific papers, are only available in Arabic. Therefore a major element of the work for this thesis has been to translate this material and make the results available in English for the first time.

The study demonstrates that the present surface of the Iraqi Western Desert overall forms an incised plateau developed during two phases of continental erosion and deposition during the Tertiary and Quaternary periods. The first phase started after Oligocene uplift formed an older plateau within the Oligocene Tayarat formation. This plateau is characterized by denudation processes associated with a semiarid climate, including the formation of

subsurface hollows and caves. The second phase, which began after the last Alpine Orogenic movement, and includes the Pliocene and Quaternary periods, formed a younger plateau developed on the Zahra formation. This younger plateau is characterized by processes indicative of climatic fluctuations from wet to arid and semiarid, which induced denudation in places and deposition in others. However, in terms of the geomorphological landforms present in the Western Desert they can be broadly divided into:

i) Structural and erosion-denudation forms

ii) Accumulation forms

Lithology landform in these two categories has resulted in the production of a new geomorphological map of the Iraqi Western Desert. A key component of this map uses the drainage networks. Four distinct drainage systems were identified:

1. The valleys which descend from west to east. These valley systems are located to the south and south east town of Rutba

2. The valleys which descend from south to north. These lie to the west and southwest of Rutba and are controlled by the north to south strike of exposed Palaeogene strata.

3. The valleys which descend from east south to north west, located north of the Garaa area like Ratga and Akash.

4. The valleys which descend from east to west. These valley systems are located to the south and south west town of Rutba, like Swab and Wallaj valleys.

Investigation of these four networks established that they were relict systems that still carried ephemerally active misfit rivers and stream. The overall control on their form was the alternating sequences of variable strength rocks that were exposed and eroded as part of the uplift of an anticlinorium (Houran) and anticline (Garaa), associated with the Alpine Orogeny .However, the unclearing Structures were much older and can be traced back to Permian tectonic processes. The drainage of the Western Desert, therefore, is antecedent and controlled by Tertiary and Quaternary tectonics. The rivers appear to have active throughout the Pleistocene incising into the Western Desert plateaux. Highest incision rates probably occurred during more pluvial periods in the Pleistocene which may have been coincident with glacial marine in the Northern Hemisphere. The contemporary rivers are misfit within larger valleys although still subject to flash floods under the right metrological condition

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My friends in the Department of Geography and also say thanks to all Dr Habeb Mohammad Farhan Head of college of Art, Dr Abeed Salah Fayad Al diliamy Head of Centre Desert Studies, University of Al anbar; Dr Khalaf Husseean Ali Al diliamy, Head of Education College, University of Al Anbar and Dr Meshaal, Mahmoud Fayad Al Jumaili, Department of Geography, Women Education College, University of Al Anbar; Mr Baligh Hamdi, Director of the General Manager of State Company of Geological Survey and Mining. I would also like to thank the state company of the Geological Survey and Mining, Ministry of Industry and Minerals for access to their library and documentation. I would also like to express my gratitude to all my friends and colleagues in Plymouth University, particularly the School of Geography, Earth and Environmental Sciences for the support they have given me since arriving of the University and especially: Mohammad Chand and Faiz Tahssen Fadial, Donella Bone, Susan Carkett; and Sally Greenwood. I would also like to extend my thanks to the laboratory technicians in the GIS and Maps unit for their help in offering me the resources in running the program Arc GIS especially Shann Lewin and John Abraham. I also thank NASA for the use of their imagery. Finally, Special thanks should be given to my brothers and sisters and all friends for their support and encouragement throughout my study in the Iraqi Western Desert.

Dedication

I dedicated this thesis to My Mother and Father whose memory will never leave my mind and his presence is still sensible in every single second for me; my sisters and brothers and their families;my cherished wife Um Hams who always has accompanied me in every stage of this thesis; and my daughters Hams and Saffa

Waleed

2015

Author's declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee.This project was financed with the aid of a scholarship from the Ministry of Higher Education and Scientific Research (MOHESR), Iraq. Throughout working on this thesis, many conferences, workshops and training courses were attended as well as several postgraduate courses for generic research skills traning phas relevant scientific seminars and conferences Poster and paper presentations were given at a relevant international conference. In addition portions of this research inspired the following scholarly output:

Conferences Talks

Waleed. H. H., (2011). The geomorphological development of ephemeral and relict river valley systems in the north part of the Iraqi Western Desert. Oral Presentation at the Postgraduate Society Conference, Plymouth University, 29th June 2011.

Waleed. H. H., (2013). The Western Desert in Iraq. Earth Science Research Seminar Series Plymouth University, 1th May 2013.

Waleed.H.H.,(2013). Geomorphology of Western Desert in Iraq. 8th IAG International Conference on Geomorphology, 27th - 31th August, Paris-France.

Conference posters

Waleed.H.H.,(2010). The geomorphological development of ephemeral and relict river valley systems in the north part of the Iraqi Western Desert. Centre for Research in Earth Sciences, Plymouth University, 24th November,

Waleed.H.H., (2011). The geomorphological development of ephemeral and relict river Valley systems in the north part of the Iraqi Western Desert. International student conference, Plymouth University, 27th May.

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Postgraduate Research Skills attended (Plymouth University):

1. Learning and Teaching for General Teaching Associates Corse (GTA),

   Plymouth, University, UK, 2011,

2. Excel conditional formatting and chart 2011.
3. Power point Enhancing a presentation 2011.
4. SPSS 2011.
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6. Work shop Geographical information system (GIS) 6/12/2012
7. Work shop Geographical information system (GIS) 2013
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Signed…… Date……

PhD SUPERVISORY TEAM

Director of Studies: Professor: James S Griffiths (Plymouth University)

2nd Supervisor: Dr. Anne Mather (Plymouth University)

3rd Supervisor: Dr. Martin Stokes (Plymouth University)

List of abbreviations

IPC: Iraq Petroleum Company

GEOSURV: Geological Survey and Mining State Company of Ministry of Industry and Minerals.

KH4/1, KH4/5, KH4/10, KH4/ Number of drill holes in Western Desert (number between 1-10/10)

K 160: Station on the Highway about 100 km east Rutba Town it contains a car park, petroleum station and police office with restaurants.

H1, H2, and H3: Oil pumping stations pumping oil towards the Haifa port on the Mediterranean. Currently out of action

T1 and T2: Oil pumping stations pumping oil towards the Tartous port on the Mediterranean

Arabic terminology that have geomorphological meaning

Karat = (in Arabic) the highest lands

Kbrat = (in Arabic) the dry lake

Khashm = (in Arabic) hill beside cliff

Azmat Garaa= big dry lake in middle of Garaa depression.

Akash = names of plateaux located south of the Town of Qaiam

Dulaim Liwa = Anbar Government before 1968; after this year it became the Anbar Government.

Sharki: (in Arabic) eastern.

Sub bear: area near Rutba Town

Belt: (in Arabic) something narrow around a bigger area. For example the Rutba belt is the area around the town of Rutba.

Locations identified in the text

1. **Rutba:** Town located in the Western Desert of Iraqi near the Jordanian border.

2. **Al Qaiam:** Town is located on the Euphrates River near the Syrian border.

3. **Anha:** Town located on the Euphrates River east Al Qaiam town.

4. **Haditha:** Town located on the Euphrates River east Anha town.

5. **Mugher Al Dheeb:** Small desert village located on the Rataga valley very near the Syrian border.

6. **Al Waleed (Tinuf):** Border crossing point between Iraq and Syria.

7. **Hussabia:** Border crossing point between Iraq and Syria located in Al Qaiam town.

8. **Traibeel:** Border crossing point between Iraq and Jordan, it located west of Rutba town.

9. **Jdadiat Arar:** Border crossing point between Iraq and Saudi Arabia.

10. **T1 and T2:** Oil pumping stations pumping oil towards the Tartous port on the Mediterranean

11. **Rutba uplift:** Anticline that arose as a result of ground movements which occurred in the mid Tertiary period and has a surface expression 100 km long (Figures 4.10).

12. **Akashat:** Phosphate mine; petrochemical and housing complex located about 75 km north west of Rutba town and about 100 km south Qaiam town.

13. **Highway Express No 1:** Highway linking Iraq and Syria via border point Al waleed and Jordan via border point Traibeel.

14. **Garaa depression:** Structural depression about 80 km north of Rutba town.

15. **Al Halgoom:** Waterway located in the north rim of the Garaa depression.

16. **Marbat Al Hosan:** Hill in the north rim of the Garaa depression.

17. **Al Kreisha**: a plateau in the Al Qaiam area.

18. **Valleys in the study area:** Houran, Walage, Suwab, Rataga, Akashat, Mulusaa, Al Nijeli, Agery, Owja, Dueklaha, Agrmayat, um Tyarat, Regla and um Adiha. (Figure 6.4)

19. **Beer Al Raha:** area in the south rim of the Garaa depression which contaibs a (Beer in Arabic means hole or well in English)

20. **Um Chaimain:** karst depression south west of Rutba town.

21. **Jabal Enza:** High area located on the meeting of the borders between Iraq, Jordan and Saudi Arabia.

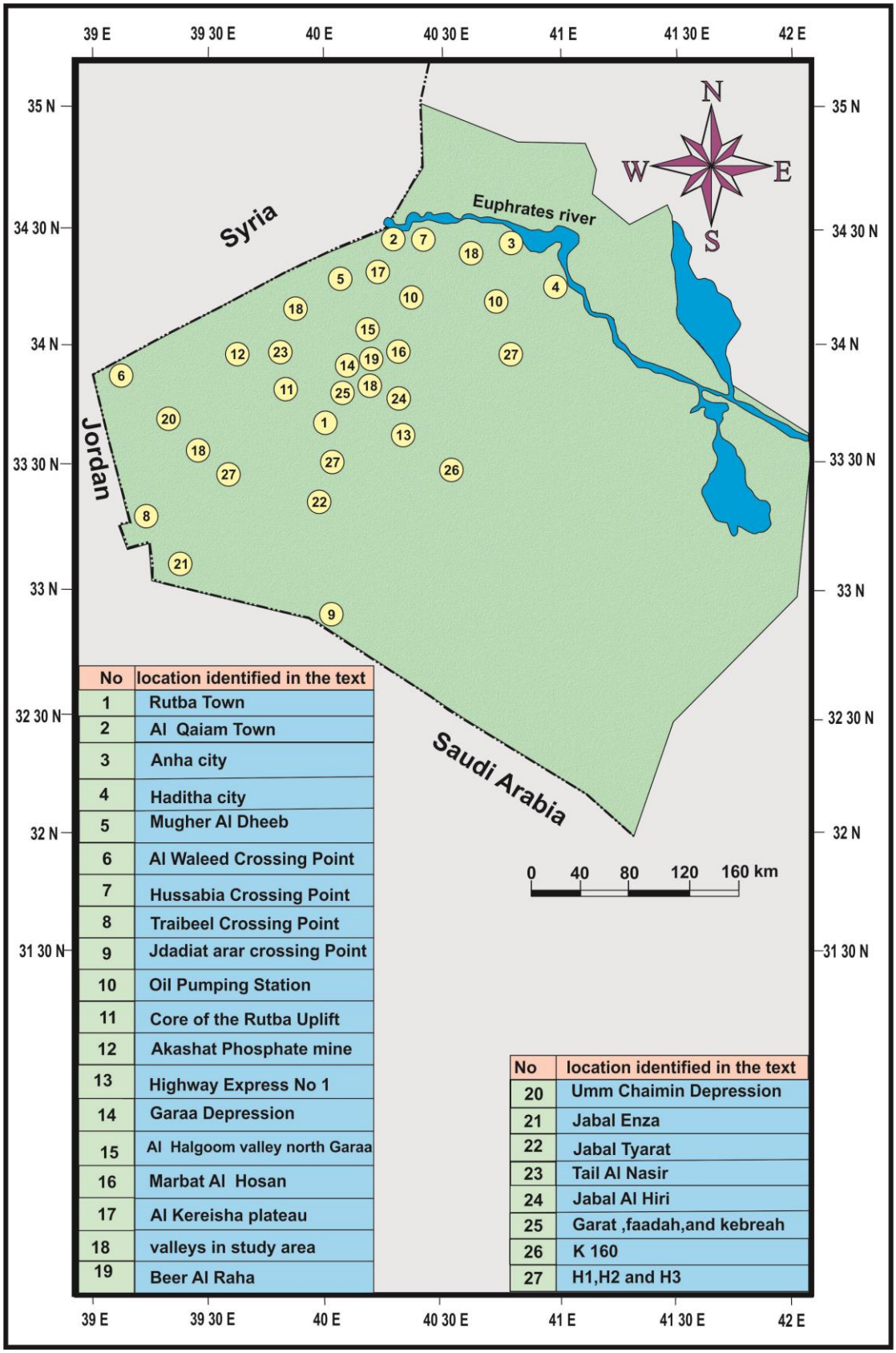
22. **Jabal Tyarat:** Hill located to the south of Rutba town.

23. **Tail Al Nasir:** Hill located to the north of Rutba town.

24. **Jabal Al Hiri:** Hill located North West of Rutba town.

25. **Garat, Faadah and Kebreah:** closed depressions and dry lakes such as kebreah Al Raha in the Garaa depression.

Figure A below shows the locations identified in the text.



No	location identified in the text
1	Rutba Town
2	Al Qaiam Town
3	Anha city
4	Haditha city
5	Mugher Al Dheeb
6	Al Waleed Crossing Point
7	Hussabia Crossing Point
8	Traibeel Crossing Point
9	Jdadiat arar crossing Point
10	Oil Pumping Station
11	Core of the Rutba Uplift
12	Akashat Phosphate mine
13	Highway Express No 1
14	Garaa Depression
15	Al Halgoom valley north Garaa
16	Marbat Al Hosan
17	Al Kereisha plateau
18	valleys in study area
19	Beer Al Raha

No	location identified in the text
20	Umm Chaimin Depression
21	Jabal Enza
22	Jabal Tyarat
23	Tail Al Nasir
24	Jabal Al Hiri
25	Garat ,faadah,and kebreah
26	K 160
27	H1,H2 and H3

Figure A: Main Locations identified in the text

Chapter 1

Introduction to the thesis and the field area

1.1 General Introduction

The study of the geomorphological history of the Western Desert in Iraq has been difficult because of the long-standing poor security situation in the region and previously the wars in Iraq between 1980-2003. Thus there has been very little scientific investigation of the geomorphology of the region for over 30 years. However through the use of remote sensing data with limited field reconnaissance studying the geomorphological landforms of the region, notably the valleys of the relict and contemporary ephemeral rivers, has been possible and this has enabled us to improve our understanding of the recent geological history and climatic changes that have occurred in this isolated and remote region. The changes in climate during the Cenozoic from humid conditions to the current dry conditions has led to a significantly reduced amount of available water and this has led to a number of contemporary misfit ephemeral streams being found in large valleys. Nevertheless, most of these misfit streams still flow and valleys are affected by flood flow during severe rain storms.

Traces of the changes to river flow regimes can be identified in the river terraces that have been preserved along the courses of some of these valleys. It is the investigation of these river valleys and the drainage network created that forms the core of this thesis. The aims are to understand the morphogenesis of the contemporary landscape of the Iraqi Western Desert.

1.2 Aims and objectives

The overall aims of this research are to understand the nature, distribution and geomorphological evolution of the dry valleys on the right bank of the River Euphrates in the Iraqi Western Desert

The specific objectives are to:

1. Carry out a geomorphological classification of the landforms in the study area

2. Analyse the river valley and terraces associated with the relict and contemporary stream network

3. Analyse the nature and properties of the valley basins and their associated relict dry valleys

1.3 Thesis structure

For this investigation this thesis has been divided into seven chapters. This first chapter provides an introduction to the thesis and field area with a section on the aims, objectives, and some of the field work issues. The second chapter presents a literature review into drainage in hot deserts and in particular the parts of the Middle East in near the field area. The third chapter presents the investigation methodology. The fourth chapter provides an up to data summary geology of the field area. The fifth chapter presents the geomorphological investigations. The sixth chapter provides the interpretation the evolution of the drainage networks. Chapter seven is a discussion of the findings from the research and provides the conclusions and recommendations for future studies.

1.4 Field area

The initial aim of the field work study was to review the geomorphological features and terrain units of the Iraqi Western Desert, especially the area located around Rutba and Qaiam, near the Euphrates River (figure 1.1). The release of classified regional data held by the Iraqi Geological Survey especially from the reports on geological surveys between 1969 to 2010 was an important element in providing geological and geomorphological data on the region. The geological maps from the Iraqi Western Desert produced at a scale of 1:250,000 provided the background data on the region and these were accessed during the first field visits.

The GEOSURV regional geological survey work included summary descriptions of the geomorphological landforms but very little evaluation of the geomorphological processes. Some of the geological maps contain detailed descriptions of rock properties (lithology), stratigraphy and the structural geology of the exposed formations. More useful geomorphological information was obtained from the GEOSURV field work in the Iraqi Western Desert that led to the creation of regional geomorphological maps of Iraq of a scale of 1:1,000,000 (appendix F on CD) which were published in 2000. For this thesis, fieldwork in the Iraqi Western Desert was limited to four exploratory trips from May to July 2010 and four further field excursions from January to March 2012. However, it should be noted that the worsening security situation in the Iraqi Western Desert between 2011-2014 meant that the amount and extent of the planned fieldwork had to be curtailed. All field excursions that took place were supported by armed guides and only limited time could be spent at any localit

1.5 The Iraqi Western Desert

The Western Desert covers a considerable part of Iraqi territory in the region south and west of the Euphrates River. It is divided into the Western and Southern deserts, formerly known as North Badiya and South Badiya respectively. Both the Western Southern Deserts are part of the stable shelf of the Arabian platform which is characterised by the presence of block tectonic and the absence of folding (Budy and Jassim, 1987) (Figure 1.2). The dividing line between the two deserts is Wadi Al Khair.

The Western Desert extends west and south into Syria, Jordan and Saudi Arabia, and covers an area of about 100, 000 km^2 (Figure 1.1). Many large misfit valleys provide the drainage network of the Iraqi Western Desert. Some of these drain into the Euphrates River such as Houran, Swab, Walaij, Akash, Ratga, Fhada, Qaiam and Al Manai valleys. Other valleys drain in to depressions such as the Mulusa, Najili, Agri, Ojia, Dwakla, Agrmyat, Tayrat, Reglia and Um adia valleys which drain in to the Garaa depression. The Euphrates River forms the eastern, north eastern and northern limits of the Iraqi Western Desert. The topography of the Iraqi Western Desert increases from the east to the west at on average of 5m / km (Sissakian and Mohammed, 2007). The highest point in the Iraqi Western Desert is 945 m above sea level in the Jabal Enza area and the lowest point is 165 m above sea level at the Euphrates River near the town of Al Qaiam. A meso - scale characteristic of the landscape are the mesas, buttes, and tablelands which range in height from a few metres to more than 50 m above the surrounding terrain. The southern desert covers an areas 76 000 km^2 and ranges in highest from 419 meters above sea level to 6 meters above sea level at the Arabian Gulf. The southern desert is located in the southern part of Iraq and bordered by the

Iraqi–Saudi Arabian and Kuwait international borders in the south west and south east respectively and bordered by the Euphrates River in the north east; and by the Al Khair valley in the north west Figure (1.1). This desert was divided into three distinct geomorphological units by (Sisskan and Mohammad, 2007)

• **Al Haijara area.**

This is characterized by karstic depressions, isolated hills, undulations, foot slope and fault scarps Mala (2009). It is an elevated terrain capped by limestone, lies in western part of the Southern Desert, and is composed of carbonate strata of Paleocene and Miocene age with a bedding slope 1-2° towards north east.

• **Al Dibdibba area**.

This is characterized by gently sloping terrain 1-7° towards the north east. It is an elevated terrain, lies in the southern parts of the Southern Desert, and is capped by pebbly sandstone of the Dibdibba Formation which is of Pliocene-Pleistocene age (Mala, 2009).

• **Periphery area**.

This is an area of subsidence along the western side of the Euphrates River, and composed of early Miocene carbonate strata which are covered by these aeolian sediments. It is a long and narrow area characterized by the existence of tectonic depression (Mala, 2009).

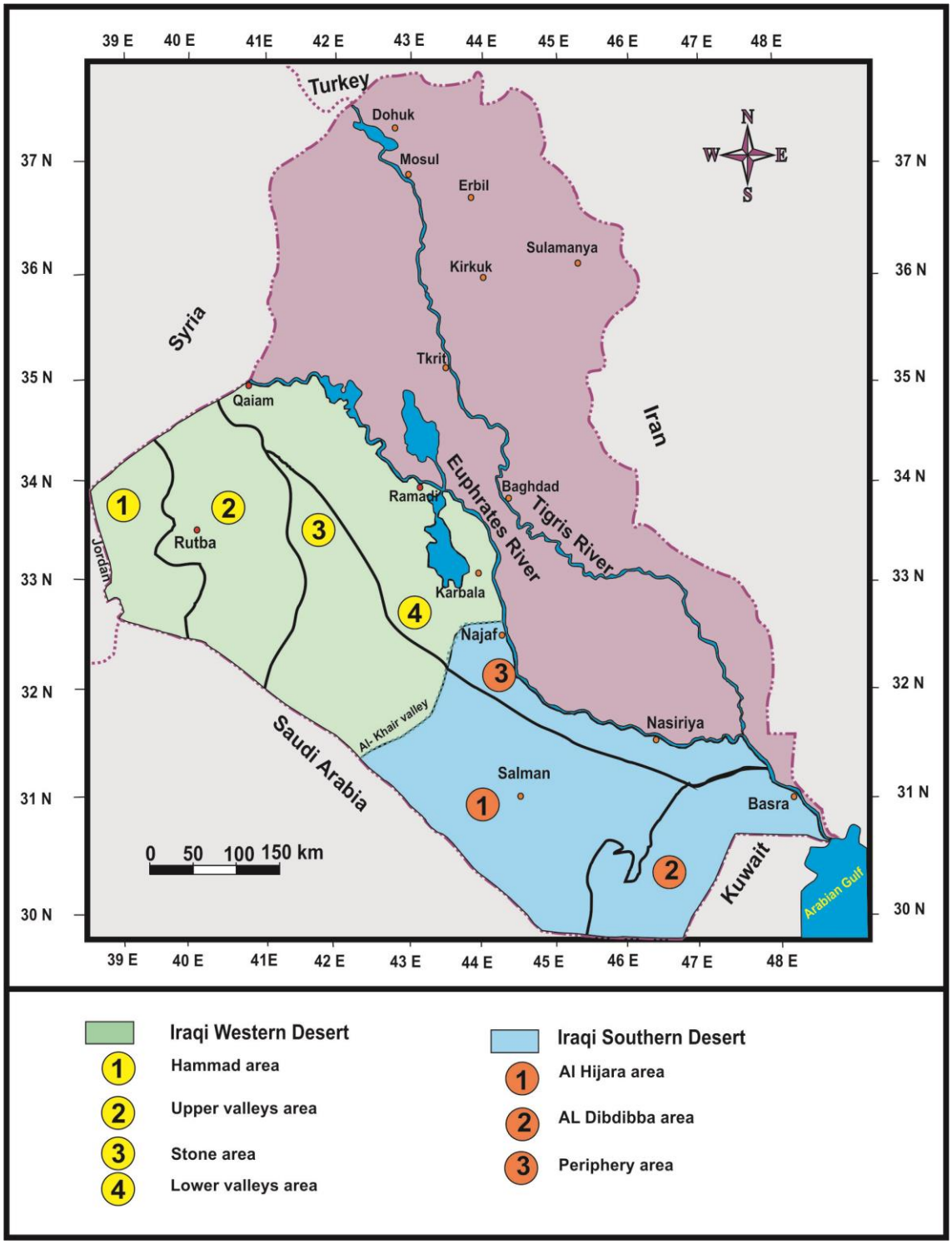


Figure 1.1: Location map of the Iraqi Western Desert (modified after Sisskian and Mohammed 2007). The Southern Desert was not investigated in this thesis.

The main landscape forms in the Iraqi Western Desert are plateaux that have been dissected by the valley networks. The oldest exposed rocks in the Iraqi Western Desert are Permian, and the youngest are Holocene (Sisskain and Mohammed, 2007). Most of the Western Desert has been an erosional landscape since the Oligocene. Sedimentation has only occurred in valleys, depressions, and the occasional but limited aeolian sand sheets. The Iraqi Western Desert also contains a number of depressions such as Al Garaa depression and the Umm Chaimin depression; these are either solution or erosional (e.g. deflationary) landforms. .The pedological soils are immature and usually clays which are very fertile when water is available. Numerous prehistoric chert artefacts and carvings on sandstone walls have been reported during the course of regional geological mapping carried out by GEOSURV in the Western Desert (Al Bassam, 2007). The distribution of these artefacts suggests that the Western Desert was widely inhabited by humans and animals in the late Pleistocene, a consequence of more favourable climatic conditions. Pleistocene cold periods in the northern hemisphere resulted in different climate conditions in this region and the Western Desert of Iraq became moderate to cool with a wetter climate during high latitude glacial maximums (Malinowski, 2000). In the late Pleistocene conditions were favourable for high human populations in the area south of latitude 40° N, which is presently classified as desert. Increased geological interest in the Western Desert started in the 1930s when gold was reported in the Garaa area by the indigenous Bedwins (a group of migrant people that live in the desert). A concession for gold prospecting was commissioned by the Iraq government and professional geological work in the Western Desert was started in the 1940s by the British. Only short and widely spaced non-systematic reconnaissance work was carried

out but this included radiometric airborne traverses. The region was not classified as having hydrocarbon potential at that time, which left this part of Iraq mainly unexplored. A pioneer compilation on the geology of the Western Desert was carried out by Al Naqib in the 1960s and was published as a professional paper by the United States Geological Survey (Al Naqib, 1967). This was the first time that the stratigraphy of the desert was accurately defined based on the reconnaissance mapping by the Iraqi Petroleum Company and the British Site Investigation Company. At this time Soviet geologists carried out several mineral exploration projects in the Western Desert which resulted in the discovery of many important mineral raw materials such as phosphorite, sedimentary ironstone and silica–sand (Al Bassam, 2007). GEOSURV (state company of the Iraqi Ministry of Industry and Minerals Company the Geological Survey and Mining) started working in the Western Desert in the late 1960s as part of the regional Geological Survey project which included numerous mineral exploration programmes. Since then the geological work in the Western Desert has continued to enable compilation of the 1:1,000,000 scale geological survey maps of the whole area (Sisskan and Mohammed, 2007). In the past thirty years mining activities in the Western Desert supplied raw materials for phosphate fertilizer, the glass industry, ceramic, and refractory industries, cement industry and the oil industry (drilling mud). The potential for mineral resources in the Western Desert has still not been fully exploited. This region contains most of the non-metallic mineral deposits and industrial rocks of Iraq (except native sulphur). Recent seismic surveys and exploratory deep drilling by the oil companies have shown promising potential for oil and gas in this region. This will obviously drive more geological work and a better understanding of the subsurface geology of the region

1.6 Location of Iraq

To understand Iraq it is important to appreciate the regional geography. Iraq shares borders with six countries: Iran to the east, Kuwait, the Arabian Gulf and Saudi Arabia in the south Jordan, Syria and Saudi Arabia in the west and Syria, and Turkey in the north. It only has a very small coastline of about 60 km on the Arabian Gulf (Figure 1.2).

Figure 1.2: Regional map shows location of Iraq modified (after Malinowski, 2000).

The study area is located in the Western Desert of Iraq. It is located between Latitude 32° 00' to 34° 30' North and Longitude 39° 00' to 41° 30' East, an area of about 30,000 km^2. The area represents part of the Western Desert of Iraq which is an extension of the Najid desert in Saudi Arabia. At the organizational level more than 95% of the Iraqi Western Desert belongs to the Al Anbar local government whilst three local governments share the remainder.

1.7 Summarizing the purpose of this research

This research is aimed at understanding the evolution of the drainage network in the Iraqi Western Desert. To help put this in context Chapter 2 provides a review of the exiting understanding of the fluvial geomorphology of hot deserts with an emphasis on research carried out in the Middle-East.

Chapter 2

The Geomorphology of Hot Deserts

2. 1 Introduction

This Chapter reviews some of the general literature on hot deserts. An overall appreciation of the nature of landforms, processes and landscape evolution in hot deserts is provided by Cooke et al. (1993). Cooke et al. (1982) and Thomas (2011). More specialist reviews are provided by: Walker (2012) on engineering geology and geomorphology; Merriam and Hawerda (1957) in a study of the Umm Chaimin depression in the Iraqi Western Desert; Parson and Abrahams (1994) on desert environments; and Bloom (1978) a systematic analysis of late Cenozoic landforms. This chapter start by defining what a desert is and describing the world distribution of hot desert (Section 2.2). Then the nature of the desert landscape is examined as some generalized terrain models are presented (section 2.3). Following on from this it is necessary to look at the way deserts have evolved over long periods, notably during the Cenozoic (Section 2.4). Incorporated in this is the work that has been underway over the past 20-30 years that has shown that climatic fluctuation throughout the Cenozoic are more complex that previously thought. This topic is reviewed in general (Section 2.4.1) and specifically in relation to Iraq and the Arabian Peninsula (Section 2.4.2). In Section 2.5 some general material from previous studies of the geology and geomorphology of Iraq are presented but most of the information on these topics are presented in Chapter 4 and 5 respectively. The final part of this Chapter concentrates on the desert fluvial environment as the core aim of this research is to understand the evolution of the drainage network in the Iraqi Western Desert (Chapter 6). To underpin this work a review of the present understanding of the contemporary desert drainage system, channel form, processes and fluvial landform (Section 2.5).

2.2 The Definition and distribution of Hot Deserts

The term ‘desert’ can be defined physically, as a large contiguous area with extensive bare soil and low vegetation cover, biologically, as an ecoregion that contains plants and animals adapted for survival in dry conditions, and climatologically as a semi-arid, arid or hyperarid (i.e. severely arid) region (UNEP, 2006). The term desertification is the diminution or destruction of the biological potential of land, and can lead ultimately to desert-like conditions. It is an aspect of the widespread deterioration of ecosystems, and has diminished or destroyed the biological potential, (i.e. plant and animal production) at a time when increased productivity is needed to support growing populations in quest of development, The concept of desertification was introduced in the late forties to designate a number of ecological degradation processes in tropical Africa, in particular the progressive transformation of tropical forests in savannahs or even drier ecosystems.

Deserts and semi deserts are the most extensive of the earth biomes occupying more than one-third of the global land surface (UNEP, 1992). Using the UNEP (1992) dryland classification scheme around 47% of the Earth’s surface falls within the arid zone and 37% can be considered as ‘true’ desert (i.e. hyperarid, arid or semi-arid). Africa and Asia contain the largest area of drylands (31.9% and 31.7% of the total global arid zone, respectively), followed by North America (12.0%), Australasia (10.8%), South America (8.8%) and Europe (4.9%); (UNEP, 1992; Thomas, 1997). Figure 2.1. Show the distribution of deserts in the world (UNEP, 1992). The term dryland, which includes both arid and semi-arid areas, refers to both climate and landscape. In Köppen’s (1931) classification, these arid and semi-arid climates belong to BWk and BSk. The BWK refers to cool dry desert climate with an annual average temperature below 18°C (64°F). It is characterized by its aridity, low relative

humidity, irregular rainfall, high percentage of sunshine, larger temperature range and more precipitation than a tropical desert. BSk is a semiarid climate usually found in the middle latitudes, characterized by semiarid, conditions, the temperatures vary with latitude, elevation, and continentally. As with the all hot drylands the geomorphological processes in the Iraqi Western Desert are primarily a result of surface and sub-surface water, solar radiation, gravity and wind, These factors are, in turn, controlled by variations in climate and the characteristics of the local topography in the region, as well as being influenced by the geological setting and the length of time the landscape has been exposed to weathering and erosion. In the case of present-day desert environments, the thin soil cover, low soil moisture and general scarcity of vegetation in the study area may make ground surfaces more prone to wind and water erosion (Nash, 2102).

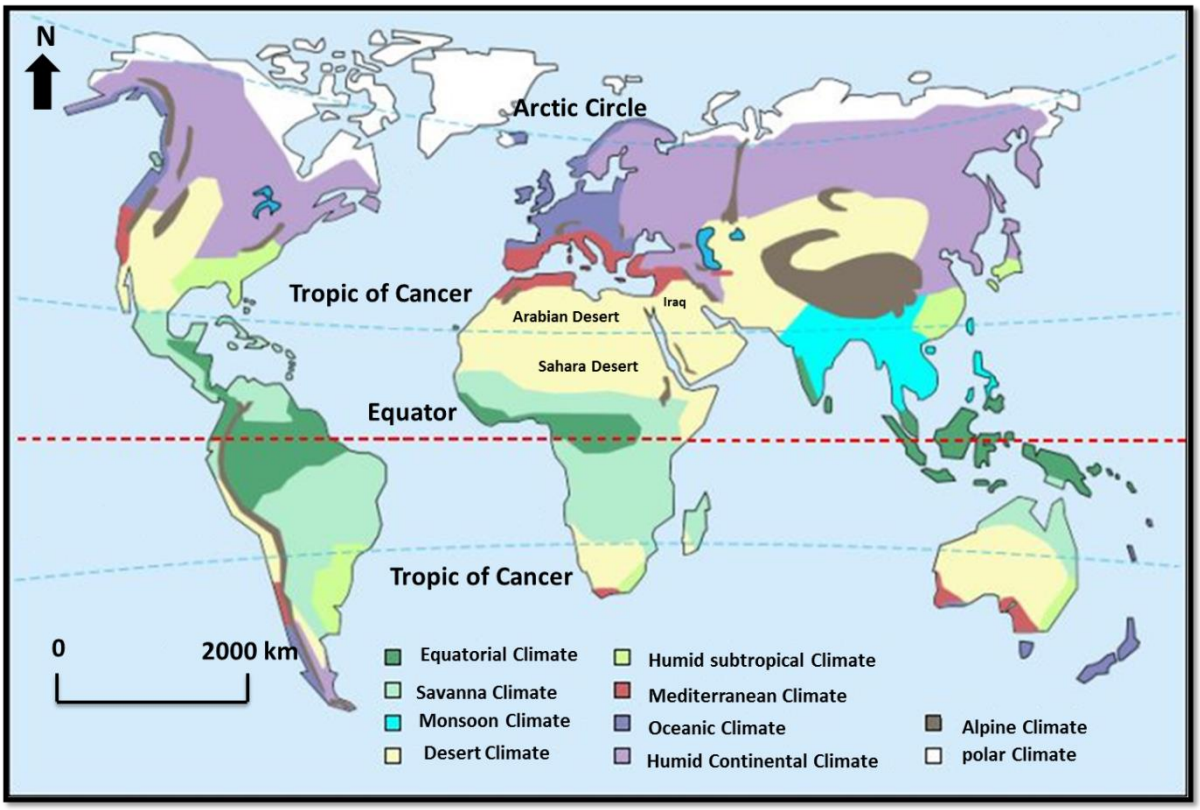


Figure 2.1: World map of Koppen-Geiger climate classification in the Earth Surface .source United Nations Environment programme (UNEP 1996).

2.3 Typical models of dry lands environments

Nash (2012) refers to the causes of aridity in dry environments and said the worlds deserts owe their aridity and distribution to a range of climatic, topographic and oceanographic factors. The five key influences are:

1. **Continentally:** distance from oceans or other moisture sources is an important cause of aridity on large land masses. Large land areas also impose their own seasonal climate upon the zonal pattern of global pressure systems (Parsons and Abrahams, 1994).

2. **Atmosphere stability :** the largest deserts are located in the zones of relatively stable atmospheric conditions associated with sub-tropical high-pressure belts situated at around 30° N and 30° S of the equator

3. **Cold ocean currents:** The western coastal margins of southern Africa and South America are arid, at least in part, due to the presence of offshore cold ocean currents produced by cold water rising from the deep ocean and moving towards the Equator.

4. **Orographic influences:** Major mountains in the pathway of moisture-bearing weather systems can significantly reduce precipitation levels in their lee. This is primarily because mountains act as a barriers to marine influences (Cook et al., 1993).

5. **High reflectivity (albedo) of desert surface:** The aridity of desert areas may be reinforced and perpetuated by the high albedo of the desert surface, particularly where they are devoid of vegetation.

These factors acting in combination but Goudie (2002) suggested that the presence of the tropical and subtropical high-pressure belts has the greatest influence on aridity.

Goudie and Wilkinson (1978), drawing on the knowledge of the controls on the occurrence of desert to develop three models of characteristic landscapes (Figure 2.2). The first (Figure 2.2a) represents a typing basis and range landscape that is formed in SW. U. S. A and SE. Spain (Mather et al., 2000). This is a landscape associated with uplifting mountains and subsiding basins. The second landscape (Figure 2.2b), labelled 'Inselberg and pediments', is regarded as one that develops on crystalline igneous rock and notably granite. The landscape is noted for the occurrence of inselbergs, rocky outcrops at the tops of low hill, and extensive pediments. The pediments are essentially erosional plains but may be alluvial deposits. The third landscape is associated with horizontally bedded sedimentary strata and known as canyon and scape (Figure 2.2c). This is a landscape that this research found was the most widespread in the Iraqi Western Desert.

Alternative synoptic developed for engineering geologist is presented in Figure 2.3 from Fookes and kinll (1969).

This relatively simple model has proved to be extremely useful for engineering geological investigation in hot deserts (Griffiths et al, 2012). The model divides the desert terrain into four zones:

1- Monitions with canyons; 2- rocky pediment foot slopes and alluvial fans; 3- alluvial plains and sand dunes; 4- base level plains comprising mudflats, sand sheet, playas and at the coast, sabkhas.

It is the adaptation of the Fookes and Kinll (1969) model that was refried by Fookes et al. (2007) to present in Figure 2.4. This model forms the basins for the engineering geology and geomorphology of hot deserts discussed in the working partly report of the Geological Society (Walker, 2012). It is this model that underpins the study of the geomorphology and drainage undertaken for this research and presented in Chapter 5 and 6. The model has also formed the basis of the work on natural hazards in hot deserts investigation by Griffiths et al (2012), elements of which are presented in Table 2.1.

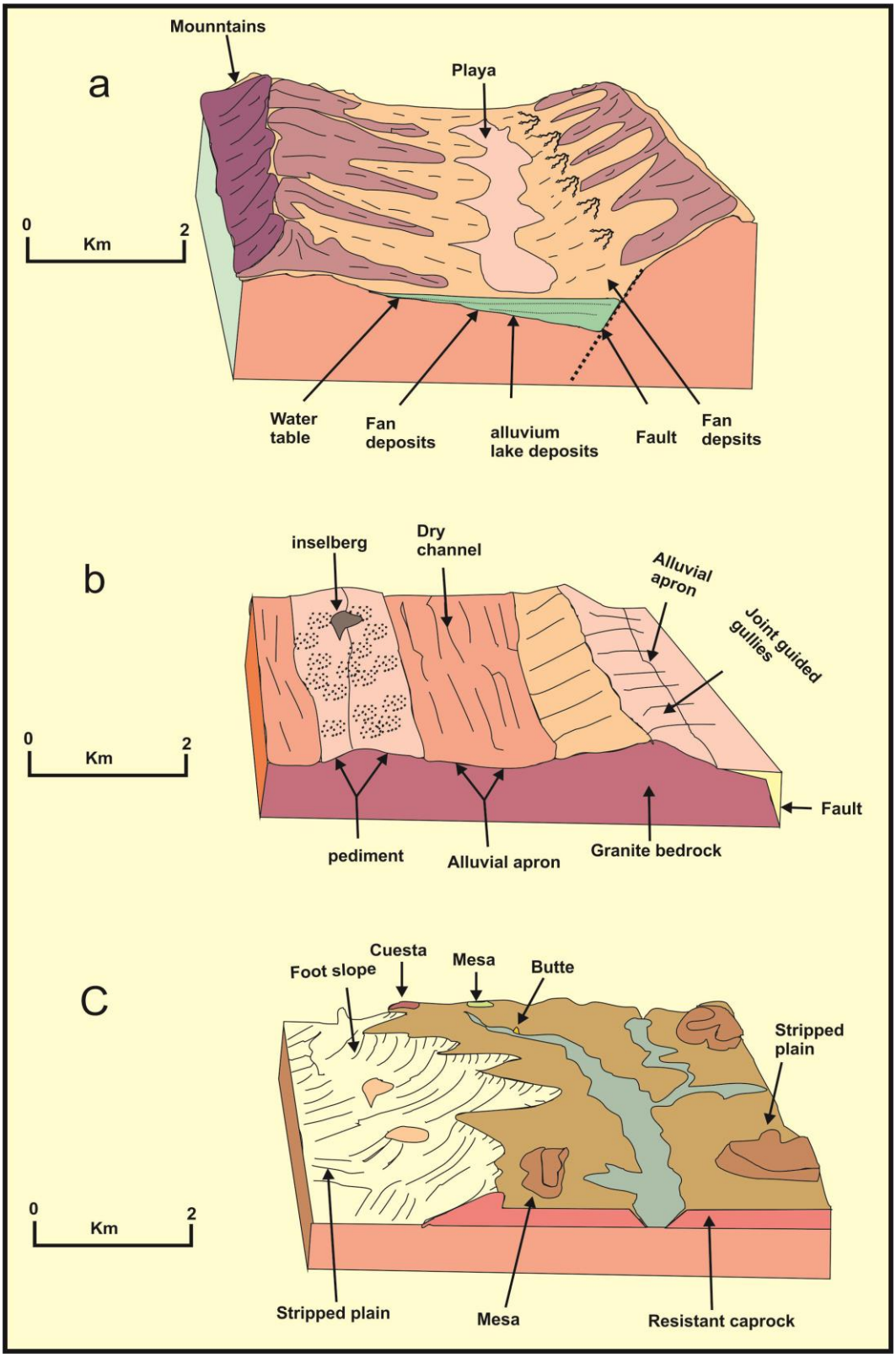
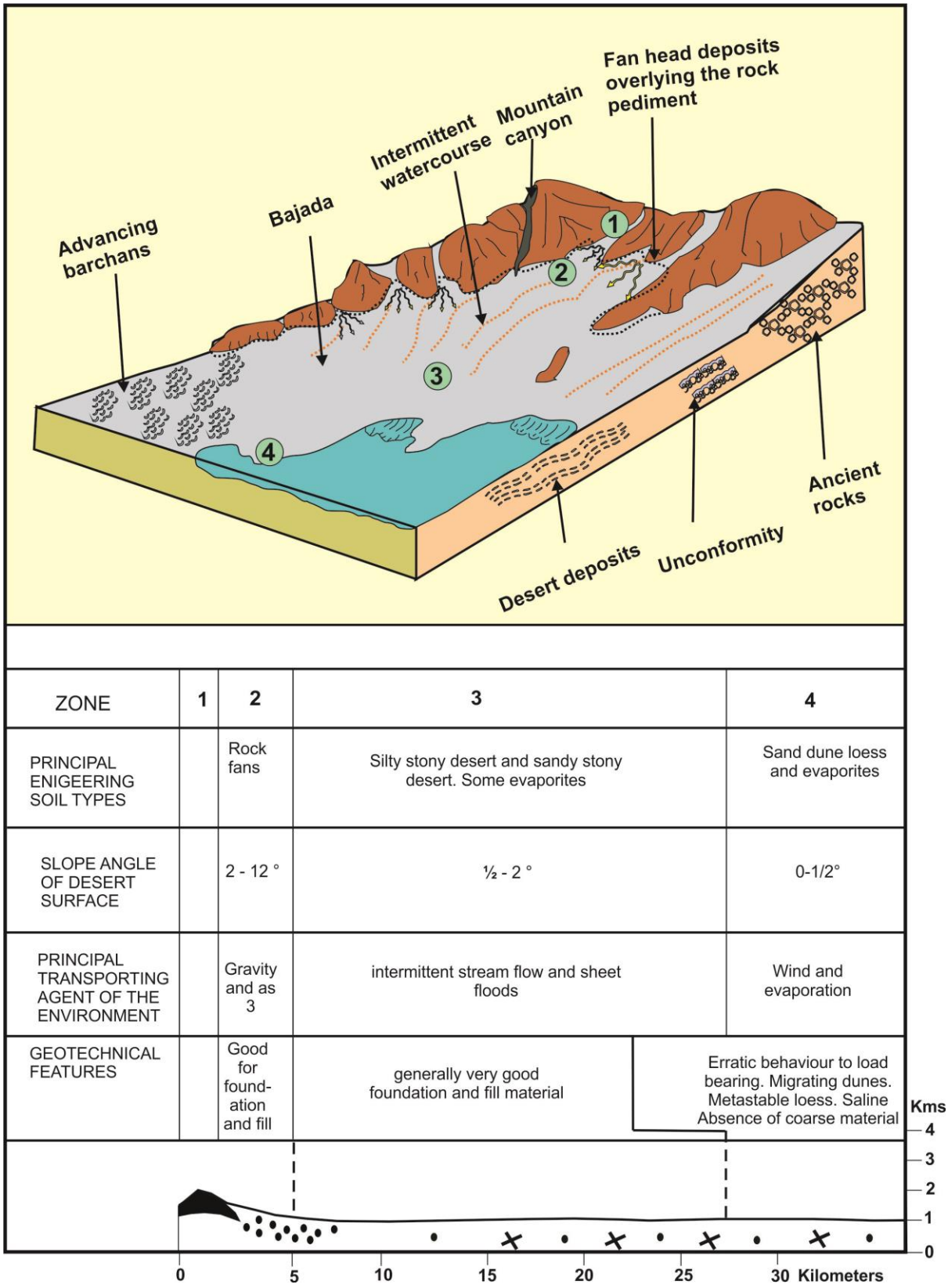


Figure 2. 2. The characteristic desert landscape from Griffiths et al. (2012); (a) Basin and range. (b) Inselberge and pediment. (c). Canyon and scarp.



ZONE	1	2	3	4
PRINCIPAL ENIGEERING SOIL TYPES		Rock fans	Silty stony desert and sandy stony desert. Some evaporites	Sand dune loess and evaporites
SLOPE ANGLE OF DESERT SURFACE		2 - 12 °	½ - 2 °	0-1/2°
PRINCIPAL TRANSPORTING AGENT OF THE ENVIRONMENT		Gravity and as 3	intermittent stream flow and sheet floods	Wind and evaporation
GEOTECHNICAL FEATURES		Good for found-ation and fill	generally very good foundation and fill material	Erratic behaviour to load bearing. Migrating dunes. Metastable loess. Saline Absence of coarse material

Figure 2.3: The original desert zonation model from Griffiths et al. (2012)

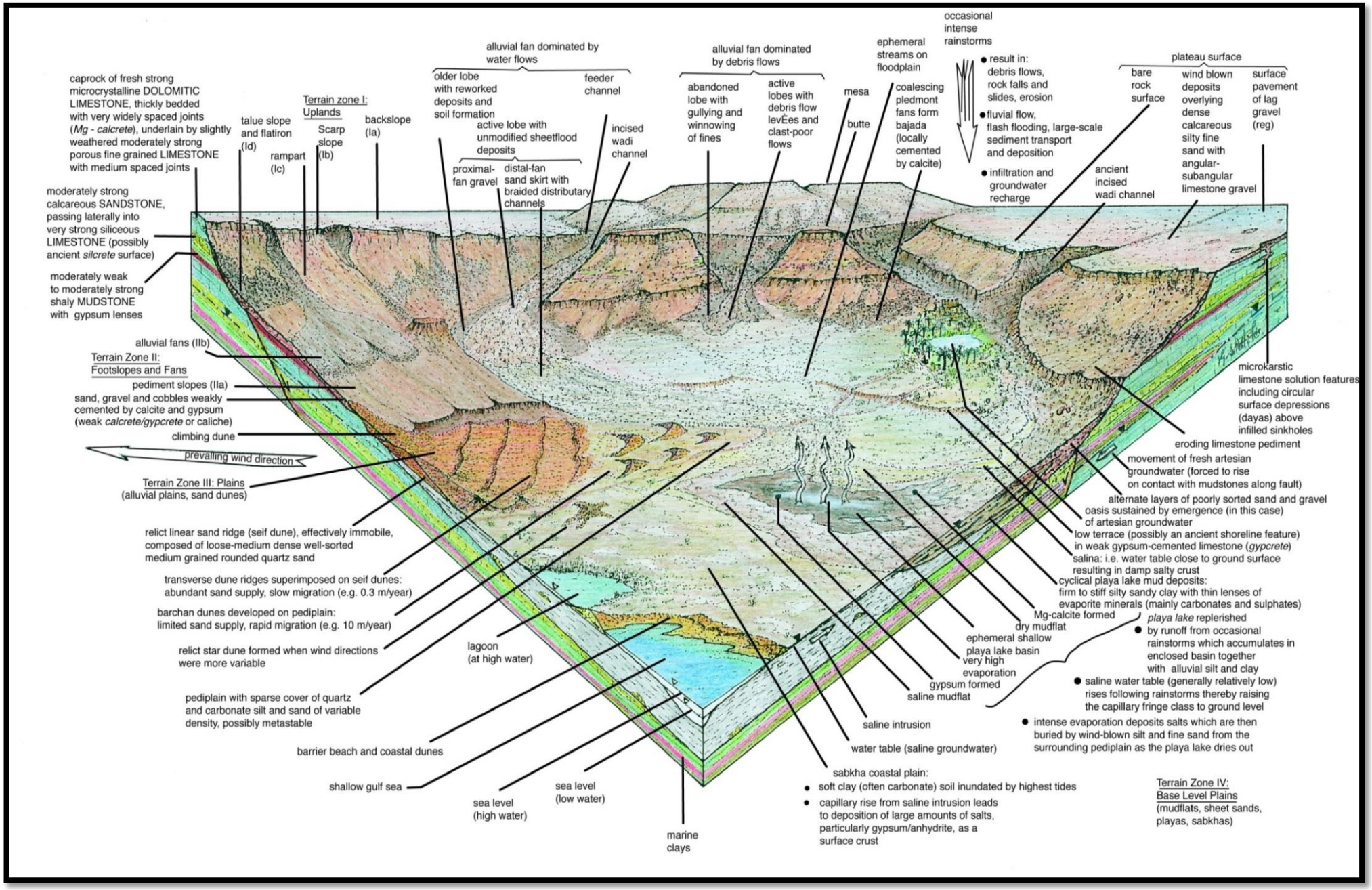


Figure 2.4. The desert model (source: Griffiths et al., 2012)

Table 2.1: Natural hazards relevant to engineering geology and geomorphology in deserts (Griffiths et al., 2012)

Hazard category	Hazard event process or form
Global event	Neotectonics climate changes
Meteorological / climate	Rainstorms; aridity; drought extreme temperature; wind
Hill slopes	Weathering; rilling and gulling; mass movement
Ephemeral streams	Flash floods; unstable channels; channel slopes; sediment loads; high bedloads; scour; transmission losses
Subsurface water	Piping; limestone, gypsum; and clay karst; hydrocompaction; collapsing soils; capillary rise gypsum / anhydrite landforms
Aeolian activity	Deflation; lag deposits; dust; sand; mobile landforms (dunes); relict dunes
Aggressive ground conditions	Chemical weathering ; salt pans; Salinas, playas and sabkha; saline groundwater; swelling / shrinking soils, gypcrusts
Environmental issues	Landscape sensitivity to change; deserfication; damage to habitats

2.4 Long term evolution of drylands

Deserts are often portrayed as ancient and timeless landscape. This is certainly the case for deserts such as the Atacama and Namib, whose origins were with the establishment of cold currents off the shores of western South America and southwest Africa, respectively, following the break-up of Gondwanaland. Arid conditions have existed in the Atacama since the late Jurassic (Hartly et al. 2005), with hyper - aridity prevalent from the Oligocene-Miocene (Dunai et al. 2005), whilst the Namib may have been at least semi-arid since the early Cretaceous (Ward et at. 1984). Long-term tectonic plate movements are also responsible for the aridification of Australia; the continent had a relatively wet climate during the early Tertiary but became progressively drier from the Miocene onwards owing to its gradual northwards migration from a position adjacent to Antarctica in the early Cenozoic (Baynes et al. 2005; Martin 2006).

In contrast, some desert landscapes are significantly younger. Although aridity has existed in north Africa for at least 20 Ma, areas of the Sahara as far as 23° N were covered by Sahelian grass and shrubs as recently as approximately 5000 to 6000 years ago (Jolly et al., 1998). There landforms and sedimentary evidence to suggest that almost all of the world's deserts experienced significant episodic expansions and contractions, most notably in response to global climate changes during the Quaternary. Large tracts of the presently semi-arid northern Kalahari Desert, for instance, were occupied by active linear dune fields on a number of occasions in the past 100 000 years (Thomas et al., 2003), with the same region also containing pollen and palaeolake evidence that indicate periodically wetter conditions (e. g. Nash et al., 2006).

It has become apparent that many desert areas are both old and characterized by an extremely varied environmental history. The great Saharan-Arabian zone, the Thar, the Namib, the Kahlari, the Atacama, the Californian deserts and the great arid expanses of Australia are all primarily 'climatic' deserts situated in the heart of trade-wind belts. Thus, any change in the temperature regime of the world, which is responsible for driving both the atmospheric an oceanic circulation pattern of deserts, and latitudinal shifts of the continents may serve to change their positions with respect to the global pattern of trade-wind belts.

2.4.1 Climatic fluctuations during the Cenozoic

Our climate has been cooling for 60 million years ago with the Antarctic ice sheet forming about 35 million years ago and the Arctic icecap growing from 3 million years ago. The Quaternary Period has been dominated by “Ice Ages”, which involve repeated global cooling and increasing advances of these ice sheets These oscillations are paced by regular eccentricities in the Earth’s orbit around the sun every (Hewitt, 2004). The large ice sheets, surrounding permafrost, lower global temperature and reduced water availability caused great changes in the distribution of species, which can be seen in the fossil record (Bennett and et al 1997; Williams et al., 1993)., The Quaternary Period, the past 2 million years, has been among the most dynamic episodes in the last 60 million years of Earth history including the Arabian lands. In the Earth as a whole glaciers expanded and retreated so that they covered from as little as 8% to over 30% of the Earth’s land surface; sea level rose and fell over a vertical distance of over 100 m; and global climates expanded poleward and retreated equatorward with each interglacial-glacial cycle. Recent decades of research have provided sufficient detail on the Quaternary to illustrate the complex nature of driving causes, feedback mechanisms, and environmental response (Williams, et al., 1993).The nature of the landscape changes caused by climatic fluctuation has been very significant. Nowhere has this been more significant than in dry land lake basins such as those of the East African Rift (Butzer et al. 1972; Gasse and Street 1978), Australasia (Bowler et al, 1976). Western North America (Benson, 1978) and Central and West Asia including the study area (Kroonenberg et al., 1979).

The implications of measurements of oxygen isotope ratios in the examinations of planktonic and benthonic foraminifera showed that regular differences in palaeotemperature occurred throughout the Quaternary (Figure 2.5). Although initially Emiliani attempted to correlate them with the then standard four-fold sequence of “Alpine” glaciations, it was not until Shackleton and Opdyke (1973), Shackleton and Kennett (1975), demonstrated they signified high continental ice volume (an ice age) and low ice volume (interglacial) events, later coupled with changeability in orbital parameters (Hays et al 1976), that the full implication of Emilianis pioneering work was revealed. Time-scales are revised from time to time (Shackleton et al.1990) and new data imposes revision of exiting data sets and theory (Raymo, 1997 and Bowen, 1999).

The evidence for climatic change in hot deserts is extensive

Paleoforms abound in deserts in deserts, and these provide the evidence for climatic changes. Table 2.2 provides a summary of the types of evidence that have been used, and the inferences that can be gained from such evidence

1. Aeolian sediments and landforms

The existence of large areas of dunes provides un-equivocal evidence of aridity, so that the existence of areas of heavily vegetated deeply weathered, gullied and degraded dunes indicates more humid conditions. There is dispute about the precise precipitation thresholds that control major dune development. The interrelationships of dunes and river systems my indicate the alternating significance of Aeolian (dry) and fluvial (wet) dominance, as is made evident by a consideration of the courses of rivers such as the Niger and the Senegal,

which have in their histories been ponded up or blocked by dunes Thomas (1997 and 2003).

2. Palaeolakes

The identification of former high shorelines around closed lake basins, and the study of lacustrine deposits from cores put down through lake floors; provide excellent evidence for hydrological changes in lake basins. These changes may in turn be related to estimates of former higher precipitation and evaporation. There are problems in assessing the relative importance of temperature and precipitation in affecting the water balance of a lake basin, and some changes can be caused by non - climatic factors (e. g anthropogenic activity, tectonic disturbance, etc.). (See Cooke and Warren., 1973)

3. Fluvial landforms

Changes in effective precipitation may be reflected in the frequency and range of floods in desert rivers and in their load: discharge ratios. In particular, in sensitive piedmont zones marked alternations may occur between deposition and incision. In extremely arid desert an increase in the sediment yield of an upland catchment might indicate increased rainfall, whereas in a marginal desert with significant surface control by vegetation a similar result might follow from diminution of rainfall.

4. Cave, karst, tufas and groundwater

Karstic phenomena (e. g major cave system) requires the presence of water and may thus give some general indication of past humidity conditions. However, of rather more significance than this is the fact that caves are major

sites for deposition, and their speleothems often provide a record of environmental changes

5. Miscellaneous geomorphological indicates

Much geomorphological evidence is often suggestive of significant change in environment conditions, but it is often difficult to be separate the role of climate from other influences. In some arid areas there are weathering crusts and paleosols that exist outside what are thought to be their normal formative climatic range, and their current state of breakdown may indicate that they are out of equilibrium with the present climate. The iron rich duricrusts of the southern margins of the Sahara and of large areas of arid Austrialia may come into this category.

6. The evidence from the oceans.

One of the most important developments in palaeo-environment reconstruction over the past two decades has been the use of information derived from deep-sea cores. Such information has the advantage of covering long time spans, and has been less fragmented by past depositional erosion and digenesis than most terrestrial evidence

Table 2.2. Evidence of climatic in deserts. (Cooke et al., 1993)

Evidence	Inference	Example
Fossil dune system	Past aridity	Thomas (1984a)
Breaching of dunes by river systems	Increased humidity	Deveau (1965)
Discordant dune trends	Change wind direction	Warren (1970)
Lake shorelines	Balance of hydrological inputs and outputs	Street and Grove (1979)
Lake – floor sediments	Dgree of water salinity, etc	Gasse et al. (1980)
Lunette sediments	Hydrological status of lake basin	Bowler (1973)
Spring deposits and tufas	Groundwater activity	Butzer (1978)
Duricrusts (latertic) and related palaeosols	Intense chemical weathering under humid condations	Goudie (1973)
Old drainage lines	Integrated hydrological network	Van der Graaf et al. (1977)
Fluvial sediments in ocean cores	Quantity of river flow	Sarnthein and Dister Haass(1977)
Aeolian dust in ocean cores	Degree of Aeolian deflection	Lever and McCave (1983)
Macro – plant remains (including charcoal) e. g. in pack rat middense	Nature of vegetation cover	Wells (1976)
Pollen analysis of terrestrial sediments	Nature of vegetation cover	Maley (1977)
Pollen analysis of marine sediments	Nature of vegetation cover	Hooghiemstra and Agwu (1988)
Fluvial aggradation and siltation	desiccation	Mabbutt (1977)
Colluvial depostions	Reduced vegetation cover and stream flushing	Price – Williams et al. (1982)
Faunal remains	Biomes	Klein (1980)
Karstic phenomena	Increased hydrological activity	Cooke (1975)
Isotopic composition of groundwaters and speleothems	Paleotemperature and recharge rates	Sonntage et al (1980)
Distribution of archaeological sites	Availability of water	Wendorf et al (1976)
Drought and famine record	Aridity	Nicholson (1981)
Frost screes	Paleotemperature	Mc burney and Hey (1955)
Losses profile and palaeosols	Aridity and stability	Pye (1984)

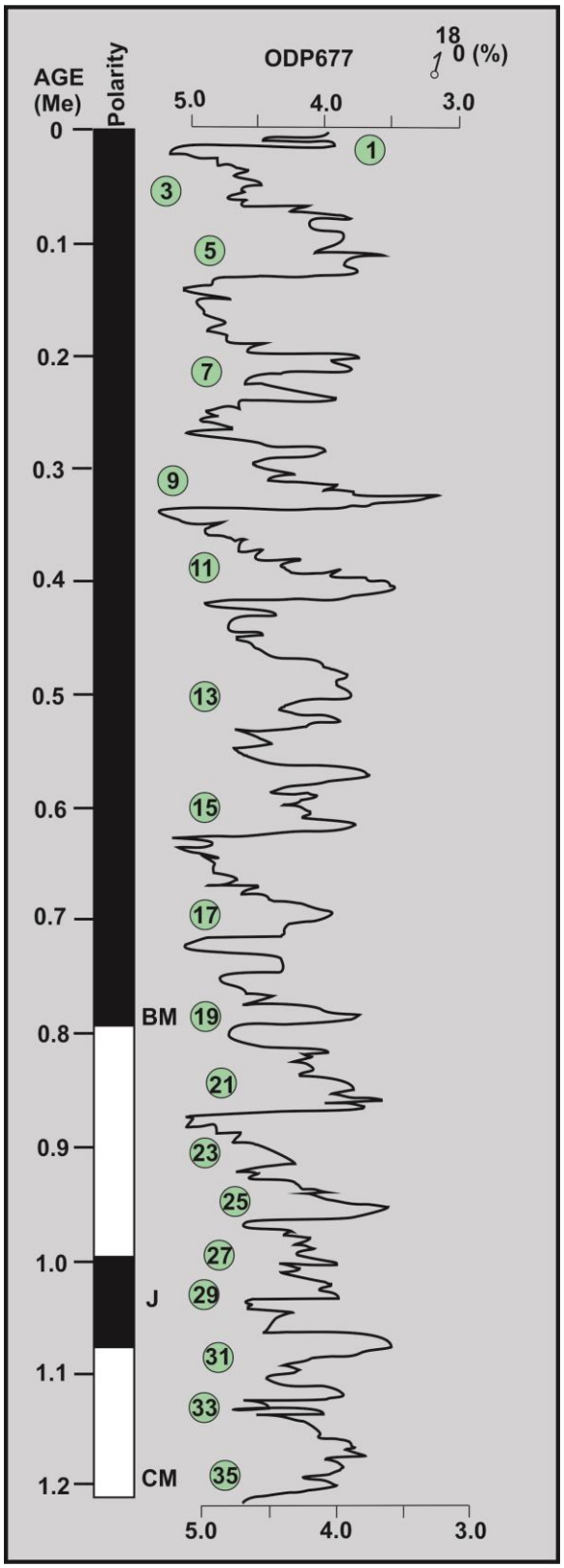


Figure 2.5 Oxygen isotope record and polarity from ODP 677 after (Shackleton et al 1990).

2. 4. 2 climate Changes in Iraq in the Cenozoic

The current climatic conditions generate insufficient flow to have eroded many of the existing valley networks in the Western Desert. Much of the present drainage network, therefore, must be related to wetter conditions that appear to have prevailed in Iraq and the rest of the Arabian Peninsula during some parts of the Pleistocene Period (Buday and Hak, 1980). However, it should noted that Anton (1984), based on studies in western Saudi Arabia, suggested that aridity has been a dominate feature of the region for most of the Pleistocene.

It is recognized that these has been a general rapid cooling of the Earth's climate over the period of the late-Pliocene and Pleistocene (the Quaternary), (Lowe and Walker, 1997), although geologically the whole of the Tertiary can been seen as period of gradual worldwide cooling (Williams et al., 1993). During the Quaternary however, the evidence from the marine isotope record is that there have been about 50 separate major cold phases in the past 2.6 million years (Catt, 2007). In the higher latitudes there major cold phases are believed to have been associated with a significant increase in glacial ice along with a global drop in sea levels. In the lower latitudes and in particular the contemporary desert region of the Middle-East, the effects of these phases of cooling are not well documented or understood. It has been suggested that the periods expansion and contraction of the high and mid-latitude ice sheets led to shifts in the main climatic belts of lower latitudes. This resulted in wide variations in precipitation and winds in the region currently described as 'Deserts'. According to Goudie and wells, (1995) in many of these areas fossil landforms and deposits can be found. These can be used to establish what changes occurred in the climate mainly during the later part of the Quaternary.

The most notable fossil landforms are those associated with lakes and dunes that have been used to infer wetter or drier periods respectively. However, data from these derived from these depositional features provides most evidence for only the Late-Quaternary. For example, work on the Niger area of the southern Sahara investigating fossil dunes, lake sediments and soils established the climate fluctuations over the past 40,000 years (Volkel and Grunert, 1990). The use of erosional features such as river valleys, as datable Palaeo climatic indicators has yet to be fully devloped, although work using in situ cosmogenic exposure dating may make this feasible in the future (Ilott, 2013).

Referring specifically to the Saudi Arabian Peninsula and the Iraqi Western Desert there have been few studies of the effects of fluctuating climatic conditions on the geomorphological history of the region. In Iraq the main literature still makes references to only four phases of glaciations (Gunz, Minde, Riss and Wurm) (Buday and Hak, 1980). This appears to be due to the adoption of the European glacial nomenclature developed over 30 years ago which has not been updated to incorporate all the latest evidence from marine cores. There are general references make by Al Fil (1966) and Al shalash (1966) to heavy rain and low temperature that occurred during wetter periods of the Pleistocene that caused in land lakes to expand and stream activity to increase. Al Shalash (1966) went on to say that between the older wetter periods the condition that prevailed in the region were similar to the present day, but he supplies no field evidence to support this hypothesis.

For the Middle-East an understanding of the nature of climate conditions during the early to mid-Quaternary remains an area requiring research. However, there is useful documented evidence for the nature of the climate fluctuations in the

North African and Middle-East for the past 35,000 years. For example, Whitiney (1983) studied datable deposits in Saudi Arabia and identified a period of wetter 'pluvial' conditions between 33,000 and 24,000 year BP. During this time quite large lakes developed in the Rubal Khali (Mcclune, 1976). Between 19,000 and 10,000 years BP these was extensive aeolian activity throughout Arabia suggesting increased aridity Whitney (1983) also established that another wetter period occurred between 9,000 and 5,000 years B.P with lakes again forming in the Rubal Khali. During this latter period Jolly et al., (1998) established that the Sahara was covered by Sahelian grrass and shrubs as for north as 23° N.

A slightly different record has been established by Bar-Matthews et al., (1997) working on speleothems frome the Soreq cave in Israel. They have shown that the conditions prevailing between 25,000 and 17,000 B.P were significantly wetter than the current climatic conditions in the region have also used a speleothem record from Southern Arabia and have been able to show that the present climatic conditions in the Arabian Gulf region are closely related to the development of the southern-western Indian monsoon. Indeed Fleitman et al (2003) showed that failure of the Asian monsoon following a period of global cooling around 8200 years BP may have triggered a 400 year long drought in the middle-East that led to people concentrating around the water resources of the Tigers and Euphrates resulting in the growth of early city states. As this section has tried to illustrate, the nature of the Pleistocene climatic fluctuations in the Iraqi Western Desert is not well understood and much of the literature refers to an out dated understanding of the complexity of the changes that are now known to have occurred during the Quaternary. References in still made to

pluvials and interpluvials based on the evidence from the Dead Sea provide by Lartet. That the Iraqi Western Desert was subject to major changes in climatic conditions during the Quaternary is unquestioned. The nature, extent, rapidity and intensity of these climatic changes has yet to be established. However, based on the morphological evidence of misfit ephemeral stream in large fluvially carved valleys, it is clear that at times during the Quaternary there has been sufficient water flowing through the catchments to have carried out significant amounts of erosion

2.5 Previous Geological and Geomorphological studies in Iraq

There are a number of previous studies of the Iraqi Western Desert but most of them concentrated on the bedrock geology. These studies showed that the study area belonged to the stable shelf of the Arabian platform which was consolidated at the end of the Precambrian. Abboud (1965, 1969, 1971, and 1972) refers to his many researches about the Iraq Western Desert over a number of years. These researches concentrated on the natural resources namely clay deposits in wadi Mulusai, preliminary prospecting on the clay in the central and south-western part of Al Garaa Depression, a report on estimation of the white clay reserve of the middle western rim of Al Garaa Depression, and the geological prospecting and exploration on Al Garaa ceramic clay deposits respectively.

Some of the research and reports were published but much remains unpublished, Al Mubarak and Amin, 1983; Jassim et al., 1984; Al Naqib et al., 1986; Al Bassam, 1986; Jassim and Goff, 2006. All the studies concentrated on understanding the geological history of the Western Desert including the tectonics. Geomorphological studies for the Western Desert, such as that by

(Buday and Hak, 1980, Buday and Jassiam, 1987), established a preliminary geomorphological model by describing the geomorphological features in the region. They divided the area into two basic morphological units: denudation of structural forms, and accumulation forms. The most important study resulted in a 1:1 million scale geomorphology map of Iraq (see map in appendix F on CD). (Sissakine and Mohammed. 2007) divided the Iraqi Western Desert in to three parts: the east desert, the middle desert, and the Western Desert. There are also unpublished reports and research which included a brief description of the Western Desert geomorphology, such as Al Naqib et al. (1986); and Al AMiri, (1978). In addition, there other works such as Al Kubaisi, (1993) concentrated on the geomorphology in the Rutba area, and Shaker (1993) who studied the area near Rutba town. Shaker, (2000) studied the geomorphology of the Houran valley whilst Al Dahi, (1996) and Hamed, (2003) studied the resources and geomorphology of the Garaa depression. Al fahdawi, (1996) looked at the Western Plateau in Iraq study of development in arid regions. Al A'athari (2005) studied the hydrogeomorphology of some dry valleys in the north part of the Western Desert between Aqaiam and Anha city. Al Jumaily, (1990) looked at the landforms of the Euphrates River valley between the Haditha and the Heet, and Al Dulaimi, (1995) looked at the geomorphology of the Euphrates river valley between Heet and Ramadi. Al Jumaily and Al Naqash (2008) studied the geomorphology of the dry wadis of the Iraq Western Plateau, and Al Heety (2012) looked at land degeneration in the Al Rutba area. However, no previous attempt has been make to bring all this published work together.

2.6 Drainage in the contemporary desert fluvial environment

Since outstanding the early contributions of Horton and others there has been an enormous interest in the geomorphological study of drainage systems. In the past five decades progress has been particularly rapid, thanks notably to research workers in the United States geological Survey. Much of the recent works has been reviewed and is readily accessible (e.g. Leopold, Wolman and Miller, 1964; Carson and Kirkby, 1972; Cooke and Warren, (1973). Our purpose here is not to repeat this information, but to select and summarize some of that which is pertinent to drainage systems in Iraqi Western Desert as a model for arid and semi-arid lands. In recent decades a few authors have studied some of these morphometric properties in dry lands and related them to other environmental variables. For example in a multivariate analysis of 22 drainage basins in the south–western United States Melton (1965) demonstrated that drainage density (the number of stream per unit area) is high on rocks with low infiltration capacities. Schumn and Hadley (1961) also investigated several aspects of drainage basin morphometrics in semi-arid areas of the United States with a study of 59 small drainage basins the showed that mean relief ratio (relief of drainage basin / basin length, measured in a straight line approximately parallel to the major drainage channel) correlated closely with mean annual sediment yield (measured from accumulations in stock-water reservoirs). Hodgkinson, (2005) refers to the relationship between geological fabric and drainage patterns in the 81.8 km^2. Laceys Creek sub-catchment of the North Pine River catchment in Australia, which he analyses using a new channel–ordination system. Other researchers have looked for the relationship between the rock fabric and drainage basin. For example Twidale, (1980). Also Twidale, (1980) He said the rock fabric has been shown to influence drainage

patterns at very fine-scales (e.g. Twidale, 1972; Scheidegger,1979a,b; Ackermann et al., 1997; Eyles et al.,1997; Eyles and Scheidegger, 1999; Beneduce et al.,2004). It has long been assumed the relationship between erosion and sedimentation occurs as a result of zones of weakness in the bedrock enhanced by weathering and erosion processes, although data mostly have been insufficient to confirm this (Ericson et al., 2005).

2.6.1 Desert drainage systems

During the Pleistocene the world endured major fluctuations in climate, and desert areas, particularly at the contemporary margins, these climatic fluctuations resulted in glaciations, in desert there were times of higher rainfall known as pluvial periods. The timing of pluvial periods and whether or not these coincided with high-latitude glaciations is still being investigated. However, it is important to recognize that not all the fluvial features that can be observed are the result of contemporary processes and therefore may not be part of the episodic change model in model in particular area. (Griffiths et al., 2012). Not all rivers have their sources within the desert areas whilst some desert rivers finish within the desert and never reach the sea such as the Euphrates River flow through the Iraqi Western Desert but it has its source in the Turkey Highlands. Dry valleys flows and natural rates of sediment yield are a critical measurement of geomorphic processes in arid environments.

There is considerable evidence of the long-term impact of tectonic activity on patterns of drainage in contemporary drylands. Frostick and Steel (1983) discuss the development of patterns of radial drainage in some dry environments such as southern Africa in response to doming of the crust at a regional scale. The development of a rift system may also result in the

reorganisation of drainage patterns, as shown by the model for the development of drainage in East Africa. (Thomas, 2011). Reid and Frostick., (1987 and 1997) also noted that the backtilting and uplift of fault footwall blocks essentially diverts drainage away from the main axial depocenter in the East African rift valley A similar effect is provided by the Red Sea-Gulf of Aden region, where rifting began in the Miocene, in which rivers approaching within 2 km of the west bank of the Red Sea are diverted into the Nile catchment (Froctick and steel., 1993). The desert drainage system presented in chapter 6 in this thesis.

2.6.2 Dryland Channel forms and processes

The hydrology of desert as elsewhere is a function of the climate. This effect can be direct, with rain falling onto the surface, or indirect through its secondary role in creating the conditions for the specialist vegetation cover found in arid areas. Desert vegetation is normally sparser than that found in areas with more temperate climates and is not as influential in acting as a collector or attenuator of the effects of precipitation. Rainfall landing on the ground surface therefore can move quite rapidly through the hill slope system into stream channels (i. e. a high runoff coefficient). The main attenuating affects on rainfall are likely to be the rate of infiltration into the slopes, which will be a function effects should not be discounted and many plants have a widespread root network that is not immediately apparent on the surface

The flow regime of ephemeral stream flows is characterized by a rapid rise to peak flow often but not always travelling down the channel as a series of bores (waves) typically labelled a flash flood. The flow is usually the result of a spatially limlted and localized convectional storm within the river catchment, there being no base flow associated with ephemeral rivers .The flow hydrograph

has a very steep rising limb, and a longer falling limb, that reflects both the pulse of ephemeral water moving through the river system and the loss of water during transmission into the river bed.

The shape and size of dryland channels adjust in response to temporal variations in dry environments areas and transmitted through the channel cross-section Leopold et al., 1964; Gregory and Walling, 1973; Richards, 1982; Knighton, 1997 . As discharge and sediment supply vary along river courses, channel adjustments also occur in the downstream direction Tooth (2000). The description and quantification of these downstream changes in river channel form and process have long been major research themes in fluvial geomorphology, particularly through analysis of the downstream hydraulic geometry exponents of rivers in different physiographic and climatic settings (Knighton, 1987) for reviews. Tooth (2000) many of previous studies have referred to downstream changes in dryland channels morphology and inferred flow conditions in dryland channels e.g., Leopold and Miller, 1956; Schumm, 1961; Thornes, 1976 and1977; Mabbutt, 1977; Clark and Davies,1988; Nouh, 1990; McCarthy et al., 1991.

Despite the increasingly of knowledge on dryland channel in dry environments, deficiencies in understanding still remain. Identification of these gaps, however, can help to prioritise future research efforts in this environments.This section has highlighted the need to develop better links between the results of short-term, process–form researches and researches of the longer term histories of dryland channels. Continued interest in dryland channels, probably ensures that dryland channel researches will develop rapidly in the presently because using the remote sensing and Geographical information system in this researches and

make Better integration in these sciences to improved scientific understanding of dryland channels, and to their environmentally sensitive management. Tooth, (2000).

2.6.3 Alluvial fans

Alluvial fans develop at the base of drainages where feeder channels release their sediment load (Parsons et al., 1994). Alluvial fans can be found in almost all terrestrial settings. (Blair and Mcpherson, 2009; Leeder et al., 1998; Harvey et al., 2005; Beaudion and King, 1994; Iriondo, 1994 and Thomas, 2003)

Most of the precise and important work on alluvial fan system their associated landforms has been accomplished work on alluvial fans and their parts of some part of the USA notably by Anstey, (1965), Beaty, (1963 and 1970), Blissenbach, (1954), Bull, (1962,1963,1964,1977 and 1997), Lusting, (1965), Melton, (1957 and 1965). Several features of deserts have been invoked to explain the occurrence of alluvial fans. Firstly, the lack of vegetation means that positions of drainage channels are relatively unfixed. Secondly ideal conditions fan formations, typical of many desert areas are long periods when debris can accumulate in the mountains Beaty (1963). Alluvial fans are a naturally unique phenomenon readily distinguishable from other sedimentary environments, including gravel-bed rivers, on the basis of morphology, hydraulic processes, sedimentological processes, and faces assemblages (Simon et al., 1995). Baltzer (1990) studied alluvial fans in the lower Mesopotamian Plain and the Arabian Gulf the major alluvial fans complex which is associated with the Tigris-Euphrates Rivers. Alluvial fans are accumulations of essentially fluvial deposits that have a cone-like where drainage out over flat-lying pediments from the point where drainage leaves a mountainous area. Because the mountain

stream suffers a dramatic change in the width to depth ratio of its channel system, flow velocity drops leading to very high sediment concentration and deposition. On the alluvial fan, ephemeral stream channels are highly unstable and can adopt anastomosing (criss-cross) network that change location during each flow event. At the fan apex the channels are often incised leaving a relict fan surface at a level above contemporary flood activity. Similarly, some alluvial fans show evidence of former conditions with relict fan fragment left in situ whilst new fans develop further downslope creating a segmented fan system .Where a series of ephemeral stream channels exit from the mountains, the active fans combine to create a feature known as ‘bajada’. For a full description of the processes of fan development. On alluvial fans, the high sediment ratios can result in an essentially fluid flow turning into a viscous semi-plastic flow. The type of mass-movement feature created is known as a debris flow, which has the consistency of wet concrete. Debris flow can be very destructive and travel quite large distances down the alluvial fan with the far-travelled fine debrise ending up as a thin mudflow.

2.6.4 Pediments

Pediments, are gently sloping erosional surfaces of low relief developed on bedrock, and occur in a wide variety of lithologic, tectonic, and climatic conditions (Parsons et al., 1994). Multiple levels of both sediments and erosional surfaces are usually reported in pediment areas, and similar to fluvial terraces, the highest level is regarded as the oldest (Pastor et al., 2012). Many of references have identified pediment landforms in widely varying lithologic, climatic, and tectonic settings suggesting the form is not unique to deserts (e.g., Gilbert, 1877, Mackin, 1936, Bull, 1997, Merritts et al., 1994, Pazzaglia et al.,

1998, Hancock and Anderson, 2002, Wegmann and Pazzaglia, 2002 and Montgomery, 2004 and 2010).

Studies of pediments go back to the 20th century (e.g. Pastor et al 2012,) but the quantitative analyse did not start until the end of the fifties. Pediments appear to has attracted more study and controversy and have sparked the imagination of more geomorphologists, than most other landforms in dry environments (Cooke 1975; Cooke and Warren, 1973). By there is little doubt that many pediments are erosional features because they are cut discordantly across structures and rocks of developed on particular rock types. Coarsely-crystalline rocks, and notably granite, are certainly commonly associated with pediments (Cooke and Warren, 1973). In addition, it may be impossible to assume that present drainage networks on a contemporary pediment are associated with its formation. See Picture 2.1 show Pediments in study area

Picture 2.1 Pediments in south rim of Garaa depression

2.6.5 Playas and Sabkhas

These geomorphic features have different names, depending upon the culture that dominates the region of their occurrence, thus we find salinas, salares, saladas, salars, and playas in many Spanish-speaking cultures;pans, saline lakes, alkali flats, salt plains, dry lakes, and salt flats in English-speaking cultures; sabkhas (inland and coastal) and its variant spellings in the Arabic-speaking world; Rosen (1994). In general they are salt pans in depressions and are a widespread feature of many of the dry environments in the world.

Playas and sabkhas are formed under hydrologically similar conditions, varying only in their boundary conditions. Thus, in evaluating geochemical processes in these systems, a generic water and solute mass-balance approach can be used

(Yechieli at el., 2002). The terms playas and sabkha are often used inconsistently because the criteria for recognition are not clearly established and because current definitions are inadequate (Briere, 2000).

Thomas, (2011) noted playas and vary in size from very small depression of a few tens of square metres in the Kalahari, western Australia and Texas (Goudie and Thomas, 1985; Killigrew and Gilkes, 1974; Osterkamp and Wood, 1987), to massive tectonic basins, which may exceed 10 000 km^2, such a lake Eyre, south central Australia, and Lake Uyuni, Bolivia (Lowenstein and Hardie, 1985). Playas and pans have been described in most hot dry land environment; particularly the Arabian desert, Australia, western USA and Africa see (Thomas, 1997). Because the criteria for recognition are not clearly established and because current descriptions are insufficient, definitions are proposed here to reduce the ambiguities and contextual problems at the present time exist taken from Briere, (2000). Sabkha is a shallow basin limited to marginal marine settings and associated with several per cent gypsum or gypsum parting laminae due to preferential halite dissolution during flooding periods. Sabkha is an Arabic word for salt flat, which has become entangled with playa. Sabkha is the correct plural, despite the prevalent use of sabkhas (Neal, 1975). Sabkha is a term widely used to describe the abundant and extensive salt flats around the Arabian Peninsula. Barth (2001), Motts' (1972) suggested that playas should be dry more than 75% of the time and salt lakes wet more than 75% of the time. Neal (1975) suggests that playa must be used as a broad term to describe many forms of topographic depressions and desiccated former lakes occurring in arid environments.

2.7 Summary

This chapter introduces the geomorphology of hot deserts. This chapter showed the defined and description the Hot deserts in world according to the classification for the UNEP. The second part of this chapter established the typical models of dry land environments. It was noted that much of the deserts have been described as remarkable repositories of Quaternary paleoclimate information. Climatic fluctuations and their related geomorphological effects during the Cenozoic are the result of climate variability. Specific environmental changes occurred in Iraq during the cenozic and notably the Quaternary which had significant effects on its landscape evolution. This period had not been studied in Iraq were neglected until the start of the regional geological survey program conducted by GEOSURV during the 1970s and completed in 1982. It is against this geomorphological background of exiting global literature but very limited Iraqi data that the investigation of the drainage evolution of the Iraqi Western Desert was undertaken. The methodology adopted is described in the following chapter 3.

Chapter 3

Methodology

3.1 Introduction

This chapter describes the compilation, revaluation and methods of analysis of the data that were undertaken for the research presented in this thesis. Data were collected both through desk studies and in the field.

For the desk studies the range of sources of information included the following:

The geological reports from the Geological Survey of Iraq 75 % of them written in Arabic.

The maps from the Geological Survey and Mining in Iraq and the Ministry of Water Resources. The age of these maps, especially the topographic maps are different with the majority published majority between 1980 and 1990. There are other maps published in the period 2000 to 2005 such as the Geomorphological Map of Iraq (2000) and Geological Map of Iraq (2000). The maps are at a range of scales from 1:1 million to 1:50,000

Google Earth satellite images: analyses and interpretation of Google Earth images and satellite images was carried out using Google Earth Pro to understand the nature of the geomorphological features in the Western Desert

Generally available publications from the scientific literature on hot deserts (in English).

Government records resources, notably data on climate and seismicity

Iraqi Library collections of scientific papers and topographic maps (most only available in Arabic)

Details of the Desk studies and how data were ratified and analyses are presented in Section 3.2. For this stage of the work data were compiled in a GIS (as described in Section 3.2.4) to enable preliminary evaluation of the terrain to be carried out (the topic of Chapter 5). Many of the maps were summarized to

allow comparisons to be made between geology, terrain and drainage and this was carried out using CorelDraw (Section 3.2.3) and Geo Map (Section 3.2.5). The combination of the GIS and CorelDraw was used to support the desert drainage analyses presented in Chapter 6.

In addition to the analysis carried out as desk studies, the combination of GIS and CorelDraw were used to compile customized topographic and preliminary terrain maps for use in field work. Two phases of field work were carried out:

1) Initial limited field reconnaissance plus numerous visits to Iraqi ministries and libraries between May and July, 2010.

2) A more extensive field season January to March 2012, (described in Section 3.3) when ground truth mapping of the terrain classification was carried out as well as identification and description of some river terraces. This was also a field season where contact was made with local people who provided information on the area.

3.2 Desk Study

This study collated existing data relating to the Iraqi Western Desert topography, geology, and geomorphology. Initially general background scientific papers and reports were collected, and then a more detailed collection exercise was undertaken focused on the areas between Al Rutba town and Al Qaiam town. Based on these studies gaps in the data were identified that established priorities for future data collection. Useful sources of desk study data included Government ministries such as the Ministry of Industry and Minerals State Company of Geological Survey and Mining, and the Ministry of Water Resources. Iraq also has a number of important and well-resourced libraries that were visited, including those at the various Iraqi universities such as:

Central Library at the University of Baghdad (site of Waziriya); Central Library at the University of Baghdad (site of Jadiriya); library of the Faculty of Science Department of Earth Science University of Baghdad; library of the Faculty of Arts Department of Geography University of Baghdad; library of the Faculty of Education (Ibn Rushd), University of Baghdad; Central Library at the University of Al Anbar; and the Centre of Desert Studies in University of Al Anbar. A number of other government and non-governmental organizations with an interest in the study of dry environments were visited including: the Department of Dams and Water Resources; the Remote sensing Department of Al Anbar University College of Engineering; the Department of Biological Faculty of Pure Science Education University of Al Anbar. Data on meteorological conditions were also collected from the weather stations at Haditha, Anha, Qaiam, Nukaib and Rutba (Chapter 1 Figure 1.1).

All these sources of data were identified through personal knowledge and by making contact with the various libraries, Government Organisations and universities. A significant amount of time was spent during the first field season organising access to the documents and maps as many were under government and or military control so there were major restrictions on their use and availability. In the initial phase of compilation the emphasis was or translating reports and papers from Arabic and scanning maps (Appendices C, D, E and F in CD). There was little attempt at this stage to access the quality of the material, although with respect those produced by the military (mainly topographic) and the Iraqi Geological Survey these were recognised as being of the highest quality available.

The compilation of data and maps in a desk study had initially been intended as the preliminary phase of an investigation that would have involved a significant period of field work. However, the deteriorating security situation in Iraq caused the project to change in form with a far heavier reliance on desk studies. In this regard the researcher, as an Iraqi Citizen, was able to gain access to information held in libraries Government Ministries and University Department that had never that had never been published and indeed has never been make available outside Iraq before.

The various data sources of the maps are presented in this section, but the information from unpublished reports have been used to underpin the work on the geology (Chapter 4) and geomorphology (Chapter 5).

3.2.1 Scientific documents

This section introduces the scientific documents compiled for this thesis:

a) **Government records resources and data:** this includes maps of different types and scales that are discussed in section 3.2.2 (Topographic maps) and 3.2.3 (Geological maps). For this research all the maps for the study area were collected and examined. There were maps of a quality that were acceptable to ministries and other government bodies. The topographic maps are notable in that they were produced in different years, as presented in Table (3.2)

b) **Government Climatic data:** Climatic data was collected from five weather stations in the Iraqi Western Dessert in (Chapter 1 Figure 1. 1). Data were also collected from the Transport and Communications Ministry General Authority who have responsibility for monitoring weather conditions (and earthquakes).

These data included rainfall, temperatures, wind speed, relative humidity, and evaporation and transpiration

c) **Iraqi Libraries in Baghdad and Anbar:** collections of scientific papers and general topographic maps (most only available in Arabic) including unpublished reports, degree theses and books.

d) **Google Earth images:** Google Earth pro satellite imagery was used to create high resolution maps for the study area. Geomorphological units and landforms could be identified on these images and by using different applications in Google Earth Pro (Section 3.2.5). The author worked with a mosaic of Google Earth images taken between 2005 and 2013 in order to produce an overall image suitable for analysis

e) **Geographical information system (GIS) data:** spatial data in the forms of maps were into a GIS framework in ArcGIS version 10. This program was used in the analysis of dry valleys which is presented in Chapter 6.

As noted above the author worked with a mosaic of various maps and images to facilitate the creation of a new maps that were a synopsis of published and unpublished maps of varying scales, such as the existing very simple geomorphological map of Iraq 1:1, 000000, (Appendix F on the CD) and topographic maps with scales of 1: 250,000, 1: 1, 00 000, 1: 50 000 (Appendices C, D and E on the CD). These data were supplemented by the inclusion of field data from the two field seasons and formed the basis for the interpretation of the terrain and geomorphological units in the Iraqi Western Desert. This led to the production of a new geomorphological map of the region in Coreldraw (section 3.6).

3.2.2 Topographic maps

Hard copy topographic maps at scales of 1:1,000, 000; 1: 250,000; 1:100,000 and 1:50,000 were collected from Geological Survey and Mining in Iraq and the Ministry of Water Resources as well as limited digital versions of maps at 1:1,000, 000 and 1:100,000 scale from Geological Survey and Mining in Iraq. All the hard copy maps were scanned and the mosaic of the compete 1: 250, 000 scale scanned maps is shown in Figure 3.1. As can be seen in Figure 3.1 the topographic maps are of varying style and this reflect their different age of production as presented in Table 3.1. The hard copy maps at 1:250,000 scale were not actually published and were retained for Government and military only. Only the 1:250,000 scale topographic maps were available for the whole of the Iraqi Western Desert therefore these formed the basis for all subsequent work on the geomorphology. In order to allow boundary issues to be reconciled the maps were compiled in ArcGIS but output was produced in Coreldraw. Some maps at larger scales were located in the Government records that covered Rutba and other areas of particular interest and these were digitised to provide base maps for subsequent field work (Figure 3.2). The purpose of the topographic maps mainly to delineate watersheds; establish dry valley network; measure slope angles; but also to plan field access routes. In total the researcher used 75 hard copy maps:

- 10 maps at 1 to 250,000 (see Appendix C in the CD)
- 27 maps at 1 to 100,000 (see Appendix D in the CD)
- 38 maps at 1 to 50,000 (see Appendix E in the CD). Also the researcher used 7 digital maps:
- 6 maps at 1 to 250,000
- 1 maps at 1 to 1,000,000 (see Appendix F in CD)

As noted there were all complied in Coreldraw after being scanned.

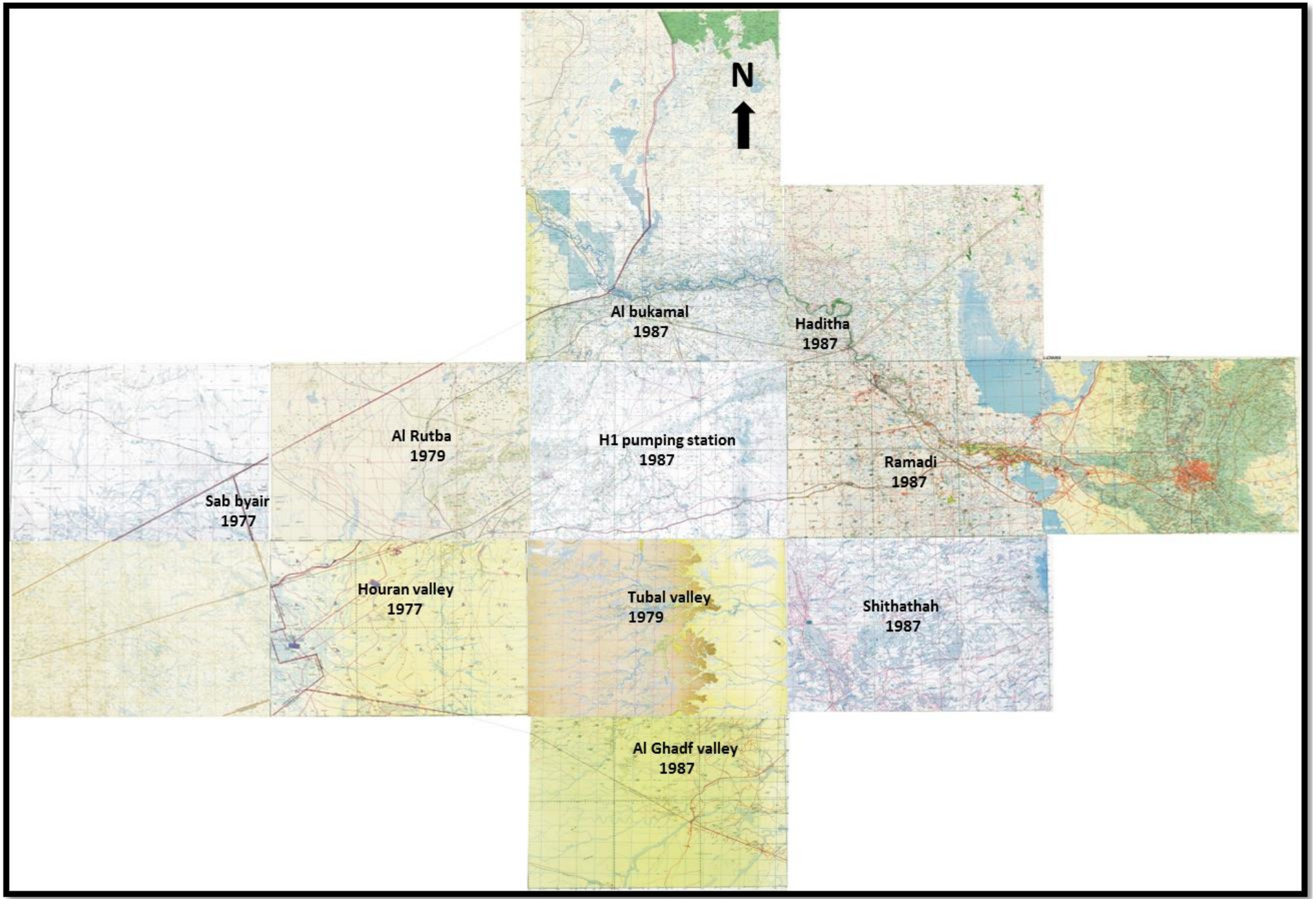


Figure 3.1: Topographic maps collected for Iraqi Western Desert. These were all originally at 1:250,000 scale

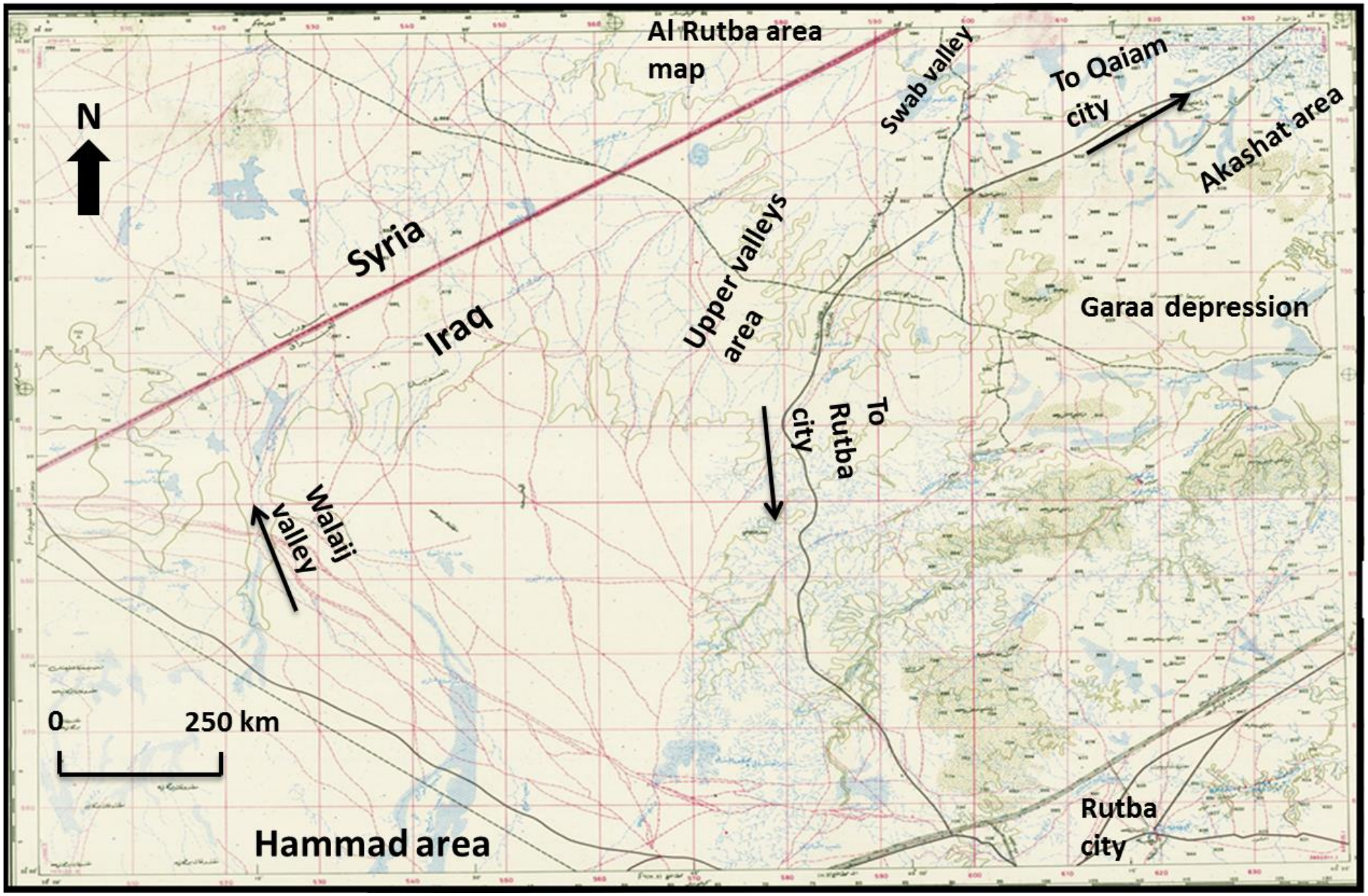


Figure 3.2: Topographic map for the AL-Rutba area in study area; original scale 1: 250, 000

Table 3.1: Shows the topographic maps that were collected to make the overall map of the Iraqi Western Desert

Map name	Scale	Compiled
Rutba	1:250 000	1979
Houran valley	1:250 000	1977
Tubal valley	1:250 000	1979
H1 pumping station	1:250 000	1987
Al Ghadf valley	1:250 000	1987
Shithathah area	1:250 000	1987
Al bukamal arae	1:250 000	1987
sab byair area	1:250 000	1977
Haditha area	1:250 000	1983
Ramadi area	1: 250 000	1979

Figure 3.2 is as an example of one of the dozens of unpublished maps which were collected as hard copy. Because all these maps were produced by the Iraqi Government they represent the high quality available and have been produced to the best standards prevailing at the time.

3.2.3 Geological maps

The overall geological map (chapter 4) was based on the Iraqi geology map available at a scale of 1:1,000,000 (Sissakian, and Mohammed, 2007). In addition, access was obtained to the following unpublished geological maps at the larger 1:250,000 scale and there were used to draw up a more detailed geological map of parts of the Iraqi Western Desert

- Rutba area geology
- Houran and H4 geology
- H1 geology
- H2 geology
- H3 geology
- Qaiam geology
- Al bukamal geology

In these maps the lithological and stratigraphical database of the geological formation were identified and there were used to develop the interpretation of the geology presented in Chapter 4.

3.2.4 Geomorphological maps

A 1: 1,000,000 scale geomorphological map of Iraq was produced in State Company of Geological survey and mining by group of technicians. This map showed the majority of the Iraqi Western Desert to be an undifferentiated purple that was labelled ‘desert’. Whilst this map was available as part of this research it was of little value. Parts of the Western Desert had mapped in more detail by Buday and Hak (1980), also at the 1:1,000,000 scale. This was of for more value and used as the basin for producing a new geomorphological map as part of this thesis that incorporated updated information on the geology and a more up to data understanding of the geomorphological evolution of landforms in hot deserts.

3.2.5 Google Earth images

Google Earth images were downloaded using Google Earth Pro and subject to compilation, analysis and interpretation. These data were digitally overlain on maps of geology and the very limited geomorphology that had been compiled in Coreldraw. Initially the study area was identified using Google Earth pro satellite imagery and the zoom feature was used to create high resolution (10m) maps. Geomorphological units and landforms could be identified at this resolution. This map of Iraqi Western Desert was then sub divided using a Google Earth grid overlay function and captured images of each grid square were used create a mosaic with snapshots of the entire municipality. The purpose of capturing snapshots of the satellite images in Google Earth and then

reconstructing the picture in CorelDraw was to allow future users to work with the complete satellite map without the necessity for an Internet connection. Picture Manager (Microsoft) was used to further manipulate the reconstructed pictures to create a smooth transition between the component snapshots. This software is not required for further production of the map since the mosaic can be fully constructed in CorelDraw; however the component snapshot images were cropped and organized in a mosaic and their orientations relative to each other were saved in an images format. At the completion of this step, the geo-referenced satellite map of Iraqi Western Desert was one composite image.

3.2.6 CorelDraw

As identified above maps of different scales collected during various visits to Iraqi ministries and libraries were compiled, registered and corrected using the cartographic software package CorelDraw. Boundaries between adjacent map sheets in particular required clarification in order to produce bespoke maps of the study area (Figures 3.1). ColeDraw x5 is a highly complex and sophisticated drawing package which has many uses in cartography. The value for this research was the flexibility that enabled a range of completed maps to be drawn, easily updated and reproduced. These maps could also be readily input to a GIS (Section 3.2.7) as raster or vector data for subsequent manipulation and analysis.

3.2.7 Geographical Information System (GIS)

A GIS is designed to manage and manipulate spatial data, carry out analyses on the data and produce summary maps. In this research raster model and vector models were developed within the GIS environment (for more details of the development of GIS see: Butler and Walsh, 1998; Walsh et. al, 1998; and Vogt. et. al, 2003).

1. A raster GIS model uses pixels, with each pixel covering a defined area having spatial co-ordinates, and for each pixel there will be a range of attributes. One attribute would be the average elevation within each of the pixels that enables a Digital Elevation Model (DEM) to be created for the whole area. The same pixel might also have details of geology, geomorphological unit presence of a river attributed to it. Thus for any pixel that is identified in a spatial location (x, y coordinates) a range of additional information on the nature of the ground in the pixel can be complied in the GIS.

2. The vector GIS model uses points, lines and polygons to represent the landscape (Walker, 2012). Given points can be elevation, and lines topographic contours the data also allows the production of a DEM. The vector model DEM can enable the automatic delineation of water flow paths, definition of watersheds, and flow networks which helps to facilitate all form of hydrologic modelling. Digital representation of the flow network is central to the production of general hydrologic models because it establishes the linkages through which flow is routed to the outlet. This also provides a measure of drainage density although field mapping is acknowledged as the most accurate way to determine channel networks and drainage density (David et al., 2001).

For this research an evaluation of the drainage network defined by dry valleys in Iraqi Western Desert was carried out and of particular importance was the identification sub-basins as they influenced flooding in the main channels. Drainage networks for the sub-basins were obtained from topographic maps scaled 1:250.000 and 1:100 000 and input in the GIS. This formed a key part of the investigation of the drainage network evolution presented in Chapter 6. Additionally an important output from this research is the GIS presented on the CD accompanying this thesis which will unable by subsequent researches of the Iraq Western Desert to utilise the data without having to undertake a full data compilation exercise. In addition to the work on drainage evolution, the GIS has been used compile a new Geomorphological Map of the Iraqi Western Desert (Chapter 5 Figure 5. 18). The data used in the production of this map were obtained from a collection of individual studies carried out over the past 50 years and brought together by this research. The map itself has been subject to a degree of ground truthing (Section 3.3).

3.2.8 Data in Geo Map

The interpretation of the tectonic elements of the study also relied on the use satellite images. These were downloaded from the NASA website http://www.nasa.gov/ using Geo Map (Figure 3.3). The data for this study was downloaded by Geo Map from this external database only. The purpose was to provide some comparative studies between the data downloaded in Google Earth and that compiled in the GIS. For this research, however, it was found that there was sufficient data already available from Google Earth Pro and exiting maps for the main aims of the thesis to be addressed. Therefore, this component of the data collection was not taken any further.

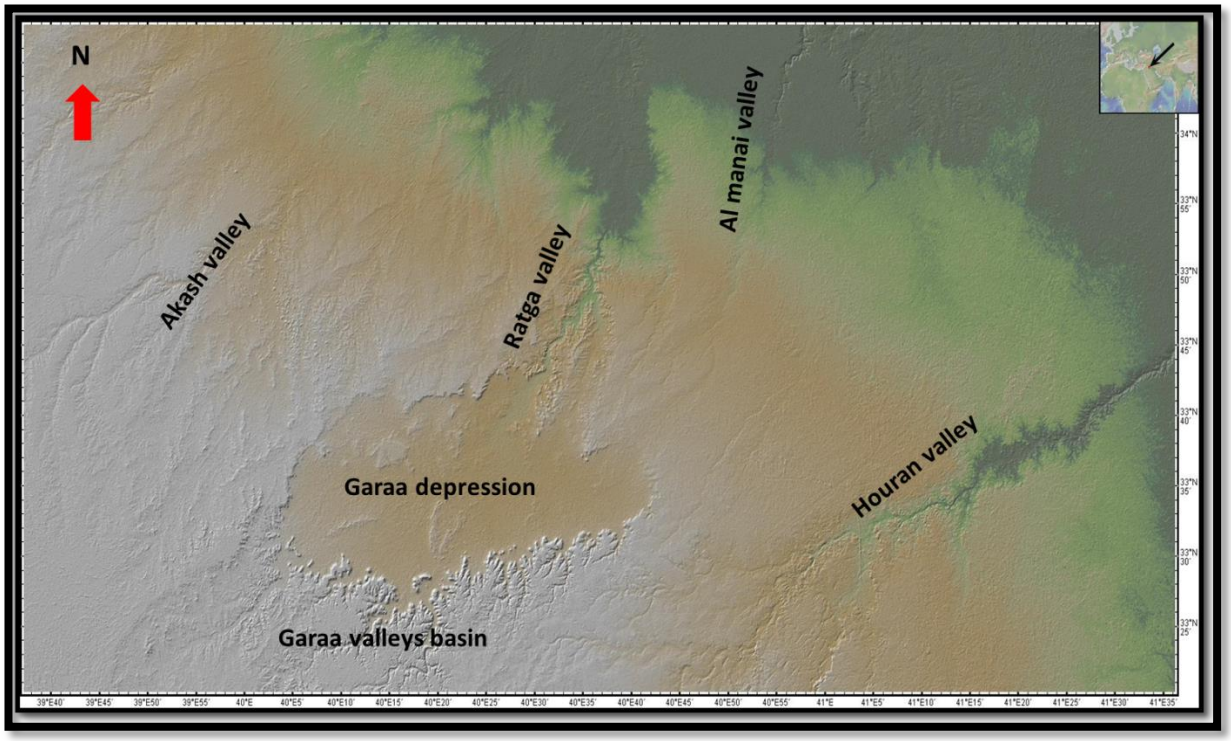


Figure 3.3: some parts of Iraqi Western Desert downloaded by Geo map program

3.3 Field studies

Following the data collection phase for the desk studies limited field work was undertaken the aim on both the visits to Iraq was to include a phase of field data collection on conditions in the Iraqi Western Desert at key sites. As noted above the first visit (April-August 2010) was spent mainly compiling maps and existing data on the field area from libraries, and ministries, but with a brief 'driveover' field reconnaissance of the northern part of the study area around Al Qaiam city at the Syria-Iraqi borders. The second field reconnaissance was undertaken December 201-February 2012 when field data were collected for the areas around Rutba city. In preparation for this second field season time was spent with the project supervisors training in field data collection techniques. The primary aims of the second field season were to confirm (ie. ground truth) and

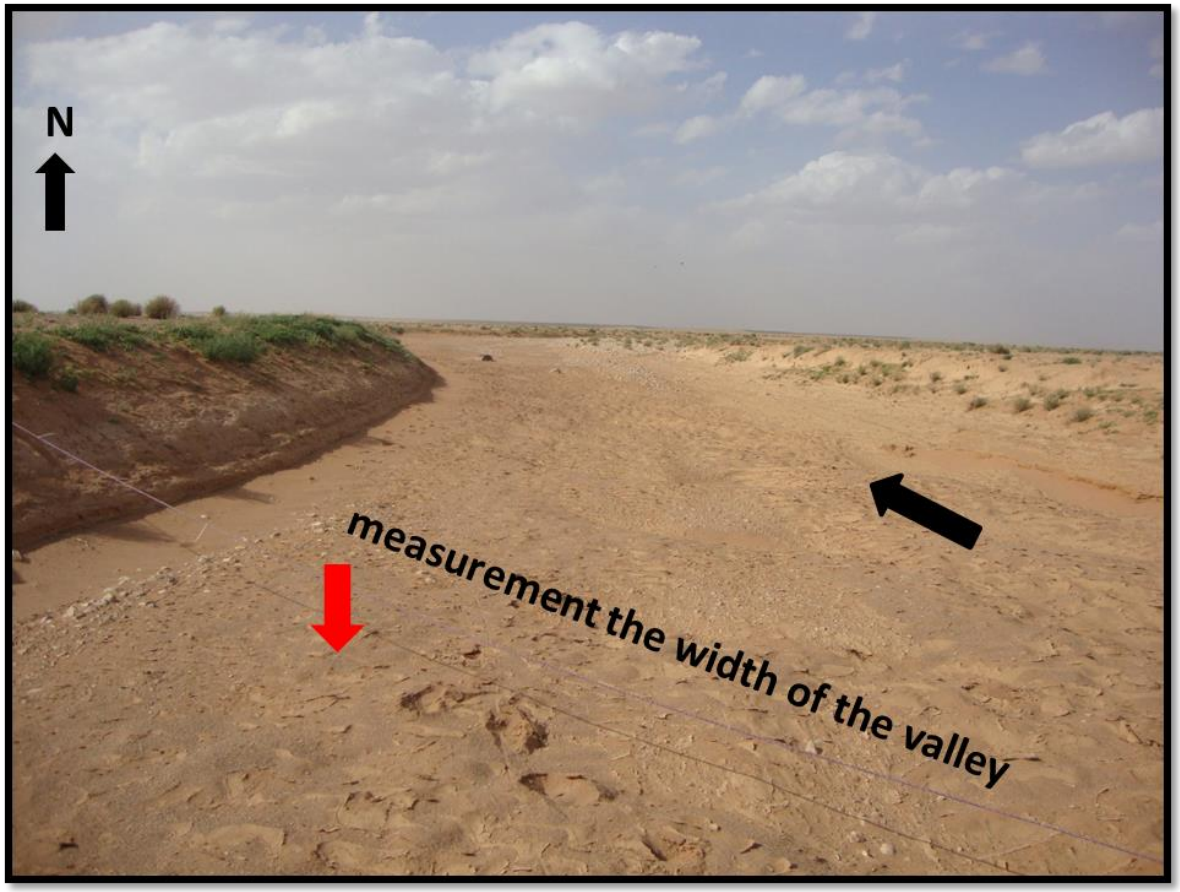
refine the preliminary terrain evaluation analysis that had been undertaken in the UK on the data collected during the first visit to Iraq; and to collect more detailed fluvial geomorphological data in selected dry valleys, one with endoreic and the other with exoreic drainage. In addition a number of river terrace sites were visited to support investigations into the nature and formation of the dry valleys, especially the main valleys such as Houran, Walaj, Ratga, Al Agrai, Manai valleys, and the valleys leading into the Garaa depression (see Figures 6.4 and 6.24). In 2003 there was US military intervention to oust the Iraqi regime under Saddam Hussein. Since that time Iraq has faced increasingly violent sectarian divisions which are undermining the fragile peace in Iraq especially in the Iraqi Western Desert. Because of the large area of the Western Desert and the fact that it shares borders with Syria, Jordan and Saudi Arabia, the Iraqi army has said that Iraq would be unable to execute full external defence of this area until 2020-2024 (Katzman, 2013). Violence has escalated in different parts of Iraq, and many armed groups have settled down in the Iraqi Western Desert, especially in the area around the Rutba town and the Horan valley. Unfortunately this is in the centre of the research study area for this thesis. Whilst the author was able to obtain security approvals in order to bypass the curfew in the region, any field activities had to be coordinated with the military who had to accompany the author in the field along with an experienced guide. For this reason with the support of the project supervisors the authors' fieldwork research was curtailed on the grounds of personal safety. This is an on-going tragedy for the people of Iraq and in particular those indigenous to the Western Desert, who have been described as the most friendly in the Middle East (War and Navy Departments, 1943).

3.3.1 Ground truth mapping

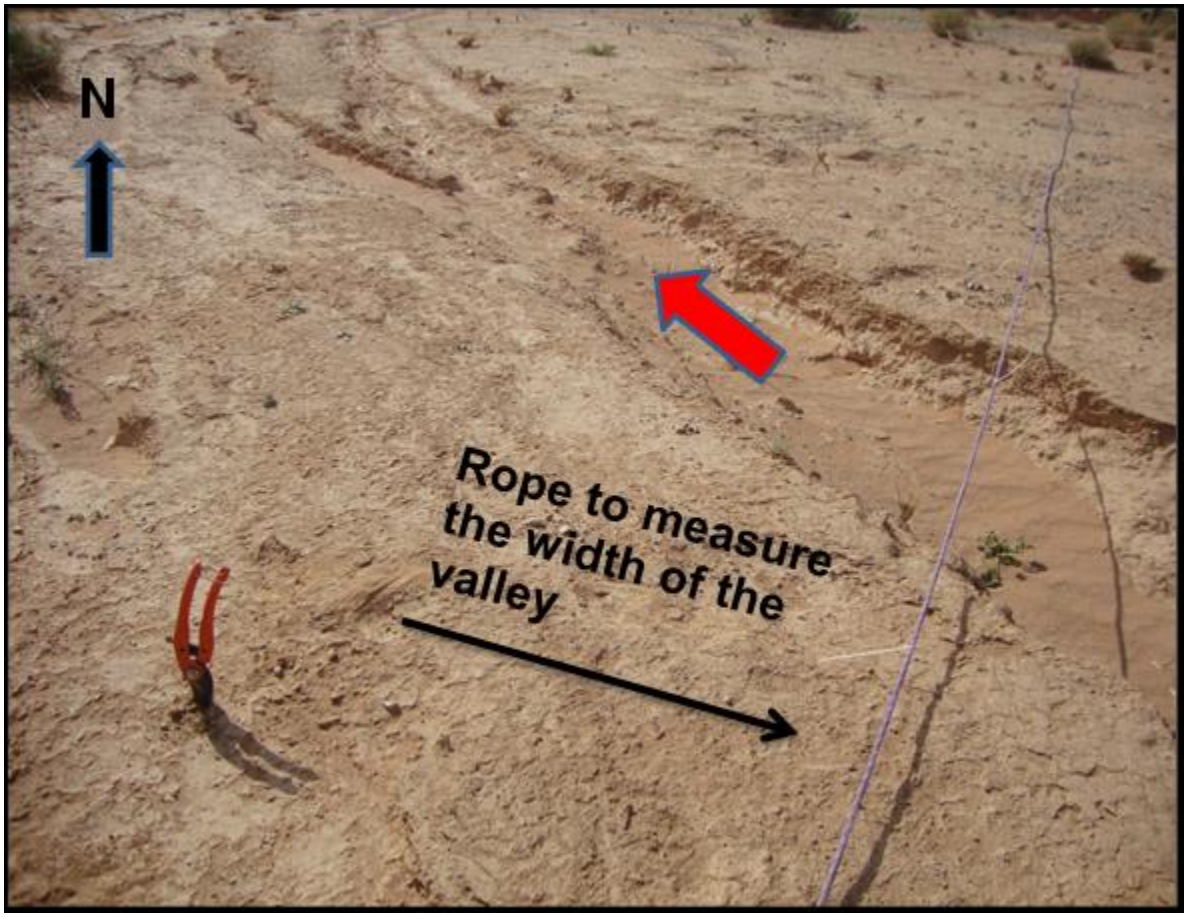
The original intention for this research had been to undertake extensive field work in the Iraqi Western Desert to examine the fluvial deposits, log river terraces and produce detailed maps of a number of the main river valleys. The deteriorating security situation in Iraq was the most difficult challenge faced by the researcher.

The actual process of ground truth mapping that could be undertaken involved visiting 16 sites identified on the newly compiled geomorphological map and comparing the actual ground conditions with those that were anticipated. At each site photographs and some videos (see Appendix G in the CD) were taken, the geomorphological environment noted, and when possible the geological outcrops were also examined. At these localities the lithology compared with those anticipated from the geological maps. Again where possible the depth and width of the dry valleys were measured (pictures 3.1 and 3.2) river terraces in Houran, Al Agari, Mulussa, Ratga, Fhada, and Al Manai valleys examined.

All the data that was compiled and notably the photographs and videos were brought back to the UK for discussions with research supervisors. In these discussions the ‘ground truth’ field observation were challenged and where necessary refined. It should be noted that the Director of Studies, professor Griffiths, had worked in the Syrian desert along the border with the Iraqi Western Desert was familiar with the landscape of the region. However, the on-going security situation produced the supervisor actually visiting the field area as part of this research



Picture 3.1: Measurements in one of the dry valleys south west Rutba area



Picture 3.2: Measurements in one of the branches in the main valleys near Rutba area

3.3.2 Logging river terraces

One element of the field data collection was a comparison of fluvial terrace sequences from around the study area including the River terraces in Euphrates River and main valleys in Iraqi Western Desert. For example, the researcher logged the river terraces in the Houran, Manai, Agarai, Fhada, and Al Qaiam valleys using the techniques described. In addition terraces in the Euphrates River were logged including those at Al Qaiam, Haditha, Al Baghdadi, Houran, and Al Mohamedi. This information is summarized in Chapter 5. The data confirmed the nature of the river terraces in study area as being part of the Quaternary fluvial evolution of the region. These terraces had been created by the combination progressive uplift in Iraqi Western Desert and the cyclic Effects of climatic changes affecting fluvial activity.

3.3.3 Discussions with local people

As part of the background research, the author met with a large number of people who lived and worked in the Iraqi Western Desert**.** The people who live in the Iraqi Western Desert became more engaged in the study when the researcher was an foot and they had the opportunity to converse directly with researcher, This format allowed people to make independent observations and for issues to be followed up in an informal way. Records of these discussions were not made as there was no way for a proper ethical evaluation to be carried out. The information concentrated on the identification of locations, place names, water sources, and any information that could be provided on natural hazards and resources. This information was incorporated in the interpretation of geology, geomorphology and drainage presented in the following chapters.

3.4 Methods of data analysis

Analysis of the data on the Iraqi Western Desert was aimed at establishing the geomorphological evolution of the drainage network. The data were obtained from the literature surveys, remote sensing interpretation, GIS analysis and fieldwork. Fundamentally it was also critical that this collection of data and the subsequent data analysis provided a database of the study area that would allow future researchers who studied the Iraqi Western Desert to use the data and in their own work. The stages in the data analysis were:

1) Compilation of all exiting data in a GIS (Section 3.2.7)

2) Undertaking a preliminary terrain classification using the techniques pioneered by Mitchell (1973) but applied to deserts Perrin and Mitchell (1969) as presented in Walker (2012) (Section 3.4.1 and Chapter 5)

3) Ground - truth mapping field work (Section 3.3)

4) Use of geomorphic indices to analyse the nature of the terrain and the drainage system (Chapter 6)

5) Reviewing multiple layers of earth science data within a GIS to identify correlation between the tectonics, lithology, landforms and drainage patterns. This phase was fundamental in the interpretation of the geomorphological evolution of the Iraqi Western Desert and the preparation of a new geomorphological map
6) Presenting the data as high quality output in Coreldraw.

3. 4. 1 Translations from Arabic

There were many sources of data and information examined by the author in the current study and most of the information, metadata and quantitative data from the multiple sources were in the Arabic language. Therefore, a key component of this research has been to translate these data into English. Much of the data were unpublished and obtaining access required considerable time and patience on behalf of the author in dealing with archivists, libraries ministries and military authorise.

3.4.2 Terrain classification

Using the desert landscape model (Figure 2.4) of Griffiths et al (2012) as a guide, a comparison was made between the exiting geomorphological descriptions of the Iraqi Western Desert and a new geomorphological map compiled from a range of sources by this researcher (Figure 5.19). The basic terrain classification of the region drew on the methods of terrain classification described by Mitchell (1973) and Griffiths (2001). The key component of the classification was to divide the Iraqi Western Desert into clearly identifiable large scale geomorphological units: This is described in detail in Chapter 5 but essentially concentrated on the distribution of:

1) Plateaux with stone pavement
2) Dry valleys with ephemeral stream
3) Depressions and salt pans
4) Euphrates floodplain
5) Bajada / pediments
6) Aeolian landforms

There features were clearly distinguishable and the various images and maps which were the basis for the new geomorphological map. Examples of the various geomorphological units were visited during field work to confirm their interpretation and provide added details on the nature of the ground conditions (Chapter 5).

3.4.3 Analysis of river valleys and drainage

Based on the new geomorphological map (Section 5.2.4) it was apparent that the Iraqi Western Desert has a network of dry valleys with a large number of tributaries. All these valleys are dry under contemporary conditions. Many do contain streams beds but based on field observations the majority appeared to be relict forms and have not recorded flows during historical times. However, some may be the result of very rare extreme flood events, and hence can be considered ephemeral

As part of the investigation of these dry valley long profiles and sequences of cross-section were measured from the Google Earth data. These were used as part of this exploration of their geomorphological evolution to identify terrace levels and any knick points in the valley long profile. Where ephemeral streams do exist in the Iraq Western Desert they are likely to be dominated by extreme events of low frequency (Griffiths at al 2012). Between 1950 and 2000 in the Iraqi Western Desert an average of about five events per year have been recorded. On average, there are 20 days per year for which some runoff is registered. Studies of the effects of rainfall in Iraqi Western Desert and on ephemeral channels have been published and the assumption is that. The geomorphological effectiveness of extreme floods increases with aridity and decreasing watershed size (Al athari, 2005).

For this research the relict network were also subject to various quantitative analysis including: stream ordering; valley ranking; values for terrain ratio; roughness; and drainage density. The various morphometric quantitative geomorphological studies were based on Strahler (1952) (Chapter 6).

3.4.4 The GIS

Geographical Information System (GIS) have played an increasing role in certain on geomorphological investigations over the past few decades (Shilston et al; 2012). There are some example in the literature where GIS have been used in desert studies (Shilston et al; 2012) but prior to this study of this study of Iraqi Western Desert the technique does not appear to been used in Iraq. Examples of GIS studies in deserts include:

- Abdullah (2005) examined remote sensing techniques (RS) to detect mass movement rather than using field monitoring in Lebanon. The research was primarily undertaken in order to show how to use Geographic Information Systems (GIS) for establishing the relationships between mass movement occurrence and different terrain parameters in a representative region of Lebanon. The results of this study indicated that mass movements constituted a hazard that is among the most widespread in the Eastern Mediterranean basin. Abdullah (2005) has since accumulated, a body of empirical research on mass movement in the Eastern Mediterranean, especially in Lebanon

- Bou Kheir et al. (2006) studied the soil erosion risk in Lebanon. In this study soil erosion was shown to be serious geo-environmental issue causing land degradation in sub-humid to arid Mediterranean countries including Lebanon. It showed that accelerate soil erosion damages vulnerable agricultural lands

particularly those having shallow soils with low organic matter content that one consequence was mudflows which may affect urban areas (Bou Kheir et. al 2006). Also Bou Kheir et al (2008) used a Geographical Information System to study the soil and bedrock distribution in Lebanon. They showed that long spells of drought interrupted by intensive precipitation intervals was often the cause land degradation in the Mediterranean region. Rapid channelling processes caused gully erosion and the formation of badlands

- Walsh et al (1998) refer to use the satellite remote sensing and GIS as effective technologies in geomorphological investigation generally

- Griffiths and Richards (1989) demonstrated how a GIS developed from a standardised relational database (dBaseIII+) could be used to model soil erosion over the 120,000 km2 River Awash catchment in Ethiopia. A critical elements of this work was the initial clarification of the terrain from Satellite Company to provide a framework for assessing soil erodability and average slopes within a raster database.

- Vogt et al. (2003) studied drainage networks as a basis for looking at the pressure on scarce water resources. GIS tools allowed for the combined analysis of digital elevation data and environmental parameters in order to derive the relevant catchment data needed.

In this study the researcher used ArcGIS mainly in the morphometric analysis of the ephemeral stream valley network (Chapter 6). Some attempts were made to utilize ArcGIS in the clarification of the terrain. However, given the nature of the scanned data, much of which was in raster format, these attempts were not followed map as they would have require extensive digitisation of the row data.

With the size of the study area this was not seen as feasible within time scale of this research hence the dicision to work primarily with Google Earth Pro.

3.5 Summary

This chapter introduces the research methodology used for this thesis and how it has directed data collection and analysis. These data are the basis for the interpretation of the geology and geomorphology presented in the next three chapters. This chapter notes that the methodology employed involved review of previous studies, collection of topographic maps and satellite images. This chapter showed how combining maps and Google Earth images facilitated the production of a geomorphological map which was followed by analyses of river cross-section and long profiles.

It was noted that much of the literature, including maps was unpublished and written in Arabic, which had to be translated by the author for inclusion in this thesis. It was also highlighted that the field data collection was severely hampered by the extremely dangerous and on-going security situation in the Iraqi Western Desert.

Chapter 4

Geology of the field area

4.1 Introduction

In this chapter the bedrock and superficial geology of the Iraqi Western Desert is described along with its tectonic setting as this is fundamental to explaining the evolution of the contemporary drainage network. With the exception of Quaternary deposits that overlie the bedrock (the Garaa Formation), all of the rocks in the Iraqi Western Desert are either completely or partially of marine origin. The Mesozoic and Palaeozoic seas in which they were deposited were generally shallow with some minor continental influences. Sedimentation was varied in nature, which is the result of the different environments in which sediments was deposited. Secondary processes also contributed to this diversity, especially diagenesis and weathering, which can have a notable impact under desert conditions (Buday and Hak, 1980).

4.2 Structural framework

The first reconnaissance geological surveys of Iraq were carried out during and immediately after the First World War (1914-1918), culminating in the discovery of oil in 1920. After Iraq attained independence in 1921, the oil industry played an important role in advancing geology as a profession in Iraq. Geologists from the Iraq Petroleum Company (IPC) published key stratigraphic information in 1959 (Jassim et al., 1984). Geological surveys in Iraq concentrated mainly on the requirements of the extractive industries until the establishment of the Directorate General of Geological Survey and Mineral Investigation (GEOSURV) in 1969 (Bardi, 1975). GEOSURV initial task was to systematically map the whole country at a regional scale of 1:1,000,000 in order to establish the potential mineral wealth of the country. Data on the geology of individual formations occurring in the field area were presented in the GEOSURV original reports supplemented by the petrological characteristics of each formation, and

to a certain extent by a brief paleogeographical commentary. The study area investigated for this thesis is part of the stable shelf of the Nubian-Arabian platform with a sedimentary cover that reaches back to the Cambrian period Figure 4.1. The sedimentary cover on this stable shelf extends from the Palaeozoic (Permo-Carboniferous) to the Tertiary (middle Miocene). It is characterized by numerous unconformities in the sedimentation. The area's oldest exposed rocks are from the Permian/Carboniferous Period, cropping out in the Garaa depression. These are overlain by Middle and Upper Triassic, and Lower and Middle Jurassic rocks. Deposition in these Mezozoic rocks is characterized by large scale sedimentary cycles, with shallow water or local continental sediments at the base, sandstone, siltstone or other clastic rocks and deposits of rather deeper sea limestone and dolomite in the upper thicker parts. The main identified sedimentary sequence started with deposition of the basal Cenomanian Rutba Formation, which unconformably overlies the older formations. This unconformity is the most significant stratigraphic boundary within the whole sedimentary complex of the Rutba area. The Cenomanian deposits are followed by those from the Upper Cretaceous, Campanian and Mastritchian Formations which are mostly carbonate units (for more details see Fouad, (1997, 2000). A sequence of Palaeocene and Eocene sediments transgresses different units of the Upper Cretaceous sequence. A summary map of the bedrock geology is presented in Figure 4. 9 (in appendix of this thesis).

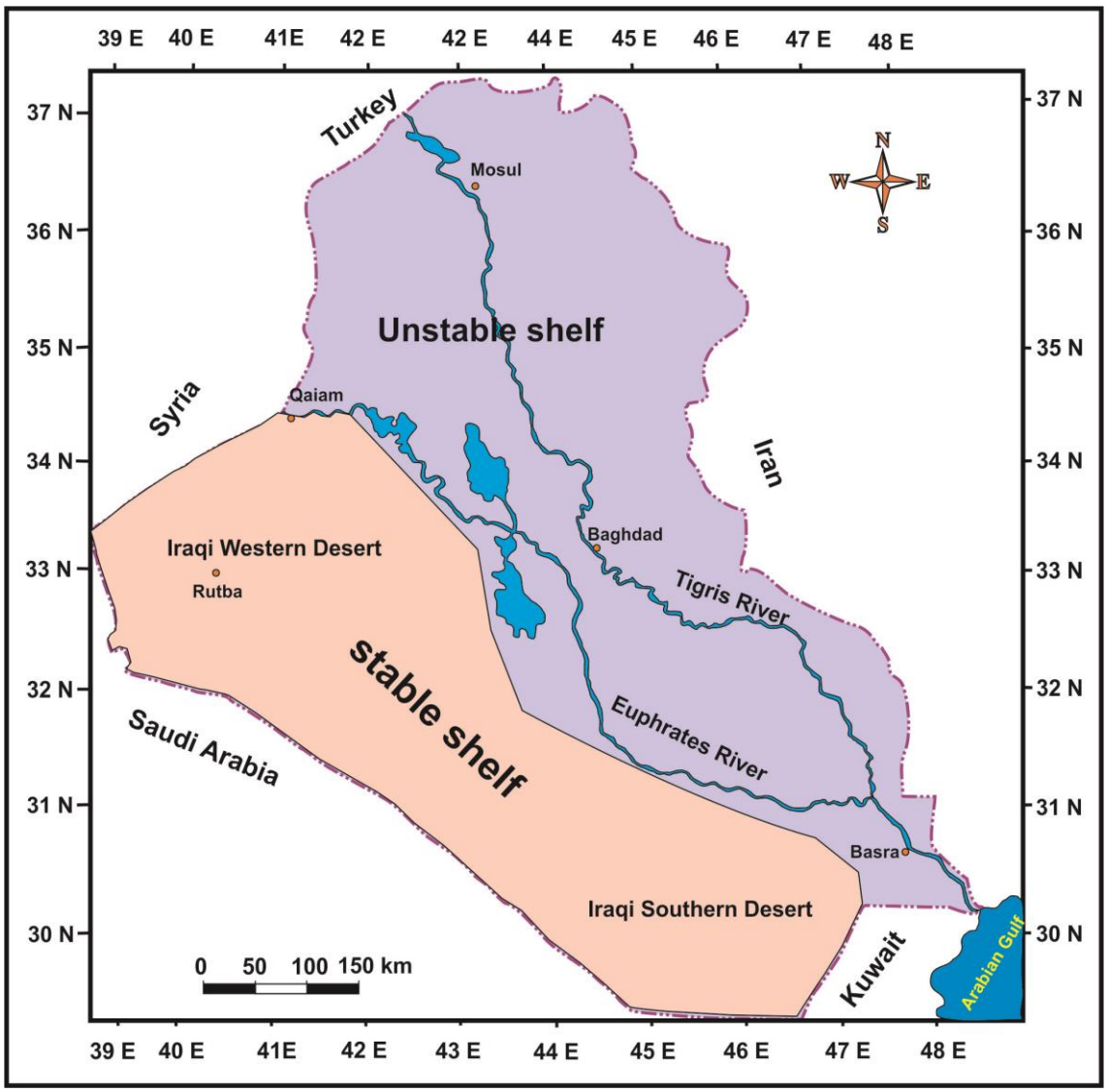


Figure 4.1: Location of the Iraq Western Desert on a stable shelf source: (Fouad, 2007).

The stable part of the Arabic-African Shield is distinguished by its relative straight forward geological sequences. It is a part of the Rutba-Aljazeera range according to the sub-division of structural zones of Iraq by Buday and Jasim (1987). It is rare to see structural phenomena on the surface and the exposed beds dip at less than one degree, making it difficult to measure dip and dip direction in the field. However, the dip is not symmetrical with the northern limb having a greater dip, which has resulted in the formation of the Garaa elevation. The study area has been affected by extensive movements that have occurred

many times since the end of the Proterozoic Era. The basement rocks were elevated during the Cretaceous Period caused by a hot spot positioned between present day Iraq and Syria. The hot spot initially uplifted the Earth's crust, subsequently leading to subsidence and faulting. The uplift occurred in three particular areas 1) Kulisa, elevated to the north of Anha; 2) Aleppo elevated in the west in contemporary Syrian territory; and 3) Rutba elevated to the south of Anah within which the study area is located. As a result of these movements there are unconformities in the geology. The subsequent depositional phases were mainly of clastic faces that were the results of the sea retreating. As a result of the effects of long term erosion in the Western Desert, topographic depressions were formed in the areas of the most stable platforms. The most important depression is Garaa.

4.2.1 Overall geological Structure of the Iraqi Western Desert

The landforms of the desert are the result of the interaction between structure, lithology and climate as indicated by the variable forms of the geomorphological units and features. The Western Desert is generally a gently sloping plain with a gradient of 5m/km towards the east and northeast. Buday and Jassim (1984) refer to the dip of the strata as almost horizontal (i.e.1-2 degrees). In the western region around the Garaa depression, the gentle plain reflects the structural position of the Western Desert within a stable shelf. According to Buday (1980), Buday and Jassim (1987), and Abbas, et al (1978), the crest created by uplift has remained as dry land since the Late-Cretaceous period. Since that time the continental uplift has led to an increase in the dry land over the whole Western Desert leading to the creation of major plateaux (see Figure 4. 2). Erosion of the plateaux has exposed the various geological sequences.

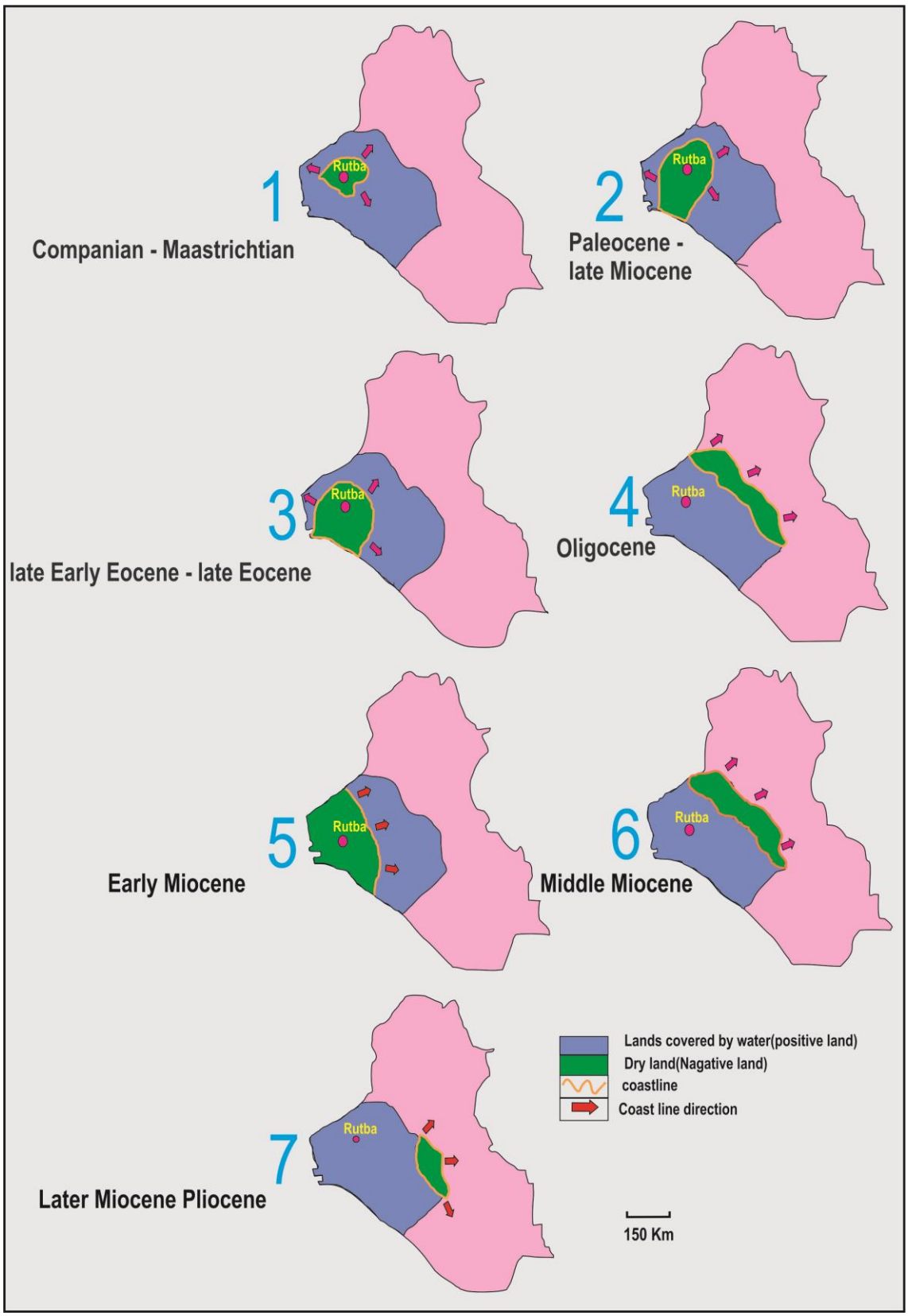


Figure 4.2: The stages by which the Iraqi Western Desert became a terrestrial landscape and was subject to sub-aerial denudation processes (Hamza, 2007)

4.2.2 Tectonics

Iraq is located between part of the Arabian plate and on a Alpine subsiding syncline. As noted above. The Arabian plate is divided into two main parts, the stable Arabian shield, and the unstable shelf (Buday, and Jassim 1987). The study area is located within the stable shelf. This has not been affected strongly by the Alpine orogenic activity that occurred in the region during the Mesozoic and Tertiary periods. The Iraqi Western Desert forms part of the Arabian platform, where a comparatively thin Phanerozoic sequence can be identified and this includes the basal Precambrian rocks. The Iraqi Western Desert lacks expressive Alpine associated compressional structures; in general the exposed Cenozoic and Mesozoic rock layers show a generally northeast, north and east regional inclination. The stable shelf divides into two parts: (Figure 4.1)

a) The Rutba-Jazeera Zone shelf.

b) Salman zone

The study area lies in the Rutba-Jazeera zone. During the Cainozoic and Mesozoic epochs this was relatively stable, but during the earlier Palaeozoic there was extensive tectonic activity (Caledonian and Hercynian) which is reflected in the structure of the Pre-Cambrian basement rocks. There were two periods within the Tertiary when tectonic activity affected the area and created identifiable structural features. In the late Tertiary significant tectonic activity caused the structural inversion of the Anah Graben and a limited right lateral strike slip movement on the Abu Jir Fault zone Fouad, (2007). The extensional phase produced numerous east-west and north-west trending fault bounded troughs as grabens and half-grabens dominated the northern Arabian platform, including north and eastern Syria and west northern Iraq (Figure 4. 3).

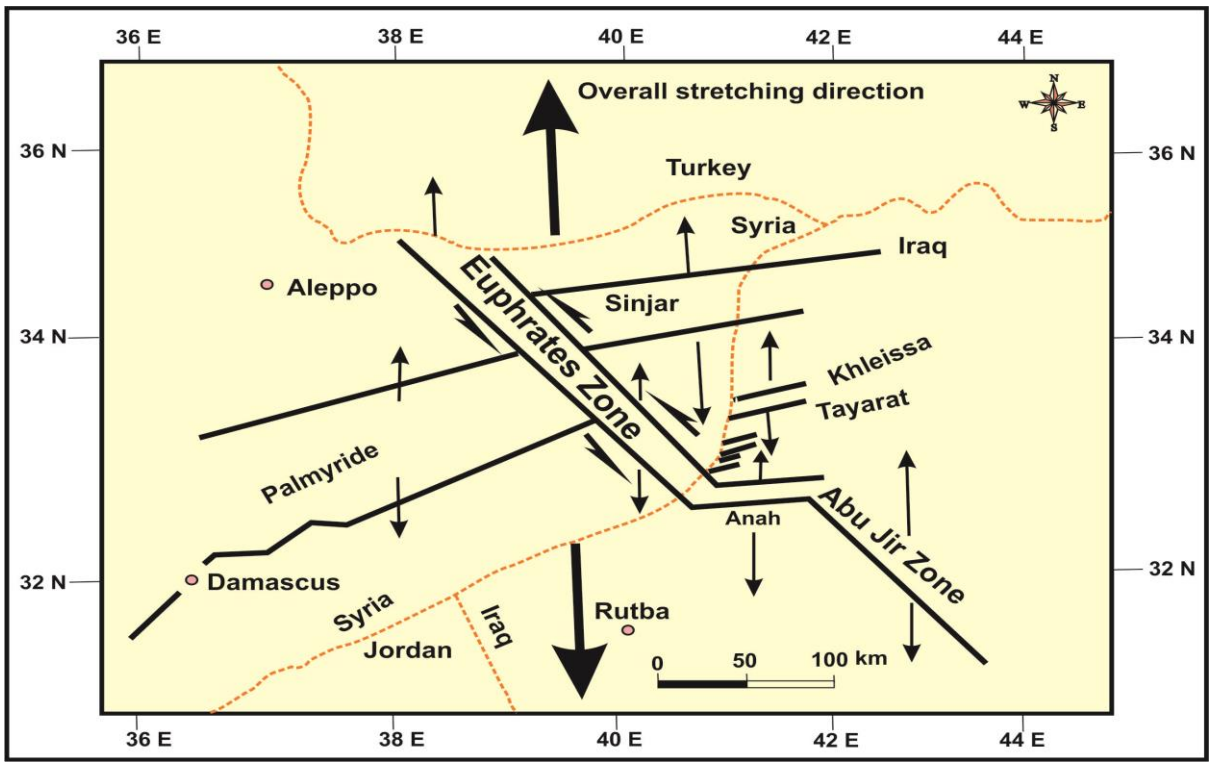


Figure 4.3: Simplified sketch map illustrating the late Cretaceous extension and the formation of the intercontinental rift basins in the northern Arabian platform (modified after Lovelock, 1984; Peel and Wright 1990; Ruiter et al., 1994; and Fouad, 1997, 2004 and 2007).

The late Tertiary compression produced regional folding and thrusting of the north Arabian plate margin. In the interior of the plate body, the far field compression caused structural inversion of the late Cretaceous rift basins, not only to the proximal basins such as Sinjar but also to the distal ones such as the Palmyride and Anah (Figure 4.4; Fouad 2007).

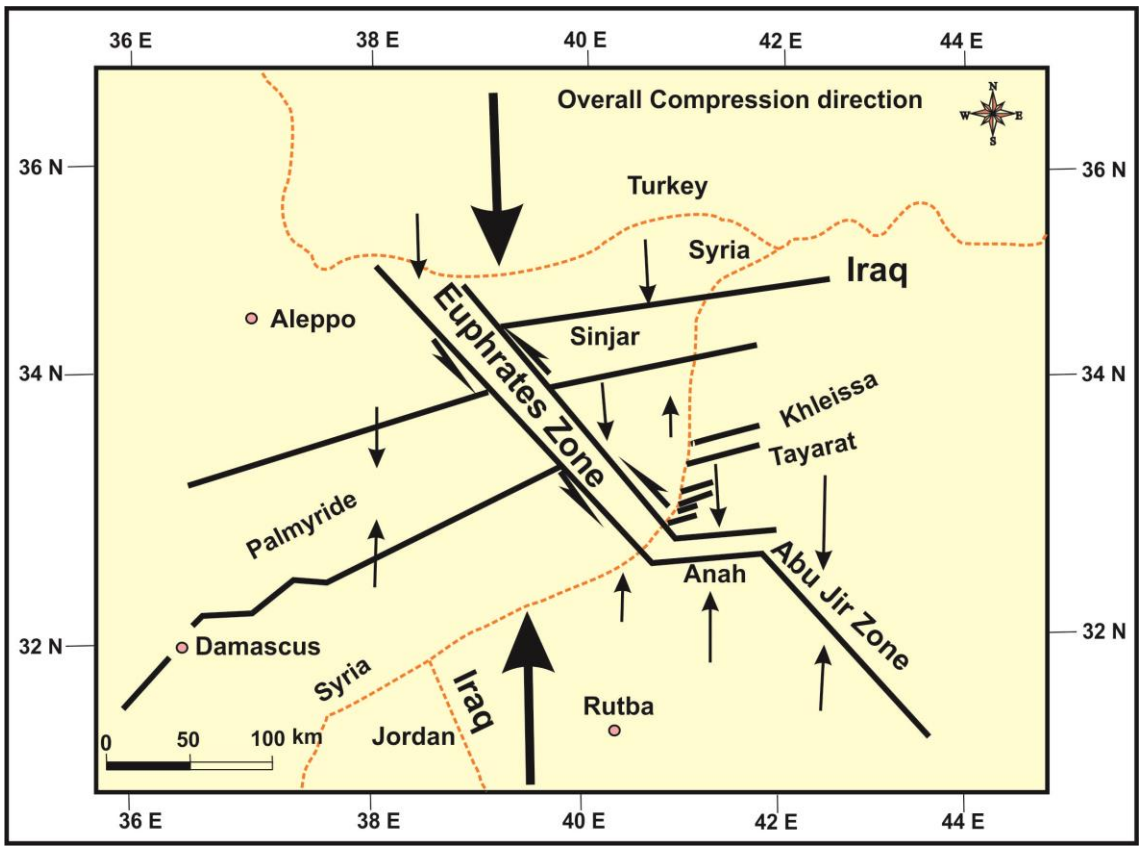


Figure 4.4: Simplified sketch map illustrating the late Tertiary compression, which produced structural basin inversion and transpressive movements on some of the north Arabian rift basins, (modified after Lovelock, 1984; Peel and Wright 1990; Ruiter et al., 1994; and Fouad, 1997, 2004 and 2007).

The main effect of the Late Tertiary compression was to cause a doming effect (at Rutba) creating an anticlinorium. Antecedent drainage developing on this dome-like structure during the Late Tertiary and Quaternary goes a very long to explain the present drainage patterns. Figure 4.5 shows the Arabian plate and the southern and western boundaries of the plate are passive margins located at the spreading ridges of the Aden Gulf and Red Sea. The north-western boundary is located along the Levant transcurrent fault. The south eastern boundary in Oman is defined by the Masirah fault zone. The northern and north-eastern boundaries are compressional due to the late Tertiary collision of the Arabian plate with the Turkish and Iranian continents (Jassim and Goff 2006).

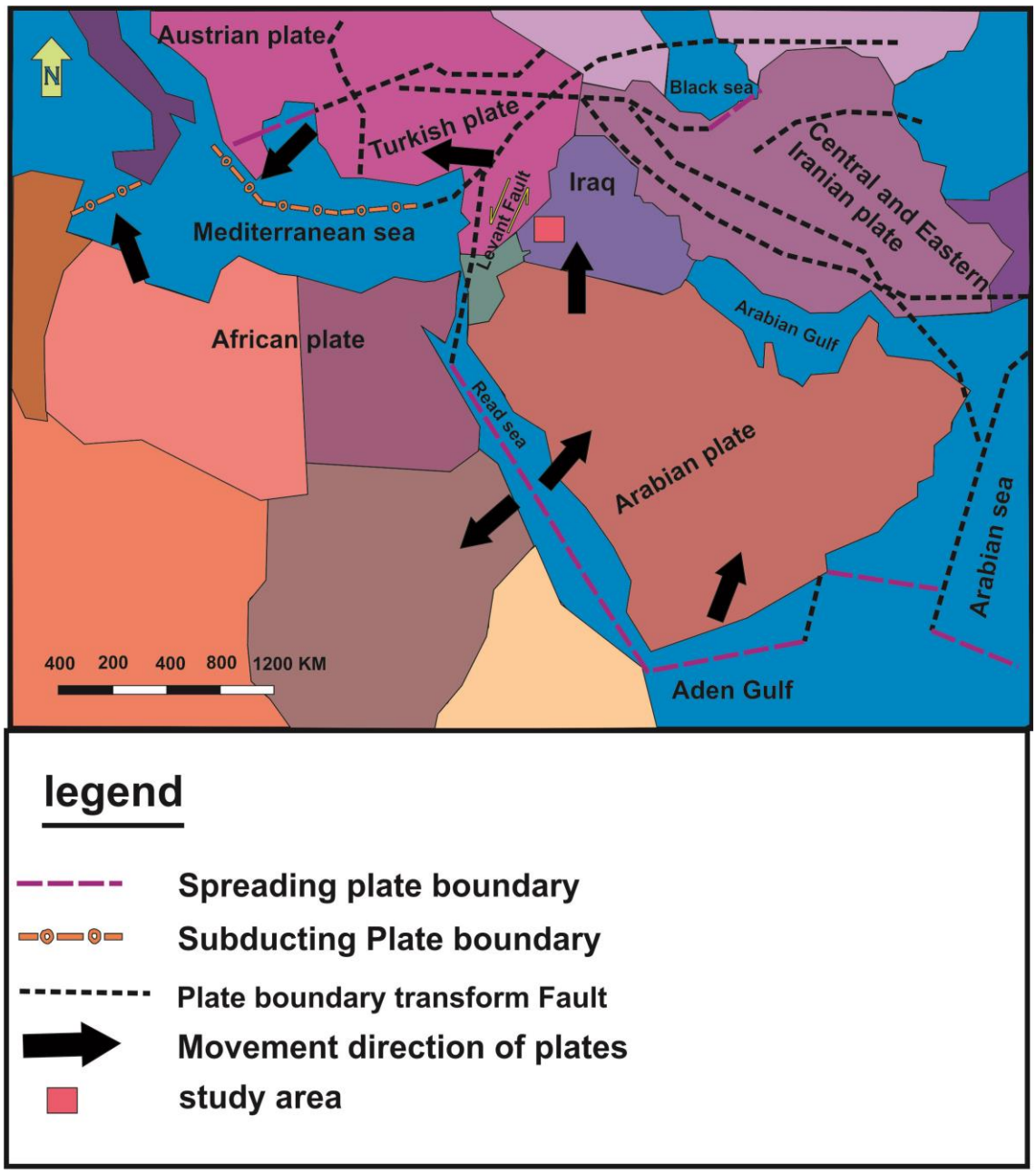


Figure 4.5: Structural units in the Middle East including Iraq (Modified after Peter et.al, 1976).

The Rutba uplift, therefore, is the ground which emerged as a result of tectonic movement in the Cenozoic periods. The spatial extent of the area uplifted exceed of 100s km,[2] it is characterized by minor folds and faults at the uplift core, which is located in the Garaa depression about 80 km north of Rutba town. It is this depression where Palaeozoic sediments can be found.

The most prominent structures were active again during the Cretaceous and Palaeogene as follows.

• The Houran anticlinorium which is over 300 km long and is represented by a series of escarpments. This extends from Saudi Arabia to the H1 pumping station north-east of Rutba town

• The Garaa anticline fold is identified as trending west to east extending for about 130 km and includes the Rutba uplift summit.

• Akashat anticline extend from east north east to west south west and is located west of Rutba town.

• Traibeel anticline extends from west to east and is located east west of Rutba town

• Tlaiha and Qatari anticline in the south east and is located east of Rutba town (Figure 4.6)

These folds dominate and control the contemporary topography of the Iraqi Western Desert. The topography is characterized by undulating plateax with an elevation gradually increasing from a low level in the Euphrates River valley in the north east at (165 m above sea level), towards the south west at the Junction of the Iraq, Saudi Arabia, Jordan and Syria borders (the elevation reaches 975 m above sea level in the Anza area). These undulating plateax are called ‘belts’ by Buday and Hak (1980) and are shown in Figure 4. 7. As discussed in chapter 5 the average land surface slope in the Iraqi Western Desert is 2 m / km which is the overall slope on these belts. The plateaux are not continuous and are dissected by many fluvial valley that now contain ephemeral rivers and streams.

4.2.2.1 Faults

The faults in the Iraqi Western Desert are thought to have originally developed in the basement rock but were reactivated during the Alpine orogeny which affected the overlying Paleozoic, Mesozoic and Tertiary sedimentary cover (Buday, 1980; Buday and Hak, 1980). The faults in the study area, therefore, are related to very old Paleozoic orogenies, (Kibiran, Hijaz and Najid), which have been rejuvenated during the Late Mesozoic and Tertiary by the Alpine Orogeny (Qasir et al., 1992). Four sets of faults can be identified in the Iraqi Western Desert from Landsat images indicated by the pattern and distribution of drainage, cliffs, mesas and depressions (Hamza, 2007). This distribution of faults are shown in figure 4.3 .Major fault zones correspond to the northwest-southeast Najid Fault system (Figure 4.6 green line), and the northeast-southwest transverse system (Figure 4.6 Indigo line) or east-west (Figure 4.6).

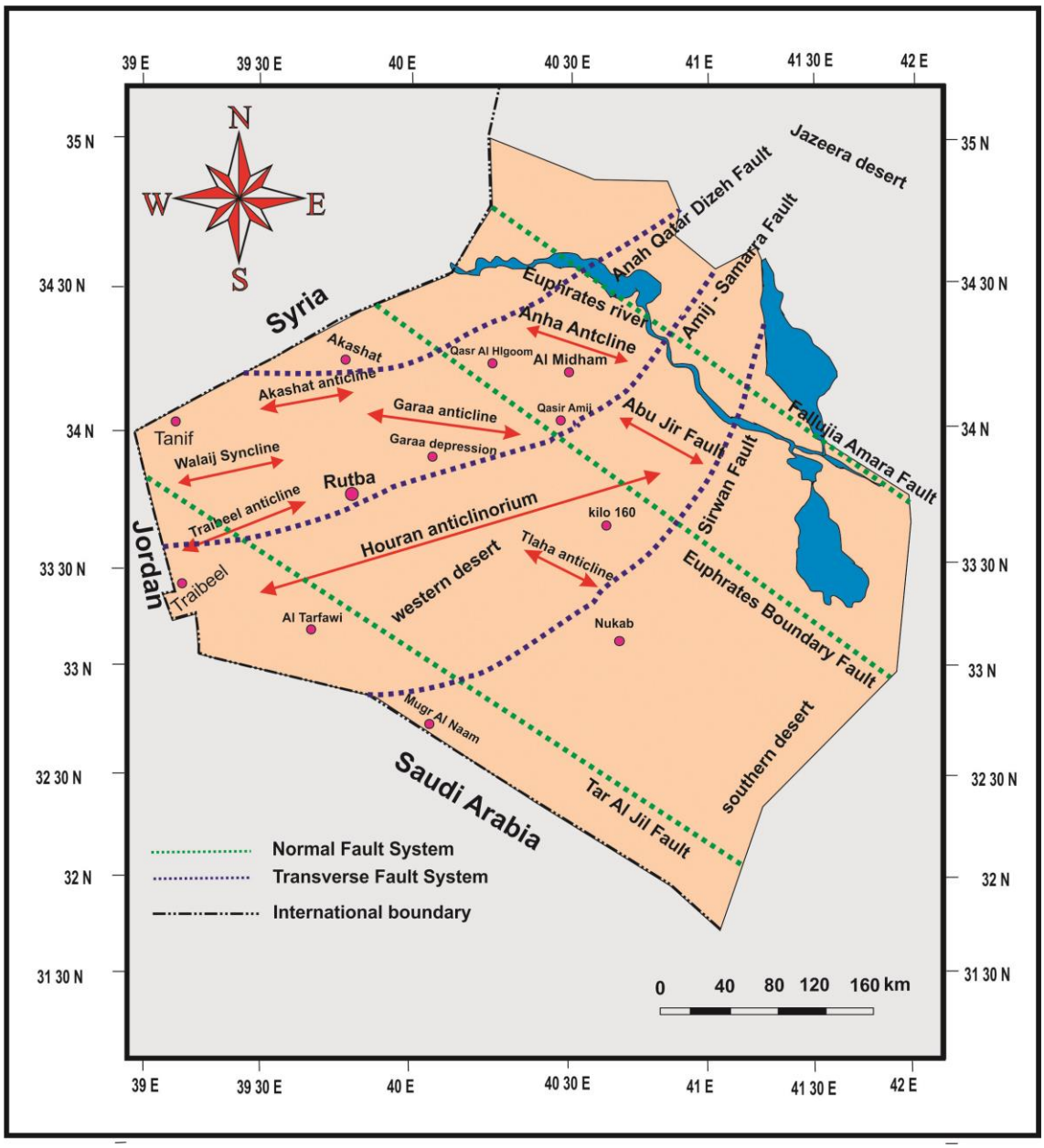


Figure 4.6: Folds and faults in the study area. Modified after (Budy, and Jassim. 1984, Tectonic Map of Iraq and Hussien et.al, 2011)

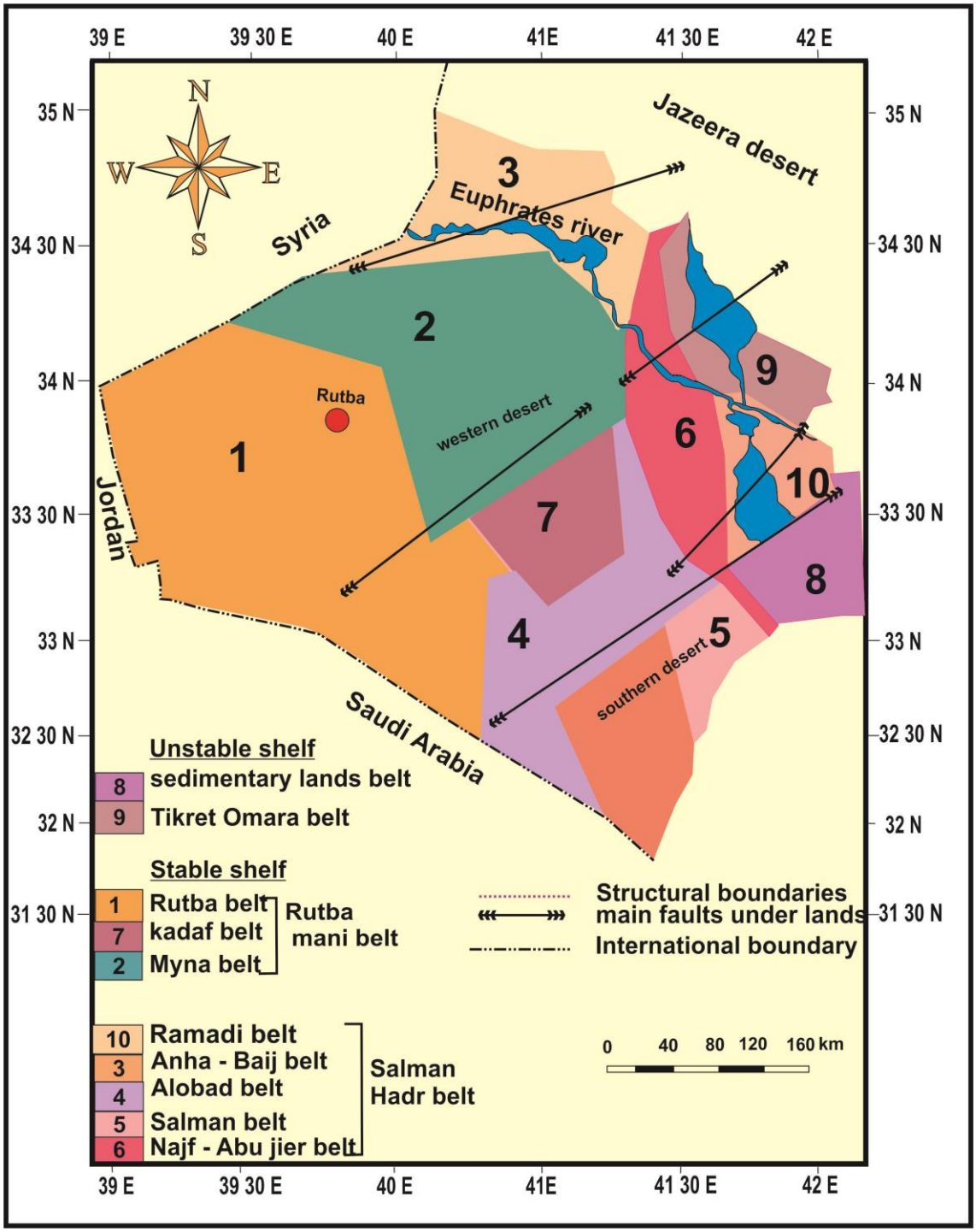


Figure 4.7: Geology borders (belts) located in the Iraqi Western Desert (Al Kadhimi et al 1996)

The Northern boundary Anah Fault zone is the most important transverse fault affecting the region. The Anah fault is 250 km long and runs east-west as a 250 km. This structure controls the course of the Euphrates River for a distance of over 100 km. The fault zone starts in the Iraqi Western Desert as a series of east to west trending step faults, producing the Anah Graben (Jassim, 2006). There were active during the late Cretaceous, producing a graben containing about 2000 metres of Upper Cretaceous sediments, which is followed by a relatively thin uniform Tertiary post-rift sequence (Fouad, 2007).

The eastern boundary of the Iraqi Western Desert, and indeed the boundary of the stable part of the platform itself, is considered to be along the Abu Jir fault zone (Fouad, 2007). The zone is composed of many northwest to south east trending faults that extend from the Anah Graben across the Euphrates River valley to Heet, Awasil, Abu Jir, and Shithatha (figure 4.9). Fouad, (2004) used data from reflection seismic sections covering the northern section of the region to show the cross-sectional shape of the fault zone.

Al Mubarak and Amin, 1983, also Al Bassam et al., (2004) described the Houran northwest to southeast trending faults which include Anah Qatar Dizeh Fault, Amij Samarra Fault , Sirwan Fault Fallujia Amara Fault, Euphrates boundary Fault, Tar Al Jil Fault, and Abu Jir Fault. In addition, Al Mubarak (1996) suggested the evolution of a series of large and small playas were indicators of the fault trace. The surface structures are considered as additional evidence for the occurrence of strike slip faulting. Many of the northwest to southeast trending faults are responsible for the development of water wells in the central part of the Iraqi Western Desert. The faults have extremely straight traces extending from a few km’s to more than 120 km, with some sharp linear vertical fault scarps such as Houran anticlinorium and Tlaha anticline.

4.2.3 Joints system

Joints are widespread throughout the rocks of the Iraqi Western Desert. However, the densest joint systems are concentrated in two areas, on the southeast slope of the Rutba uplift, and in the southern part of the study area. Joints in the first area trend southwest-northeast and northwest-southeast and are conformable with the main structural elements of the Rutba uplifit. They are the result of the tectonic movements that created minor folding and faulting. The joints in the second area included are oriented mostly west-east and partly correlate with depositional flexures, which are suspected to be of sedimentary origin. The joints in this case might be connected with sedimentary movements and early digenetic processes.

4.3 Stratigraphy (Type locations show in Figure 4.14)

4.3.1 Stratigraphic Column

Data on the geology of individual formations occurring in the Iraqi Western Desert are provided below. They are supplemented by petrological characteristics of each formation and comments on the paleogeography. The information is presented in stratigraphic order based on the stratigraphic column divided by Jassaim et al., (1984) and shown in Figure 4. 9 (in appendix of this thesis) and Figure 4.8 and 4.10.

In spite of the study area lying within the stable shelf, it is the tectonic history that has controlled the nature, distribution and thickness of the exposed rocks. The Garaa Depression and Rutbah Uplift have exposed Permian rocks, which are absent in other parts of the study area. The Rutba Uplift also affected the nature of the rocks themselves with lateral facies changes as the depositional basins were variably affected by the uplift. In addition, the development of the Nukhaib Graben resulted in the deposition of large amounts of gravel deposits during the Pliocene. These Pliocene rocks created the Zahra Formation and the graben development led to the separation of some depositional basins (Sissakian and Mohammed, 2007). For the type locality locations of the geological formations and lithological indexes of formations see Figures 4.14 and 4.15.

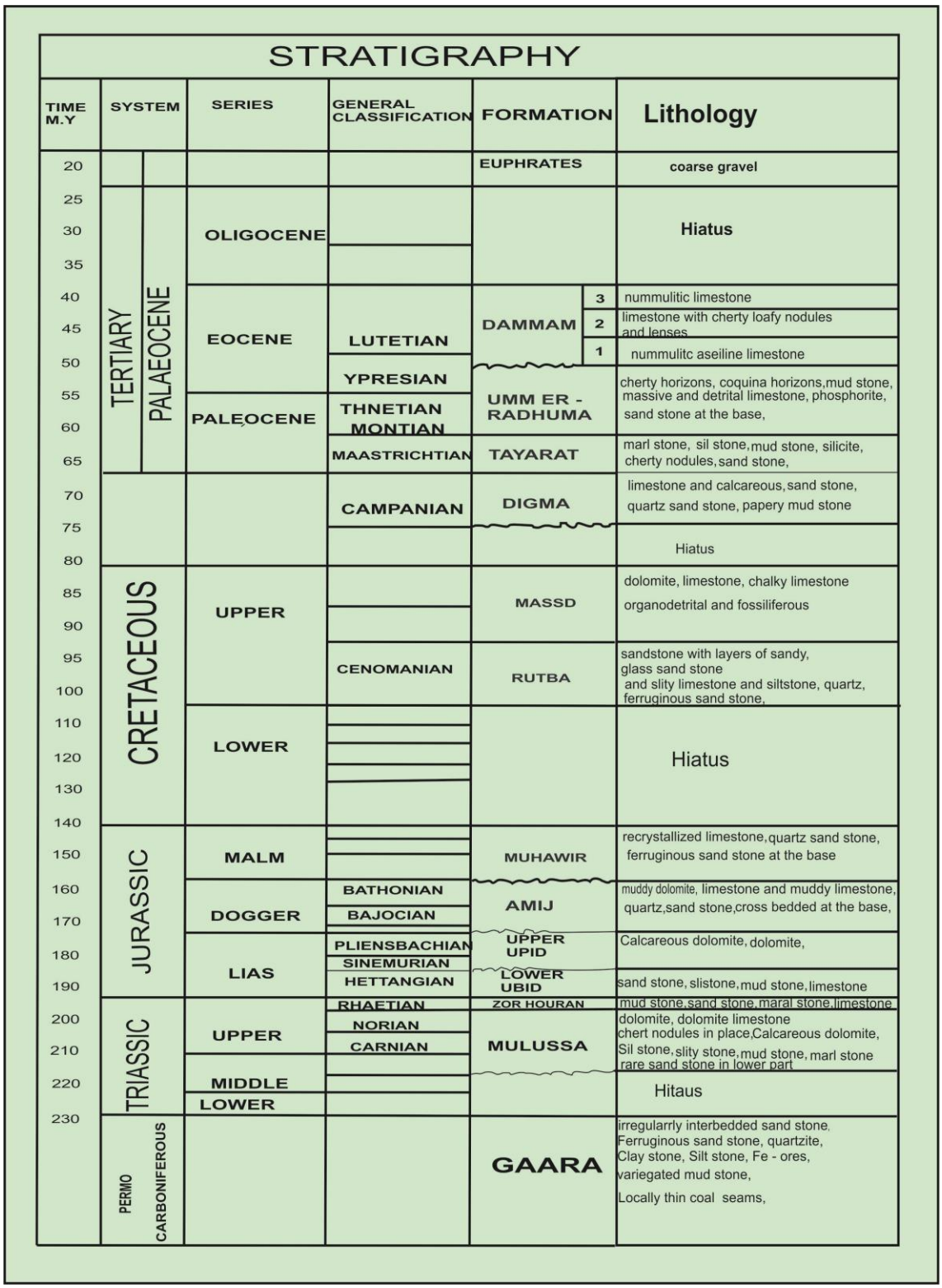


Figure 4.8: Stratigraphic column of the exposed rocks the Iraqi Western Desert (adapted from Jassim et al., 1984).

4.3.2 The Palaeozoic Era (570-245) Ma

Only limited Permo Carboniferous rock units are exposed in Garaa region of the study area. According to Al Habba et al., (1994); Al Siddiki et al., (1994) and Aqrawi, (1998), the Akkas1 well, which is located in the northern part of the Western Desert, is the only well that penetrated part of the Palaeozoic sequence, revealing 3133 m of a predominantly siliciclastics of form the Late Devonian to Early Carboniferous Kaista and Ora formations (Fouad, 2007). The sequence was overlain by 148 m of Red Beds of undeterminable age, which in turn are overlain by the Mesozoic Maastrichtian Tayarat Formation (Fouad, 2007) (Figure 4.9 in appendix of this thesis).

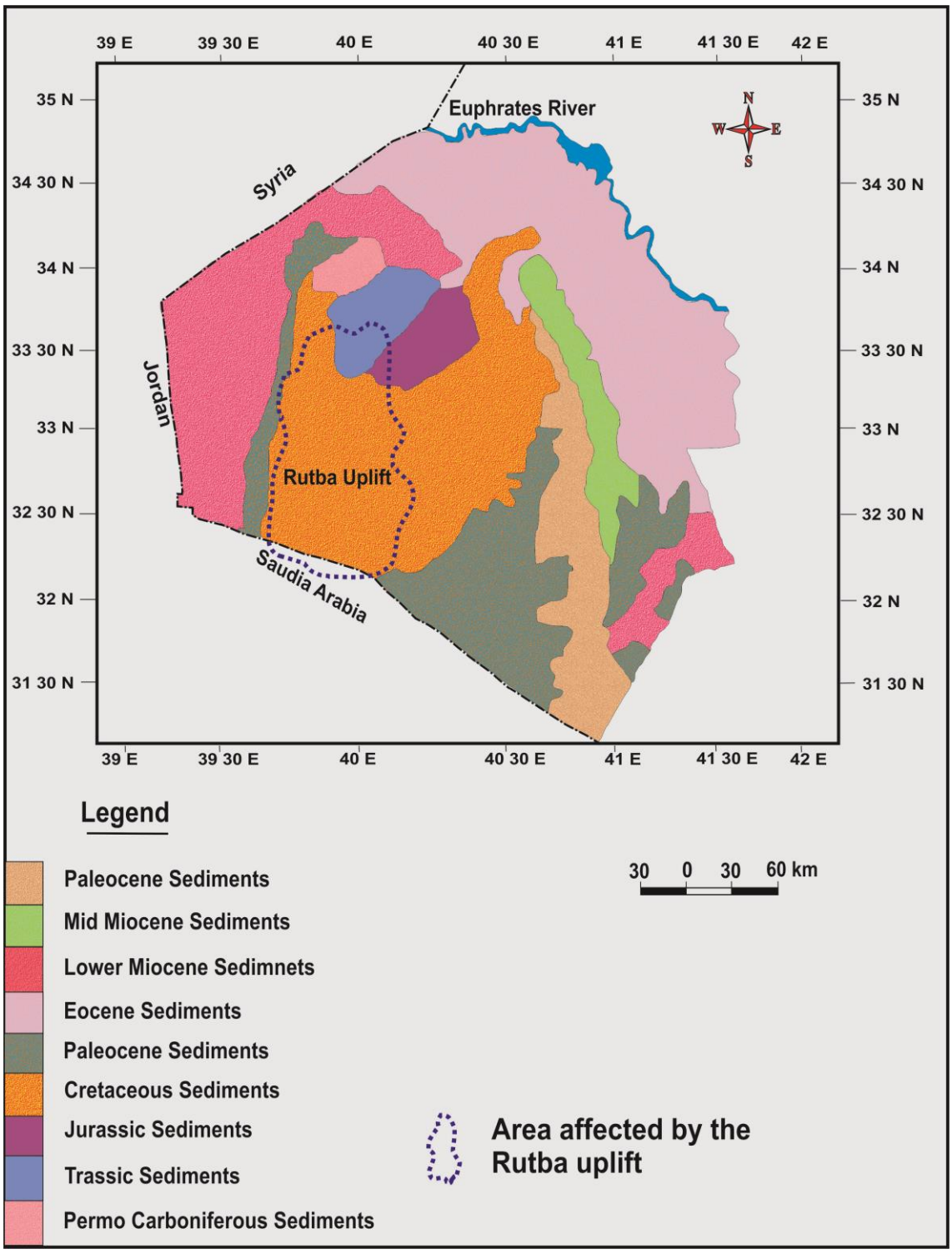


Figure 4.10: Sedimentary rock ages in the Iraqi Western Desert.

4.3.2.1 Garaa Formation (Early Permian-Late Carboniferous)

This formation (Figure 4.9 in appendix of this thesis) appears in the “Agrmyat” valley (Figure 4 .11), on the south rim of the Garaa depression. This formation makes up the oldest rocks of the Western Desert, with a regional thickness of up to 80m (Al Kubasi, 1993). It consists of sandstone, mudstone and shale. The identified extent of the Garaa formation has been modified during this investigation through the inclusion of data from water well K5-1 south of the town of Qaiam. The thickness of the exposed Garaa formation, after including the original type section in the Al Afyf hills and the Duwaikhl valley (picture 4.1), is therefore amended to 120 m at the north rim of Garaa the depression (Jassim and Goff, 2006). Some researchers do refer to the thickness of the Garaa formation as “mysterious”. For example, (Budey and Hak 1980) state the exposed thickness is 140m whilst subsurface sections show different thicknesses, for example 565 m in KH5/1; 655 m in KH5/6 or 770 m in KH 7/5 (Sissakian and Mohammed, 2007). The Gaara formation was deposited by large river systems which were found in the Iraqi Western Desert during the Permian to Carboniferous Periods. The deposits were also affected by prolonged periods of exposure of the flood plains, resulting in desiccation. The abundance of red claystone and ironstone suggests frequent long periods of drought (Jassim and Goff, 2006). The formation contains plant fossils, which have been described by Antonents and Aksenov, (1962) and Jassim and Goff, (2006). The sediments of the Garaa formation crop out on the floor and at the rims of the Garaa depression, covering a surface area of about 2000 square kilometres. Only the uppermost part of the formation, about 100m thick, is exposed, and the present knowledge of the development of the lower part is very poor. Ctyroky, (1973) suggested that the uppermost carbon rich layer was

Permian. This was confirmed by a study of a fossil plant obtained in the area (Buday, 1980) who proposed that the sediment of the Garaa Formation was deposited in continental fluviatile and lacustrine environments. The sedimentary basin is thought to have been flat and the sedimentation itself very variable. Salman, (1977) states that the two main lithological units of the Garaa Formation were sandstone and mudstone, with thickness varying from several centimetres to tens of metres. The most common occurrence of iron materials is at the boundary of a mudstone and the overlying sandstone. Iron ores seem to have originated from the precipitation of colloids during the quiet periods of the sedimentation cycles, which were then interrupted by the deposition of a new sandstone layer.

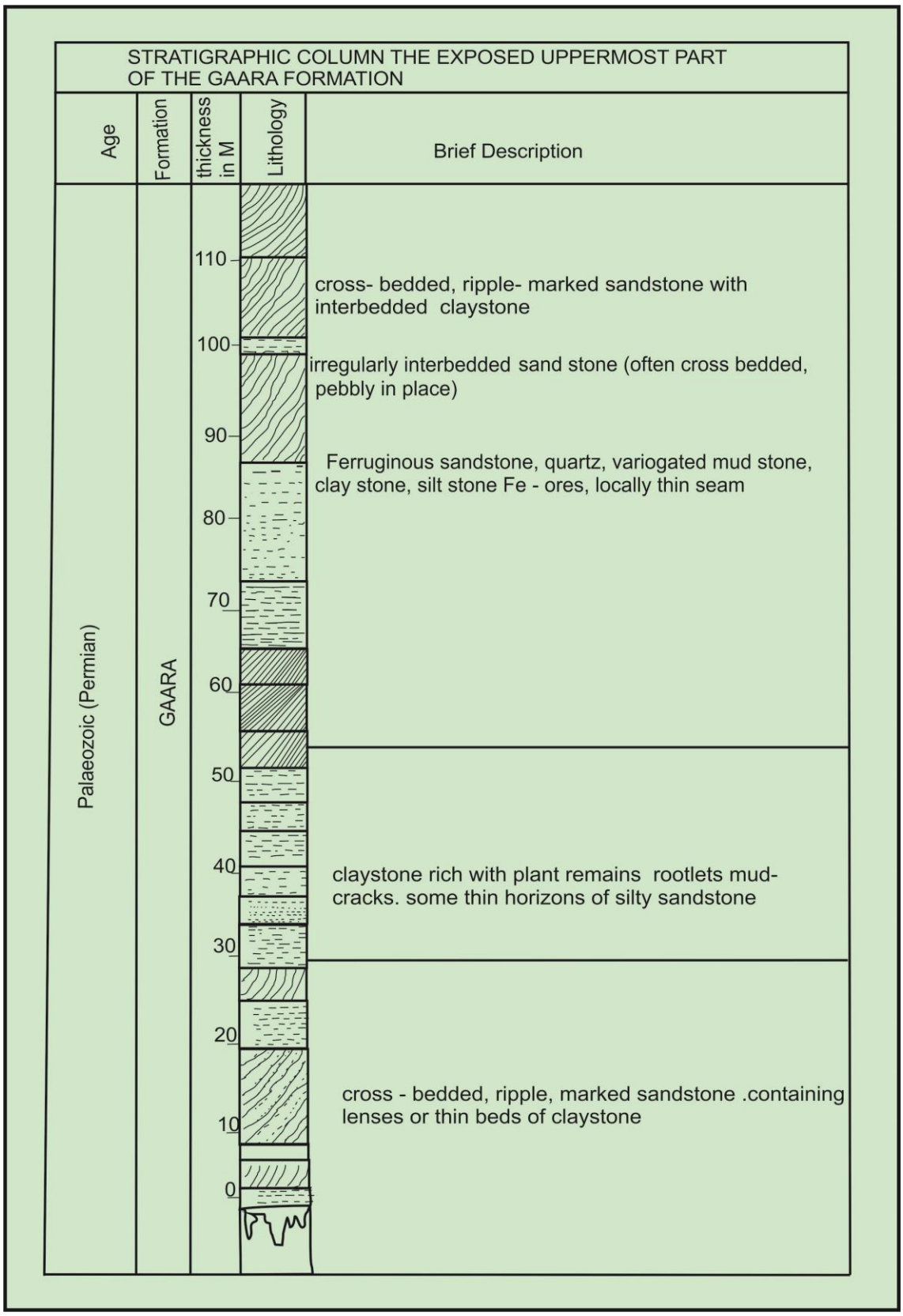
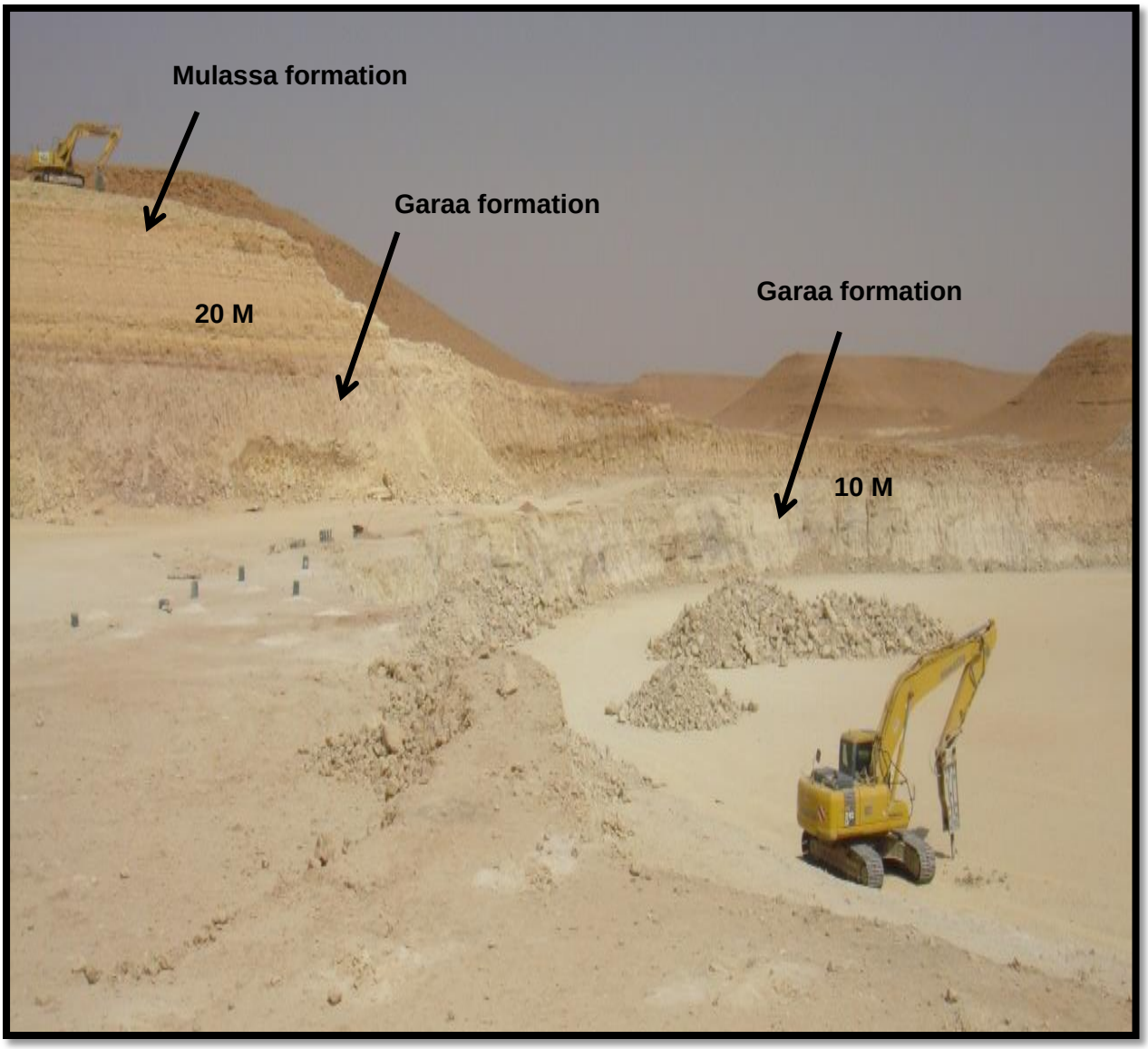


Figure 4.11: Stratigraphic column of the exposed uppermost part of the Garaa Formation (Jassim et al., 1984).



Picture 4.1: Garaa and Mulassa formations in Garaa depression

4.3.3 Mesozoic Era (245-65 Ma)

The formations of this era are exposed only in the middle part of the Iraqi Western Desert. The exposed rocks belong to three periods and are described below, from the oldest to the youngest (Fouad, 2007).

4.3.3.1 Triassic Period

The rocks formed during this period are exposed only in the middle part of the northern plateau in Iraqi Western Desert. Within this period two formations are exposed, the Mulussa and the Zor Houran.

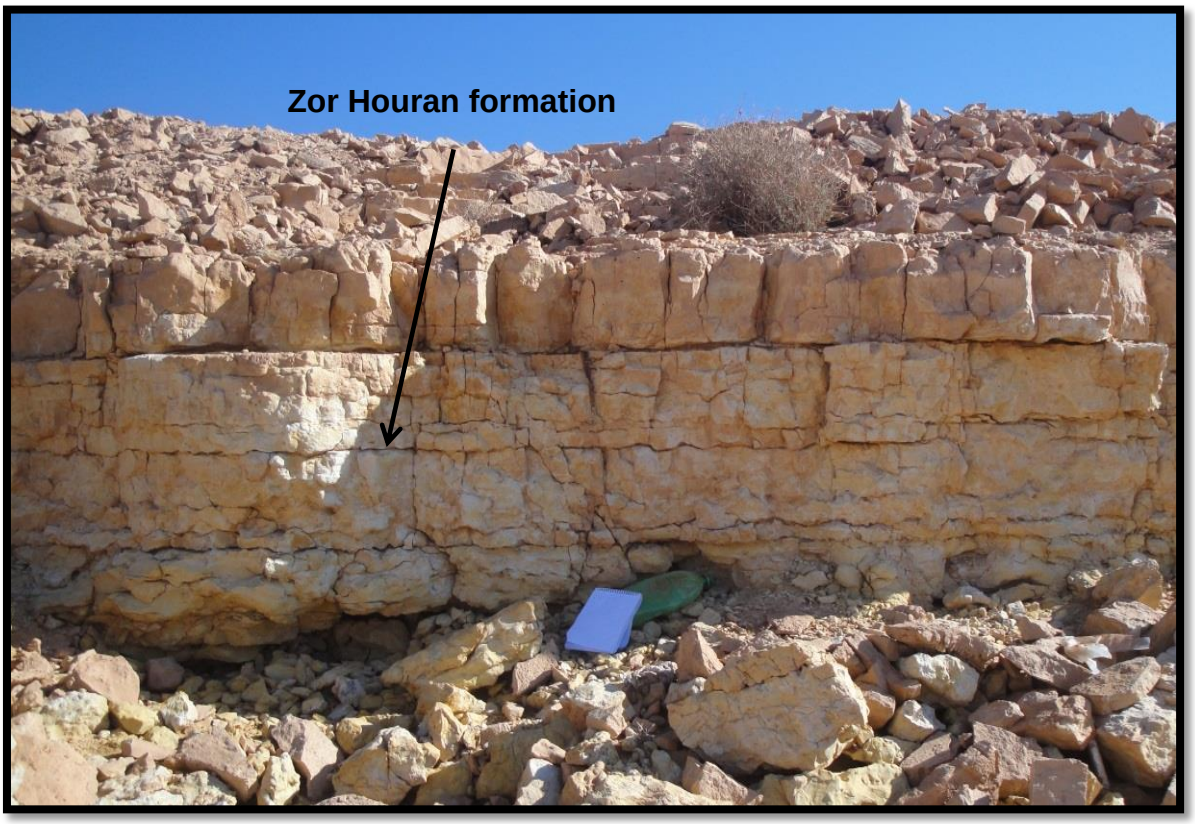
4.3.3.1.1 Mulussa Formation (late Triassic)

This formation appears in the Al Rutba area, at the southern rim of the Garaa depression, and in the Houran valleys region linking Iraq and Jordan borders (Figures 4.12) (Jassim et al., 1984). According to Buday and Hak (1980) the formation thickness is up to 140 m at the southern rim of the Garaa depression, although studies in 1994 identified the thickness as only being up to 100 m (Jassim and Goff, 2006). The Mulussa formation also appears in the area between the Euphrates River and the north rim of the Garaa depression. The lithology is relatively uniform in the area around the town of Rutba (picture 3.1). The thickness of the Mulussa formation is probably between 140 to 150 m but it has most likely been removed by erosion towards the north and northwest. It has been completely eroded in the central part of the Garaa depression (Jassim and Goff, 2006). The type locality of the Mulussa formation is composed mainly of limestone in the lower part, with subordinate yellow marls (Figure 4.10). A number of depositional environments have been suggested by different authors, including intertidal and lagoonal by Buday and Hak, (1980). Skocek and Hussain (1980) suggested a sabkha (salt flat) environment can be found in the upper part of the Formation. Tamar Agha (1986) and Qasir et al (1992) regard the Mulussa Formation as being deposited in marine, lagoon, tidal flats and shallow shelf environments, within a region of an arid to semi-arid climate (Sissakan and Mohammed, 2007). Wiliamsn and Pickles (1931) said the relatively homogenous complex of carbonate sediments of the Mulussa

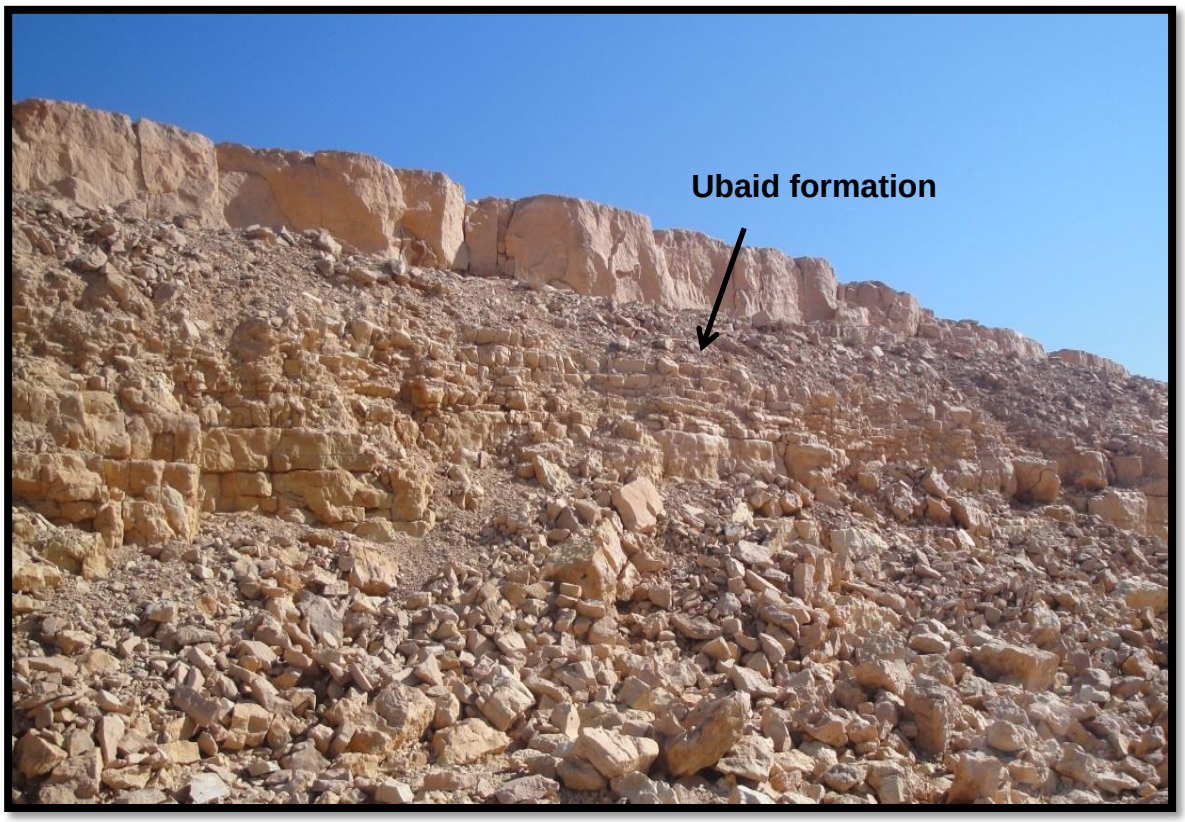
Formation appears to have been the product of a quiet and continuous (i.e. uninterrupted) period of sedimentation in a shallow sea. The sedimentary sequence of the formation consists of dolomite, calcareous dolomite and dolomitic limestone. Buday and Hak (1980) said the boundary with the underlying Garaa formation is lithologically distinct, and in overall terms the contact is usually sharp. In detail, however, the erosional boundary is locally smooth, transitional and difficult to recognize (picture 4.1). The material weathered from rocks of the pre-Triassic surface deposited in to the basal sediment of this formation is red and white in colour.

4.3.3.1.2 Zor Houran Formation (Late-Triassic, Rhaetian)

The Zor Houran formation is made up of 45 metres of predominantly yellow and grey gypsiferous marl, interbedded with yellow-green marly limestone (Jassim and Goff, 2006). This formation appears in the Houran valley, north west of Al Rutba, and is exposed along the southern rim of the Garaa depression. It extends for about 55 km across the Rutba region (picture 4.2). The sedimentary formation is characterized by the presence of evaporites, whereas both the underlying and overlying formations are mostly marine carbonates. The sediments of this formation are yellowish green and less commonly, whitish, thin bedded calcareous mudstone, marlstone and siltstones. The boundary with the underlying Mulussa Formation is gradual and not distinct or conformable. The base of the formation is identified by the presence of the first continuous layer of yellowish or yellow-green marlstone or calcareous mudstone. The lowest part of the formation is characterized by inter bedded yellow-green mudstone marlstone and whitish laminated carbonate (Figures 4.9, 4.10 and 4.13).



Picture 4.2: Zor Houran formation north of Rutba town.



Picture 4.3: Ubaid formation North West of Rutba town

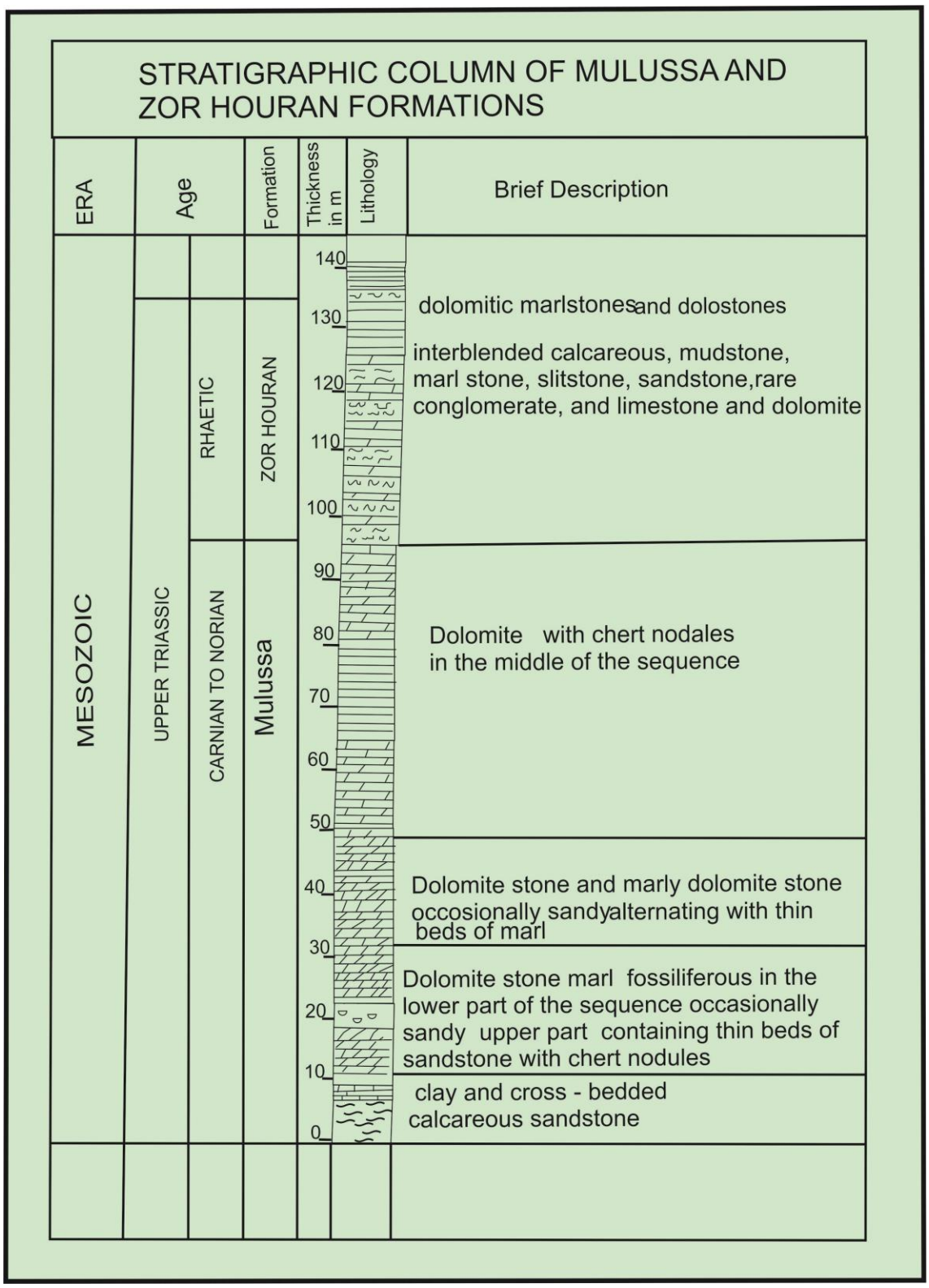


Figure 4.12: Stratigraphic column of the Mulussa and Zor Huran Formations (Shaker 1993).

4.3.3.2 Jurassic

The formations of this period are exposed only in the middle part of the Western Desert, mainly near to the Rutba area. The frequent break in sedimentation and the cycle of regression and transgression of the sea caused cyclical deposition of fluvial to fluvial-marine clastics followed by inner shelf coastal carbonates. The exposed formations are described by (Sisskian and Mohammed, 2007).

4.3.3.2.1 Ubaid Formation (Early Jurassic)

The Ubaid formation is exposed 25km northeast of Rutba town and extends along the Houran valley as far as Qasir Muhawir, forming a narrow strip 10km wide. The exposed Ubaid formation was described by Jassim et al., (1984) as a 100 metres thick section within the Houran Valley (picture 4.3). The subsurface extension is obscured and it is not penetrated by any nearby wells (Sisskian and Mohammed, 2007). The formation consists of crystalline dolomitized limestone with abundant chert nodules, and an indeterminate upper boundary (Figure 4.10) (Bellen et al., 1959). The following thicknesses are recorded by different authors from different parts of the outcrop: Jassim et al, (1984) gives the thickness for this formation as 120 metres in the Houran Valley type locality; Al Azzawi and Dawood (1996) suggest a maximum of 32 metres in the north-eastern part of the exposure; (Hassan and Hassan, 1994) ascribes a thickness of about 60 to 80 metres along the Al Hussainiyat area northeast of Rutba town. Budy and Hak (1980) divided the formation south of the Garaa depression into two members:

a) Hussainyat Member: 25-30m thick composed of sandstone with interbeds of marl and iron or ironstone.

b) Ubaid Member: 40-50m thick comprising sandy limestone with abundant chert at the base and at the top, occasional interbedding of limestone and dolomite.

Al Mubarak and Amin (1983) also divided the formation northeast of Rutba into two members:

a) Lower clastic member with an exposed thickness of 10 m. It consists of coarse sandstone interbedded with claystone lenses and ferruginous sandstone.

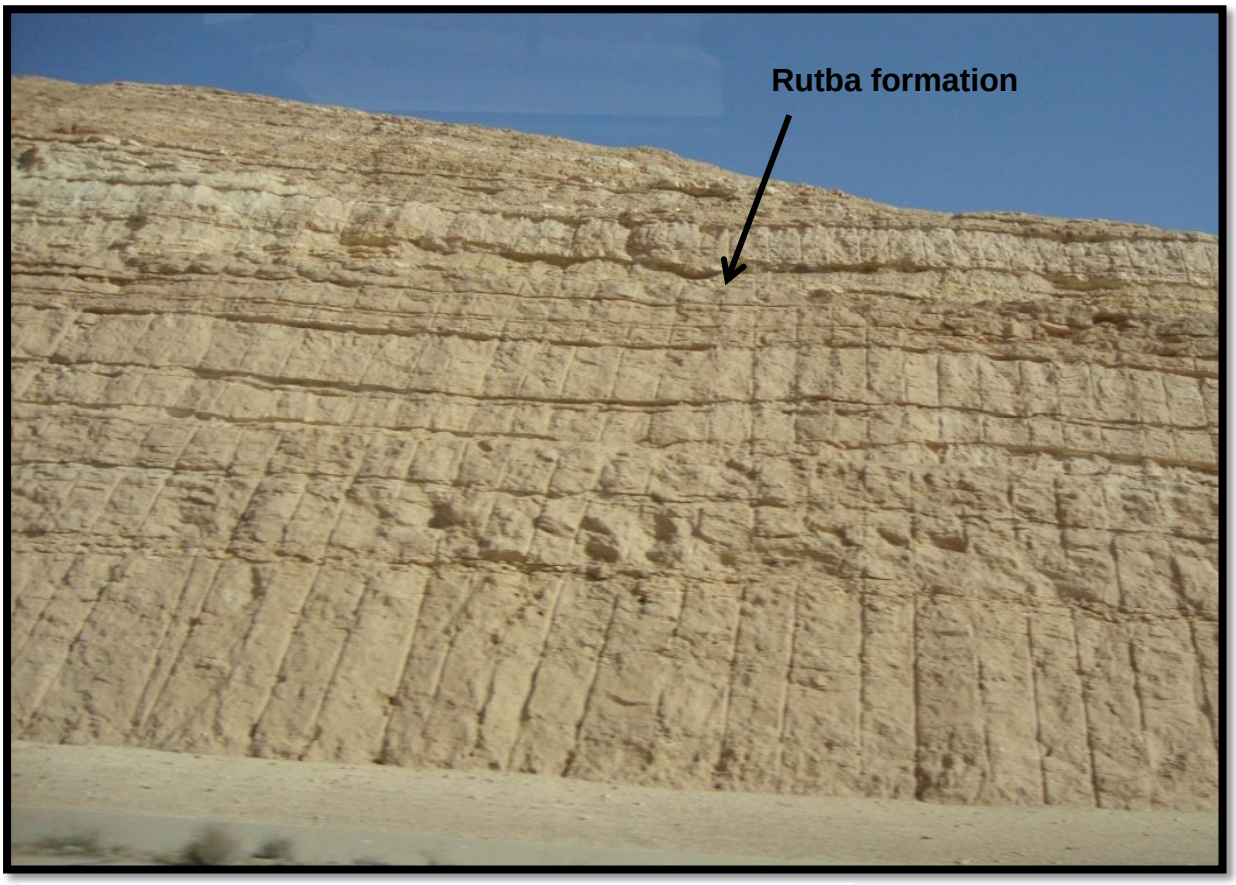
b) Upper carbonate member with a thickness of 70-80 metres and consisting of three parts: the lower part (28m) being a yellow grey dolomite and dolomite limestone and chert nodules; the middle part (40m) is a recrystallized dolomite and shelly limestone with abundant chert nodules; the upper part (20m) consists of interbedded gypsiferous marl and recrystallized shelly limestone (Sisskian and Mohammed, 2007).

4.3.3.3 Cretaceous

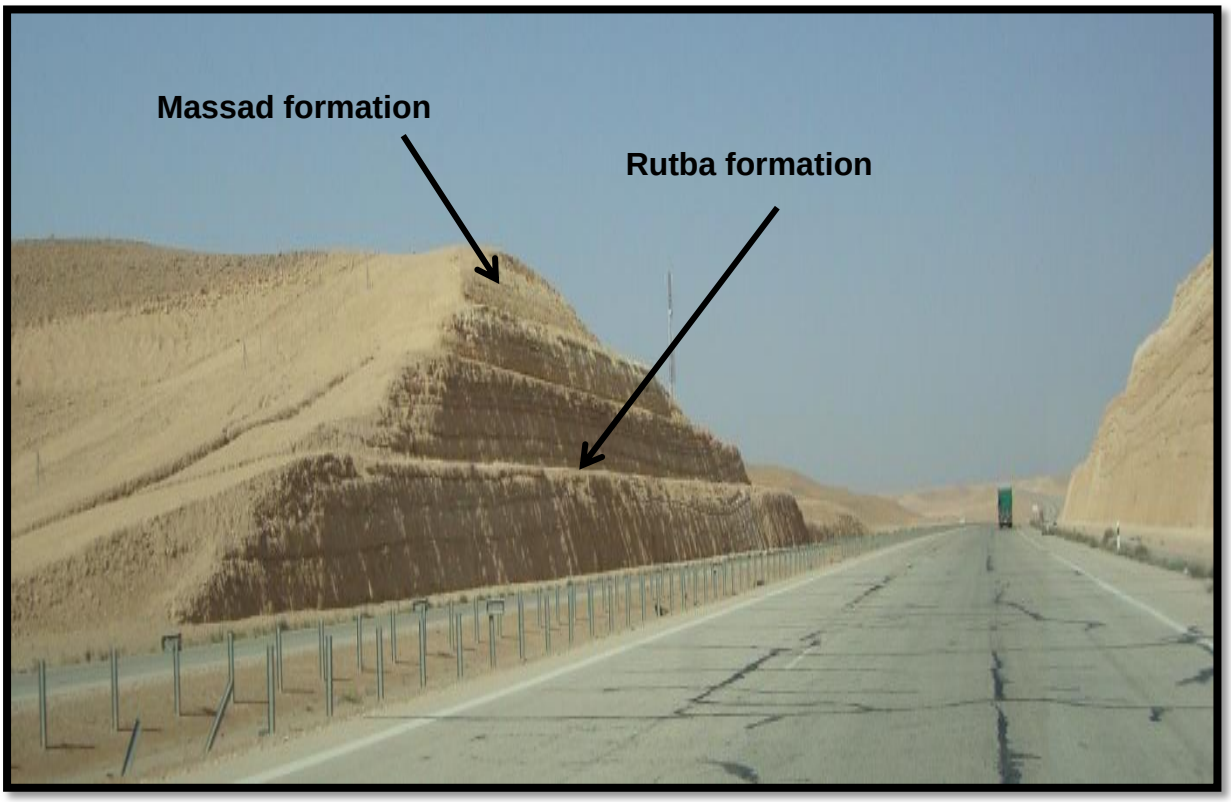
The formations of the Cretaceous period are exposed mainly in the middle part of the Western Desert and locally in the Rutba area. Five sedimentary cycles are identified in the Cretaceous period rocks, which includes four formations and the Marbat Beds. The exposed formations are described below.

4.3.3.3.1 Rutba Formation (Late Cretaceous-Cenomanian)

This formation is exposed in several places along the express way from Baghdad to Amman (pictures 4.4 and 4.5). Near Al Rutba town the thickness of this formation is up to 23 m (Figures 4.9 and 4.13), (Buday, 1980). It was during the 65 million year break in sedimentation between the deposition of the Rutba Formation and the underlying Ubaid Formation that the Garaa surface originated. This surface was later subject to a phase of sub-aerial denudation and a phase of sedimentation, which lasted the whole of the Upper Cretaceous. Foran and Keller (1973) first described the Rutba sandstone formation as a sequence of fine to coarse sandstone passing locally into quartzite (Figure 4.10). The percentages of silt and calcite within the sandstone increases eastwards of Rutba. Lenses of sandy limestone, silica, siltstone and calcareous sandstone appear in this area, which interdigitate with quartzite calcareous and silty sandstone (Figure 4.9 in appendix of this thesis). Buday and Hak (1980) described the Rutba formation in the area near Rutba town as white coarse-grained sandstone, occasionally conglomeratic and quartzitic. Al Naqib et al (1986) divided the Rutba formation east of Rutba town into three units. The first unit (8.5 m) consisting of white quarzitic sandstone; the second unit (18.5 m) consisting of yellow and yellowish brown sandstone, including two fossiliferous dolomitic limestone horizons, topped by 2.25 m of yellowish grey calcarenite with limonite nodules; the third unit (5.9 m) consisting of sandstone. (Al Azzawi and Dawood, 1996) described the Rutba formation in the North West of Kilo 160 and east Rutba town as yellow and white sandstone.



Picture 4.4: Rutba formation west of Rutba town.



Picture 4.5: Rutba and Massad formation west of Rutba town.

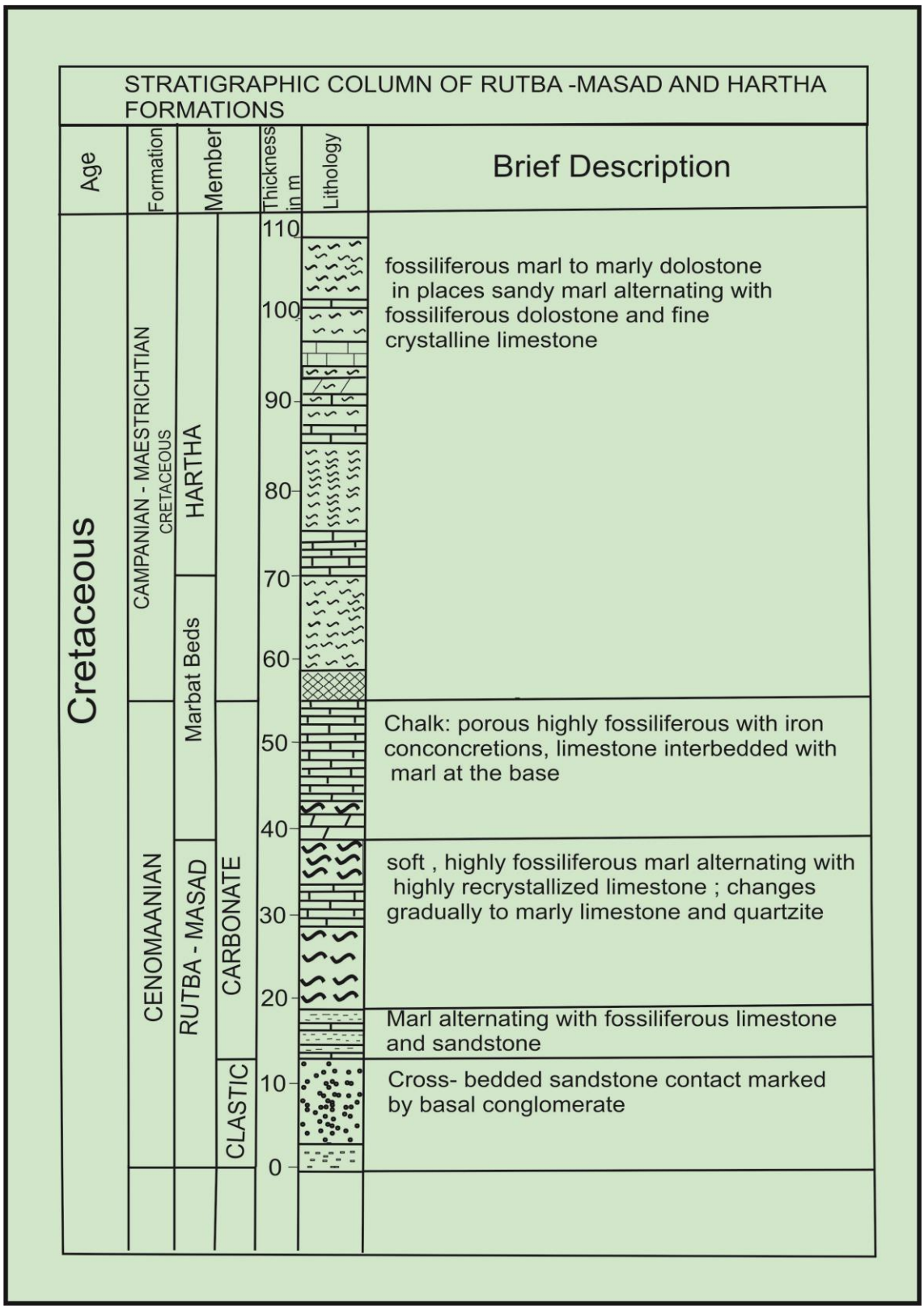


Figure 4.13: Stratigraphic column of the Rutba, Massad and Hartha formations (Shaker 1993).

4.3.3.3.2 Massad Formation (Late Cretaceous, Cenomanian-Turonian)

Henson (1940) identified the Masad Formation as cropping out in the Masad valley southwest of Rutba town. Bellen et al., (1959) described the formation 36 km north of Jabal Tayarat in the Masad Al Rutba valley, where it joins the Houran valley north of Rutba town and established this as the type locality (Figures 4.13 and 4.14). There is a gradual transition between the Rutba formation and the overlying Masad formation (picture 4.5), but locally there are sedimentation breaks with sections at the base of the Masad formation composed of sandstones with iron concretions (Figure 4.15). The formation as a whole is lithologically heterogeneous, particularly the lower part where different types of limestone, siltstone, marlstone and sandstone intercalate in a cycle of sedimentation (Figure 4.15). Sandstone interchanging with siltstone is characteristic for the lower part of the Massad formation, while the upper part of the formation is composed of calcareous dolomites with some sandstone. The upper part of the Massad formation is richer in fossils than the lower part but overall the Massad formation had been characterized as poor in microfossils (Buday and Hak, 1980). The Massad formation appears to be just the upper part of a large cycle, the lower part of which is the Rutba formation. Both formations are of Cenomanian age and even if their superposition is indisputable, lithologically they only represent two different facies. Because of the interdigitation of the Rutba sandstone and impure carbonates, calcareous siltstone and marlstone in the area east of Rutba town, the boundary is obscure. It is easier to identify in the area west of Rutba town, where thin layers of variegated mudstone and siltstone with nodules and small lenses of iron ores oxides at the base of the Massad Formation can be found. These sediments,

which are considered to be the products of fossil (i.e. relict) weathering, prove the existence of short breaks in sedimentation.The interdigitated sandstone and carbonate sediments formed east of Rutba town would have been deposited further from the coast in a shallow sea with terrigenous influx (Budy and Hak, 1980).

4.3.3.3.3 Marbat Beds (Late Cretaceous, Campanian-Maastrichtian)

The Marbat Beds are only exposed along the northern rim of the Garaa depression from the Al Halgoom valley westwards to Marbat Al Hosan (Figure 4.8). Al Bassam et al. (1990) refer to these beds for the first time as being located in the Iraqi Western Desert as previously they were included within the Garaa Formation. The Marbat Beds consist of brown pebbly sandstone, claystone and sandy dolostone. Southwest of Marbat Al Hosan they change to coarser clastics, with conglomerate at the base passing upwards into sandstone, silt claystone, claystone and sandy conglomerate and rare fossiliferous detrital

imestone (Al Bassam et al., 1990) (Figure 4.11).

4.3.3.3.4 Hartha Formation (Campanian-Maastrichtian)

The Hartha Formation (figure 4.11) has been defined by Bellen (1959), Buday and Hak (1980) and Al Mubark and Amin (1983). It is exposed in the Al Ragass valley and Massad Al Rutba valley south west of the Rutba town respectively. In the Western Desert, especially in the Rutba area, the Hartha formation consists of beds of dolomite and marl. The Hartha formation includes 10-15 accumulation cycles. Each cycle consists of cross-bedded limestone sandstone, locally ferruginous sandstone, passing up into siltstone, mudstone or shale capped by coarse-grained dolomite and dolomite limestone (Figure 4.8 and 4.10) .The sandstone beds wedge out to the southeast of Rutba town (Jassim

and Goff, 2006). The formation then extends in both the Al Ragas and Massad Al Rutba valleys northwards for 30km and 11km respectively. North of Rutba town the formation is exposed along the western rim of the Garaa depression for about 45 km (Sisskian and Mohammad, 2007). It comprises organic detrital and glauconitic limestone beds with grey and green shale. The limestone is locally strongly dolomitised and beds of chalky limestone occur frequently. Anhydrite and oolitic limestone beds and lenses are recorded in the Hartha formation between Ramadi and Makhul where the beds are 50 m thick (Jassim and Goff, 2006). The Hartha formation now includes parts of the formerly recognized Pilsner formation. According to Bellen et al (1959) the Pilsner facies comprises organic detrital limestone with beds of argillaceous limestone with fossil debris, and medium-grained dolomites.

4.3.3.3.5 Tayarat Formation (Campanian-Maastrichtian)

The type locality of the Tyyarat Formation is on Jebal Tyyarat approximately 30km south of Rutba (Figures 4.10 and 4.11). Henson (1940) defined the unit as the Tayarat Limestone formation and identified it as being of the Maastrictian stage. In detail it has a very varied lithology. According to the description of the type locality, the Tayarat Formation is underlain by sediments of the Massad Formation. The base of the Tayarat Formation is at the foot of Jabal Tayarat, as proved by geological mapping (Buday and Hak, 1980), where it is underlain by the Campanian Digma Formation, rather than the assumed Massad Formation. In the Massad Al Rutba valley the Tayarat formation has been divided into upper and lower parts, based on the different lithologies in each part. In the lower Tayarat there are conglomerates at the base, followed by varied strata of siltstone, cherts, marlstone, and nodular cherts with geodes (Figure 4.11)

(Buday and Hak, 1980). In the upper Tayarat formation the conglomerate disappears in the area between Jebel Ayarat and Jabal Tayarat.

4.3.3.3.6 Digma Formation (Late Cretaceous Maastrichtian)

The Digma Formation is exposed along the northern rim of the Garaa depression from Marbat Al Hosan hill and extends westwards along the western rim, crossing Highway No.1, and extending to the Iraqi-Saudi Arabian border (Figures 4.9 and 4.10). Buday and Hak (1980) described it as having basal conglomerates, overlain by sandstone, marlstone and organic limestone. Yellow and green thinly-bedded calcareous claystone and calcareous siltstone are present in the north and northwest parts of the Garaa depression (Figure 4.11). Al Bassam et al., (1990) described the Digma Formation, which they called the Sfra Beds, as white to creamy limestone, dolostone with phosphorite, and with green to ochre papery shale horizons. Hassan (1998) divided it into two units in the Garaa area:

The Lower unit consisting of white creamy dolomite, within a phosphorite horizon, overlain by green papery shale and topped by a phosphorite horizon.

The Upper unit consisting of oyster-rich limestone alternating with marl horizons. Southwards, the fossiliferous limestone increases in thickness and passes laterally into shelly limestone, with chert nodules and geodes in the middle and upper part of the unit. Al Hazaz (2001) divided this into two parts: the lower part consisting of ochre marl, occasionally with oysters, whereas the upper part consists of oyster-rich limestone which alternates with dolostone. Southwards the upper shelly part increases in thickness and passes into a bivalve-rich limestone.

4.3.4 Cenozoic

Cenozoic formations are widely exposed in the Western Desert. The exposed formations are divided by age as discussed below

4.3.4.1 Palaeocene

The deep sedimentary basin of the late Tethys Sea shallowed during the Middle-Late Palaeocene leading to the deposition of phosphates (Sisskian and Mohammed, 2007). The phosphatic facies were formed due to the upwelling of clouds of nutrient rich water that was one of the significant effects of the closing of the Tethys Sea. The formations of the Palaeocene Epoch are the most widespread formations in the Iraqi Western Desert. As discussed below these are divided into the Umm Er Radhuma and Akashat formations (Sisskian and Mohammed 2007).

4.3.4.1.1 Umm Er Radhuma formation (Middle-Late Palaeocene)

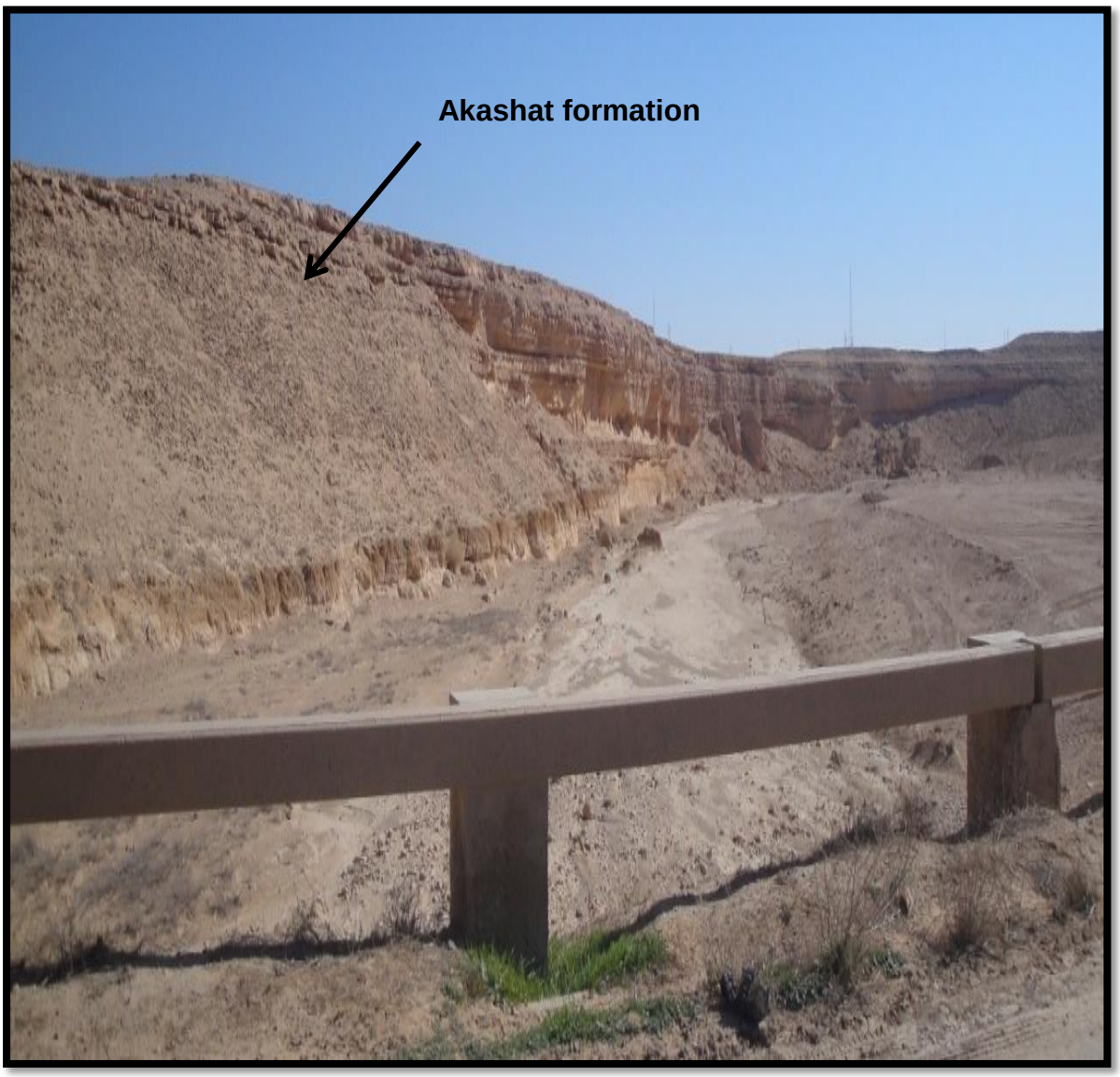
The type locality of the Umm Er Radhuma Formation is in Saudi Arabia (Steineke and Bramkamp, 1952; Steineke et al., 1958). However, Owen and Nasr (1958) refer to a supplementary type section from the Rutba area (picture 4.6). The lithology comprises anhydrite and dolomitic limestone with cherts in the higher part of the formation. Though deposited at the same time, the Umm Er Radhuma formation in the study area has a different facies. The formation surrounding Akashat is well known from numerous reports dealing with the Akashat phosphate deposit (Cobbet, 1955; 1956: Antoents and Aksenov 1962; Antonets and Passekov 1963). According to Zainal (1970) the formation is shown to be exposed along the northeast, north, west and southwest rim of the Garaa depression, and its thickness decreases gradually towards the southwest, away from the Garaa depression. This may be caused by primary

sedimentation changes as well as later erosion. The Umm Er Radhuma formation finally pinches out about 40km west-north-west of Rutba. The later Eocene Dammam Formation (Figures 4.9 and 4.10) lies directly on the late Cretaceous sediments further towards the south. Another area of the exposed Umm Er Radhuma Formation is in the extreme south of the mapped area, at the Saudi Arabian border south of Hazimi village.

Picture 4.6: The Umm Er Radhuma formation west of the town of Rutba.

4.3.4.1.2 Akashat Formation (Early-Late Palaeocene)

The Akashat Formation has been recently added to the stratigraphic column of Iraq. Formerly, the succession was considered as part of the Umm Er Radhuma Formation (picture 4.7). However, the differences in the lithological composition, facies development and paleogeogaphical distribution between Akashat and Umm Er Radhuma Formations were recognized by Buday (1980) and Buday and Hak (1980). Jassim et al. (1984) called it the Akashat Formation, and Al Bassam and Karim (1997) announced it as such officially. The Akashat Formation is exposed along the northern rim of the Garaa depression, extending westwards along the rim as far as Akashat, then southwards to the Iraq-Saudi Arabian borders, crossing Jabal Al Hirri in the form of a strip 2-10 km wide, until the Highway No.1, when it becomes 10-30 km wide. The Akashat Formation of the type locality consists of alternating grey phosphorites and limestone (Al Bassam et al.1990). (Sissakian and Mohammed, 2007) describe it as comprising phosphatic conglomerate or breccia followed by an oyster bed (Figure 4.11), overlain by a sequence of calcareous siltstone with layers of silty limestone and calcareous mudstone, locally phosphatic.



Picture 4.7: Akashat formation south town of Qaiam.

4.3.5 Eocene

The formations of the Eocene period are well exposed in the Iraqi Western Desert, and they cover almost the entire territory. They are represented mainly by the Rataga and Dammam Formations and partly by the Jaddala Formation.

4.3.5.1 Ratga Formation (Early-Late Eocene)

The type locality of this formation is in the Swab Valley located along the Syrian border area, northwest of the Garaa depression, and it unconformably overlies the Triassic Mulussa Formation. The Ratga Formation has also recently been added to the stratigraphic column of Iraq as it was formerly the rock sequence which included the Dammam Formation (Sissakian and Mohammed, 2007). The name was introduced by Jassim et al., (1984) but officially the Ratga Formation is distributed over four localities, since it is not possible to identify a complete sequence of the formation within any one locality. There is the Swab member in the Swab valley near Iraq-Syrian border; Damluk A member, in Akash valley northwest of Akashat mine; Damluk B Member, in Halgum valley north of the Garaa depression; and the Muger Member in Ratga valley, near the Muger Al Deheeb area. The Ratga Formation is widely exposed only in the Western Desert of Iraqi. It is exposed along the northern bank of Houran valley and extends westwards as far as the Iraqi-Syrian border in the form of a 35-45 km strip parallel to the northern rim of Garaa depression. In the vicinity of Muger Al Deheeb (Figure 4.10) it extends southwards covering the whole western plateau (Sissakian and Mohammed, 2007). The Ratga Formation in the type locality consists of nummulitic limestone, phosphorite and phosphatic limestone, and fine crystalline limestone with several chert horizons (Figure 4.11) (Al Bassam, and Karim 1997). The depositional environment of the Ratga Formation is marine tropical to sub-tropical (Jassim et al., 1984). The Swab member indicates a marine sandbar facies with a water depth not more than 10m. The Ratga Formation in the type locality is underlain conformably by the Akashat Formation (Al Bassam and Karim, 1997).

4.3.5.2 Dammam Formation (Middle-Late Eocene)

The formation was defined by Sander (1952) and by the Geological Survey of Iraq (Jassim and Goff, 2006) although the type locality is in Saudi Arabia. A supplementary type section was chosen by Owen and Nasar (1958). Buday and Hak (1980) divided the Dammam Formation north of the Garaa Depression into three units which are:

1. Nhadaine Unit Dammam 1 Formation /Lower Dammam Member
2. Umm Chaimin Unit Dammam 2 Formation /Middle Dammam Member
3. Anaza Unit - Dammam 3 Formation /Upper Dammam Member

The Dammam Formation in the type locality consists of dolomitized limestone and whitish grey porous limestone. The limestones are sometimes chalky and at or near the base of the drilled section a persistent grey-green waxy shale body is encountered (See Figure 4.10 and 4.11) (Owen and Nasar 1959, and Bellen et.al, 1959, cited in Sisskan, and Mohammed 2007). The Dammam formation crops out on the north and west slopes of the Rutba anticlinorium. The best developed sequences occur north of the Garaa depression (Figures 4.10 and 4.11), where the profiles have been studied around the Halqume valley (Buday and Hak 1980). Valuable information on the lithology of the formations is held in unpublished reports on the Akashat phosphatic deposit mentioned above. The sedimentary facies and depositional environments of the Dammam and Rutba Formations were described by Hashimi (1973) in a discussion of the stratigraphy and palaeontology of the Eocene to the lower Oligocene in the Western Desert. The results of the geological mapping of the Al Tinf- Nhadain area were described by Hagopian (1979).

4.3.5.3 Jaddalah Formation (Middle Eocene)

The existence of the Jaddalah formation in the Iraqi Western Desert is debatable but it is described in this chapter to clarify its possible presence. According to Jassim et al., (1990), based on Hagopian (1979), the Jaddalah Formation is exposed in the Iraqi Western Desert in the Traibeel area and extends northwards to the Iraqi-Syrian border, then north-eastwards parallel to Suwab valley for about 20 km. The possible formation then crops out again parallel to Swab valley and extends for about 35 km along the Iraqi-Syrian border for about 15 km southwest of Damluk hill (Figures 4.10). The Jaddalah formation type locality it comprises marly to chalky limestone and marls with occasional thin intercalations of shoal limestone (Avanah limestone tongues) (Bellen et al., 1959). Hagopian (1979) considered the Al Tinif Unit of the Ratga Formation to be the equivalent of the Jaddalah Formation

4.3.6 Oligocene

The rocks of the Oligocene Epoch in the Iraqi Western Desert are very limited in extent. This is because by the Oligocene the Tethys was a narrow seaway forming back reefs and fore reef basins as a result of the tectonic tilting of western Arabia which occurred at the end of the Eocene. The outcrops are limited to the Hauran valley in the Muger Al Dheeb area and Anah anticline. In all other areas, they are exposed only in deep cut valleys (Sissakian and Mohammed, 2007).

4.3.7 Miocene

During the Middle Miocene the marine transgression in the Western Desert extended south and southwest forming shallow basins with carbonate deposits. In closed lagoons evaporites were deposited. According to some of the studies of the Miocene the period was characterized by warm and wet conditions but there were no clear seasonal characteristics (Al Hasseni, 1978). As a result of uplift the marine phase changed to continental when only clastics were deposited. The formations of this epoch are exposed in all parts of the Iraqi Western Desert and are represented by two formations; these are the Ghar and Euphrates:

4.3.7.1 Ghar Formation (Early-Middle Miocene)

The Ghar Formation is exposed only in the North West Rutba area. It is exposed along the Iraqi-Syrian borders, 10 km north of Muger Al-Dheeb and extends south-eastwards. It is a 15-18 km wide strip crossing the Akash, Ratga and Manai valleys (Figures 4. 11). The Ghar Formation of the type locality consists of sands and gravels, rare sandy limestone, rare clay and anhydrite (Bellen, 1959). (Al Jumily, 1974) described the Ghar Formation north of Muger Al Dheeb village as white, pink and pale reddish brown calcareous sandstone in which, very rarely, thin horizons (0.2-1.0 m) of limestone are developed which increase in thickness and abundance northwards, changing to an alternating sequence of sandstone and limestone (Figure 4.11). The limestone is white grey, rarely pink, slightly fossiliferous and burrowed; in the lowest part a basal conglomerate is developed and the pebbles are mainly derived from the Ratga formation.

4.3.7.2 Euphrates Formation (Early Miocene)

The type locality of the Euphrates Formation is along the streams of the Euphrates River. It is widely exposed in the eastern, middle and western part of the Iraqi Western Desert (picture 4.8). The formation crops out along the Iraqi-Syrian border near Al Qaiam town and extends eastwards parallel to the Euphrates River. It is exposed south of Highway No:1 that links Iraq and Jordan, and crops out in the deep valleys of Akash and Ratga, as well as along both sides of Houran valley at the H1 oil pumping station (Figures 4.5 and 4.6). The Euphrates Formation at the type locality consists of shelly, chalky, well bedded recrystallized limestone (Figure 4.11) (Sisskian and Mohammed, 2007). The thickness of the Euphrates formation in the supplementary type section is 110m (Jassim et al 1984), and in the type locality is 80m (Bellen et al., 1959). In the Akash, Ratga and Mannai valleys the sequence is 20-30m (Al Jumaily 1974); in the eastern part of the Western Desert this increases to 40-50m (Al Mubarak and Amin, 1983). In the Al Qaiam area it is 128-145 metres (Al Mubarak, 1974), but it is believed that part of this thickness belongs to the Nafayial Formation (Middle Miocene) which lies outside the study area (Sisskan, 1997 cited in Sisskan and Mohammad, 2007). The type section proposed by Jassim et al., (1984) consists of:

Lower unit (A): 20m of basal conglomerate with subrounded limestone boulders and pebbles mainly derived from the Anah Formation (Late Oligocene) which lies outside the study area. The conglomerate is overlain by 10m of recrystallized, fossiliferous limestone changing to coralline limestone.

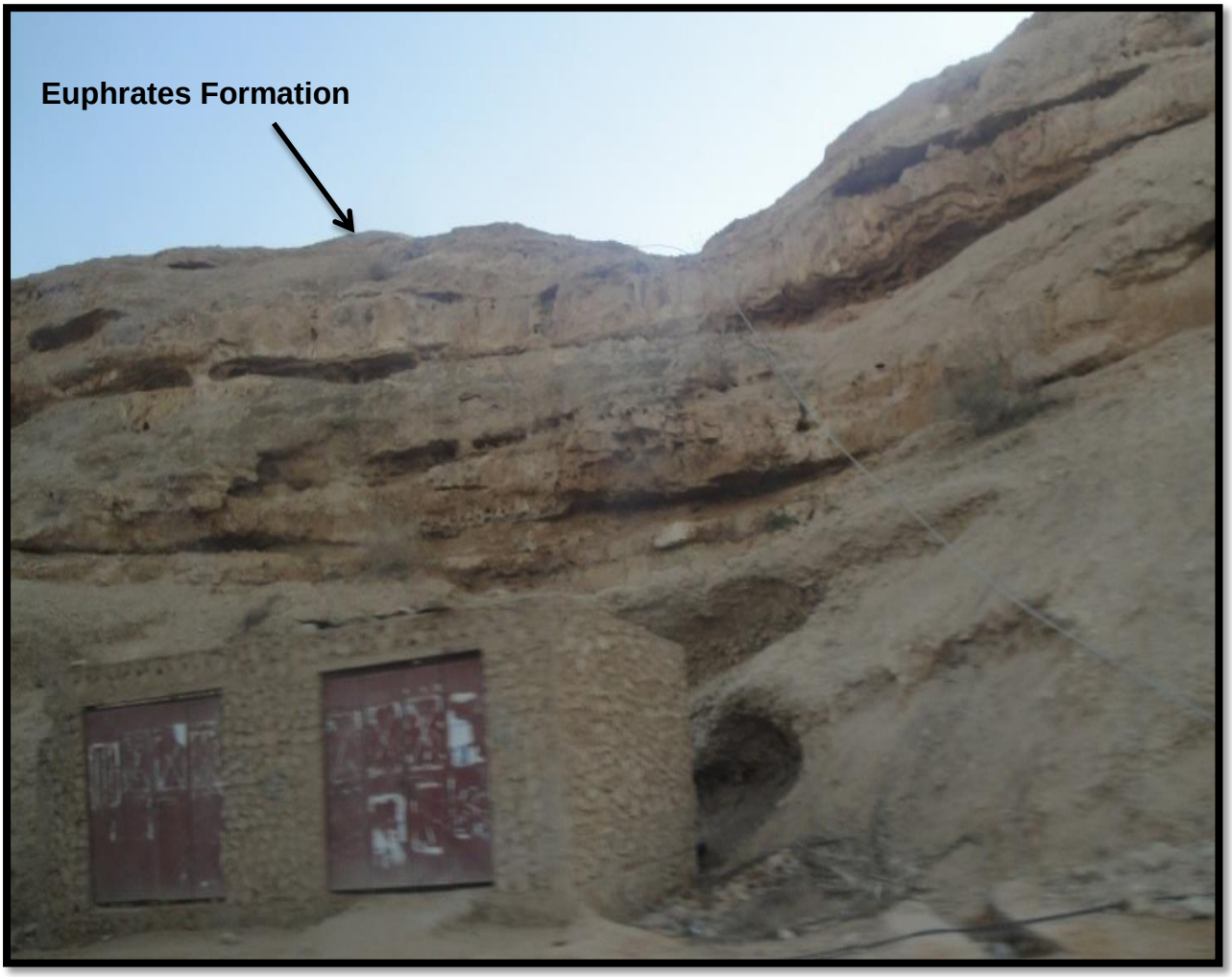
Upper unit (B): consisting of alternating hard limestone and pseudoolitic limestone.

Al Mubark, (1974) divided the Euphrates Formation in the Al Qaiam and Anah vicinities into three members

a) Lower Member consisting of a basal conglomerate, followed by dolostone and dolomitic limestone.

b) Middle Member consisting of white fossiliferous limestone alternating with pseudoolitic chalk-like limestone.

c) Upper Member consists of alternating grey limestone with green marl.



Picture 4.8: Euphrates Formation on the way to the town of Al Qaiam.

4.3.8 Pliocene, Pleistocene and Holocene

The whole Iraqi Western Desert continued to be uplifted throughout the Pliocene to the Holocene due to the collision of the Arabian plate with the Tethys terranes (Buday, 1980) therefore, unconsolidated continental fluvial deposits occur over a considerable area. However, the Pliocene Epoch is represented by one bedrock formation in the study area, the Zahra Formation,

4.3.8.1 Zahra Formation (Pliocene-Pleistocene)

The Zahra Formation at the type locality consists of whitish and reddish limestone that is locally sandy, with red and purple sandy marls and calcareous sands (Bellen, 1959). (Al Mubarak, and Amin., 1983 and Al Jumaily., 1974) described the thickness of the Zahra Formation at the type locality as about

30 m (Bellen et al., 1959). Al Jumaily (1974) recorded the thickness of the

Zahra formation as 15 m in the Al Kherish area, which decreases to a few metres towards the south and southeast. (Al Mubark and Amin., 1983) reported a thickness of 20-25 m in the Mugher Al Deap area which is located south of the town of Al Qaima (Figures 4. 9 in appendix of this thesis). Although of limited occurred the Zahra formation has a wide distribution in the Iraqi Western Desert. It is exposed northwest of H1 oil pumping station for about 50 km, forming a wide plateau, which is dissected by deep valleys, such as Ratga and Akash, exposing older formations. It is also present as a caprock on almost all isolated hills and small plateaus, like the south T1 oil pumping station and town of Al Qaiam.

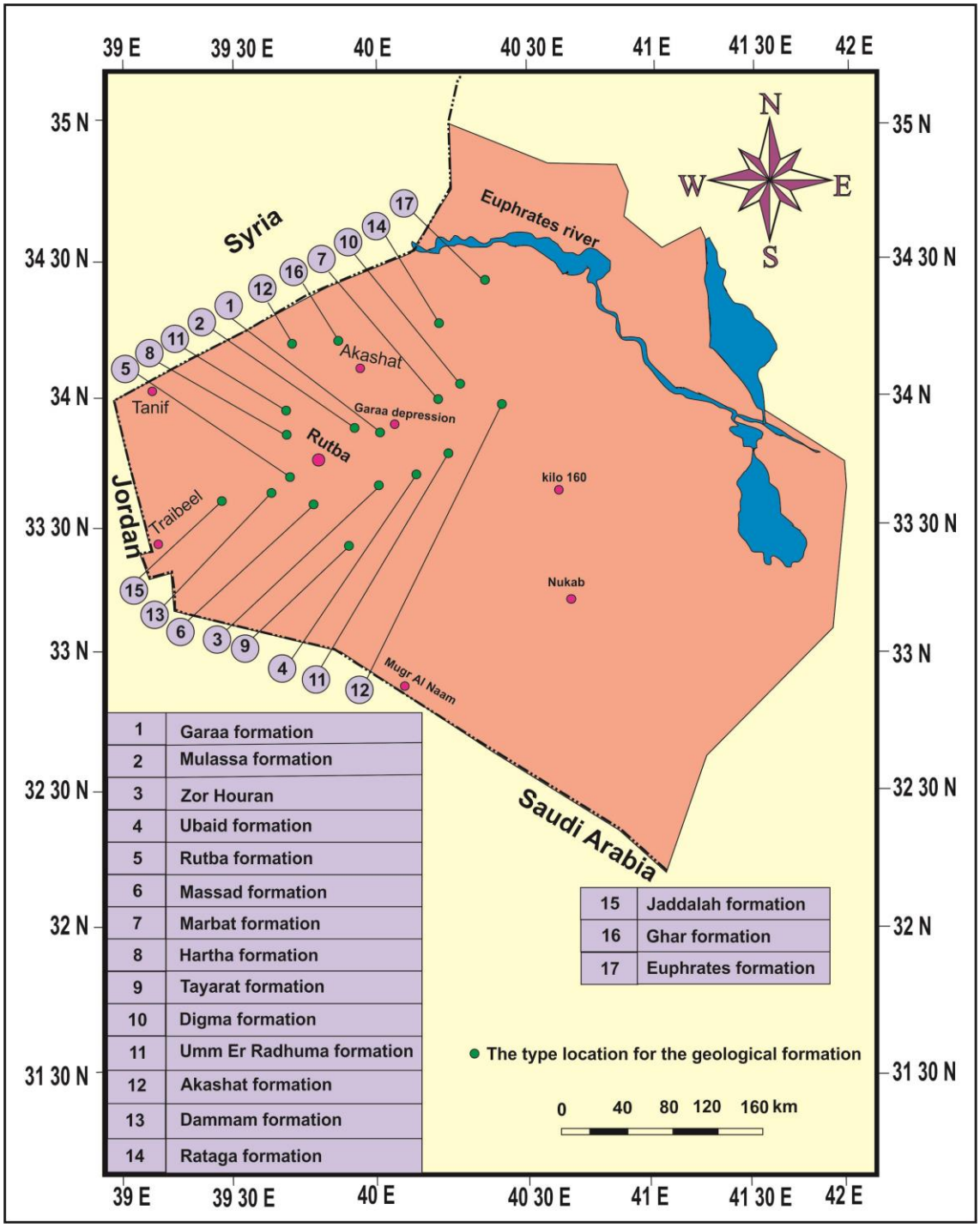


Figure 4.14: The type locality locations of the geological formations in the Iraqi Western Desert (Geological Map of Iraq 2000).

Lithological index of formations in study area

No	Formation	Lithology
1	Garaa formation	
2	Mulassa formation	
3	Zor Houran	
4	Ubaid formation	
5	Rutba formation	
6	Massad formation	
7	Marbat formation	
8	Hartha formation	
9	Tayarat formation	
10	Digma formation	
11	Umm Er Radhuma formation	
12	Akashat formation	
13	Dammam formation	
14	Rataga formation	
15	Jaddalah formation	
16	Ghar formation	
17	Euphrates formation	

Lithological legend

Sandstone	
Siltstone	
Limestone	
Clay stone	
Marl stone	
Dolomite	
Quartzite	
Shale	
Phosphorite	
Gypsum	
Conglomerate	

Figure 4.15: Lithological indexes of formations in Iraqi Western Desert.

4.3.9 Quaternary including Pleistocene and Holocene Deposits

Quaternary deposits are well developed in the Iraqi Western Desert. Only the main types in the study area are reviewed in this section. The Iraqi Western Desert can be classified as a denudation area from the viewpoint of Quaternary sedimentation. Consequently, the extent, preservation and the distribution of Quaternary sediments were controlled by local geomorphological factors. Many genetic types of Quaternary sediments were found to occur in the study area. Only brief characteristic of individual types and their extent are given in this thesis. More detailed lithological and stratigraphical data on these sediments, their palaeographical importance and correlation with some other areas are presented in Chapter 5 on geomorphology.

4.3.9.1 Houran Gravels (Pleistocene)

Al Mubark and Amin, (1983) and Sisskian and Mohammed, (2007) identified the Houran Gravels for the first time and these are well developed in the Rutba area (picture 4.9 and 4.11). They comprise loose rounded pebbles of different sedimentary rocks; the sizes of the pebbles ranges from 1-10cm, but locally reach up to 25cm, with a unit thickness of 2-3m although this may occasionally reach 7m. The source and origin of the pebbles are obscure (Sisskian and Mohammed. 2007).

4.3.9.2 Habbariyah Gravels (Pleistocene)

The Habbariyah Gravels are well developed in the Iraqi Western Desert in the Habbariyah area which is located in east of Rutba town. They are composed of loose, rounded to subrounded limestone pebbles with few cherts, the size of the pebbles range from (12-20) cm. The thickness of this level ranges from (5-6) m,

exceptionally reaching 8-12 m in the northern bank of the Ghadaf valley. (Sisskian and Mohammed, 2007).

4.3.9.3 Terraces (Pleistocene)

The Euphrates River has deposited at least five main terraces levels (see section 5.3.3.3), but they are not well developed, and extend over a limited area (Sisskian and Mohammed, 2007). The cobbles in the terraces are well rounded to rounded, mainly limestone and silicates, with rare igneous and metamorphic rocks. The size range is from a few cm, up to 15cm and may reach 35cm. The thickness of each level is variable, but generally does not exceed a few metres, and is usually cemented by gypsum. The main valleys, like Houran, Swab, Ratga, and Akash, also contained river terraces. In these terraces the cobbles are limestone and silicates, rounded to sub rounded; their sizes are mostly 1-10 cm, but may reach 20 cm. They are generally, cemented by calcareous materials. The thickness is highly variable, depending on the valley, but is generally 1-3m (Sisskian and Mohammed, 2007).

4.3.9.4 Valley Fill in Depressions (Holocene)

Infilled valley depressions are common on surfaces of all plateaux. The depressions are of variable sizes and in age. The main valleys are filled by various clastic deposits, which are highly variable in composition, size and thickness, and include clay rich oxides of aluminium, materials from running water, and wind re-worked alluvial deposits (picture 4.10). The main materials are carbonates and silicates. The pebbles are rounded to sub rounded, with an average size of 1-10 cm, but may reach to 20 cm. The thickness ranges from 1-3m but locally may exceed 5 m.

4.3.9.5 Depression Fill Deposits (Holocene)

These are restricted to the Rutba area, extending to the northwest and south of Rutba town up to the Iraqi borders with Syria, Jordan and Saudi Arabia. It mainly forms in flat areas, called playas (flat lands occupied by ephemeral lakes that are rich in carbonates), and locally known as “Faidhah” or “Khibrah”. The deposits are largely of clay and rich in sulphates. The thickness is 1-1.5 m but may be more. The average area is less than 2km^2 but can be as much as a few tens of square kilometres (Sisskian, and Mohammed, 2007). Studies show that the difference between the infilled valleys and infilled depressions are the sediment thicknesses and areas. According to Al Bassam et al (1990) the thickness in the area north Rutba town near Garaa depression reach between few centimetres to few meters in the thickness and few square meters up to few hundred square kilometres. (Sisskian and Mohammed, 2007).

Picture 4.9: Houran Gravels in Houran valley south town of Rutba.

Picture 4.10: Valley fill depression deposit South west town of Rutba.

Picture 4.11: stones cover the area south west of the town of Rutba.

4.4 Economic Geology

The structural history and stratigraphy of the Iraqi Western Desert has resulted in the availability of a wide range of non-hydrocarbon economic minerals. During the process of compiling data for this thesis it became possible to compile an overall economic geology map of the Western Desert and this is presented in Figure 4.16 [for more details see Al Bassam (1984, 2007) and Al Azzawi et al. (1996)].

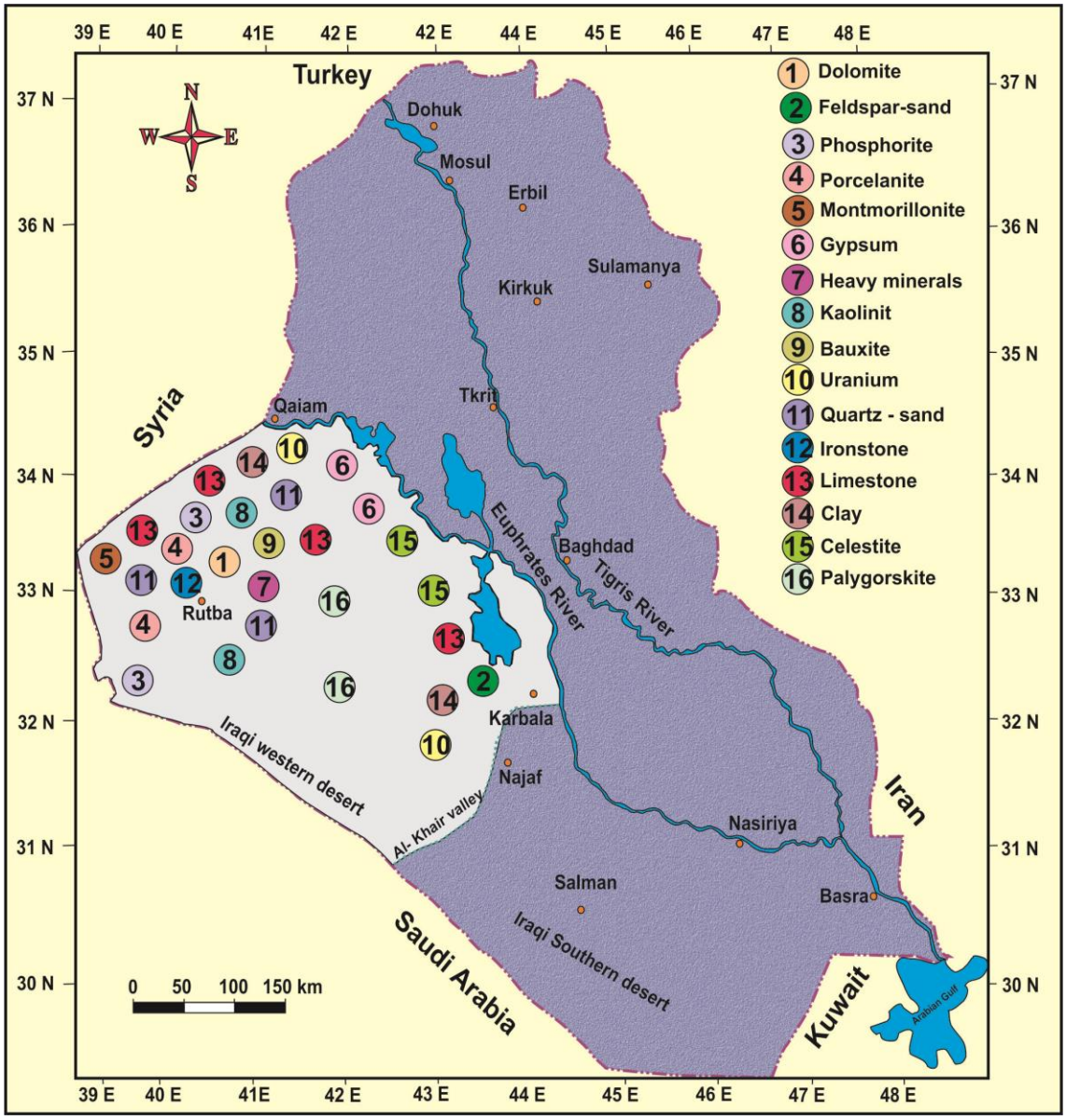


Figure 4.16: Distributions of minerals and raw materials in the Iraqi Western Desert (drawn from Al Bassam 2007 and multiple sources).

4.5 Summary and Conclusions

The Iraqi Western Desert is a large area and a number of contradictions in scientific opinion have arisen between the various writers who have studied the geology of the region. Therefore the purpose of this part of the research was to attempt to describe and discuss the structural geological and stratigraphic formations as clearly as possible as they have a significant bearing on the geomorphological development of the ephemeral river network. This chapter has provided data on the geology of individual formations occurring in the Iraqi Western Desert. The geological investigation indicates that the Iraqi Western Desert belongs to the stable shelf of the Nubian-Arabian platform, which was established at the end of the Precambrian. The platform's sedimentary cover spans the Palaeozoic Mesozoic and Cainozoic. It is characterized by mostly shallow water deposits and numerous breaks in the sedimentation.

The bedrocks geology and unconsolidated deposits represent the foundation of the land scape on which the drainage of the Iraqi Western Desert has developed it is the geomorphological evolution of the drainage that is investigated and presented in the following two chapters.

Chapter 5

Geomorphological Investigations

5.1 Introduction

Geomorphology is the study of the development of landscapes, the landforms that combine to make up the landscape, the processes that create the landforms and material they are composed of (Hamza, 2007). In this chapter following an evaluation of the contemporary climatic condition in Iraq (Section 5.2) the geomorphology of the Western Desert of Iraq is examined. Initially this is placed in the context of the overall physiographic subdivision of Iraq (section 5.3) into four regions (Section 5.3 figure 5.7) namely the desert (39% of the Iraqi land area), alluvial plains of Mesopotamia (30% of the Iraqi land area), the mountainous highlands (10% of the Iraqi land area) and the area of foothills (21% of the Iraqi land area). In Section 5.4 the study concentrates on the Iraqi Western Desert dividing the area into six main geomorphological units based on an investigation of the literature (translated from Arabic), unpublished Government maps and reports (again translated from Arabic), use of satellite imagery and field reconnaissance mapping. The final Section 5.5 takes the geomorphological units of the Western Desert as the basis for the compilation of the unique 1: 100,000 geomorphological map of the region which allows for the investigation of the ephemeral stream network presented in Chapter 6. The basis for the identification of the desert landforms in the study area is Figure 5.6, taken from Griffiths et al (2012), and the background to the fluvial geomorphology of hot deserts presented in Chapter 2.

5.2 Climatic data

Climatic data (rainfall, temperatures, wind speed, relative humidity, and evaporation and transpiration) in the study area from weather stations shown in Figure 1.1 were compiled in a database. This allowed an investigation of the prevailing climatic conditions in the study area as background to understanding the nature of the contemporary fluvial environment. This information involved an evaluation of the spatial variation of the climate in the region in order to provide an assessment of its possible impact on contemporary geomorphological processes and landforms

5.2.1 Climate in Iraq

In very broad terms the contemporary climate of Iraq is characterized by two prominent seasons. The summer season is very hot, (temperature range 35-50 °C) and very dry (mean summer rainfall 0 mm).The winter season is usually characterized by lower temperatures (range 15-25 °C) with rainfall common (mean winter rainfall of 112.54 mm at Anha station). Iraq is also affected by weather related hazards such as sand storms and drought (Malinowski, 2000). Iraq as a whole is a zone affected in the summer season by subtropical high pressure. These high pressure regions affect desert areas across North Africa and the Arabian Peninsula and migrate towards the north in the summer season because of increased solar radiation (Malinowski, 2000). During the winter season the northern hemisphere faces away from the sun and the subtropical high pressure systems move from west to east across Iraq causing winter rains and a little snow in the mountain regions in the north. The annual migration of the pressure system is clearly reflected in Iraq's climate and three featured climate zones can be identified using the Köppen climate classification system (Malinowski, 2000):

1. The Western Desert and the Southern Desert, down to the coastal areas on the Arabian Gulf which are classified as subtropical desert (Bwh)
2. The highland area in the north of Iraq which is significantly wetter especially in the winter season and can be classified as a subtropical steppe (Bsh).
3. The mountain area in the north of Iraq (especially north of 36° longitude) which is cooler in comparison with the deserts with more precipitation and the climate would be classed as dry summer subtropical or Mediterranean (Csa).

5.2.2 Climate in the Iraqi Western Desert

The Iraqi Western Desert climate is hot dry continental in summer and cold wet in winter (Al Khfaji, 2009) Sand storms are very common and especially in the last ten years the precipitation is very low (less than 100 mm annually). The mean temperatures in the Iraqi Western Desert exceed 50°C between the end of May and the end of August but can drop below 10°C between January and February. Most rain falls between middle January to the end of March. Two main anticyclone tracks influence the climate of Iraqi Western Desert and are the main cause of rainfall between January and end March (Al Khfaji, 2009):

1. Depressions from the Mediterranean Sea cross westward into Iraq. This depression track is responsible for the rainfall that falls on the northern parts of Iraq.
2. The second weather depression track, called the Sudan depression, begins in South Sudan, crosses eastwards to affect the south and middle of Iraq.Occasionally these two depressions affect Iraq at the same time.

As noted above as part of the investigation for this thesis access to climate data was obtained for the five relevant weather stations at the study area: Al Qaiam, Al Nukaib, Al Rutba, Haditha and Ramadi (Figure 5.1 and Table 5.1). Data from these weather stations provided the basis for the analysis presented below

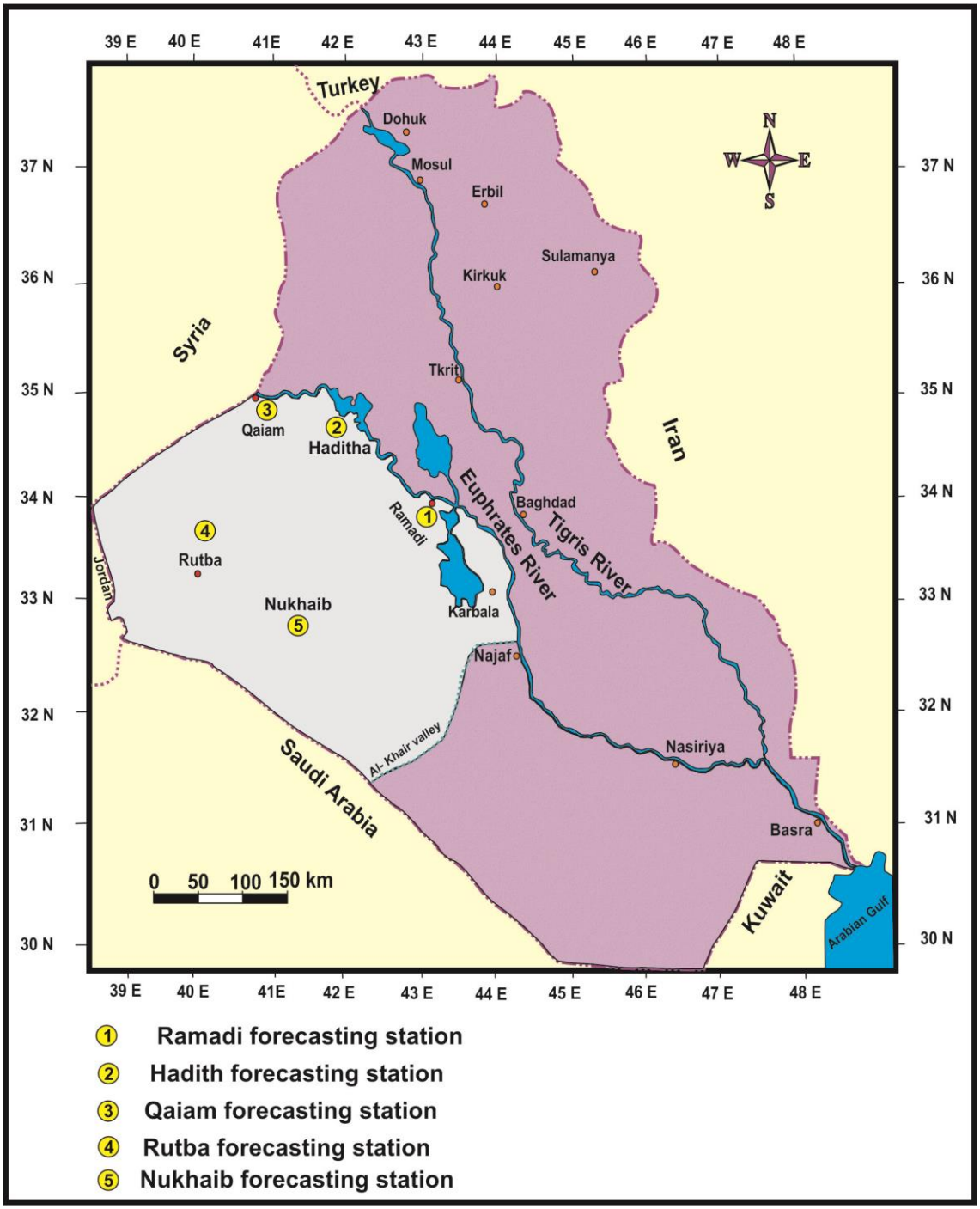


Figure 5.1: location of forecasting weather stations in Iraqi Western Desert

Table 5.1: Coordinates of climatic stations.

Station	heights above sea level	longitude	latitude
Al-Rutba	630 metres	33° 23' N	40° 17' E
Al-Nukaib	305 metres	33° 22' N	42° 15' E
Al-Qaiam	177.5 metres	34° 23' N	41° 41' E
Haditha	139 metres	34° 40' N	41° 44' E
Ramadi	48 metres	33° 25' N	42° 18' E

Resource: General Authority for monitoring weather conditions and earthquakes, Iraq climate atlas, (1990)

- The average annual minimum and maximum air temperature values which were recorded in the five weather stations for the period 1981 to 2010 are shown in Table 5.2.

Table 5.2: The average annual temperature in the forecasting stations in study area

Months	Ramadi			Haditha			Qaiam			Nukaibe			Rutba		
	min	max	aver	min	max	aver	min	max	aver	min	max	aver	min	max	aver
January	**4.7**	**15.2**	**9.2**	**5.1**	**16.1**	**9.8**	**4.1**	**15.7**	**9.3**	**4.5**	**16.2**	**10.4**	**4.3**	**15.5**	**9.4**
February	**5.9**	**18.1**	**11.7**	**9.2**	**22.4**	**15.1**	**8.1**	**22.0**	**14.7**	**9.3**	**22.7**	**15.1**	**8.4**	**21.1**	**14.3**
march	**10**	**24.1**	**16.2**	**16.4**	**31.7**	**23.7**	**15.5**	**30.6**	**23.0**	**16.6**	**32.4**	**23.7**	**15.1**	**29.6**	**22.2**
April	**14.8**	**29.2**	**21.9**	**21.4**	**38.5**	**29.8**	**20.5**	**36.6**	**28.5**	**21.8**	**39.6**	**30.1**	**20.1**	**36.0**	**28.1**
May	**20.1**	**35.3**	**27.7**	**25.7**	**42.6**	**34.2**	**24.6**	**40.9**	**32.7**	**24.8**	**42.1**	**33.5**	**23.5**	**39.1**	**31.6**
June	**23.9**	**38.2**	**31.9**	**26.0**	**42.8**	**33.1**	**25.4**	**41.2**	**33.6**	**25.3**	**42.7**	**34.0**	**23.4**	**39.0**	**31.6**
July	**26.2**	**42.3**	**34.2**	**22.0**	**39.8**	**29.9**	**22.8**	**38.5**	**30.9**	**23.6**	**40.2**	**32.0**	**21.0**	**36.4**	**29.1**
August	**25.2**	**42.4**	**33.3**	**19.1**	**35.0**	**27.3**	**18.3**	**33.9**	**26.4**	**19.8**	**35.2**	**28.0**	**16.7**	**31.9**	**24.8**
September	**21.5**	**42**	**29.7**	**14.0**	**28.3**	**21.2**	**13.3**	**28.0**	**20.6**	**14.7**	**29.4**	**22.5**	**12.5**	**26.4**	**19.5**
October	**17.1**	**38.6**	**24.5**	**7.6**	**21.3**	**14.0**	**8.3**	**21.6**	**14.8**	**9.0**	**22.5**	**16.3**	**7.2**	**19.8**	**13.4**
November	**10.3**	**32.4**	**11.6**	**4.5**	**16.4**	**10.3**	**5.0**	**16.4**	**10.4**	**4.7**	**17.8**	**11.1**	**3.6**	**15.7**	**9.5**
December	**6.1**	**25.2**	**11.6**	**2.8**	**13.9**	**8.0**	**2.6**	**12.9**	**7.8**	**3.1**	**15.5**	**9.6**	**4.2**	**13.6**	**7.6**
average	**15.5**	**30**	**22.5**	**14.5**	**29.1**	**21.4**	**14**	**28.2**	**20.1**	**14.8**	**29.7**	**22.2**	**20.1**	**13.7**	**20**

Sources: 1) Transport and Communications Ministry General Authority for monitoring weather conditions and earthquakes, Department of Climate Unpublished data (2010). 2) Al Heety, (2012)

- Details of the rainfall are important for an appreciation of the surface and underground water resources in the Iraqi Western Desert and help in the understanding of contemporary fluvial geomorphology. In the Western Desert the rainfall normally occurs between October and May (Table 5.3 and Figure 5.2).
- The average annual rainfall has been recorded at Al Qaiam, Haditha, Ramadi, Al Rutba and AlNukhaib meteorological stations for the period 1981 to 2010 and ranges between (50-100) mm year (Figure 5.3). Generally the rainfall is intermittent but some extreme events can occur (e.g. 50-40 mm in 24 hours) and a single daily event can exceed the total annual average rainfall. In general 50% of rainfall occurs in winter months whilst the rest falls in autumn and spring (Parsons, 1955, 1957). The 'wet' season, which extends from October to May, has a bimodal precipitation distribution (Table 5.3) with the first peak in January, ranging from 10 mm at the Nukhaib station to 23.2 mm at the Qaiam station, while recorded following values of 21.7, 18.4 and 13.3 in Ramadi, Hadith and Rutba respectively, and the second in April with 11.4 mm at the Rutba station and 61.6 mm at the Nukhaib. The monthly totals are noticeably different at the five stations. The highest value is 127.5mm at the Haditha station, and the lowest are at the stations of Al Nukhaib 101.6 mm and Rutba 114.2 mm. The total annual average rainfall for the five stations is 112.54 mm.

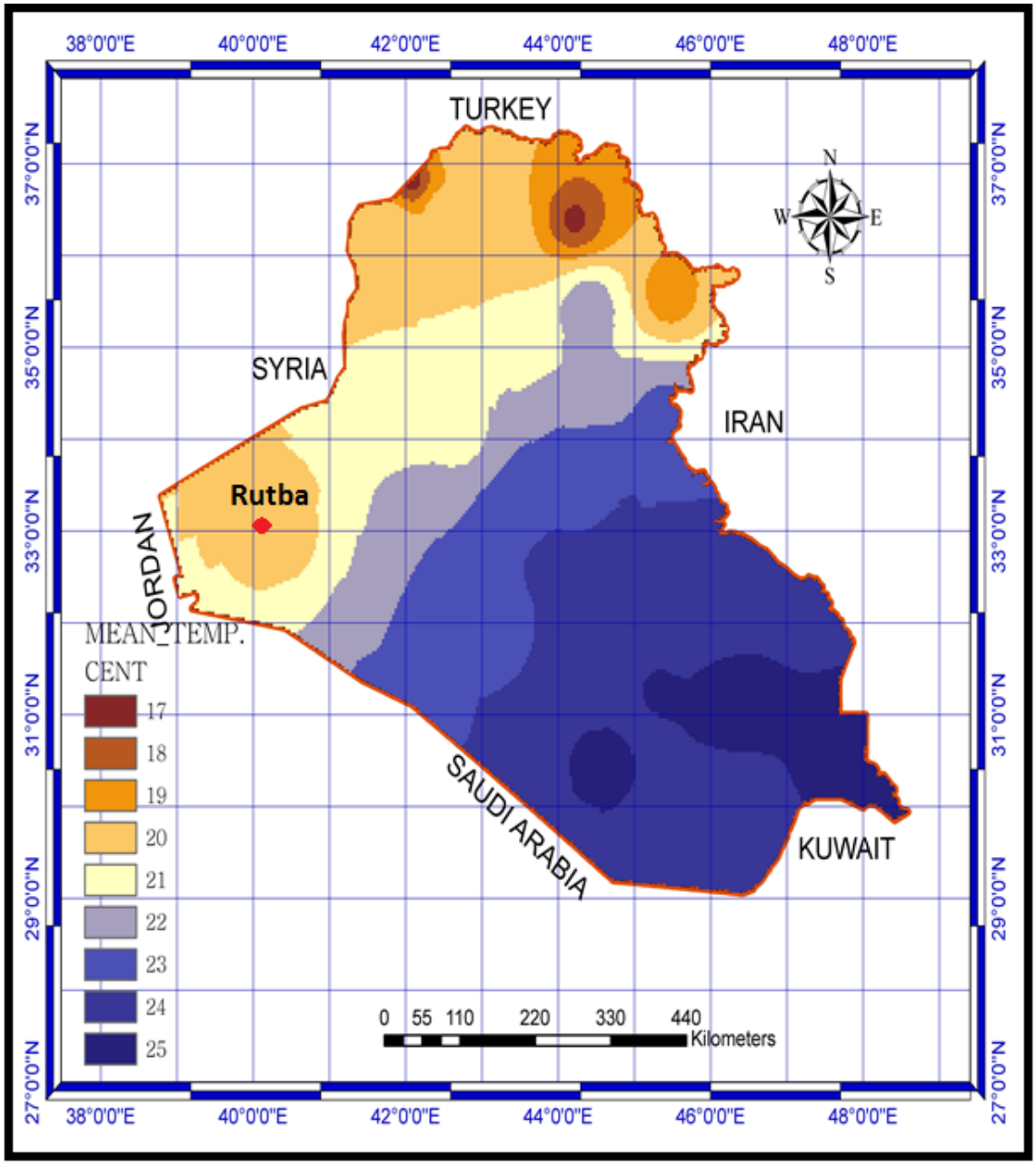


Figure 5.2: Map of the average mean annual temperatures in degrees Celsius (°C) source: Al Khfaji, (2009).

Table 5.3: Monthly rainfall amounts and the annual total in study area stations / mm for the period 1981- 2010.

months	forecasting stations				
	Ramadi	Haditha	Qaiam	Nukaibe	Rutba
January	21.7	18.4	23.2	10	13.3
February	16.7	22.8	23.5	14.9	20.4
march	12.7	18.4	18.9	14.7	15.2
April	14.4	14.5	12.9	16.6	11.4
May	5.3	6.6	4.8	3.4	6.5
June	0	0	0	0	0
July	0	0	0	0	0
August	0	0	0	0	0
September	0	0.4	0.1	0.8	0.1
October	0.1	4.6	7.6	8.4	14.8
November	8.2	18.8	17.9	16.6	16.4
December	15.7	23.0	15.7	16.2	13.7
Annual rate	94.8	127.5	124.6	101.6	114.2
Standard deviation	8.04	9.53	9.38	7.22	7.22

Resource: (1). Transport and Communications Ministry General Authority for monitoring weather conditions and earthquakes, Department of Climate Unpublished data (2000. (2). Al Heety, (2012)

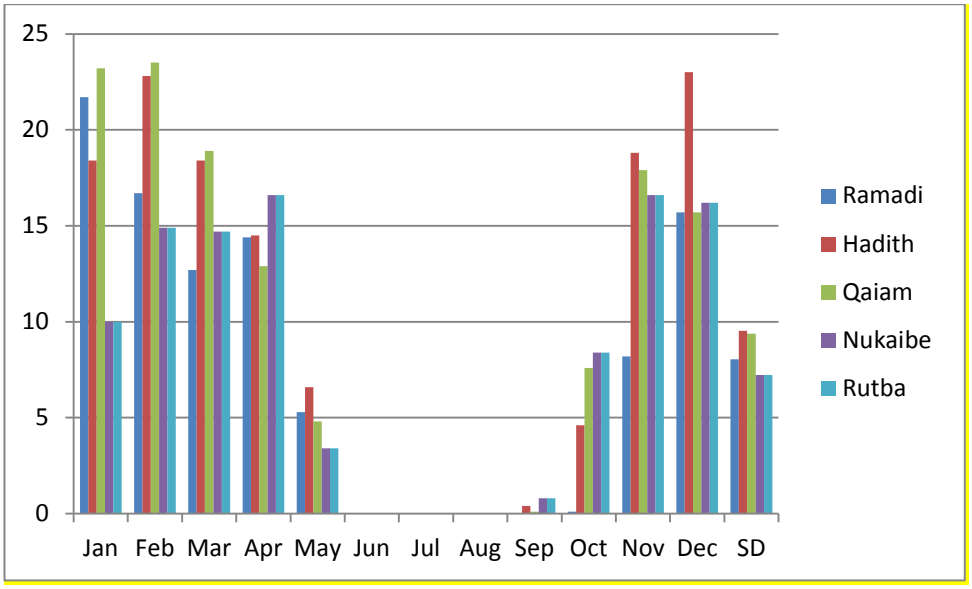


Figure 5.3: Monthly rainfall amounts and the annual total in study area stations in mm for the period 1981- 2010. Resource: Transport and Communications Ministry Data of Climatic Unpublished for the period 1981 to 2010.

- The average mean evaporation varies considerably between the different parts of Iraq (Figure 5. 7). In the north it is 1200-1600 mm whilst in the Western Desert it is 1400 mm-2200 mm (Al Khfaji, 2009). The average monthly and annual evaporation within the study area ranges between 3500mm-3800mm respectively (Figure 5.4) but sometimes it reaches 4000-5000mm in the summer months of July and August

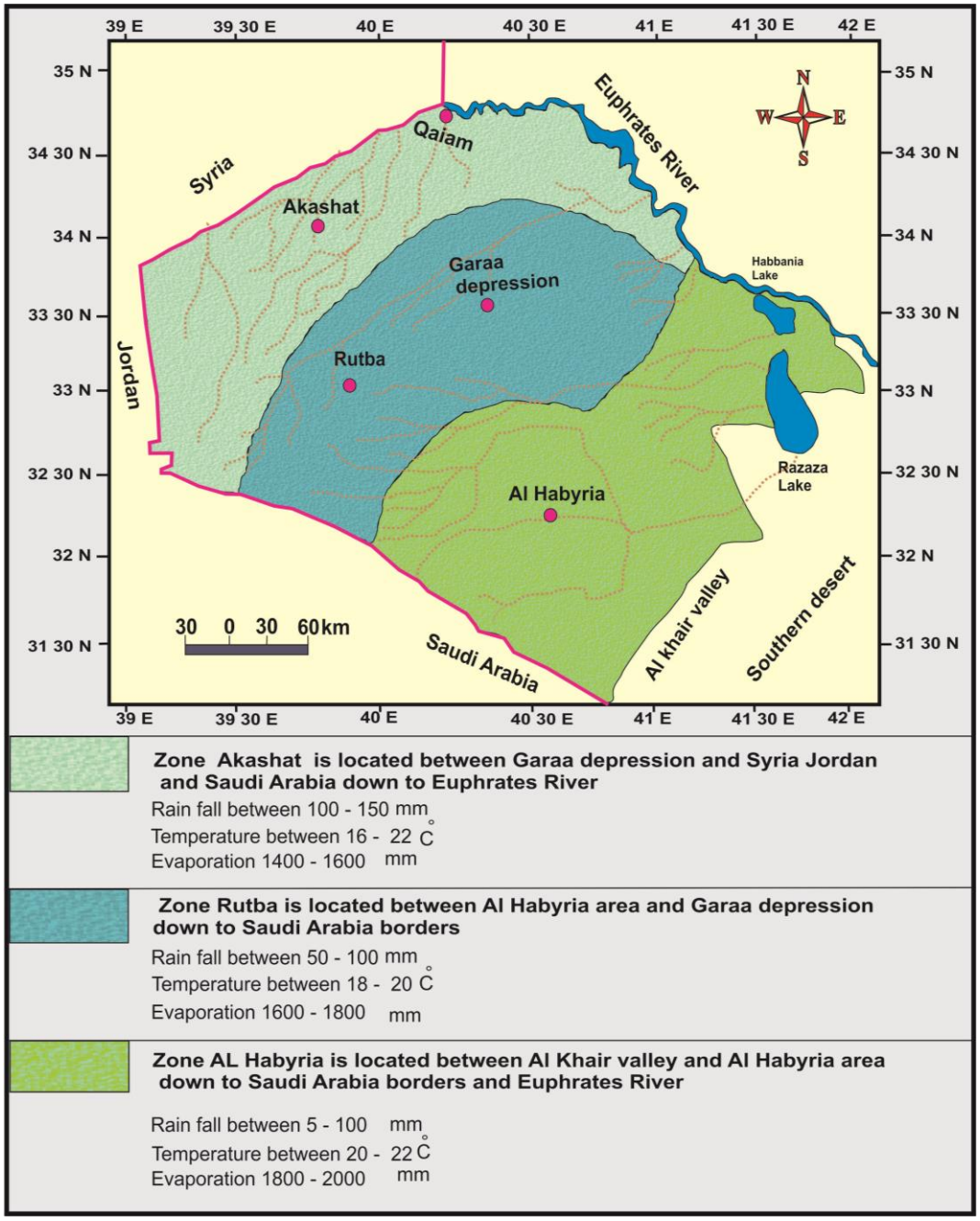


Figure 5.4: An overall summary of average temperature, rainfall and evaporation for the period 1981-2010 in the Iraqi Western Desert.

The relative humidity in Iraqi Western Desert usually ranges from a very dry 26% in the summer months to between 60 to 75 % humidity in winter months. The data from the five weather stations are presented in Table 5.4 and shown graphically in Figure 5.5

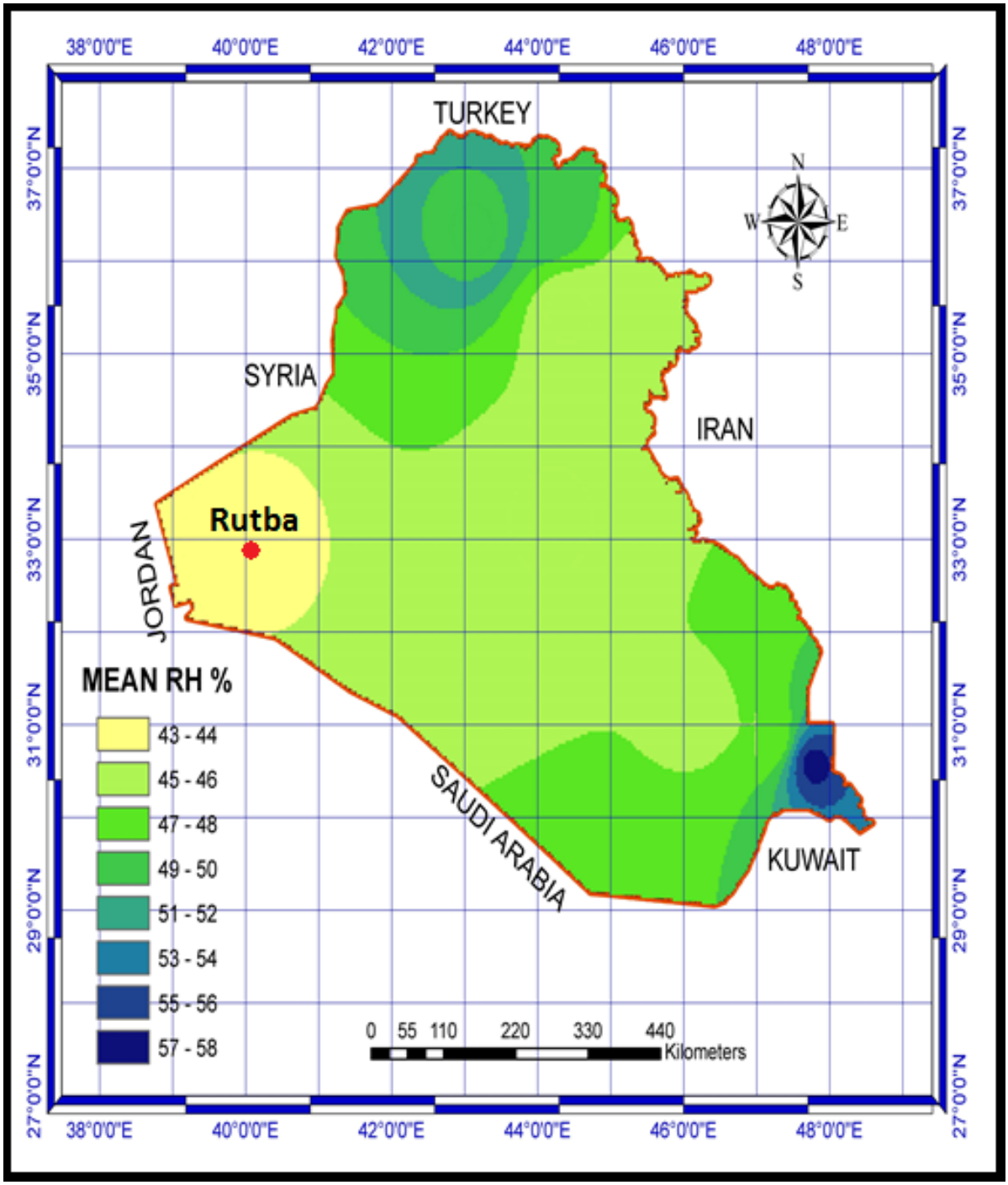


Figure 5.5: Map average means around relative humidity. Source: Al Khfaji (2009).

Table 5.4: Monthly values of relative humidity of the study area stations as a percentage

months	stations				
	Ramadi	Haditha	Qaiam	Nukaibe	Rutba
January	**75**	**73.4**	**73.9**	**63.9**	**69.8**
February	**65.3**	**62.3**	**63.3**	**55.6**	**62.7**
March	**56.4**	**52.9**	**54.9**	**48**	**54.9**
April	**50**	**41.8**	**45**	**36.1**	**43.3**
May	**41**	**32.9**	**35.4**	**26.9**	**34.8**
June	**34.4**	**24.8**	**29.8**	**22.5**	**29.5**
July	**32.4**	**23.4**	**28.4**	**21.2**	**28**
August	**35.2**	**25.2**	**30.6**	**23.6**	**28.7**
September	**40.1**	**28.8**	**30.3**	**25.7**	**31.9**
October	**51.8**	**42.4**	**45.6**	**38.6**	**43.7**
November	**65.4**	**58.3**	**60.7**	**55.7**	**56.5**
December	**76**	**72.4**	**71.9**	**66.3**	**69.2**
Annual rate	**51.9**	**47.9**	**47.9**	**40.3**	**46.1**

Source: (1) Transport and Communications Ministry General Authority for monitoring weather conditions and earthquakes, Department of Climate Unpublished data (2000) (2) Al Heety (2012).

The average monthly wind speeds in m/sec. over the year from 1981 to 2010 in the study area is presented in Table 5.5. This shows that the average monthly wind speed throughout the year averages between 1.6 to 5.8 m/sec.

Table 5.5: Wind speed m/sec in study area stations

months	stations					
	Rutba	Nukaibe	Qaiam	Haditha	Ramadi	wind direction
January	2.4	2.9	2.0	2.6	2.0	W
February	3.1	3.7	2.4	3.1	2.5	NW
march	3.1	4.0	2.5	3.3	2.6	W
April	3.1	4.5	2.6	3.5	2.5	W
May	2.9	4.9	2.8	4.0	2.6	W
June	3.0	4.7	3.1	5.1	2.8	NW
July	3.4	4.7	3.5	5.8	2.9	W
August	2.7	4.1	2.9	4.7	2.6	W
September	2.0	3.0	2.1	3.4	2.1	NW
October	2.0	2.9	1.8	2.6	1.7	W
November	1.8	2.4	1.6	2.4	1.7	W
December	2.0	2.3	1.7	2.4	1.7	W
Annual rate	2.6	3.7	2.7	3.6	2.2	W

Source: (1).Transport and Communications Ministry General Authority for monitoring weather conditions and earthquakes, Department of Climate Unpublished (2000). (2). Al-Heety (2012)

As can be seen from the climatic data, the present Iraqi Western Desert is a true desert and any rivers in the region will be ephemeral unless they are allogeneic such as the Euphrates River. The high rate of evaporation and magnitude of the water deficit will lead to extensive accumulation of salts in the upper parts of the soil horizons and the development of salt pans (playas or salinas). The lack of water and high salt content will restrict the plant cover leaving many areas of bare soils. This combined with the wind region results in the development of aeolian landforms

5.3 The Four Physiographic Regions of Iraq (based on the Iraqi Geological Survey, 2000)

Much of Iraq is composed mainly of lowland areas that rarely exceed 400m above sea level. The Iraqi land surface has typically been divided in to four main physiographic or terrain units (Iraqi Geological Survey, 2000); the Desert; the Mesopotamian Alluvial Plains; Foot hills; and Mountainous High Lands. These areas are shown in Figure 5.6 and on the 1:1,000,000 scale geomorphological map of Iraq produced in 2000 by the State Establishment of Geological Survey and Mining (Appendix F in CD). The Deserts Lands are located to the west of the Euphrates River and also the area between the Tigris and Euphrates Rivers, known as the Al Jazera area. The Mesopotamian Alluvial Plains lie in the central and southern parts of Iraq. The Foothills area is in the north and north east of Iraq beside the Mountainous High Lands. The Mountainous High Lands area is located in the north and north east of Iraq. Each of these areas is discussed in more detail below. Table 5.6 and Figure 5.6 show the extent and location of these areas within Iraq.

5.3.1 Desert

The Desert in Iraq lies west of the Euphrates River and also covers the area between the Euphrates and the Tigris rivers. It is a continuation of the desert lands of Saudi Arabia, Jordan and Syria (Malinowski, 2000). The desert in Iraq has been divided in to two parts: the Western and Southern deserts. The Al Khair valley separates these deserts, which are also known as the northern Badia and southern Badia (Badia = desert in Arabic). The Southern Desert shares a border with Saudi Arabia in the south, Kuwait and the Arabian Gulf in east, the Euphrates River to the north east and the Western Desert in the west. The southern desert extends into Saudi Arabia and Kuwait. The Western Desert

shares a border with the Euphrates River in the north, Syria to the North West, Jordan in the west, Saudi Arabia to the south and the Southern Desert in the east. The Iraqi Western Desert slopes overall slopes towards the north east with a general inclination of only 2 m/km. The elevation in the west in the Anaza area (Figure 5.8) is around 975m, whilst the elevation in the Euphrates river flood plains ranges between 100 to 200m (Jassim and Gof, 2006). The Western Desert is predominantly covered by desert gravels although locally there are bare rock outcrops. The Southern Desert is mostly a flat region rising to the south (the differences and boundaries between the Western Desert and the Southern Desert were presented in Chapter 1). The main landscape features of the Western Desert are the plateaux surfaces that are dissected by dry valleys. The valleys are generally aligned from west and southwest towards east and northeast. The valleys range in length from tens to hundreds of kilometres.

5.3.2 Mesopotamian Alluvial Plain

This is a flat plain that generally slopes down from the northwest to the southeast. It is covered with recent fluvial and some localised aeolian sediments. The Mesopotamian flood plains are located in a syncline which is experiencing on-going subsidence as it accommodates the massive amount of alluvium that is contributed annually by the Euphrates and Tigris rivers. The Quaternary sequence of the Mesopotamian floodplain was built up by the fluvial gravels and the outwash alluvial fans developed on the western sides of the region. The Mesopotamia alluvial plain begins west of Ramadi city, specifically in Heet city on the Euphrates River, and beyond Samara on the Tigris (Malinowski et al., 2000). It extends to the south until Al Basrah city on the Arabian Gulf. Through the hundreds of thousands of years silt from the Euphrates and Tigris rivers and the tributaries was deposited in their combined deltas (Malinowski, 2000). With

the passage of time the delta region prograded southwards and now a large part of south Iraq comprises sands, silts and gravel from these sedimentary formations.

5.3.3 Foothills (i.e. undulating terrain)

This area comprises the hills located at the foot of the mountains. The maximum elevation of these foothills is between 500 to 1000m. At the surface they are composed of beds of uncemented coarse aggregates and sandstone. There are layers of loam and clay within the unconsolidated and weakly cemented aggregates in some areas. Where these loam and clay layers occur they are subject to erosion, forming badlands. Overall the foothills are an area of rolling landscape with low parallel hills and wide valleys and plains. Within the area are three identifiable river terraces related to different phases of uplift and erosion in the Pleistocene (Buday and Hak, 1980).

5.3.4 Mountainous highlands

The Mountainous Highlands are located in the north of Iraq near the Iranian and Turkish borders. This is an area rising to 3600m above sea level and the highest point is Holkord in the Haji Ibrahim Mountain. The mountains are the result of folding centred on the Taurus Mountains in neighbouring Turkey. In the northeast the mountains become part of the Great Zagros mountain region located in Iran. These mountains form the headwaters of rivers such as the Little Zab, Great Zab, Khabur, Diyala and Udhaym which flow west to join the Tigris River. Many of these mountain areas are still very remote with few access routes. Prominent features are the Spilak Pass in the Ruwanduz River gorge; the Shinak Pass and the Ali Bag Gorge west of the Ruwanduz (Held, 2000).

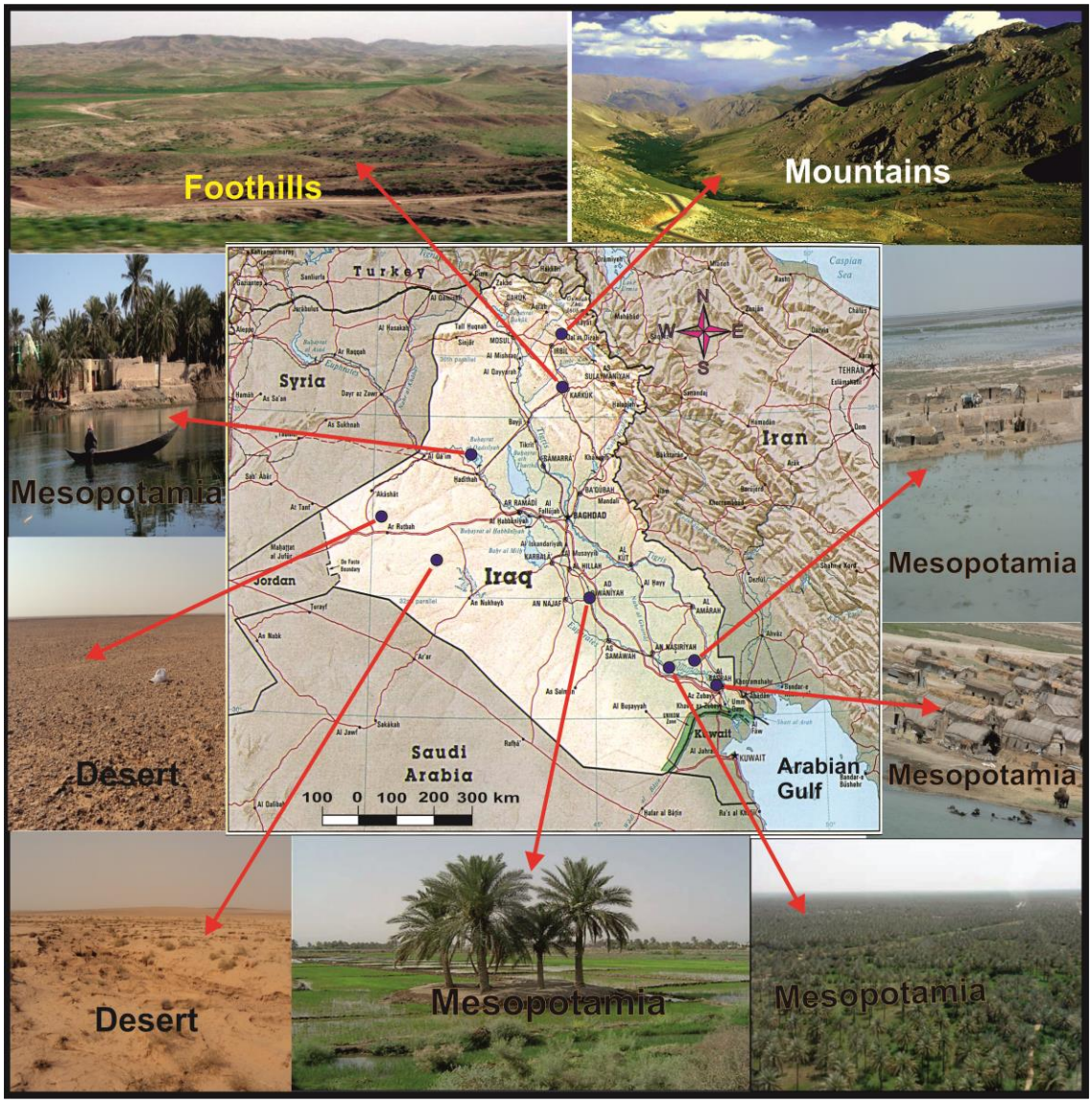


Figure 5.6: The four physiographic regions of Iraq (pictures taken by researcher and others)

Table 5.6: Types of terrain, landforms, Iraq. Source: Ministry of Agriculture Directorate General of Horticulture, Forest and Rangelands (2007)

Main physiographic units	Area / km^2	%
Desert	198 000	42
Mesopotamian alluvial plain	132 000	30
foothills (Terrain Land)	15 000	10
Mountainous highlands	92 000	18
Total	437 000	100

5.4 Preliminary subdivision of the terrain of the Western Desert

The subdivision of Iraqi in to four physiographic region leads on to the need to subdivide the Desert region further as a preliminary stage into the investigation of the geomorphological development of the region. This is carried out in this section. In the study area the maximum difference in height for the Western Desert is 778 m. This is derived from a minimum height of 162 m on the Euphrates River, and the highest elevation in the Jabal Anza area around 940 m above sea level (Figure 5.7). The Jabal is located at the confluence of the Iraq, Saudi and Jordan borders and is the watershed of most of the valleys in the area. Having reviewed the geomorphological subdivision of Western Iraq proposed by Parsons (1955) this matched the the criteria subsequently established by Mitchell (1973) for the classification of terrain in to geomorphological units. Parsons study divided the Western Desert of Iraqi into four geomorphological zones: Hammad area, Upper valleys area, Lower valleys area, and "the Stone area". The zones are based on terrain units that comprise landforms assemblages with similarities in topography, soils, vegetation and geology. The geomorphological units in the study area are affected by many factors including tectonic movements development of rift basins, fluvial and aeolian processes, and limited solution weathering. These factors have led to a range of landforms, namely the plateaux, valleys, depressions, and hills. The most important differeces between these four geomorphological units in Iraqi Western Desert are presented in Tables 5.7 and the units are described in the following sub-sections.

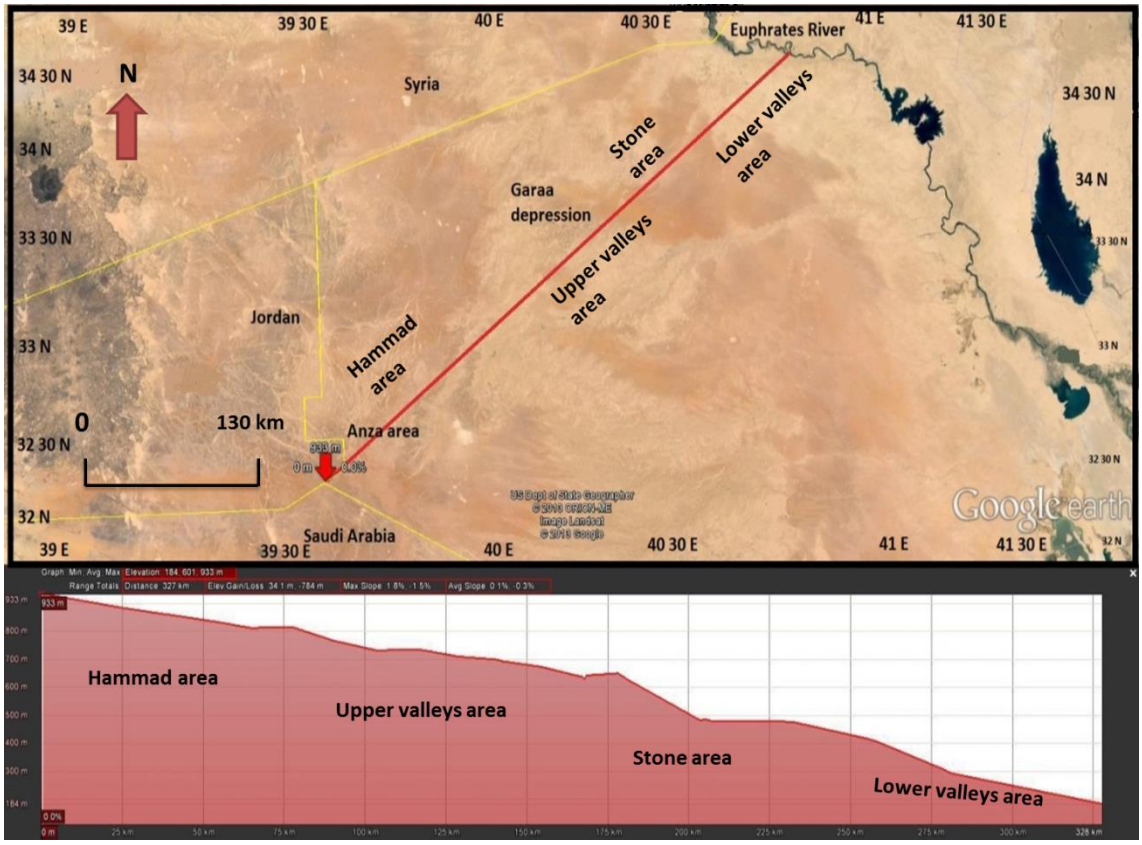


Figure 5.7: Topographic profile across the Iraqi Western Desert (Google Earth images).

5.4.1 Hammad area

This is a flat plain that descends from the west to the east. This area contains a number of valleys such as Al Wallage, Swabe, and Akashat. This unit contains the Jabal Anza area and it is located at the border of Iraq, Saudi Arabia and Jordan with the highest elevation in the region (942m above sea level) (Hassan, 1984). The Al Wallage valley is the most important in this area. It is a characteristic of this area that it contains ephemeral lakes, solution depressions such as Umm Chaimin depression (Figure 5.15) and some parts are covered by stone pavement gravel whilst others area covered by boulders (Picture 5.1, 5.2 and 5.3).

Picture 5.1: Hammad area south west Rutba town in Iraqi Western Desert

Picture 5.2: Upper valleys area west Rutba town in Iraqi Western Desert.

Picture 5.3: Stone area north Rutba town in Iraqi Western Desert

5.4.2 Upper valleys area

This is located east of Al Hammad. It is a broad plain which slightly rises towards the west. This unit is identified by a network of deep, wide valleys. The most important valleys are Swap, Akash, Al Ratga Houran and Al Manai. There are some depressions, the most important of which is the Al Garaa depression. This area includes rock formations of Triassic, Jurassic and Cretaceous age. This area was so named due to the large and complex network of dry valleys most of them emanating from the south western part of the study area in Saudi Arabia and Jordan. It is found between elevation 400m to the east and 800m to the west. (Figures 5.8 and 5.9) Dendritic patterns dominate the drainage in this region because of the relative homogeneity of the near and sub-surface geology.

5.4.3 Parsons “Stone area”

The stone zone, an area lying west of the Euphrates River, covers sections of the Western and Southern Desert. The unit consists of a wide stony plain interspersed with rare sandy stretches. The widely spaced valleys are occupied by watercourses that are dry most of the year and these which runs from the border to the Euphrates River. Some valleys are over 400 km long and carry short-lived but torrential floods during the winter rains. This area is located between the Upper Valleys area of the West and the Lower Valleys area of the east. It extends from the south to the Saudi Arabia-Iraqi borders and continues to the Southern Desert. This is a flat rocky region which acquired its name from the limestone and gravels and boulders which largely covers the surface area region. This area is characterized by variable slopes. It is found between elevations 200m to the east and 400m to the west (Figures 5.8, and 5.9). This area is notable for its lack of dominant geomorphological features beyond the extensive stone pavements.

5.4.4 Lower Valleys area

This area is located between the Euphrates River in the north and east and the Stone area in the west. In this area it appears the valleys are shallow and short and drain into the Euphrates River. The area is characterized by its varied topography. It is found between elevation 100m to the north-east and 200m to the south west (Figures 5.8 and 5.9).

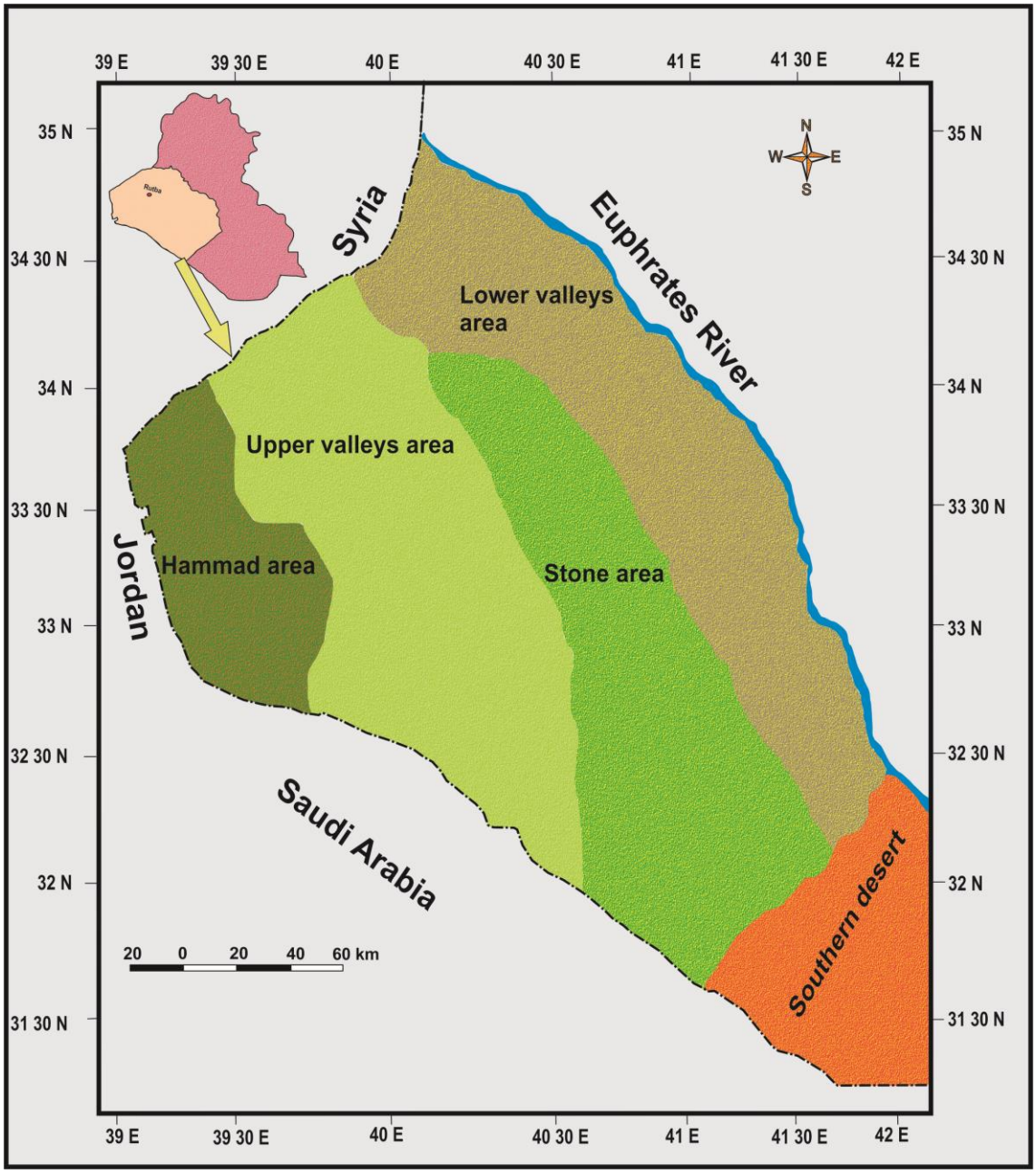


Figure 5.8: The four terrain units of Iraqi Western Desert (Parsons, 1955)

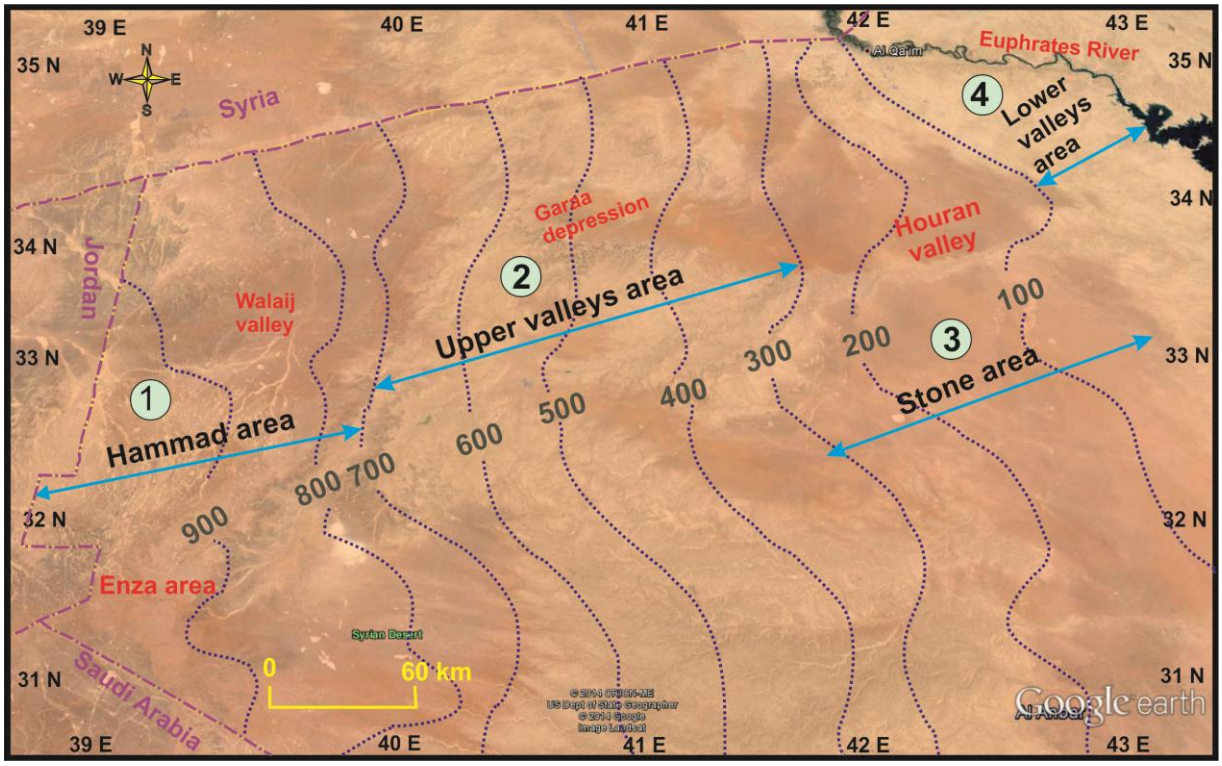


Figure 5.9: The main terrain units in the Western Desert of Iraq (Google Earth images).

Table 5.7: Characterises of the geomorphology in the Western Desert (see Figure 5.10)

Area / Characterises	Hammad area	Upper valleys	Stone area	Lower valleys
Location	Flat plain descending toward the north and northeast	Wide plain rises slightly westward	Flat area in the north and northwest	Include the northern and eastern parts of the Western Desert
Geomorphological units	Flat area, number of plateaux	Network of valleys slopes down toward the east and north-east; number of plateaux	Stone pavement covered areas with sharp cliffs of limestone and granite; number of plateaux	Variety of topographic features including a number of plateaux
Names of valleys	Walaij, Houran	Garaa valleys basin	Rtaga,Houran,Manai	Qaiam,Manai,Fhadia
Depressions	Umm chaimin	Garaa	----------	----------

This preliminary terrain subdivision is clearly over-simplistic although does provide a useful stage in the production of the terrain classification the Desert region. However, it is now necessary to undertake a more detailed evaluation of the geomorphology and this is provided is the following sections which bring more primary data into the analysis

5.5 Geomorphology of the Iraqi Western Desert

The key focus in the investigations for this thesis is the geomorphology of the Iraqi Western Desert. In the broad terms the intention is to establish the extent to which geomorphology of the study area is controlled by Tertiary tectonic activity (Chapter 4) and the climate fluctuations during the Plio-Pleistocene and asses how this has led to the present pattern of drainage. Many of the geomorphological features identified in this study were formed under arid conditions similar to those prevailing today. However, the well-developed drainage pattern, the relicts of older patterns, and the number of river terraces provide evidence for the influence of more humid and wetter periods in the past (Dennis, 1953). In this thesis the detailed understanding of the Western Desert produced by the author has utilised the latest published and unpublished data of the Geological Survey of Iraq and the Transport and Communications Ministry General Authority. These authorities hold data on the geology, geomorphology, climate and seismicity which have been accessed as part of this investigation. For the compilation of a detailed geomorphological map of the study, a terrain analysis was undertaken in order to identify landforms, and their relationship to bedrock lithology. A number of geomorphological traverses were completed during two field seasons and some important types sections and localities were described in detail. The landforms of the Western Desert have been grouped into different broad scale terrain units related to their mode of formation using

the approaches identified in Griffiths (2001) and Fookes et al. (2007). These were used as the framework for the compilation of the detailed geomorphological map presented in Figure 5.18 (contained in separate file at the end of this thesis). The legend of this map is presented in Table 5.9 and the map is discussed in Section 5.4. The landforms of the Iraqi Western Desert are grouped in to six major units based on their morphology, bedrock and the processes contributing to their development.

5.5.1 Geomorphic units of structural origin-the plateaux

Buday and Hak (1980) said the exposed rocks in the Western Desert are predominantly of marine origin comprising limestone, dolomitic limestone, dolomite sandy limestone, clay, limestone, marl, sandstone and clay stone with rare gypsum and phosphorite. The nature of the exposed rocks has played a significant role in the development of the landscape and its associated landforms. For example, the hard rocks result in a plateau form; interbedded rocks of variable hardness have accelerated the dissection of the plateau into steps or minor plateaux; the soluble rocks have led to the formation of karst; the soft rocks are easily eroded and have contributed materials for the aeolian areas; and all rocks and soils have contributed to the valley fill and floodplain.

Examination of the satellite imagery indicates that the Western Desert of Iraq is dominated by a series of plateaux, each with a generally level surface and delineated by steep scarps (Al Kubasi, 1993). The plateaux gradually fall from the west and south west towards the east and north-east. The most notable plateaux in the area are Kherish and Akash (Figure 5.9). The Kherish plateau extends from the Iraqi-Syrian borders north of the study area towards the south and southeast for a distance 50 km. The surface is dissected by a number of

valleys.The plateaux form is one of the most extensive landform types of the Western Desert, and demonstrates the stable tectonic history of the area. According to Bellen (1959), Kassab (1972, 1976), Buday (1980), Al Mubarak and Amine (1983), Al Bassam (1990), Qasir (1992) and Tamer Agha (1993) the anticline of the Garaa uplift (Chapter 4) underwent continuous uplift, faulting and erosion from the Maastrictian until the late Tertiary. Sub-aerial denudation has exposed the sub-surface and developed the plateaux. The plateaux form crescent shaped belts around the trough of the Garaa Depression in the south. The plateaux in the north terminate close to an east-west lineament, which runs nearly parallel to the axis of the Garaa Depression. The plateaux, therefore, are surfaces which are variable in extent and composition, and have developed as identifiable landforms units as a consequence of sub-aerial erosion. Some of the plateaux represent contact surfaces between geological formations; others are formed on members within geological formations.

The study area contains eleven plateaux which can be clearly distinguished and tend to develop on the specific geological formations. The plateaux identified are those developed on:

1. The Zahra Formation
2. The Euphrates formation
3. The Ghar Formation
4. The Dammam Formation
5. The Ummam Eradhuma Formation
6. The Tayarat Formation
7. The Hartha Formation
8. The Rutba and Masd Formations
9. The plateau on the Ubide Formation
10. The Zor Huran Formation
11. The Mulussa Formation
12. The Garaa Formation

These plateaux have been investigated in order to understand how the dry valleys that separate and dissect them have been formed (summarized in Figure 5.10).

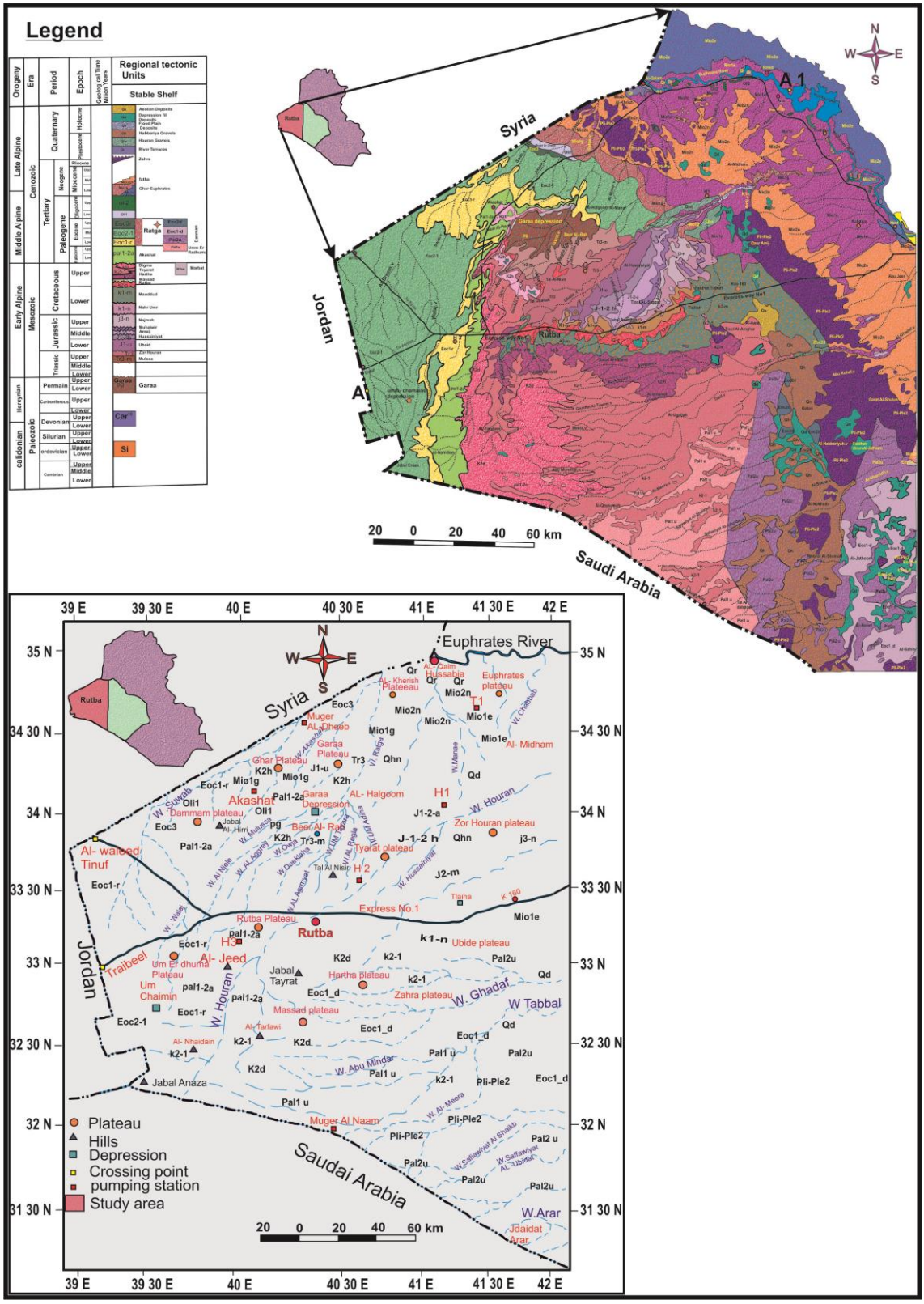


Figure 5.10: Plateaux locations in Iraqi Western Desert (Modified after Al Bassam 2007).

5.5.1.1 Plateau on the Zahra Formation

The Zahra formation covers a considerable area in the Iraqi Western Desert and the plateau is developed in three localities. In the first locality the plateau covers the area extending between the Houran valley in the north and Al Ubaiyidh valley in the west. The plateau is bordered by the Al Qusair fault and the Al-Habbariyah Depression. In the second locality the plateau occupies a wide area in the southern part of the Western Desert. The surface of the plateau in this area is covered by a sand sheet. In the Al Birreet area parts of the plateaux are developed across the Umm Er Radhama and Dammam Formations. The third locality lies in the north-western part of the Western Desert due south of Al Qaiam (Kherish area). This plateau covers a large area but its surface is highly weathered and eroded (Al Mubarak and Amin, 1983). It is dissected by three valleys (Akash, Rataga, and Manai), and is separated from the Euphrates plateaux by a continuous cliff 25-35 m high called the Al Kherish Cliff.

5.5.1.2 Plateau on the Euphrates formation

This plateau is formed on the upper member of the Euphrates formation. The plateau forms in a belt about 20 to 40 km wide between Thumail and Al Manai valley and the plateau also extend on both sides of Houran valley. The surface of the Euphrates formation is covered by a granular soil therefore it is exposed as patches of variable size which consists of limestone and dolomite stones (Hamza, 2007).

5.5.1.3 Plateau on the Ghar Formation

This plateau is restricted in its extent. It covers two small areas on both sides of Al-Ratga and Akash valleys northwest of the Garaa depression. The area of the plateau in the first locality is about 20 x 10 km and about 5 x10 km in the second. Near the valleys the plateau has been dissected to form a series of lithological benches.

5.5.1.4 Plateau on the Dammam Formation

This plateau extends over the area west of the Huran valleys. The Dammam plateau merges laterally into the plateau on the Ratga Formation. This plateau is formed at two levels. The older higher level is formed on the Damlug Member. This level covers the extreme north-western part of the Western Desert on both sides of Al Walaj valley. The surface of the plateau is dissected by shallow erosion depressions with infilled valleys. The younger lower level is formed on the Swab Member. Buday and Jassim (1984) noted that it covers the northern slope of the Garaa Uplift in the upper reaches of Swap valley, Hirri valley and Akash basins. The plateau lower level is dissected by a dendritic pattern of ephemeral stream valleys.

5.5.1.5 Plateau on the Umm Er Radhuma Formation

This plateau is found in a wide area between the Tabal valley and the Iraq-Saudi Arabia border. The plateau surface is dissected by a ‘deranged’ valley network and small shallow depressions. The plateau changes laterally into the plateau on the Akashat Formation, which is the temporal equivalent of the Umm Er Radhuma Formation. There the plateau covers a narrow strip along the west side of the Houran valley. Its width ranges between 1-20 km. The plateau has a

stepped appearance because it is developed on both members (Traifawi and Hirri) of the Akashat Formation. The steps represent lithological benches.

5.5.1.6 Plateau on the Tayarat Formation

Based on its elevation this plateau is believed to be the oldest plateau in the Western Desert. The plateau developed as part of the Rutba Uplift during Palaeocene times when the top of the uplift was subjected to erosion on one side whilst the rest of the Western Desert was submerged on the other side. According to Bellen (1959) and Kassab (1972 and 1976) a break in sedimentation occurred between the Maastrichtian and the Palaeocene period. In the upper reaches of the Tubal valley, in the middle part of the Western Desert, the plateau is developed on the upper member of the Tayarat Formation and is preserved on the watersheds between the valleys but much of the formation has been dissected into badlands. The plateau surface is rugged and its rims are irregular due to headward erosion. It forms a very wide flat area between the Garaa Depression and the Iraq-Saudi Arabia borders. A few shallow depressions are visible on its surface and the plateau forms a wide divide line between the upper reaches of the basins of Tubal valleys in the east and the basin of Houran in the west.

5.5.1.7 Plateau on the Hartha Formation.

The plateau covers a wide area in the northern part of the Tubal valley. The surface of the plateau is irregular because of the wellbedded rocks. The plateau changes locally into badlands along the main valleys (Hamza, 1975). The back cliff of the plateau has undergone retrogressive erosion as indicated by the mesas on top of the Rutba plateau. The northern part of the plateau is in

contact with the plateau on the Tayarat Formation, because of the Tlaiha-Rutba Fault along which the second plateau has been downthrown.

5.5.1.8 Plateau on the Rutba and Massd Formations

The surface of the plateau is in the Tubal valleys area and the surface is rich in karstic depressions and dissected by small valleys. Northeast of Tlaiha area and east of Rutba town, mesas of the Euphrates and Zahra Formations form high ground on the plateau.

5.5.1.9 Plateau on the Ubide Formations

The plateau is narrow varying in width between 2-10 km. It extends along the old Ramadi–Rutba road due west of the Tlaiha area which is located west of 160 station, itself located east of Rutba town. The plateau is dissected by wide shallow valleys which are either branches of Houran valleys or are structural valleys developed along northweast-southeast lineaments (Hamza, 1997). The plateau overlooks the low lying Najmah plateau. The back cliff that has been created is irregular in extent because of retrogressive erosion. It also separates many mesas from the main plateau surface.

5.5.1.10 Plateau on the Zor Houran Formation

This plateau is developed over the well-bedded Zor Houran Formation with hard rocks alternating with soft rocks. The surface of the plateau is slightly dissected by valleys and the plateau is separated from the underlying Mulussa plateau by a low cliff.

5.5.1.11 Plateau on the Mulussa Formation

This formation consists of silty sandstone, dolomitic limestone and dolomite (Barwary and Slewa, 1996, 1997). The plateau covers a wide area along the southern rim of the Garaa Depression. The surface of the plateau is of a stepped form and rugged because it is dissected by a dense relict drainage network. The drainage is controlled by northwest-southeast and eastnortheast-westsouthwest joints. River canyons cut the plateau in a north-south direction (Hassan, 1994, 1998). The plateau is inclined gently southwards and overlooks the underlying Garaa plateau from a cliff 120m high.

5.5.1.12 Plateau on the Garaa Formation

This plateau represents the youngest one developed in the western part of the Western Desert and is essentially a pediment. The plateau is exposed in parts of the Garaa Depression notably on both sides of Mulussa valley, which dissects the depression from west to east. At the southern part of the depression and along the base of the cliff, the plateau is covered by thick sediments of a recent bajada. The surface of the plateau is dissected by wide infilled valleys.

5.5.2 Erosion-Denudation landforms

In Iraqi Western Desert five types are developed within this type:

5.5.2.1 Remnant Erosional Hills

These are the hills at the southern rim of the Garaa depression and could be described as monadnocks or kopje (Al Kubasi, 1993). The hill slopes and pediments around them occur in the plateaux areas (Figure 5.11). There remnant erosion hills are very common in the Iraqi Western Desert. The hills are relicts of mesas which have been reduced in size and changed in shape by headwards erosion and toppling (Hamza, 2007). In H1 area, hills within the Ghar formation are common on surfaces of the plateau developed on the Euphrates formation. The remnant erosion hills appear in the north of the Garaa depression and south; south west and east of Rutba town (see pictures 5.4, 5.5 and 5.6). The hills are the result of selective and retrogressive erosion by streams in the steeper dipping rock sequences (Buday and Hak, 1980)

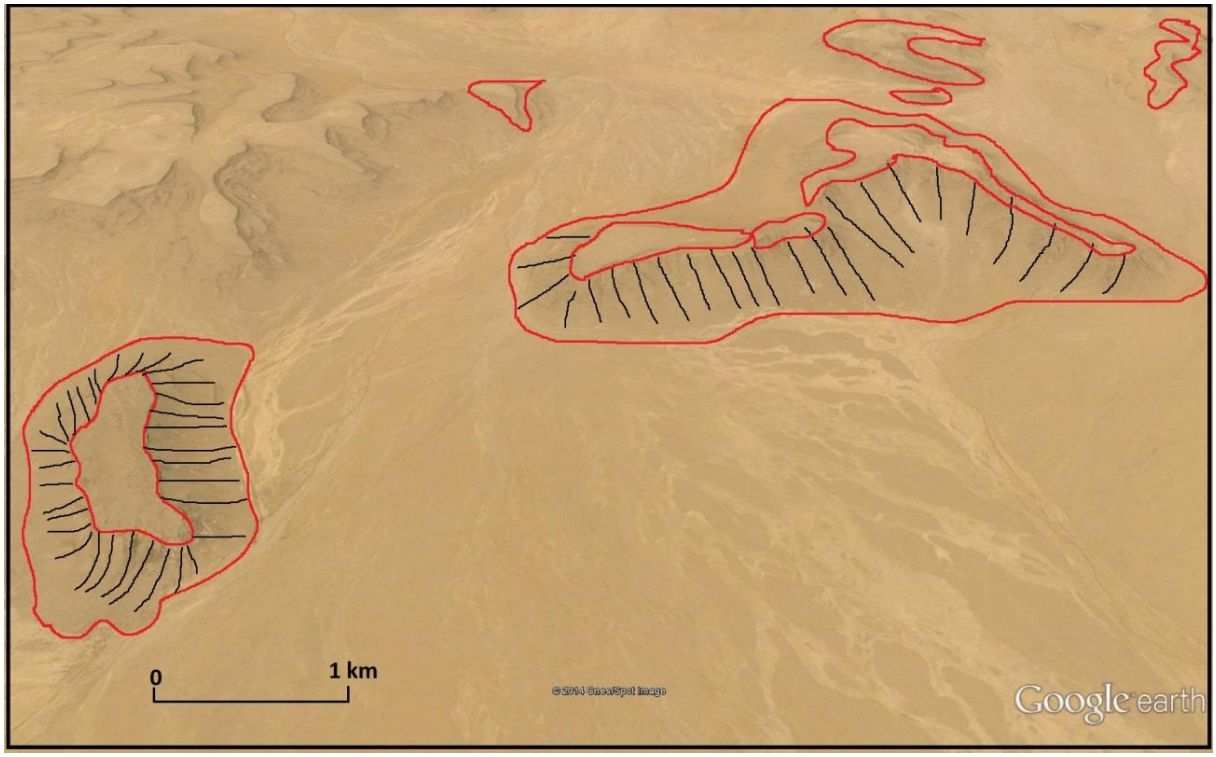


Figure 5.11: Remnants of erosional hills to the south west of Rutba town. (Google Earth images)

Picture 5.4: Hill located in the south town of Rutba

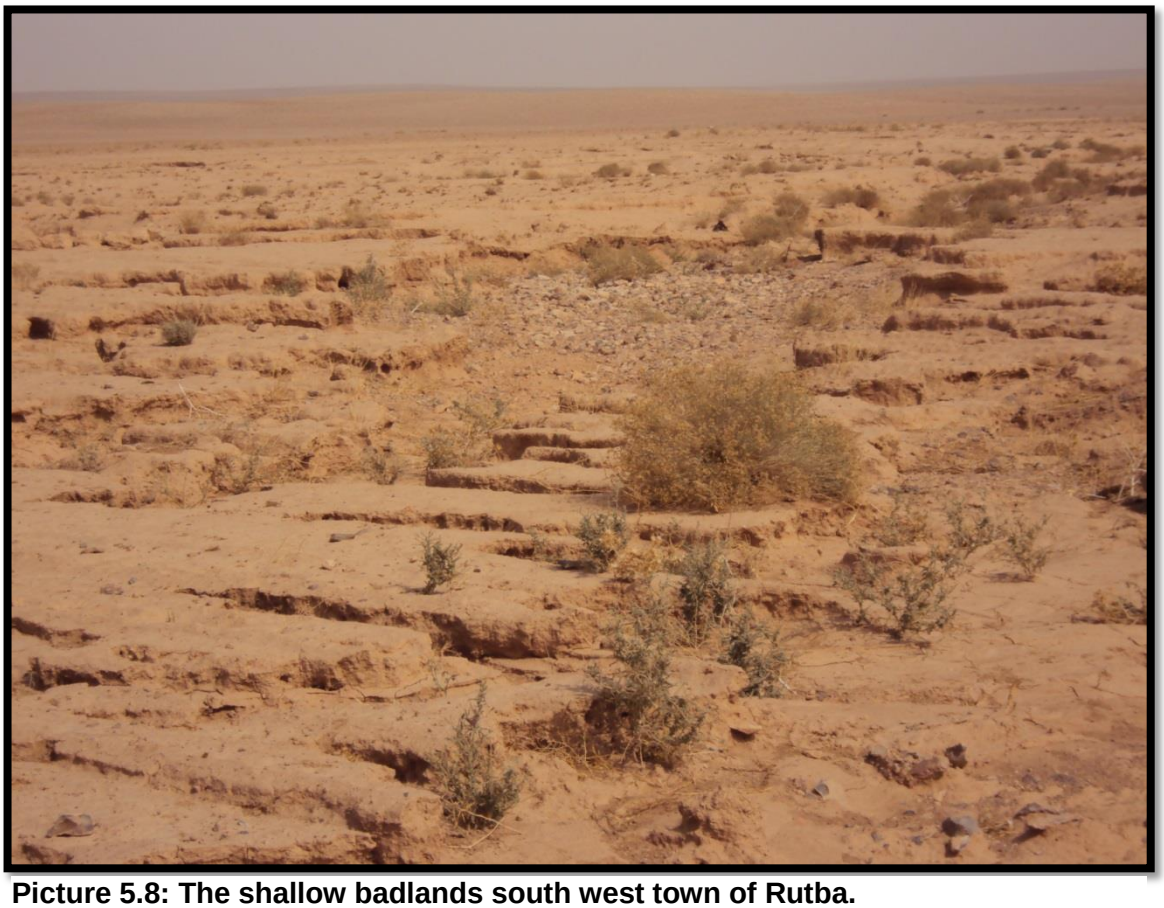
Picture 5.5: Hill located in the south west town of Rutba.

Picture 5.6: Hills located in the south west town of Rutba.

5.5.2.2 Badlands

Shallow badlands topography is well developed in the Western Desert. Its formation is related to structure (fault and joints), lithology and climate (Hamza, 2007). Percolation of rain water through jointed and faulted permeable rocks during wet seasons causes erosion of the rocks and development of rills, gullies and valleys. The density of the features depends on the structural features, rock strength lithological type and quantity of water. Bablands are well developed in the Upper Valleys area on the both sides of Horan valley (a tectonically controlled valley). They developed during the early Holocene because the area had limited vegetation and the soft clastic Pliocene sediments were easily dissected by running water. (Maala, 2009). The Badland areas display intense dissection with widespread gullying and rilling (Hamza, 2007) (picture 5.7, 5.8, and 5.9). Most evaluation of badlands indicates that they often develop on calcareous marls with high plasticity (Griffiths et al., 2012). Badlands are also developed along the lower reaches of the Houran valley, downstream of the junction of Hussainiyat and Amij valleys (Hamza, 2007).

Picture 5.7: The shallow badlands south of Rutba.



Picture 5.8: The shallow badlands south west town of Rutba.

Picture 5.9: the shallow badlands west Rutba.

5.5.2.3 Mesas and Buttes

Mesas and buttes are very common in the Western Desert. They occur in front of the cliffs which separate the plateaux from each other and are developed as a result of erosion, possibly along conjugate joints. They are denudational relicts of the larger plateaux. They usually form flat tableland features, often in groups. Their summit levels show congruence with the dissected original plateau surface.

5.5.2.4 Depressions

Large size depressions are relating common in the Western Desert and the two largest are Al Garaa and Umm Chaimin. The formation of these depressions is described below:

5.5.2.4.1 The Garaa depression

The tectonic development of the Garaa depression has defined its geomorphological form. The erosion of the Al Garaa anticline exposed the Palaeozoic rocks at the core and left it surrounded by a series of low escarpments (Figures 5.12, 5.13 and 5.14).

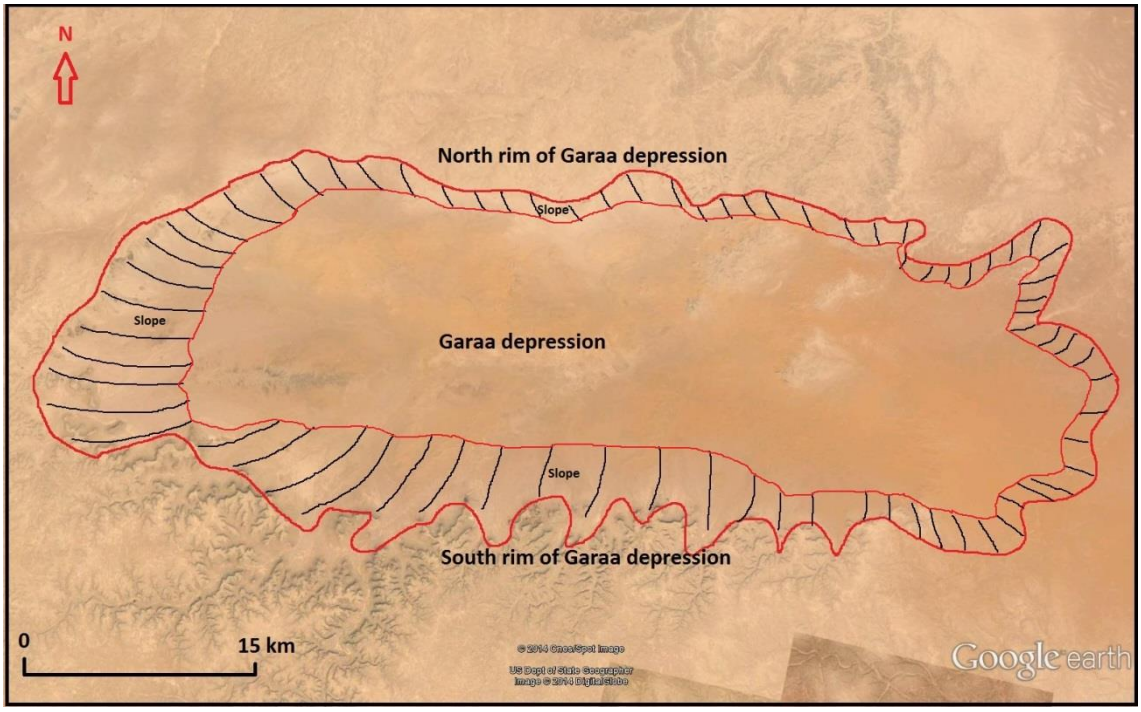


Figure 5.12: Garaa depression in Iraqi Western Desert (Google Earth images).

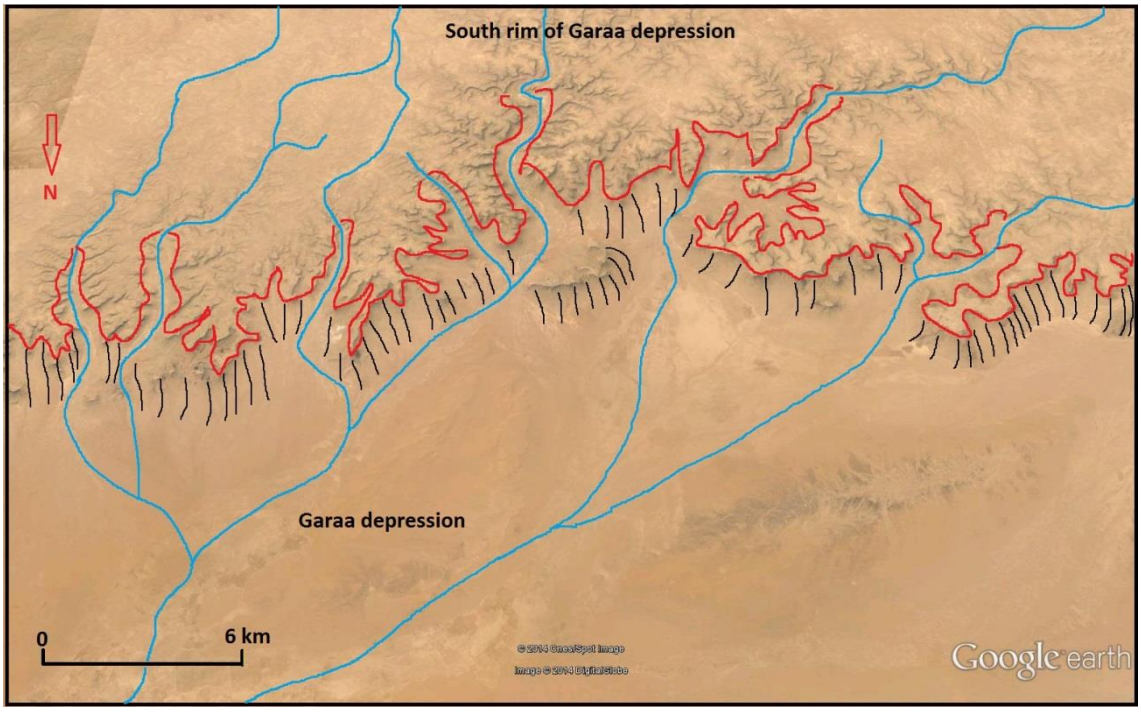


Figure 5.13: South rim of Garaa depression in Iraqi Western Desert (Google Earth images).

The Garaa depression is at the core of the Rutba uplift (Pictures 5.10, 5.11 and 5.12). The Rutba uplift is part of the regional tectonic development of the Western Desert and the effects extend to the south west into Syria, east into the Jordan and to the north west are Saudi Arabia (Chapter 4). It is the largest discreet depression in the Western Desert. Its dimensions are about 30 x 60 km (Hamed, 2003). The Garaa depression is oval shaped, and longer east to west than north to south. It is surrounded by cliffs of variable height. The cliffs in the south edge reach up to 120m while in the north and east they are much lower ranging between 15-55 m (Hamza, 2007). The cliffs are still degrading and retreating as result of weathering and erosion. Rocks of the oldest formation found in the Western Desert Garaa formation, are exposed in the floor of the depression. The depression is in filled with valley fill, and debris associated with alluvial cones and fans. Tectonically the area is part of the Garaa Uplift, which has undergone continuous denudation since the end of the Cretaceous (Hamza, 2007).

Figure 5.14 provides details of the topography within the Garaa depression. In the south a whole series of ephemeral stream valleys enter the depression. Fewer valleys enter from the north but the overall impression is that the depression represents the core of a centripetal drainage system (Chapter 6). However, there is a single stream outlet in the northeast of the depression through the Ratga valley; therefore, it is not a fully enclosed depression.

There are a number of salt lakes within the depression indicating that this is predominantly an area where ephemeral stream waters are removed by evaporation.

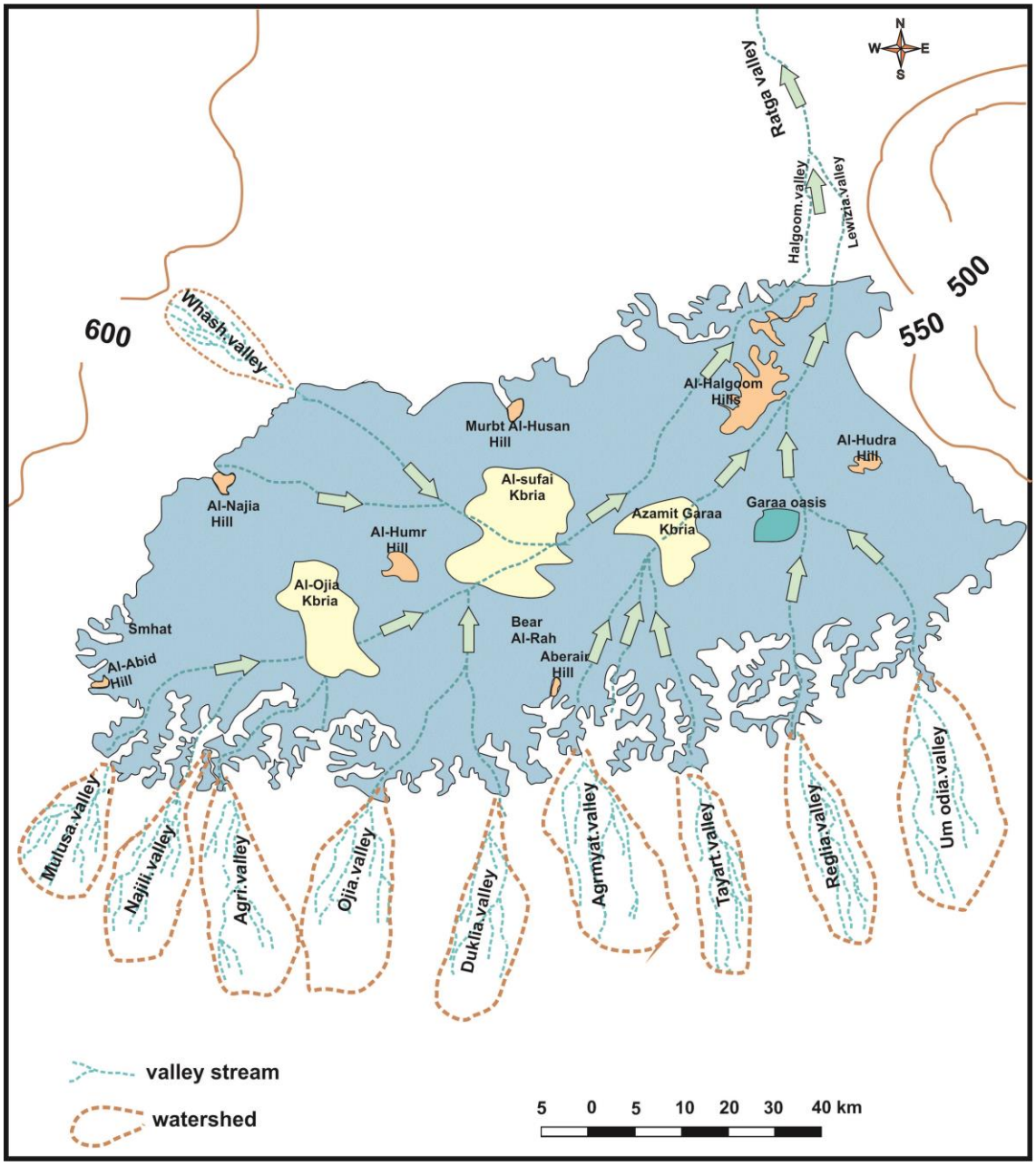


Figure 5.14: Garaa depression in the Iraqi Western Desert.

Picture 5.10: Southern rim of the Garaa depression.

Picture 5.11: Desert plain in the Garaa depression.

Picture 5.12: Construction of a dam on one of the valleys, which ends in the Garaa depression.

5.5.2.4.2 Umm Chaimin Depression

The Umm Chaimin depression is 2.7 km long and 3 km wide (Merriam and Holwerda 1957). The height difference from the depression edges to the centre is between 33m-42m. The Umm Chaimin depression was initially believed to be a result of folding in the sedimentary layers (Figure 5.15) (Picture 5.13). However, because of laminations in the sediments there are natural pipes that allow groundwater movement. Din et al (1970). Therefore Al Naqib (1967) suggested that the Umm Chaimin depression was as a result of dissolution (i.e. a doline) and piping. From the field observations carried out for this thesis it is concluded that this is appear to be the most likely explanation

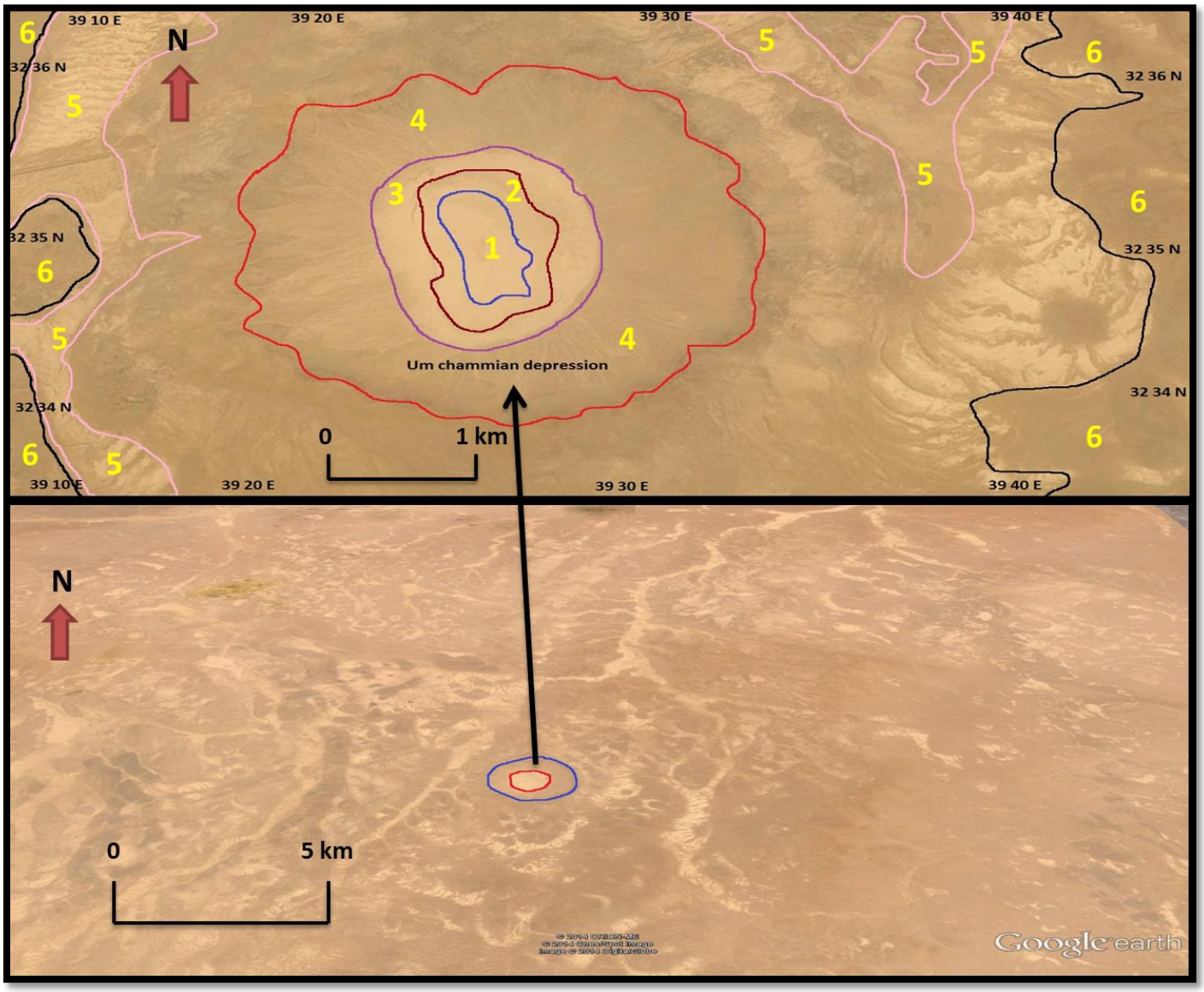


Figure 5.15: Solubility depression of Umm Chaimin (Google Earth images). Key:

1.Sedimentary basin,

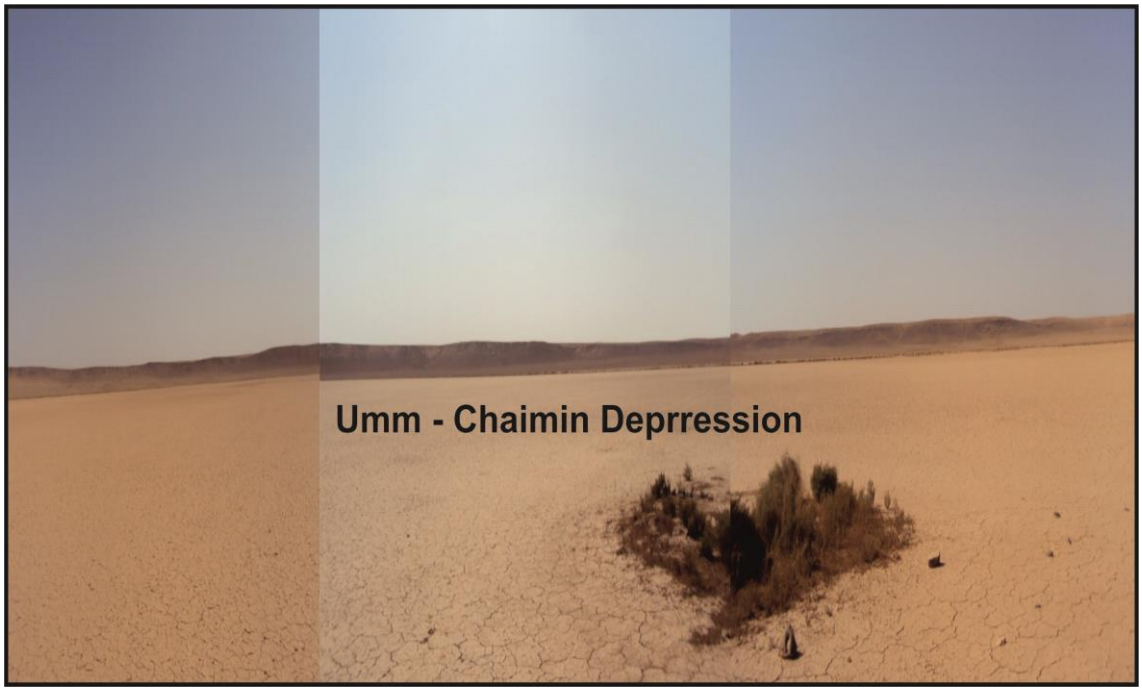
2. Concave slope

3. Steep near vertical slope

4. Hill wash sediments

5. Fluvial sediments

6. Rock outcrop



Picture 5.13: Umm Chaimin depression in Iraqi Western Desert

5.5.3 Fluvial Landforms

Topography associated with fluvial landforms is common in the Iraqi Western Desert. Included within this category are the numerous alluvial fans which have formed along the base of the southern rim of the Garaa depression where many large valleys, such as Mulusa, Najili, Agri, Ojia, Dwakla, Agrmyat, Tayrat, Reglia, and Um adia, drain into the depression from the south rim. Almost all of these fans are still active and have surface areas measured in 10s of square kilometres. Also an extensive bajada is developed to the west of the Al Habbariyah depression. It extends from the Al ghadaf valley south east of Rutba to the Iraqi-Saudi Arabia border, a length of 10 km.

5.5.3.1 Ephemeral stream valleys

These relict and active ephemeral river valleys are very significant landforms and are discussed in detail in Chapter 6 .They can be divided in to two types:

a) Endoreic ephemeral river valleys

These are valleys containing ephemeral rivers which begin and end within the desert land. They do not reach the Euphrates River. These valleys included the Um Adiaha, Al Reghela, Um Tayara, Al Agrmyat, Duejlaha, Owja, Al Aggrey, Al Njeli, and Al Mulussi.

b) Exoreic ephemeral river valleys

The second set of ephemeral river valleys begin in the Western Desert and end in the Euphrates River. These are represented by the Houran, Swab, Ratage, and Akash valleys (Al Aa'thari, 2005). There is a clear variation in the length of these valleys, with small valleys formed on the limestone, marl, and gypsum. One of the shortest valleys in the study area is the Al Qaiam valley at 80km in length. These valleys generally start at an altitude of 400 m above sea level. The medium size valleys such as the Swab, Al Rataga and Akash have length range between 175-200 kms. These valleys pass through Pliocene and Miocene rocks. These valleys begin at an altitude in the range of 350-700m above sea level. Some of the longer valleys are more than 350 km in length. These are formed as a result of the confluence of a number of small to medium valleys. These longer valleys are characterized by clearly identifiable ephemeral streams courses and steeper long profiles as they pass through the Al Rutba Uplift. These valleys descend from the tilted plateaux surfacs which slope down from the south-west towards the north-east. The networks of dry valleys are characterized by being generally wide and are filled with unconsolidated

sedimentary deposits. The valleys in the region generally have north-northeast orientation.

5.5.3.2 Alluvial fans and bajada

Alluvial fan topography is common in the Western Desert. And some of the fans have coalesced together in the form of a bajada (see Cooke et al., 1993). Local breaks in slope on the bajada suggest there have been stages in their development which are probably related to changes in climate during the Pleistocene and Territory period

5.5.3.3 River terraces on the River Euphrates

The climatic fluctuations that occurred in Iraq and the Arabian Peninsula during the Tertiary Period had a major role in the sedimentation processes that lead to the formation the highest level terraces in the study area. Also during the Pleistocene Iraq was subjected to ‘fluvial’ periods of increased rainfall where river discharge increased which changed the regime of sedimentation and erosion in the River Euphrates and is its tributaries (Tyracek, 1987). The end result of these climatic fluctuations is an identified staircase of river terraces (Figure 5.16). Changes in the main river flow location of the River Euphrates have led to the occurrence of non-paired river terraces where the river eroded on the outside of meander bends.

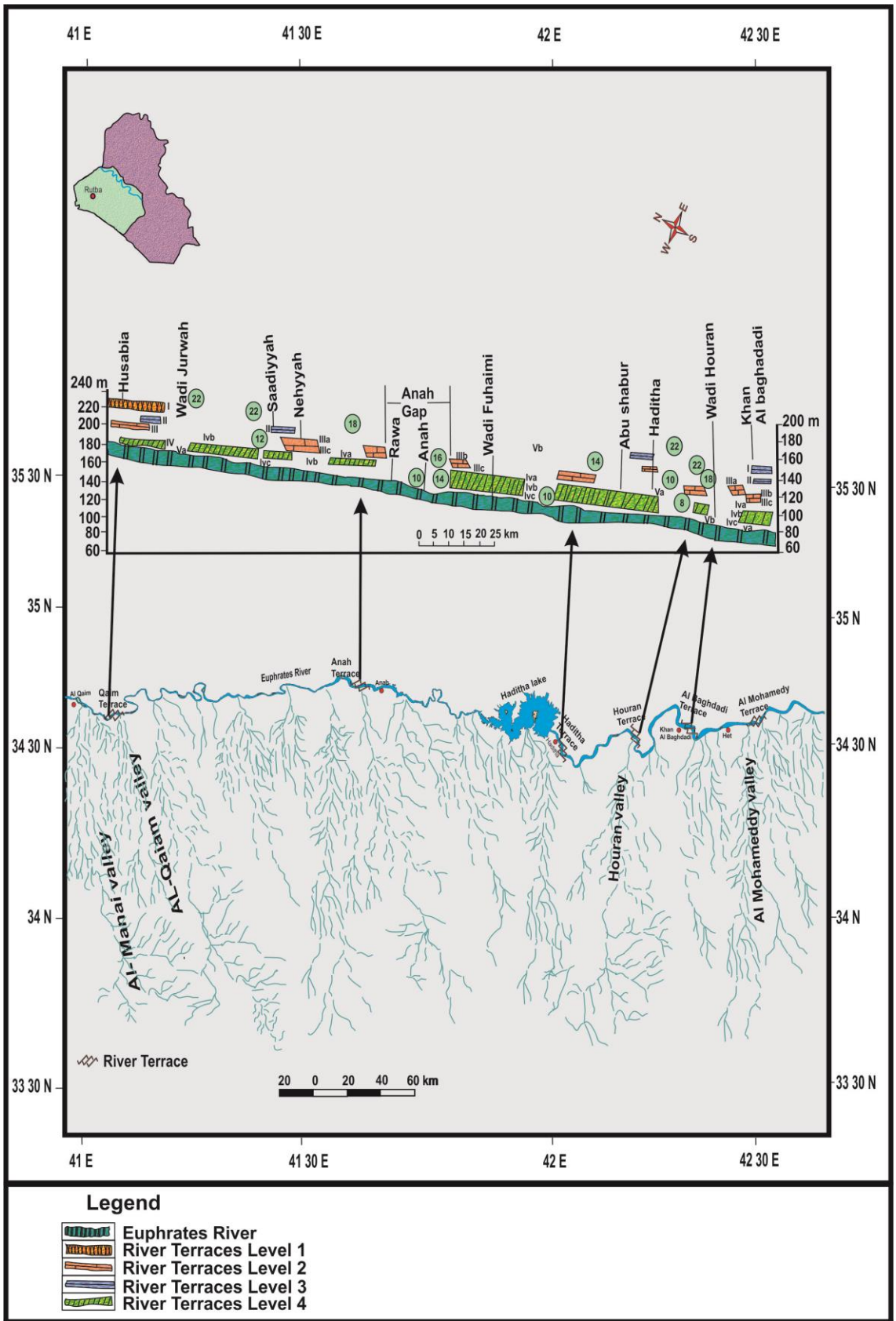
In Table 5.8 and Figure 5.16 details of the main terraces between Al Qaiam city at the Syria-Iraqi border and the mouth of the Houran Valley west of Heet city. The numbers in circle on Figure 5.16 refer to terraces level in the study area above the present water surface of the Euphrates River.

The Roman numerals I, II, IIa, IIb, IIc, Ia, Ib, Ic, Va, Vbrefer to the terrace level number in study area (Lower Terrace has up to four separate units thus the L1, L2, L3, L4 occur in same terrace).

Table 5.8 shows the elevation of the main terrace both in absolute terms and with respect to the Euphrates River.

	Husaiba			Saadiya – Nihayyah			Above Rawn			Wadi Fuhaimi			Abu Shabur – Haditha			Wadi Houran		
	Abs elevate		Relative altitude above river level	Abs. elevation		Relative altitude above river level	Abs. elevation		Relative altitude above river level	Abs. elevation		Relative altitude above river level	Abs. elevation		Relative altitude above river level	Abs. elevation		Relative altitude above river level
	Terrace	River		Terraces	River		Terraces	River		Terraces	River		Terraces	River		Terraces	River	
I Oaiam terrace	218	162	56										171	98	73	152	72	80
II Jurwah valley	210	163	47	198	148	50							132	98	54	140	72	68
IIa Saadiyyah																135	79	66
IIb Nehyyah	200	164	36	185	142	43	174	137	37	165	118	47				125	76	49
IIc Anah terrace				180	147	33				157	117	46	141	102	39	120	76	44
Ia Fuhaimi valley				172	147	25	165	140	25	146	112	34	130	101	29	100	72	34
Ib Haditha terrace	185	164	21	166	148	18	160	141	19	141	116	25	125	102	23	96	72	26
Ic Houran terrace	185	167	18	165	150	15				128	112	16	115	99	16	92	72	20
Va Al Baghdaidi terrace	175	164	11	154	144	10				125	114	11	110	99	11	94	82	12
Vb Mohammadi terrace	168	164	4	150	144	6	142	137	5	120	114	6	105	99	6			

Table 5.8: River Terraces in the Iraqi sector of the Euphrates (Tyracek, 1987)



Legend

- Euphrates River
- River Terraces Level 1
- River Terraces Level 2
- River Terraces Level 3
- River Terraces Level 4

Figure 5.16: Longitudinal profile of the Euphrates terraces between Al Qaiam and Al Baghadai Modified after Tyracek (1987)

In the surrounding area of Anah the Euphrates River flows through Oligocene limestones of the Anah Formation, which forms the core of the Anah anticline. Tyracek (1987) has studied the river terrace sequences of the Euphrates River in Turkey and Syria. He said the Euphrates River initially flowed southward into the Arabian platform. After entering Syria it turned east towards Iraqi and the Arabian Gulf. The terrace sequence of the Euphrates River in Iraq has also been studied by Tyracek (1987) and in Syria by Ponikarov et al (1967). Tyracek (1987) in Syria (Figure 5.16) showed that Euphrates gravels form a broad zone up to 12 km wide in northwest Syria adjacent to the Iraq border. Deposits are restricted to the valleys in the desert and are mainly Quaternary in age although the oldest probably dates to the end of the Pliocene (Tyraceck and Youbert, 1975).

It is recognised that river terraces are the result of a complex interaction of a multitude of processes. In the study area the base level control on the ephemeral streams flowing out of the Western Desert is the Euphrates River. The terraces occurring in the tributaries should, therefore, tie in with the River Euphrates terraces. The complications of erosion, partial removal of the material by humans and the effects of variable tectonic uplift can make such linkages problematic. Nevertheless, a five-fold subdivision of the River Euphrates is recognised by Tuncer et al., (2007), as described below, which can be also used to understand the terrace sequence in the tributary valleys. Tyracek (1987) and Tuncer et al. (2007) studied the terraces of the Euphrates River in seven localities. They identified ten terrace levels and put them in five groups at 218, 210, 200, 185, and 175 m above sea level (Table 5.10). The first three are missing in the Anah area because of the tectonic activity around the Anah anticline (Chapter 4). In the Heet area there are four terraces at 100, 70,

50 and 20m above the Euphrates river level (Hamza, 1975). The terraces are composed of loose and cemented gravels and cobbles of chert and carbonates with rare, igneous and metamorphic material. Tyracek and Youbert (1975) have mapped two terrace levels along tributary Houran valley. The highest level is in the H1 area; and is 50 m above the valley floor. The second level is 7 m above the floor of the valley. These terrace gravels are composed of chert, carbonates and sandstone with conspicuous amounts of gravel. Al Mubarke and Amin (1983) termed the deposits of the highest level as the Houran Gravel and mapped them as an old floodplain (Chapter 4 Section 4.3.3.9). The present author investigated the gravel on both sides of Houran valley and as part of this study and re-defined the highest level as alluvial fan deposits. Terraces are also formed in the Garaa Depression, but are restricted to the main ephemeral streams of Wadi Mulussa and Wadi Al Oja. Tamer Agha (1993) has mapped three terrace levels in the depression. The Euphrates River enters the Arabian platform at Al Qaim town in the Western Iraq and the main terraces developed downstream are described below.

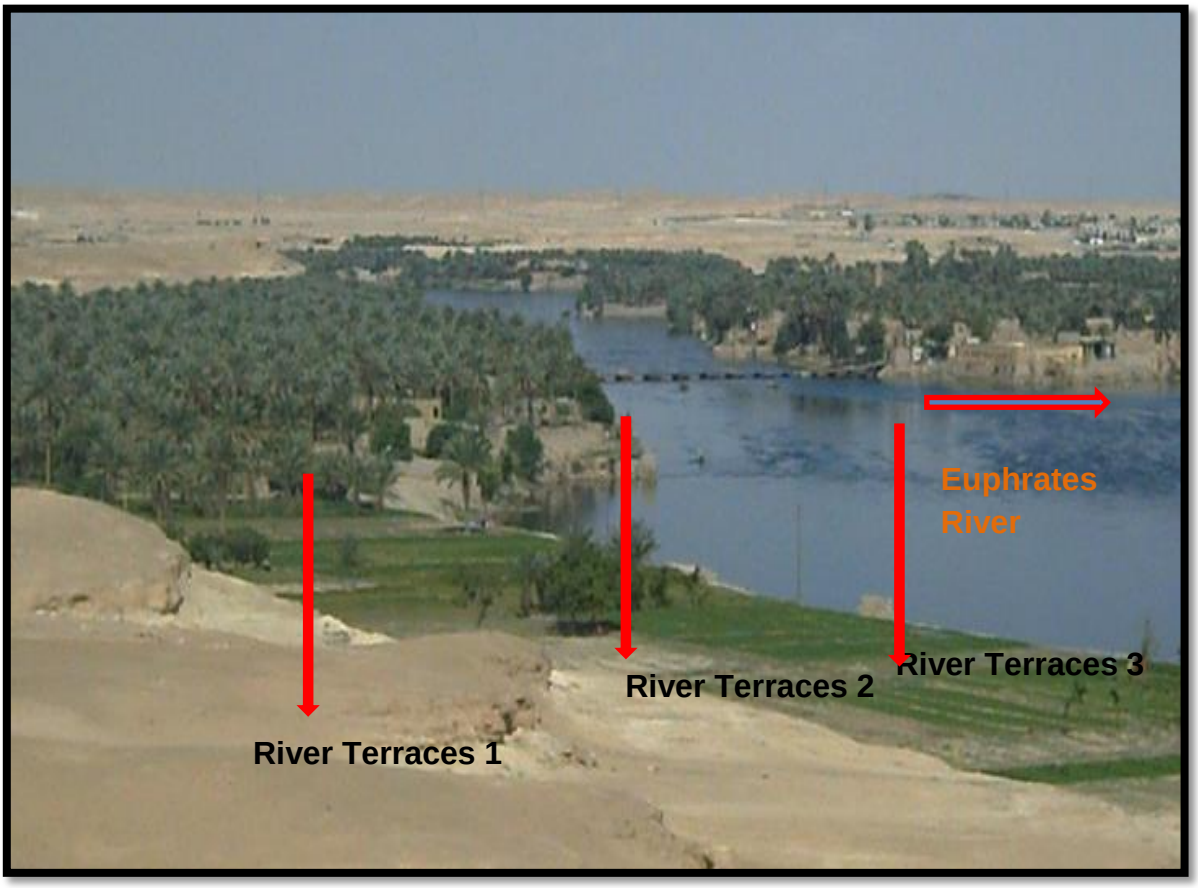
5.5.3.3.1 Al Qaiam terrace

Tyracek (1987) first refers to the Al Qaiam terrace in the town of Al Qaiam this terrace in 65-70 m above the flood plain level, and at a height of 150-152m above sea level (figure 5.16). The terrace remnants are just sparse remnants and are about 6-10 m thick (Picture 5.14 shows the Euphrates River at the town of Al Qaiam).

5.5.3.3.2 Haditha terrace

The Haditha terrace is the second oldest riverine terraces in the study area occurring 50-60m above the Euphrates flood plain level (picture 5.15). At a height of 150-152m above sea level, there are only sparse remnants remaining which are about 2-8m thick. The terraces consist of sand, gravels with some silt and clay. Secondary groundwater gypsum can be identified in the various voids and discontinuities.

Pictuer 5.14: Euphrates River at the town of Al Qaiam.

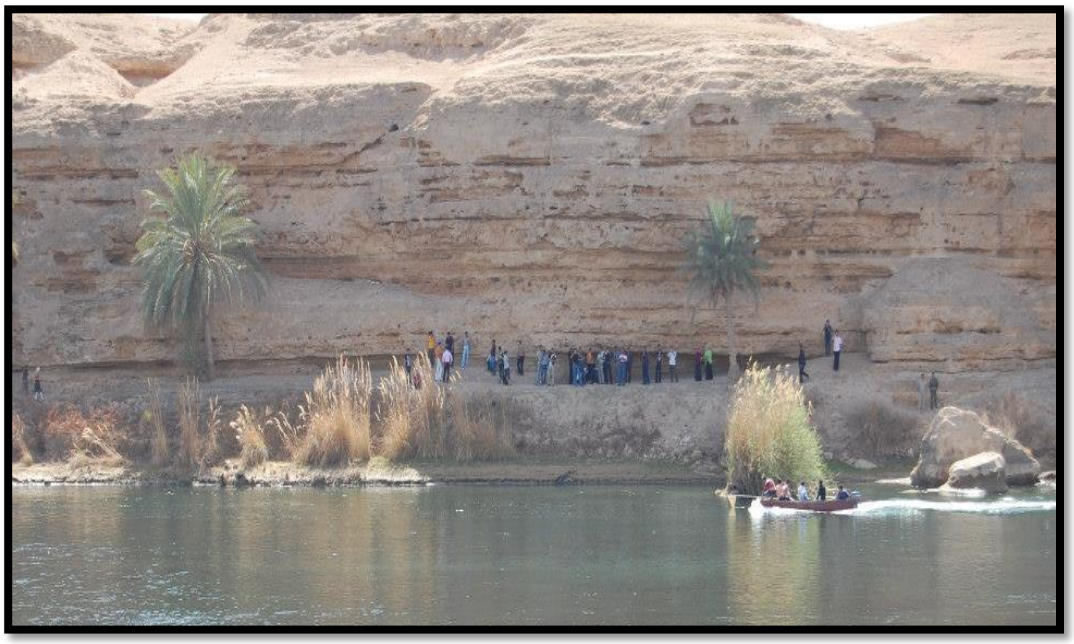


Picture 5.15: River terrace near the town of Haditha

5.5.3.3.3 Al Baghdadi terrace

The Al Baghdadi terrace is the third oldest terrace level in the study area and is approximately 40-50m above the Euphrates floodplain (Pictures 5.16, 5.17, and 5.18). It is present south of the Al Baghdadi area on the River Euphrates right bank, 125m above sea level, and also opposite of Alflewy island (Figure 5.16) on the left bank of the river at a height of 100-110m (Picture 5.16)

Picture 5.16: Al Baghdadi River terrace



Picture 5.17: Al Baghdadi River terrace

Picture 5.18: Agriculture in the Al Baghdadi River terrace

5.5.3.3.4 Houran terrace

The Houran terrace is about 25-40 m above the Houran valley floodplain and its sediments are found near the Houran valley mouth by Heet City (figure 5.16). Here the terrace can be found on both sides of the river between 120-130m above sea level. It is also located south of Brwana at Al Bakria village opposite Alous Island on the left bank of the River Euphrates at a height of 125-130m above sea level. Some parts of this terrace appear opposite of Guba Island on the right bank of the River Euphrates where they obtain a thickness of 10m and lie 110m above sea level. Other locations of the terrace remnants are in the vicinity of the Dolliah, Teba, and Khazraj villages at heights of 95-100 m above sea level. The terrace sediments comprise gravels, sand, silt and clay.

5.5.3.3.5 Al Mohamedi terrace

The lowest and youngest terrace is in Al Mohamedi and this is close to the Euphrates River level between 5-25 m above the floodplain. These terrace sediments are extensive in the study area and are also found to the south of Heet City at Almohamedi village at heights of approximately 65-80m above sea level. The thickness of the terrace sediments reaches 15m. In some localities five alluvial layers can be differentiated based on their component particle sizes. This is a paired terrace on the two sides of the river (Figure 5.16) in some localities.

Development and survival of the river terraces are the results of two main factors; climatic fluctuations; and river channel migration process.

5.5.3.4 Ephemeral lakes

Ephemeral lakes are another fluvial geomorphological feature in the study area. Lake beds are flat, and they show on satellite images as lighter patches in the desert. These lakes contain water following rainfall but rapidly dry out (Picture 5.19). Where ephemeral stream flows enter enclosed depressions the waters of ephemeral lakes form salt pans as they dry out (playas) (Figure 5.17).

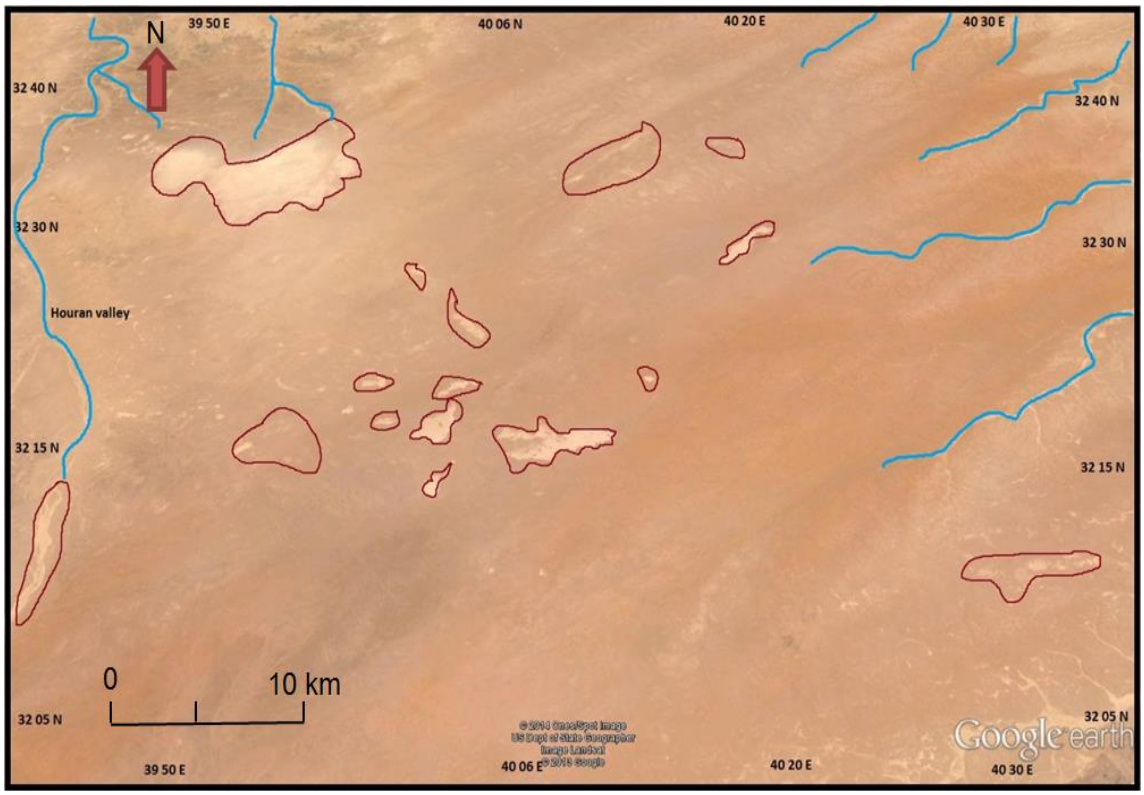


Figure 5.17: Ephemeral lakes in study area by (Google Earth images).

Picture 5.19: Ephemeral lakes south west Rutba town.

5.5.4 Solution features

Sinkholes formed by sub-surface drainage and solution of limestone or gypsum (malaa, 2009). These are relatively rare in the surveyed area but one was located north of a residual hill in the Al Garaa Depression. It had a collapse dome form and was about 20 m in diameter. Buday and Hak (1980) described the sinkhole forms of variable shape and dimension on the surface of the plateaux at Southwest of Rutba. The subterranean entrance was 60 x 100 cm in size and is formed in a thin bed of epigenetically indurated limestone of the Mulssa Formation (Buday and Hak, 1980). As part of this study the author was able to establish that sinkholes were also present in karstic terrain in the Hadith area.

5.5.5 Evaporite landforms

High rates of evaporation from ephemeral lakes or near surface groundwater will result in the precipitation of salts either within rocks or on the surface. The typical evaporate landforms, therefore, are salt pans that develop in flat low-lying areas. When the salt pans contain ephemeral lakes they are known as playas. Where the evaporation is predominantly from groundwater then the salt pan is known as a salina. In the Western Desert both types are commonly known a sabkha, although in much of the scientific literature sabkha is usually associated with coastal salt flats (Griffiths et al, 2012). In the Western Desert there are numerous salt pans, notably between the towns of Heet and Haditha and the area to the southwest of Rutba. The existing salt pans will be of late Pleistocene-Holocene age (Hamza, 2007) but within the geological record of the region older salt pans are indicated by the presence of halite and gypsum beds. The other forms of evaporate landform are the duricrusts, or cemented unconsolidated deposits. There are the result of crystallisation of carbonates in groundwater which can form strong ‘rock’ and can be up to 5 meters think. The two forms identified in the Western Desert are calcrete and gypcrete.

- **Calcrete (unconsolidated deposits or weak porous rock cemented by calcium carbonate)**

According to Tamer Agha (1993) calcrete is locally preserved in the Western Desert in the dry valleys which end in the Garaa depression. These include the Ojia, Um idyai valleys. The thickness is normally between 1- 4 m but where they have developed on the north edge of the Garaa depression at Marbat Al Hissan these reach 5m. They consist of heterogeous rock fragments of variable composition cemented by silty, sandy calcareous materials.

• Gypcrete (unconsolidated deposits or weak porous rock cemented by gypsum)

Al Mehaidi et al. (1975) refers to gypcrete as being well developed on the surfaces of the plateaux of the Euphrates and Nfayial formations. The gypcrete is locally massive and fairly well compacted.It is well developed around the south rim of the Garaa depression. Another locality is west of Rutba town, in which the gypcrete is deposited as sheets.

5.5.6 Aeolian features

Aeolian bed forms have a range of morphologies that reflect interactions between wind direction, velocity, sediment supply, vegetation and topographical obstacles (Griffiths et al., 2012). Three types of aeolian landforms are developed in the Iraqi Western Desert. There are small fields of nabkha in the Manai area and the east part of the Garaa depression, but elsewhere sand sheets and sand dunes have developed (Tamer Agha, 1993). The aeolian landforms are in a strip with northwest-south east orientation reflecting the main direction of the wind. Fields of sand dunes and sand sheets are located at three sites:

1. North of the town of Rutba; notably in Qasir Amij area, both sides of the Manai valley, and east of the Garaa Depression.

2. South of Rutba. The dune in this area covers a wide belt in Al Bireet area along Iraqi - Saudi Arabia border.

3. Sand sheets are developed to the west of Rutba town along the Iraqi-Syria and Jordan borders, occurring on both sides of the national expressway No 1 which links these countries. Amplitudes between trough and crest range

between 0.5-1m. The sand sheets also accumulate in shallow valleys and depressions and in these areas you can also see the nabkha developed to heights of between 20 - 60cm (Hamza, 2007) (See pictures 5.20, 5.21, and 5.22).

Picture 5.20: Sands west town of Rutba

Picture 5.21: Sands on the national expressway No 1 near the town of Rutba.

Picture 5.22: Ripple bed forms superimposed on a sand accumulation the walls of a building south west of Rutba town.

5.6 The New Geomorphological map of the Iraqi Western Desert (figure 5.18 in appendix of this thesis)

5.6.1 Background data field observation

By building on the knowledge of the geomorphology presented in the previous sections a critical and unique part of this study was the opportunity to compile a new map of the geomorphology of the Western Desert. The existing Iraqi Geological Survey (2000) 1:1 million scale geomorphological map showed the whole of the Western Desert as an undifferentiated purple (see Appendix F on CD). There are a number of types of geomorphological maps. In this study the geomorphological map that could be compiled was essentially a morphographic one and showed dry valleys, plateaux, depressions and various other geomorphological phenomena (Gebremariam, 2010). The geomorphological map was derived from remote sensing data, including Google Earth images, and various pre-existing published and unpublished maps of varying scales such as the geomorphological map of Iraq 1:1,000,000, topographic maps with scales of 1: 250,000, 1: 100, 000 and 1: 50, 000, These data were supplemented by the inclusion of field data from the two field seasons.

A geomorphological map must contain information about features, general morphology and details of materials, genesis and processes (Seijmonsbergen, 2008). Aerial photography used to be the crucial tool in resource and landscape studies (Palmer, 2013) but this has been surpassed in part by recent developments in the use of satellite imagery. In this study use of Google Earth images along with field work and accessing unpublished data were key to the production of the new geomorphological map. A useful features of Google Earth programme is that it permits zooming and oblique perspective of the Landscape to be viewed (Belden, 2008). The author worked with a mosaic of Google Earth

images taken between 2005 and 2013 in order to produce an overall image suitable for analysis. In addition the morphological characteristics obtained from the GIS database analysis of compiled maps were compared with the results derived from an interpretation of the satellite imagery in Google Earth. This comparison of information helped in the interpretation of the terrain and identification of the geomorphological units in the study area. Thus the author was able to combine the data review presented in Sections 5.3 to 5.5 with remote sensing interpretation, ground truth reconnaissance field surveys and GIS data base analysis to produce the new geomorphological map.

5.6.2 Geomorphological Evolution

The new 1:1,000, 000 scale geomorphological map of the Iraqi Western Desert which has been produced for this thesis is presented in reduced form in Figure 5.18 and is available at full scale on the Appendix A in CD. The elements of the legend to the map are produced in Table 5.9. In this section the components of the map are described with an emphasis on the elements which have been instrumental in the study of the development of the ephemeral stream drainage network of the Western Desert. As noted previously the study area is essentially a dissected plateau. Examination of the geomorphological map shows that two main landform assemblages can be identified: structural and erosion denudation forms and accumulation forms. Within the first category various plateaux levels can be identified that link to the pre-existing interpretation of plateaux developed on different geological formations (Section 5.2). Based on the more detailed unpublished data some of these have been further sub-divided, but is apparent there are five main plateau groups labelled A-E on the geomorphological map (Table 5.9 Figure 5.18).

Structural and Erosion-Denudation forms

- Cuesta
- Small Hills
- mainstream valley
- valley floor of ephemeral stream
- canyon like valley
- Erosion grooves
- Prominent mesa shaped Hill
- Escaprment
- Slope and pediment
- Depression

Plateaux Levels

A 1	Level A 1	Oligocene - Miocene structural plateaux
A 2	Level A 2	
A 3	Level A 3	
B 1	Level B1	Relicts of Lower Miocene Drainage system in the Euphrates
B 2	Level B 2	
B 3	Level B 3	Formation; lower Miocene relief near the Euphrates formation shore line
C 1	Level C 1	Upper Miocene relief characterized by the development of the post - Euphrates drainage system
C 2	Level C 2	
C 3	Level C 3	
D 1	Level D 1	Mio -Pliocene relief with defined cliffs
D 2	Level D 2	
D 3	Level D 3	
E 1	Level E 1	Plateaux of Pliocene drainage system
E 2	Level E 2	
E 3	Level E 3	
E 4	Level E 4	
Q 3	Level Q 3	Middle erosion terrace
Q 2	Level Q 2	High erosion Terrace
Q 1	Level Q 1	Highest erosion terrace

Pleistocene

Accumulation forms

- valley fill in ephemeral valleys and fluvial depressions
- closed depression
- Dry Lake
- Landslides
- Q 4 lower fluvial accumulation terrace Q 4
- Q 3 Middle fluvial accumulation terrace Q 3
- Q 2 High fluvial accumulation terrace Q 2
- Q 1 Highest fluvial accumulation terrace Q 1
- Expression of outwash fan of larger valley
- Relicts of older outwash fan
- Region of small accumnlations of wind blown sand and nebkhas
- Residual pebbles of the littoral facies of Euphrates Limestone formation

Morphological Forms

- Plateau limited by prominent cliff
- Plateau limited by cliff
- sandy lands
- Gravel pavement developed on Euphrates limestone formation
- Rockfall debris
- Dam
- Expressway No 1
- border crossing point
- River Islands
- Sinkholes

Table 5.9: The legend of the Geomorphological Map of Iraqi Western Desert presented in Figure 5.18 (Attached as a separate file hardcopy at the end of this thesis and on the CD).

The use of five main plateaux groups (A-E) differs from the existing description of the plateaux which was based on the geological formation names (Section 5.5.1) and was set up initially by Al Kubasi (1993). The approach presented on Figure 5.19 links the plateaux to the tectonic and climatic history of the Western Desert. Thus plateaux level A are the result of the tectonic uplift in the Oligocene and Miocene: Plateaux level B are the result of fluvial erosion during the early Miocene which led to the formation of the Euphrates formation. Plateau level C represents the topography created by fluvial erosion following the deposition of the Euphrates formation during the late Miocene. Plateaux level D are the result of the sub-areal denudation during the Late Miocene-Pliocene. These D level plateaux are clearly younger than the A-C plateaux as they are delimited by well-defined cliffs. Plateaux level E are the result of a Pliocene drainage system. In addition there are Pleistocene erosion terraces (straths) labelled 'Q' on Figure 5.18 and these are an age defined sequence of erosional and depositional terraces, with Q4 the youngest and lowest, and Q 1 the oldest and highest. In addition to the plateaux there are smaller scale erosional features, such as mesas and escarpments. The extent of these is somewhat symbolic given the small map scale. Accumulation forms are less extensive but nevertheless have beem delimited wherever possible.The map does show some of the large playas. The Playas are found west of Rutba, to the north and south of the international highway between Iraq and Jordan and in the area between the Mulasai valley and the Jordanian border.

Erosional and depositional pediments are found along the base of the Al Garaa Anticline. The erosional pediments are formed on bedrock of the Euphrates Formation (Hamza, 2007) whilst the depositional pediments are formed on relicts of bajada deposits resulting from the erosion of the higher plateaux areas. The pediments form a connecting link between colluvial deposits on steeper slopes and the fluvial sediments in the valleys. Pediments and their sedimentary covers were formed predominantly by sheet wash. Alluvial fans form a connecting link between alluvial deposits on steeper slopes and the fluvial sediments in the valleys. They represent depositional landforms of arid to semiarid subtropical deserts (Buday and Hak, 1980). Numerous alluvial fans occur in the valleys that end in Garaa depression (Shaker, 1993). There are also alluvial fans found in the valleys that end at the Euphrates River floodplain.

5.6.3 Comments on the Tectonic control on the geomorphology

Examination of the geomorphological map (Figure 5.18 in Appendix of this thesis) in conjunction with the maps of structural geology (Figure 4.5 Chapter 4) and bedrock lithology (Figure 4.6 Chapter 4) suggest that the geomorphology of the Iraqi Western Desert is controlled predominantly by tectonics. The main structures are associated with Palaeozoic orogenic episdes affecting basement rocks, but the overlying Mesozoic and Cainozoic sediments have been affected by a reactivation of these deep structures (Chapter 4). The combination of uplift and subsidence, the creation of anticline and synclines within variable lithologies, and faulting, are the dominant controls on the geomorphological evolution of the region.The most significant tectonic features is the Rutba Uplift (Sutor and Dube, 1977). This can be divided into two components.

i) Northern anticline centred on the Garaa Depression

ii) Southern Houran anticlinorium to the South of Rutba

These two components are separated by the Amij-Samarra Fault which is a major control on the path of the Houran valley, the most important exoreic drainage network in the Western Desert. The importance of understanding the link between there tectonic controls and the development of the ephemeral drainage network is explored in detial in the next chapter

5.7 Summary of the future geomorphology investigation

This chapter outlines the geomorphology of the Iraqi Western Desert. The first part of this chapter divided the Iraq Western Desert into four parts: Hammad area, Upper valleys area, Stone area and Lower valleys area. This symplistic sub–division provided a useful basis for understanding the overall surface morphology of the study area but examination of the literature, geological data, and interpretation of satellite images indicated that a more detailed evaluation was required. Initially this led to a description of the geomorphological features that had been observed with recognition that the dominant landforms were the flat lying plateaux. The indications were that these were mainly related to differing bedrock lithlogies. However, variations in elevation suggested that the development of the plateaux occurred at various times during the Cenozoic.

It was established that a new geomorphological map of the Iraqi Western Desert could be compiled (figure 5.18 in Appendix of this thesis).

This unique map brought together previous unpublished studies and was supplemented by the pre-existing more detailed geological studies and remote sensing and field observation data undertaken as part of this research. The new geomorphological map clearly demonstrates the importance this drainage network in the creation of the Western Desert landscape, which is essentially a dissected plateau. The map, therefore, formed the basis for the final investigative component of the thesis, the evolution of the drainage network (Chapter 6) and how this explains the newly identified pattern of plateaux shown on the geomorphological map (Figure 5.18 in Appendix of this thesis).

Chapter 6

Drainage Investigation

6.1 Introduction

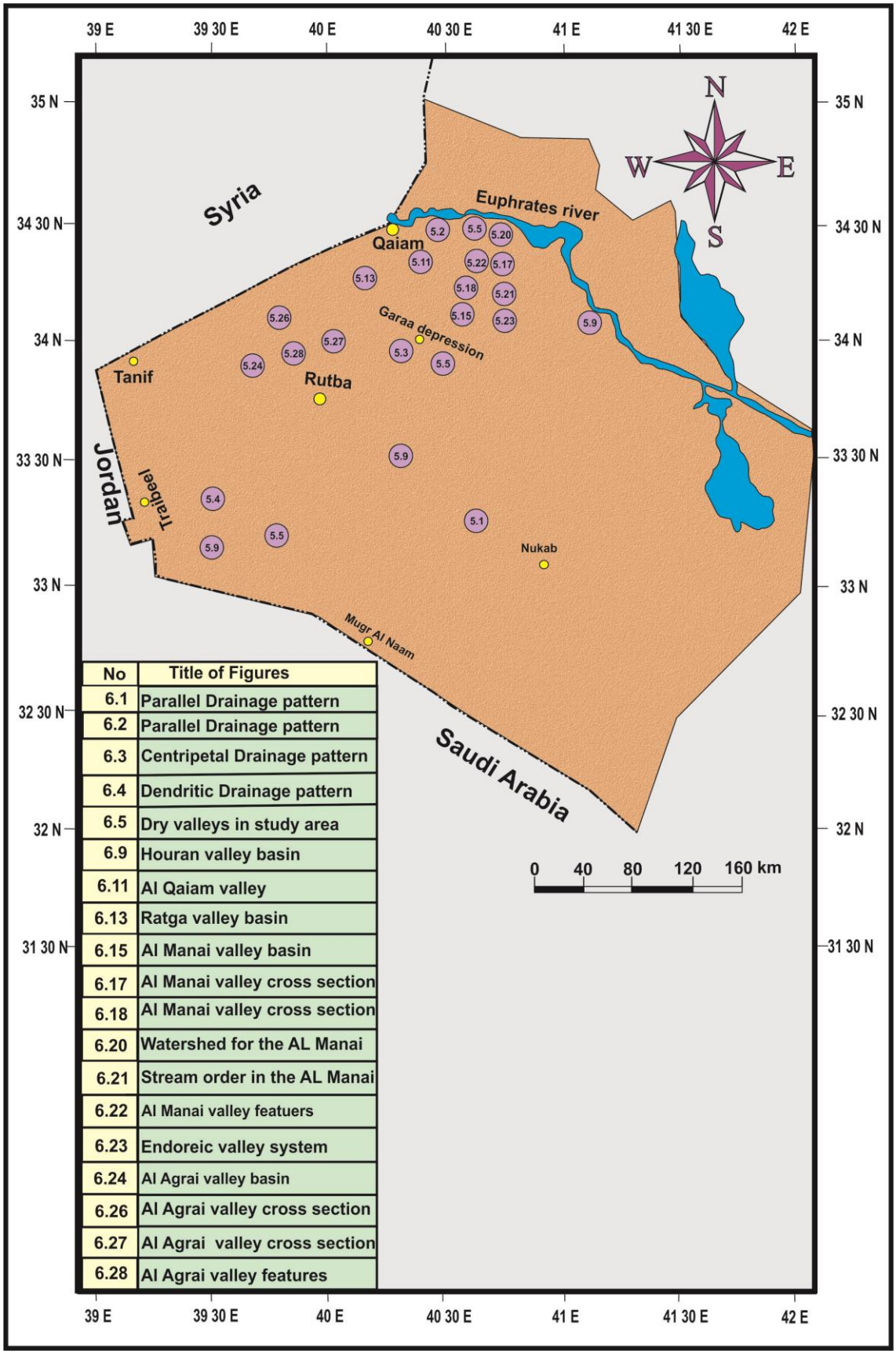
The Iraqi Western Desert area to the north and south west of the town of Al Rutba is distinguished by its pattern of relict drainage valleys which are occupied by ephemerally active but misfit rivers. One of the principle aims of this research was to investigate the morphological form of these valleys and establish their geomorphological history. The valleys and catchments described in this chapter are shown in Figure 6.1.

6.2 Drainage system types

Because the literature (e.g. Hamza, 2007) suggests the general form of the drainage basins is heavily influenced by the underlying geology this formed are important element of the investigation of the drainage in the region. There are four main drainage patterns in the Iraqi Western Desert region which are described below and their location represented in figure 6.4

6.2.1 Parallel Drainage pattern

The parallel drainage system in the Iraqi Western Desert is a pattern of dry valleys which all flow in the same direction to the north and northeast. In this pattern the river streams extend parallel to each other (Figures, 6.2, 6.3, 6.4, 6.5, 6.6 and 6.34). This pattern appears in the Western Desert valleys where ephemeral rivers enter the Euphrates river valley near Qaiam town (Figures 6.4, 6.6 and 6.34). It is also formed in the south east near Rutba town. Here the drainage takes the form of parallel streams that appear to be controlled by the rock structure and the tectonic situation (see figure 6.2 and 6.3). For example the Abu mintar and Ghadf main valley system have the same orientation as the outcrop of the Fatha and Hartha formations respectively Excellent examples of parallel streams are the Al Walaj, Swab valleys and the valleys in the north of Al Rutba that end in Garaa depression.



No	Title of Figures
6.1	Parallel Drainage pattern
6.2	Parallel Drainage pattern
6.3	Centripetal Drainage pattern
6.4	Dendritic Drainage pattern
6.5	Dry valleys in study area
6.9	Houran valley basin
6.11	Al Qaiam valley
6.13	Ratga valley basin
6.15	Al Manai valley basin
6.17	Al Manai valley cross section
6.18	Al Manai valley cross section
6.20	Watershed for the AL Manai
6.21	Stream order in the AL Manai
6.22	Al Manai valley featuers
6.23	Endoreic valley system
6.24	Al Agrai valley basin
6.26	Al Agrai valley cross section
6.27	Al Agrai valley cross section
6.28	Al Agrai valley features

Figure 6.1: Location figures in Chapter 6 in Iraqi Western Desert

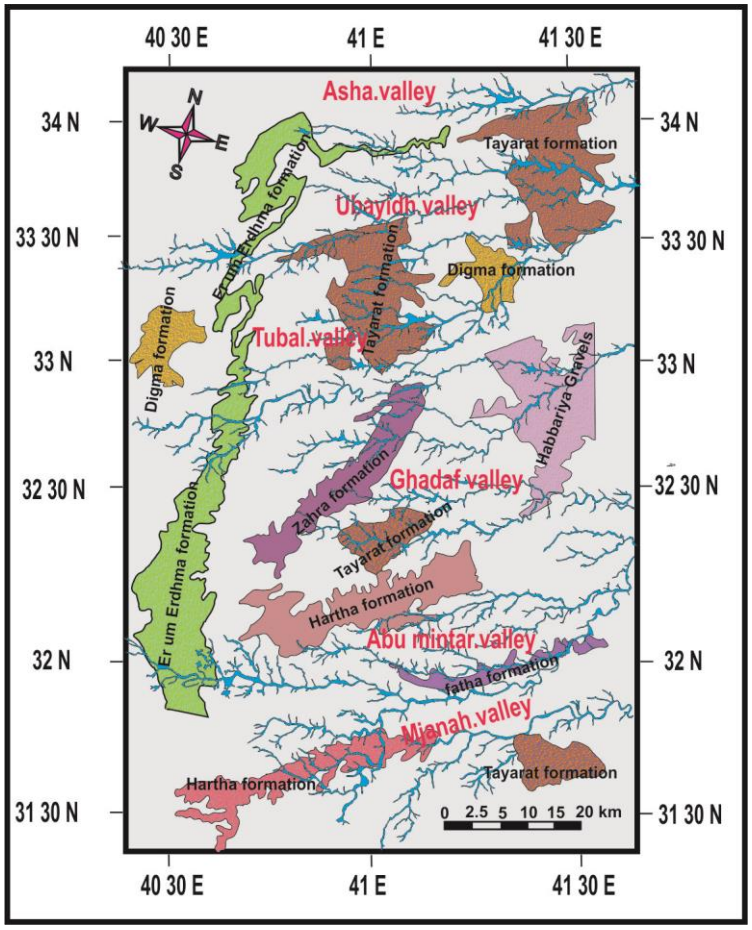


Figure 6.2: Parallel Drainage Pattern In Iraqi Western Desert

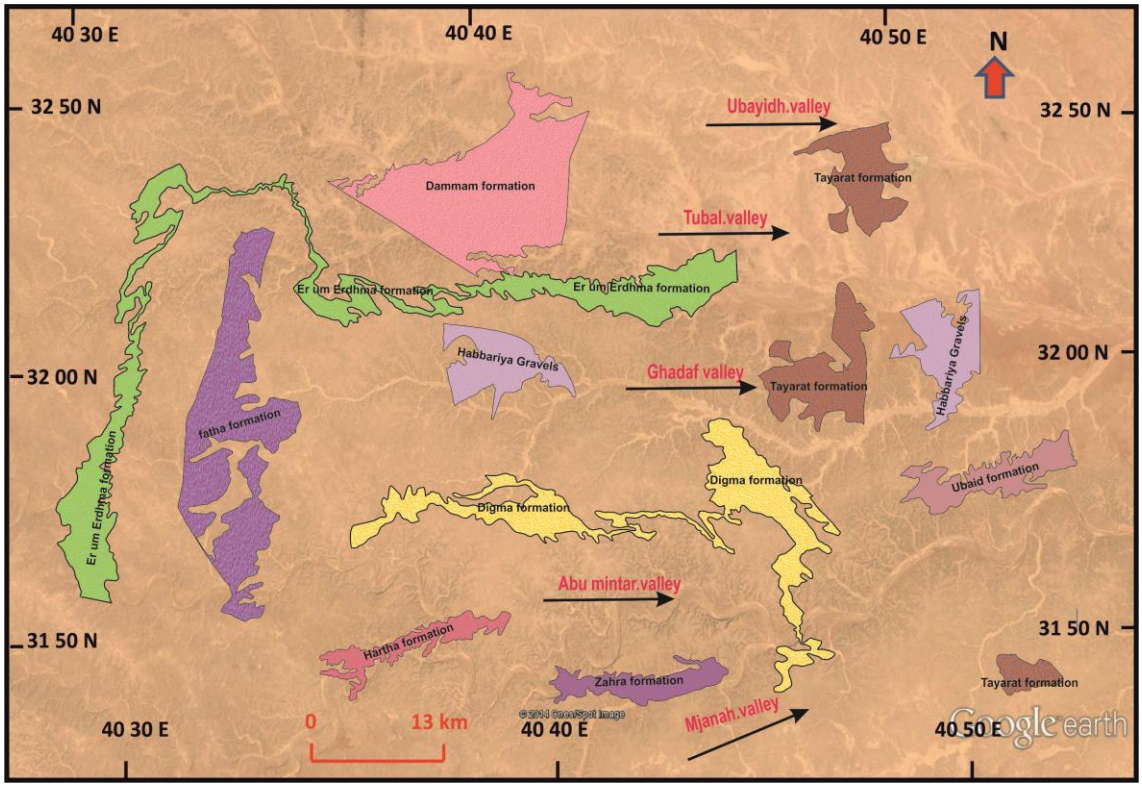


Figure 6.3: Parallel Drainge Pattern in Iraqi Western Desert (Google Earth images)

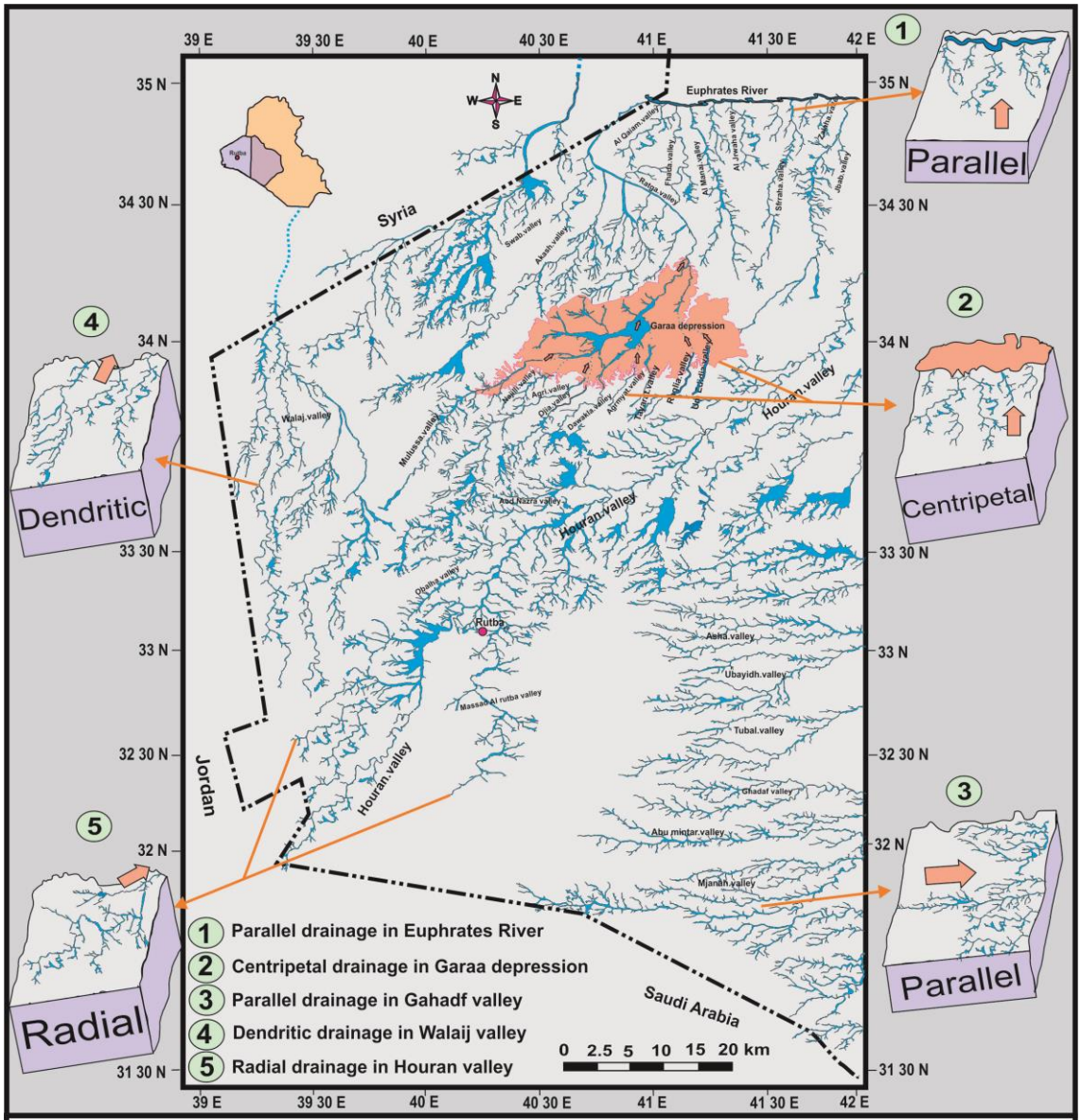


Figure 6.4: Patterns drainage for dry valleys in Iraqi Western Desert

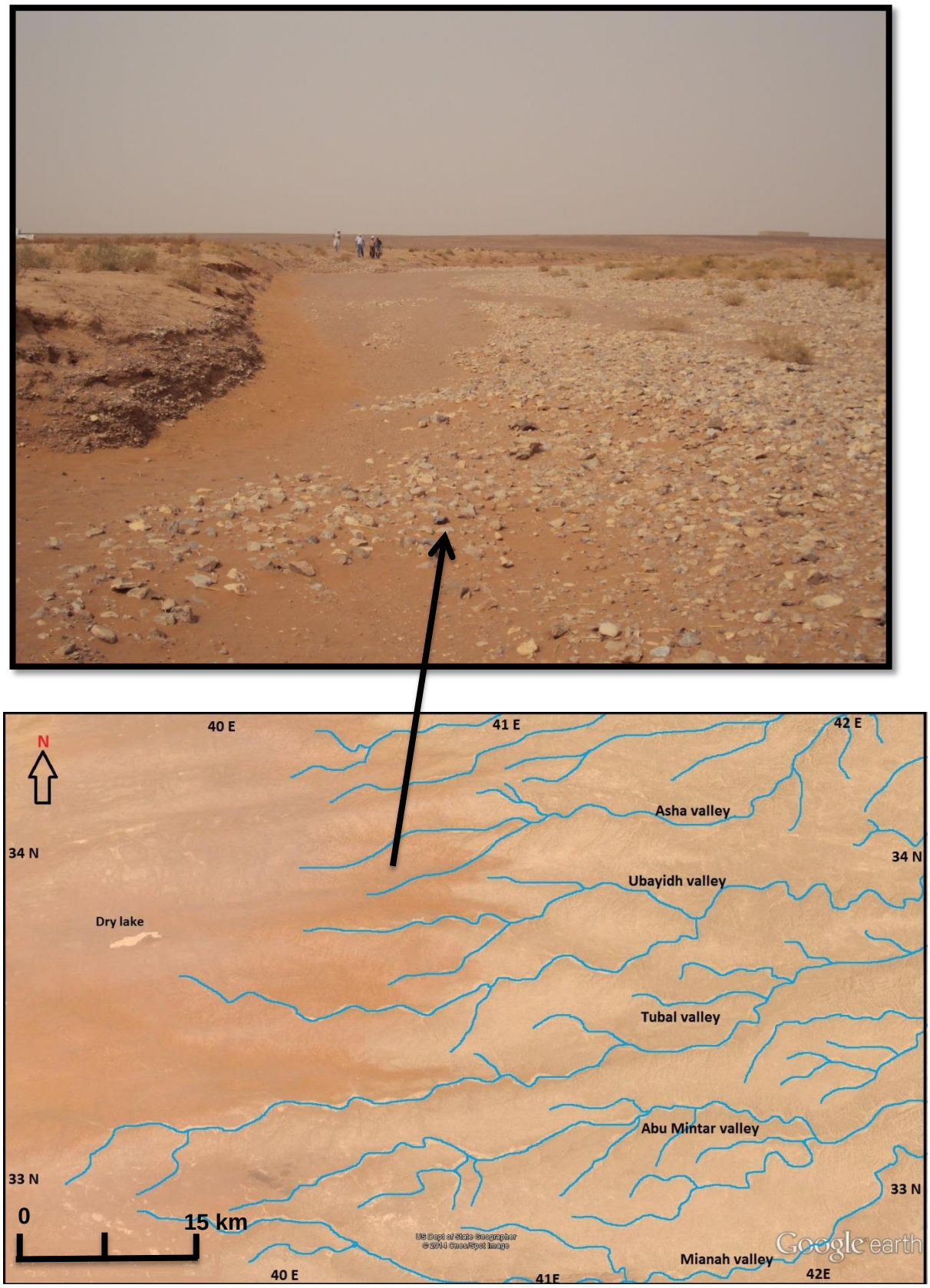


Figure 6.5: Parallel Drainage Pattern South east Rutba area in Iraqi Western Desert (for a general location map see figure 6.1) (Google Earth images).

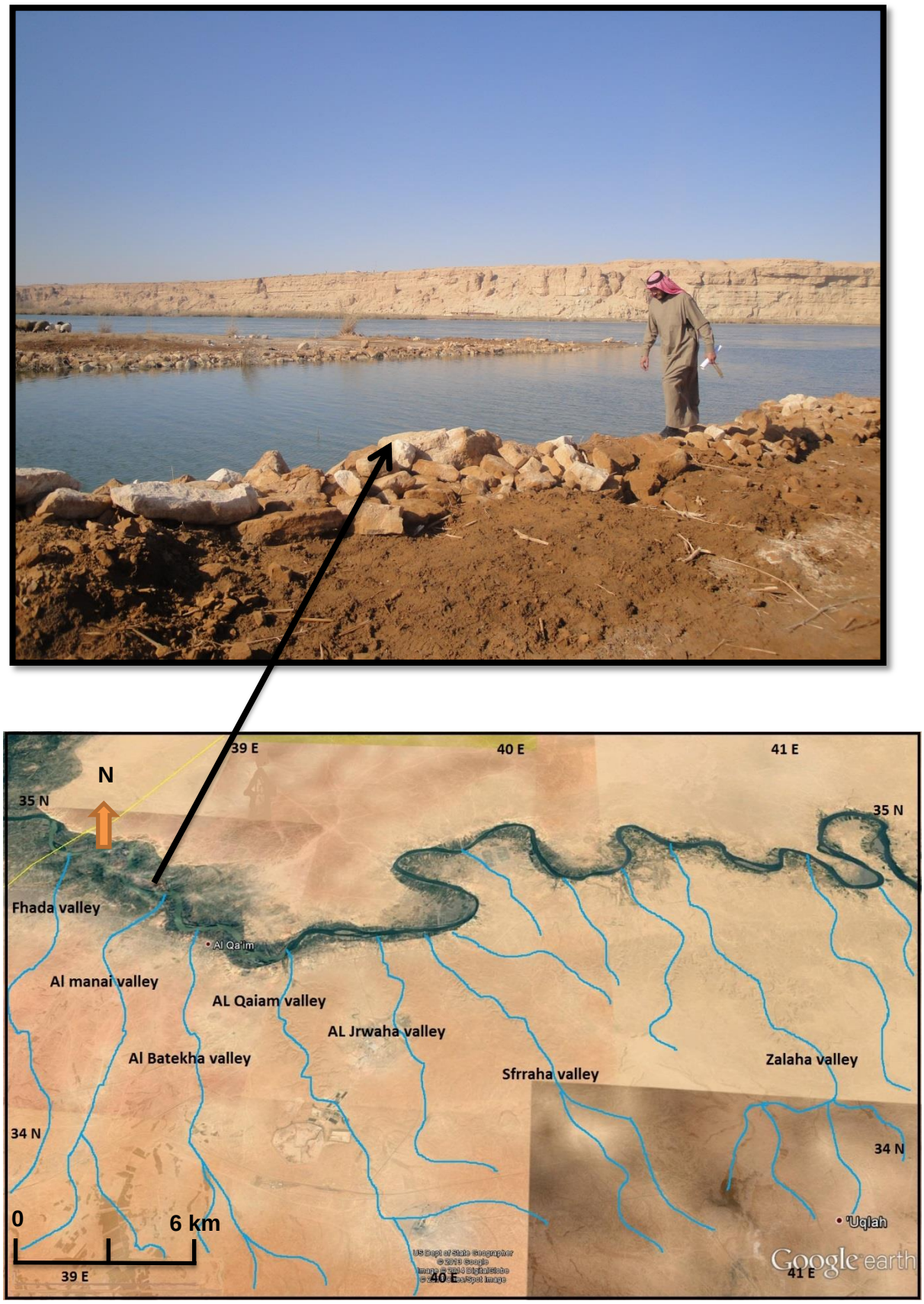


Figure 6.6: Parallel Drainage pattern in Al Qaiam Area near Euphrates River (for a general location map see figure 6.1) (Google Earth images).

6.2.2 Centripetal Drainage pattern

Centripetal drainage is formed in the Iraqi Western Desert notably around ephemeral lakes such as the dry lake in Garaa depression (Azmat Garaa) (figures 6.4, 6.7 and 6.34) where these ephemeral rivers drain from the surrounding highest plateaux and hills into the central depression (these rivers flow maybe I year in 20). Although there is actually one outlet to the northeast of the depression but essentially this is predominantly is a centripetal system.

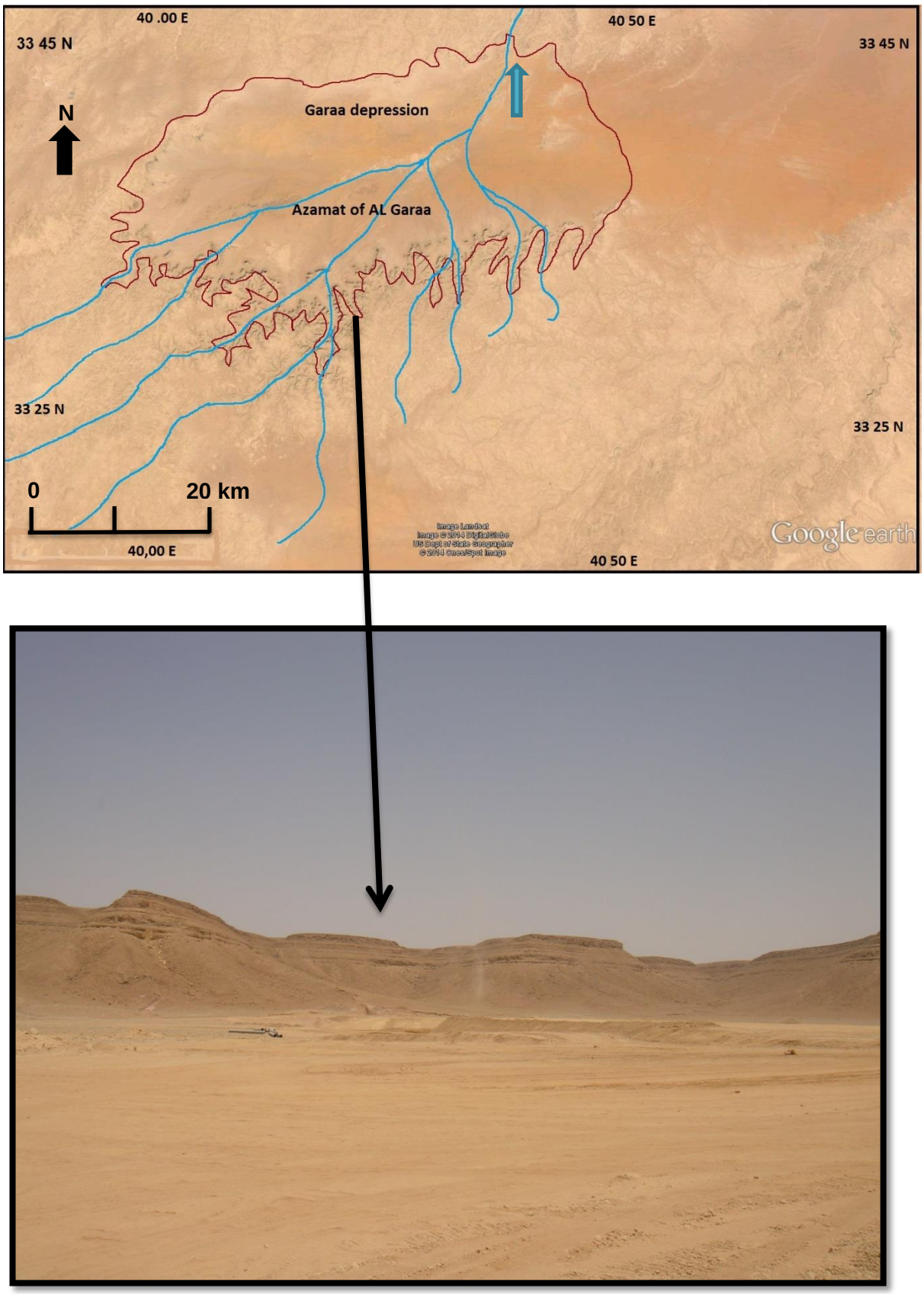


Figure 6.7: Centripetal Drainage pattern (for a general location map see figure 6.1) (Google Earth image).

6.2.3 Radial Drainage pattern

This pattern is a reverse of the centripetal drainage pattern and consists of river streams radiating away from a central point. It is formed in the study area on the remains of higher level abraded erosion surfaces. In the study area this drainage pattern is formed in some valleys south west of Al Rutba (figures 6.4 and 6.34).

6.2.4 Dendritic Drainage pattern

The drainage pattern of most dry valleys in the Western Desert is dendritic. This is because of the relatively homogenous bedrock strata. Streams with dendritic drainage in the Western Desert typically have an average slope of 1m/2km.This pattern consists of tributaries that form a network similar to tree branches. Examples in the area include the Al Walaje and Sawab valleys (figure 6.8) and these valleys are characterized by bedrock comprising sandstone, and claystone, with rare gypsum and phosphorite. The average slope of the rivers in the Al Walaije valley is 2m/km. This drainage pattern is also found in some valleys in the west Rutba area, (figures 6.4, 6.8 and 6.34).

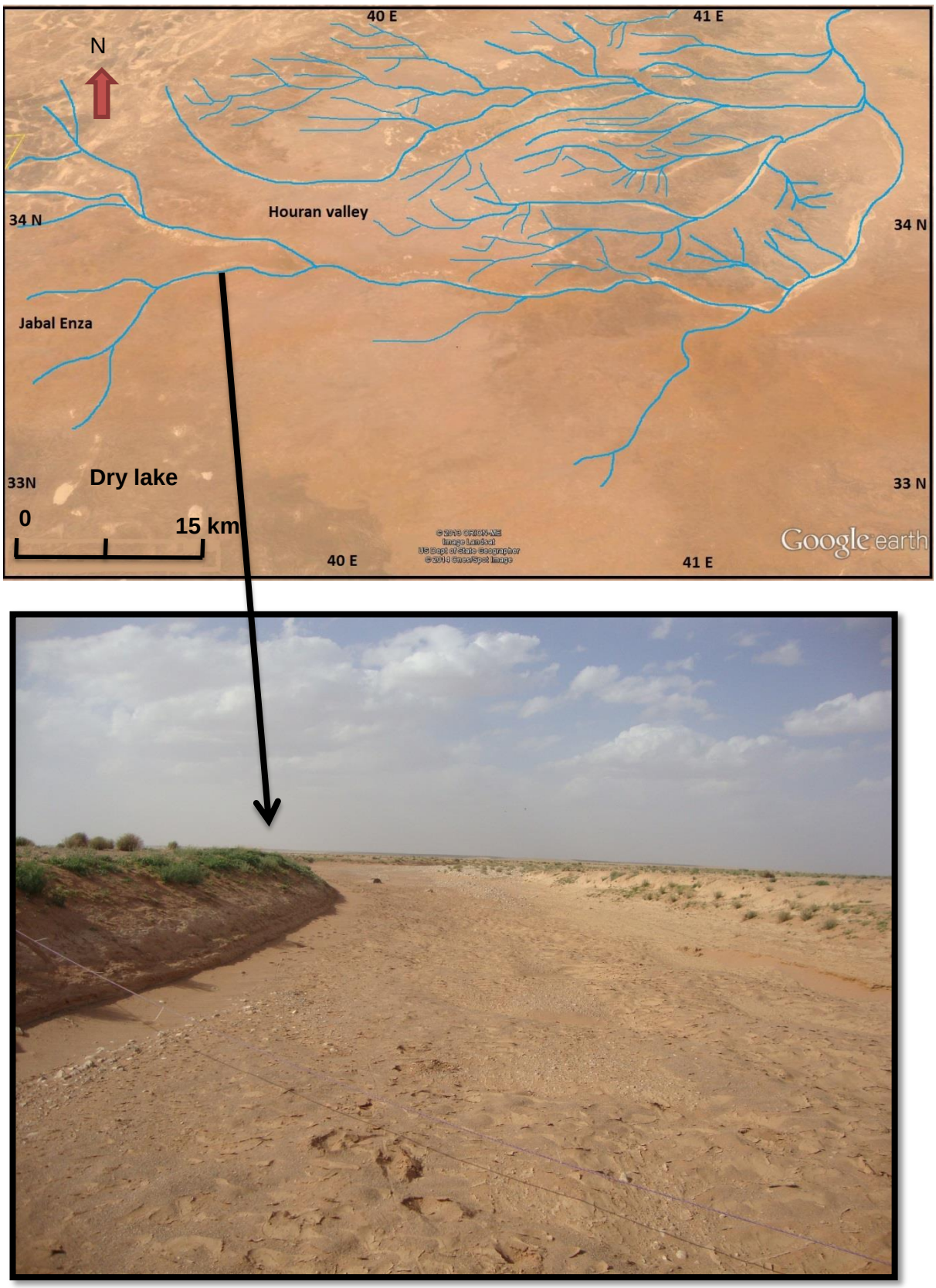


Figure 6.8: Dendritic Drainage pattern near Iraq, Jordan and Saudi Arabia borders (for a general location map see figure 6.1) (Google Earth images).

6.3 Morphometric Analysis of dry valleys

Morphometric quantitative geomorphological studies (see Strahler, 1952 and Horton 1945) of the river basins were carried out as part of this research. In the study area there is a network of seasonally flowing (annual flow) ephemeral streams in valleys which end in the valley of the perennial Euphrates River which flows in to the Arabian Gulf. These ephemeral stream valleys take different directions according to the surface slope but the general drainage pattern is parallel, sometimes dendritic. These valleys are most likely to have formed during wetter periods that prevailed in the desert in the Arabian Peninsula during periods in the Pleistocene where the rainfall was sufficient to result in perennial and high flows in streams causing significant fluvial erosion (Hamza, 2007). The difference in the surface geology resulted in different valley cross-section forms (Al Kubasi, 1993). For example Figures 6.9 is a long section of Manai valley and figure 6.10 the Houran valley. Figure 6.10 show the geological formations in Houran valley stream these are Dammam, Umm Er Radhuma, Rutba and Massad, Mulussa, Tyarat, Euphrrates and Houran gravels formations. In each case an area of harder rock (e.g the Massad and Rutba formations) can be identified on the long section as ‘steps’ or ‘knick points’. Some deep valleys are characterized by steep side slopes sides such as the Houran, Alwalj, Alratga and Al manai valleys. Others are characterized by their broader width and flatter slope sides such as the Al Aghry valley. For this research the morphometry of the Al Manai valley as a model of exoreic drainage and Al Aghry as a model of endoreic drainage pattern were analysed in detail. However, the overall conclusion is that there is a network of dry valleys containing ephemeral stream in the study area which are obviously misfits as the area is now characterized by a dry desert climate.

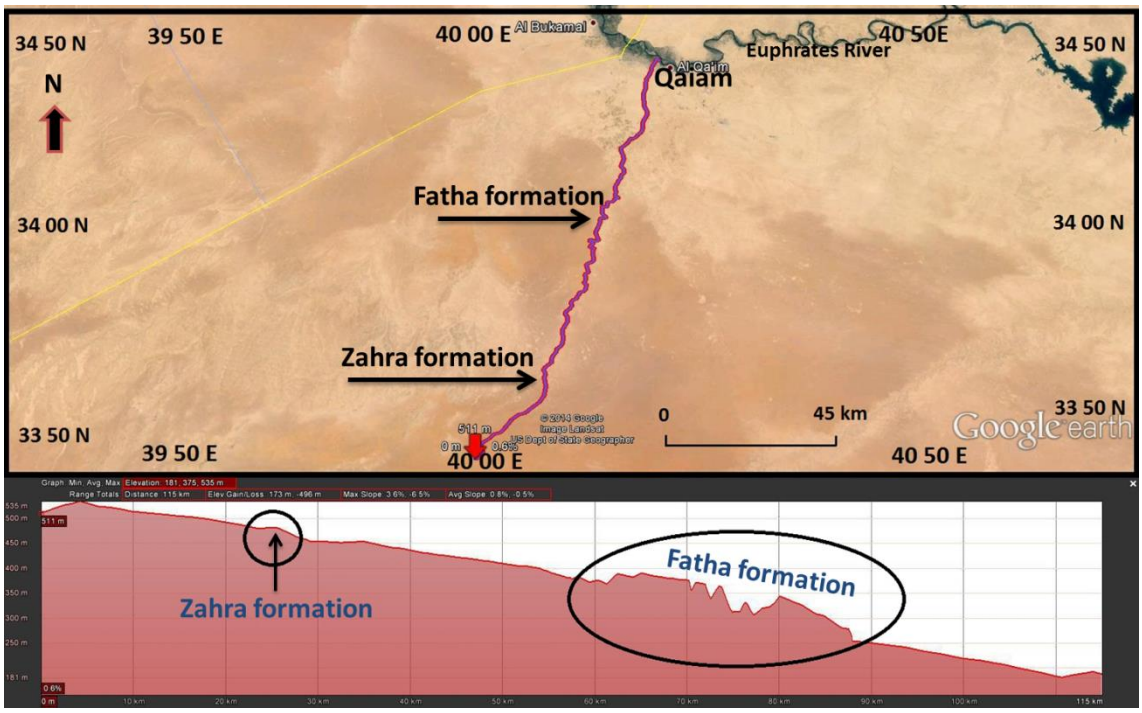


Figure 6.9: show the bedrock geology affect in the Manai valley long section.

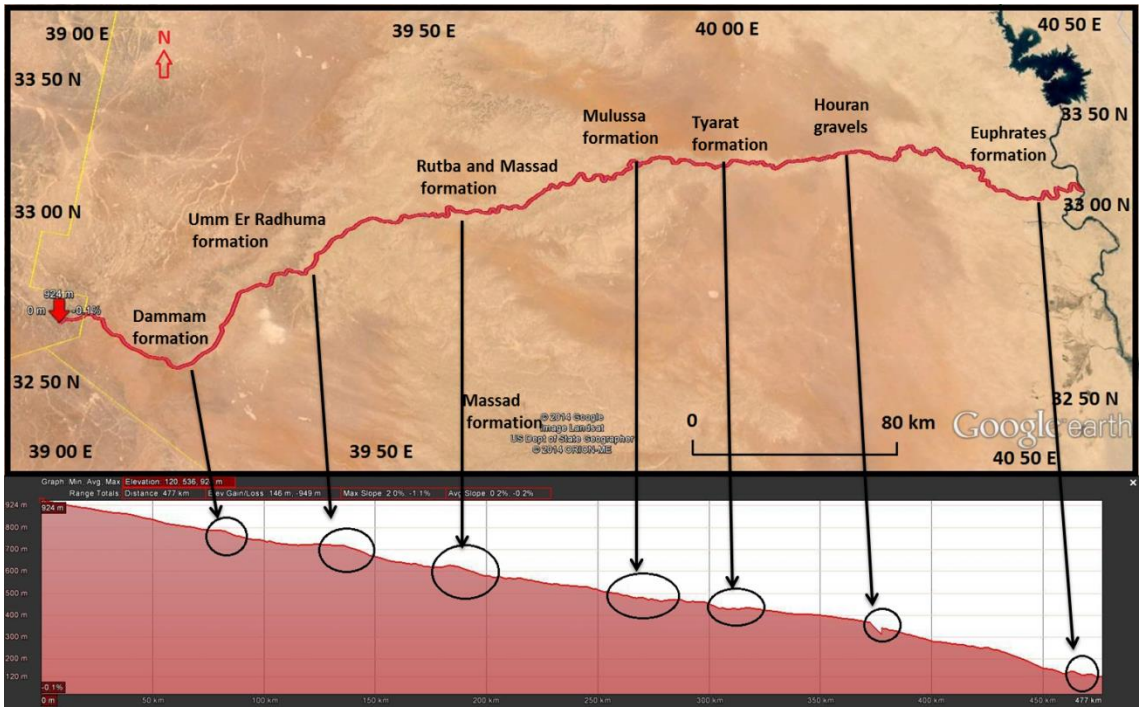


Figure 6.10: show the bedrock geology affect in the Houran valley long section.

6.4 Valley systems that feed into the exogenic drainage

These ephemeral rivers flow into the exogenic Euphrates River, which represents the local base level. Most of these valleys start from the higher land in the south west (figure 6.11) and their catchments extend into Syria, Jordan, and Saudi Arabia. Many of these valleys are characterized by their clearly defined dendritic drainage pattern (Buday, and Hak, 1980). The most important of these valleys are show in figure 6.36 and are discussed below. A summary of some of their morphometric characteristics are presented in Tables 6.1, 6.2, 6.3 and 6.4. Their topographic stream ordering and morphometric data help provide information to support watershed development and management plans. In all desert areas these are critical to ensure maximum use of limited water resources can be properly planned (Sreedwvi et al, 2005). For this study analyses were undertaken to determine the drainage characteristics of dry valleys using the topographic data compiled in the GIS (Chapter 3) and the images collected in Google Earth Pro (Chapter3).

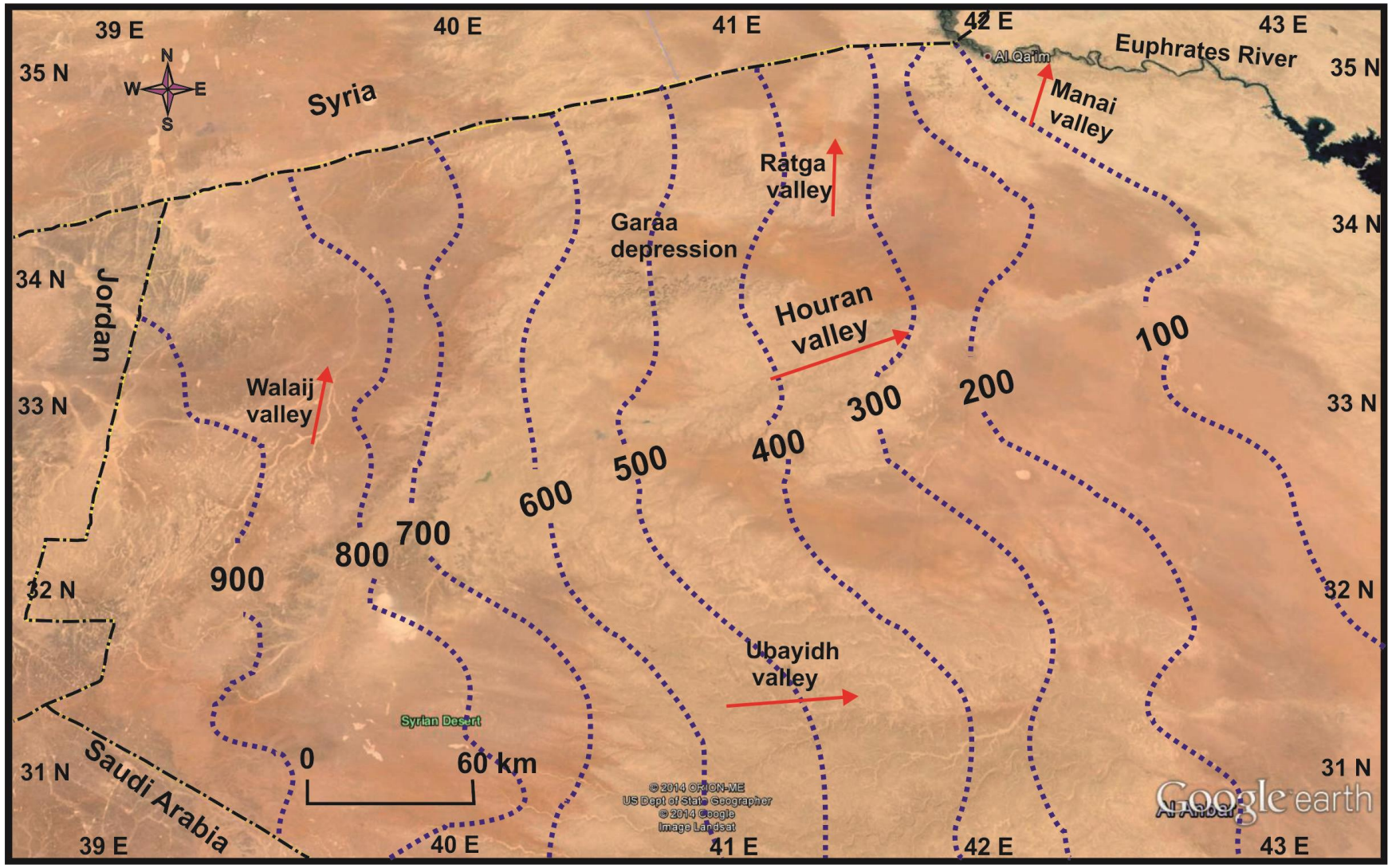


Figure 6.11: Directions for some dry valleys with contour lines in Iraqi Western Desert by Google Earth (for a general location map see figure 6.1) (Google Earth images).

Table 6.1: Topographic characteristics for the endogenic ephemeral stream valleys in Iraqi Western Desert obtained from an analysis of data held in the GIS and Google Earth Pro.

Basin name	Area km^2	Contour line highest	Contour line lowest	Main stream km	Slope M/km
Houran valley	20 000	915	140	482	1.6
Qaiam valley	1196	389	180	81	2.5
Ratga valley	4775	510	232	124	2.2
Manai valley	3457	530	188	101	3.3
Walaij valley	3110	872	665	181	1.1
Swab valley	4890	712	208	223	2.2
Akash valley	2259	643	275	126	2.9
Jbab valley	956	373	183	64	2.9
Fhada valley	340	352	201	43	3.5

Table 6.2: Valley ranking for the exogenous dry valleys in the Western Desert

Valleys streams number / Basin name	Ranked valleys number 1	Ranked valleys number 2	Ranked valleys number 3	Ranked valleys number 4	Ranked valleys number 5	Ranked valleys number 6	Ranked valleys number 7	Ranked valleys number 8
Houran valley	8565	2486	1352	130	80	12	3	1
Qaiam valley	235	103	14	4	1	0	0	0
Ratga valley	4960	1937	279	10	1	0	0	0
Manai valley	959	376	45	8	1	0	0	0
Walaij valley	4587	436	84	23	2	1	0	0
Swab valley	4191	1440	167	35	3	1	0	0
Akash valley	607	76	14	4	1	0	0	0
Jbab valley	529	205	31	9	1	0	0	0
Fhada valley	177	67	7	1	0	0	0	0

Table 6.3: Average values of terrain ratio, roughness and drainage density for the endogenic ephemeral stream valleys in Iraqi Western Desert. Terrain ratio average: difference between highest and lowest point in the basin/basin length km (From the lowest point of exit and the furthest part of the watershed), Roughness value: Relative relief = Total elevation/Basin circumference X 10. Drainage density: This is divided in two types. 1) Length density (km / km) = Number of valleys in basin / the length of the basin. 2) Numerical density (valley / km2) = Number of valleys in basin / the area of the basin.

Basin name	Terrain ratio average	Roughness value	Drainage density	
			Length density km/km	Numerical density Valley/km^2
Houran valley	1.6	0.003	26.2	0.6
Qaiam valley	2.5	0.030	4.4	0.2
Ratga valley	2.2	0.017	58.4	1.5
Manai valley	3.3	0.026	11	0.4
Walaij valley	1.6	0.008	28.4	1.6
Swab valley	2.2	0.009	26.2	1.1
Akash valley	2.1	0.016	5.5	0.3
Jbab valley	1	0.02	12.1	0.8
Fhada valey	3.5	0.081	5.8	0.7

Table 6.4: Deflection coefficient for the endogenic ephemeral stream valleys of the study area. Real length km = length of the valley from its source to its estuary. Ideal length km = the shortest distance between the upstream and downstream. Deflection coefficient = real Length km / ideal length km

Basin name	Real Length km	Ideal length km	Deflection coefficient
Houran valley	482	368	1.3
Qaiam valley	81	66	1.2
Ratga valley	124	95	1.3
Manai valley	126	102	1.2
Walaij valley	181	152	1.1
Swab valley	223	188	1.1
Akash valley	126	103	1.2
Jbab valley	64	50	1.2
Fhada valley	43	35	1.2

Reviewing Tables 6.2, 6.3 and 6.4 some observation can be made:

- Only the Houran valley has eight levels of stream order, with 8565 first order stream being identified
- Despite its size the Houran valley has a high length density of 26.2 km / kmThe highest length density is in the Ratga valley at 58.4 km / km

  Not surprising the smallest investigated catchment, Fhada valley, has the highest terrain ratio average of 3.5 m /km
- The Al Manai valley, at 3457 km2, has a high average terrain ratio of 3.3 m /km
- The lowest length density is in the Akash and Fhada valleys at 5.5 km / km and 5.8 km / km respectively
- Despite its size the 4890 km2 Swab valley has a high length density of 26.2 km / km

  Table 6.4 presents the relationship between the real length and ideal length giving the deflection coefficient (definition provide in the table 6.4)

  The Houran valley has high the highest deflection coefficient in the study area at 1.3

  The deflection coefficient average between 1.1 and 1.3 in all the catchments in the study area. This indicates there is a similarity in shape in the catchments.

6.4.1 Houran valley network

This is the largest of the valleys basins in the Iraqi Western Desert with a catchment area of over 20,000 km^2. The catchment extends from the borders with Jordan and Saudi Arabia in the south-west of Iraq down to the Euphrates River in the north east part of the study area (Shaker, 2000). The Houran valley appear to contain 12563 identifiable tributaries, it has a length of 482 km and is up to 93 km in width. Flow depths have been recorded as between 10 to 15 metres at Al Husanyat area east the Garaa depression (Shaker, 2000). The valley starts in the Jabil Anza area (Figure 6.12), which lies at a height of 915 metres above sea level. The river flows northeast and ends at the Euphrates River, to the northwest of Heet town (Figure 6.12). The long section along the main stream of the Houran valley is presented in figure 6.13. Its annual average drainage volume has been measured over the period 1993 to 2002 as 5,615 billion cubic metres (Shaker, 2000).

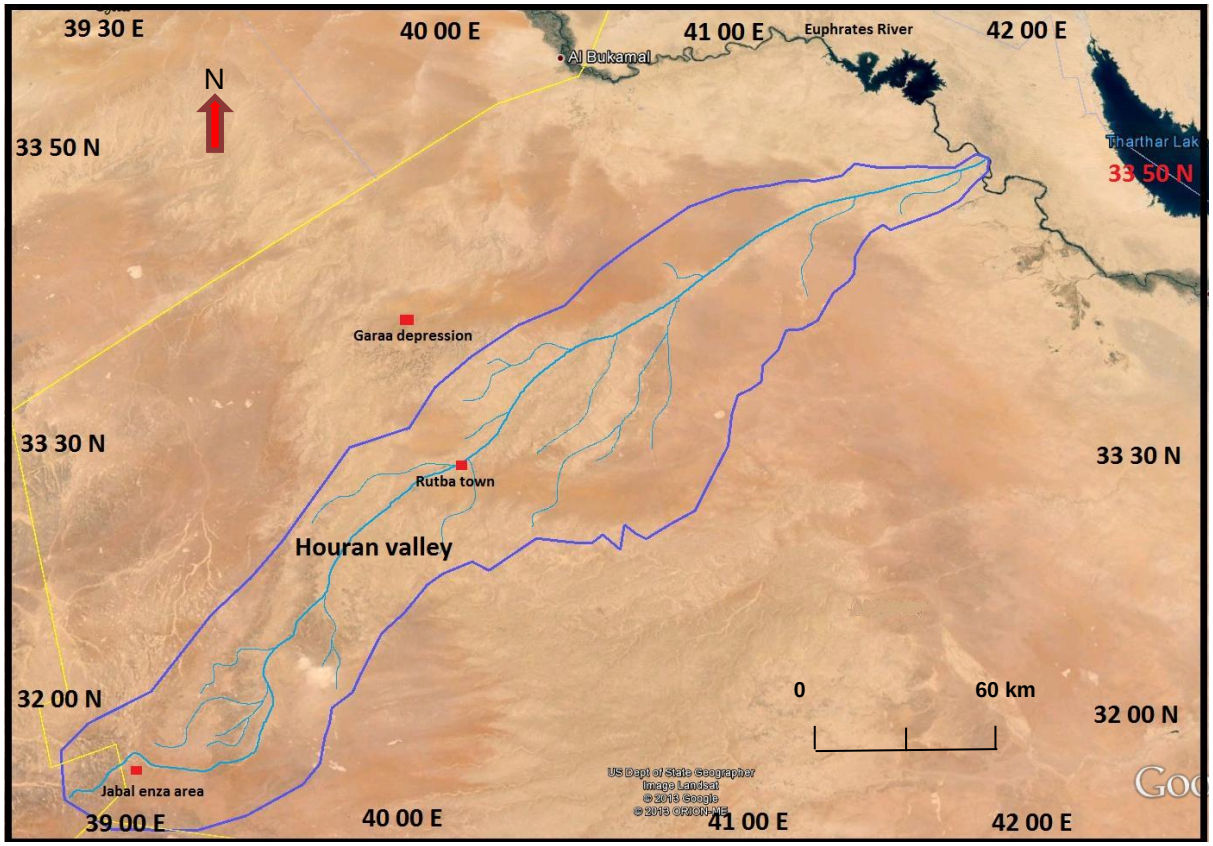


Figure 6.12: Houran valley basin (for a general location map see figure 6.1) (Google Earth images).

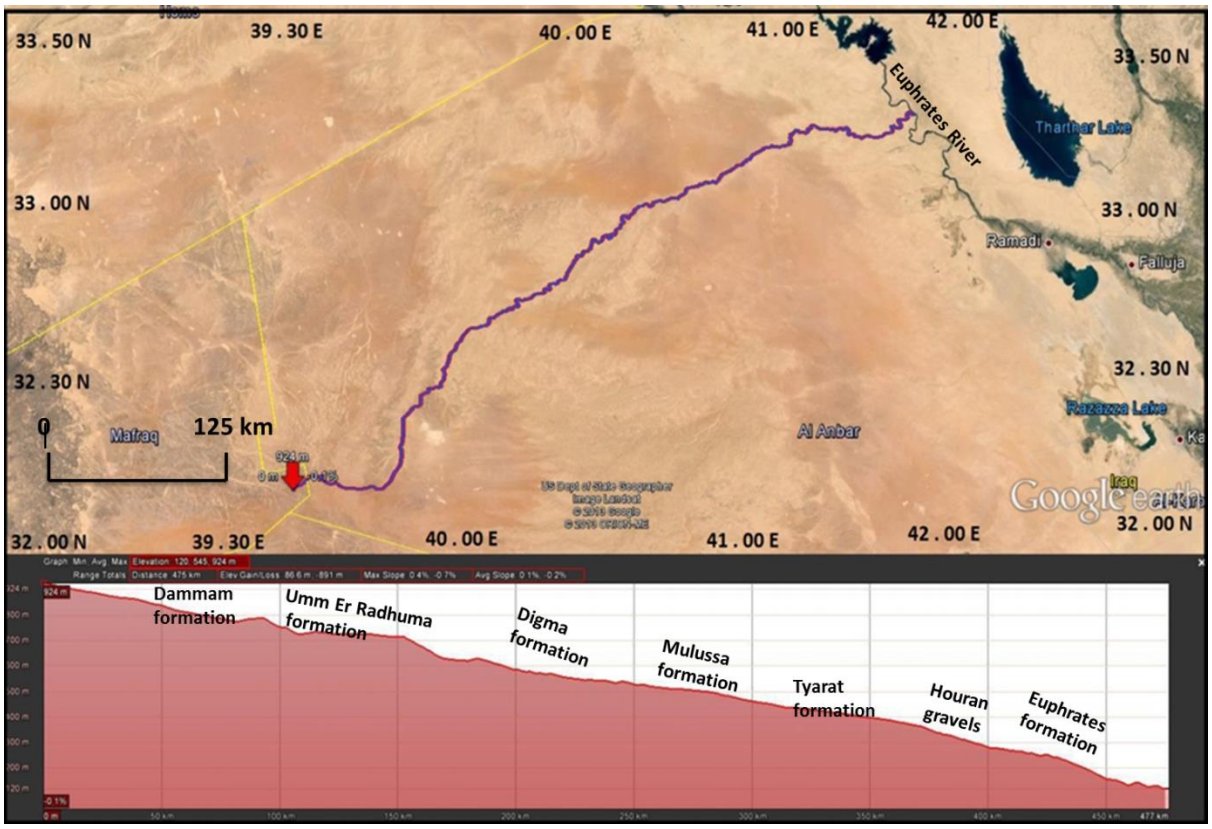


Figure 6.13: Houran valley length long section (for a general location map see figure 6.1) (Google Earth images).

6.4.2 Al Qaiam valley network

The Al Qaiam valley network is made up of main four streams in the north west of the Western Desert that flow into the River of Euphrates by the town of Al Qaiam (figure 6.14). This valley network is located between the Ratga and Al manai valleys system (Shaker, 1993). The Al Qaiam valley network has an average length of approximately 42.6 km and a catchment area of 322 km^2. The long section along the main valley is shown in figure 6.15. This shows the Qaiam valley stream pass through five geological formations these are Ratga, Ghar, Fatha, Euphrates formation, and the Euphrates River Terraces.

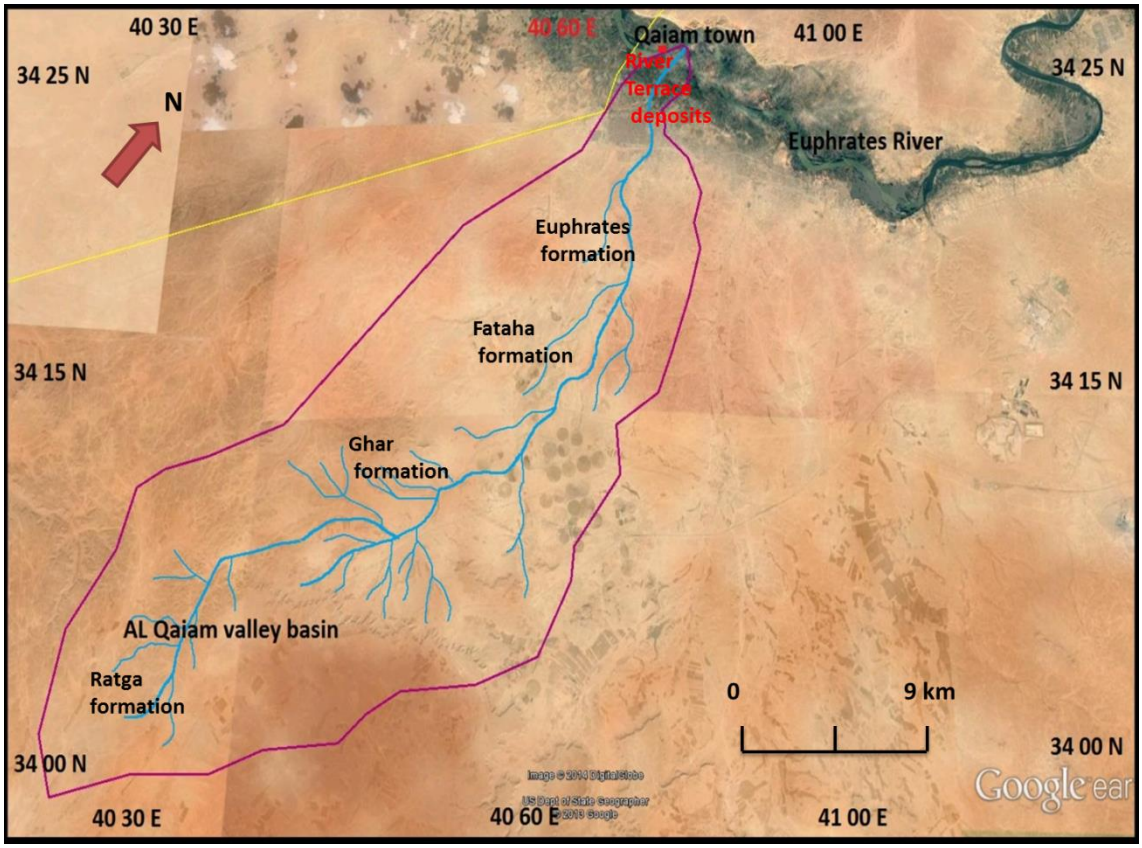


Figure 6.14: Al Qaiam valley basin (for a general location map see figure 6.1) (Google Earth images).

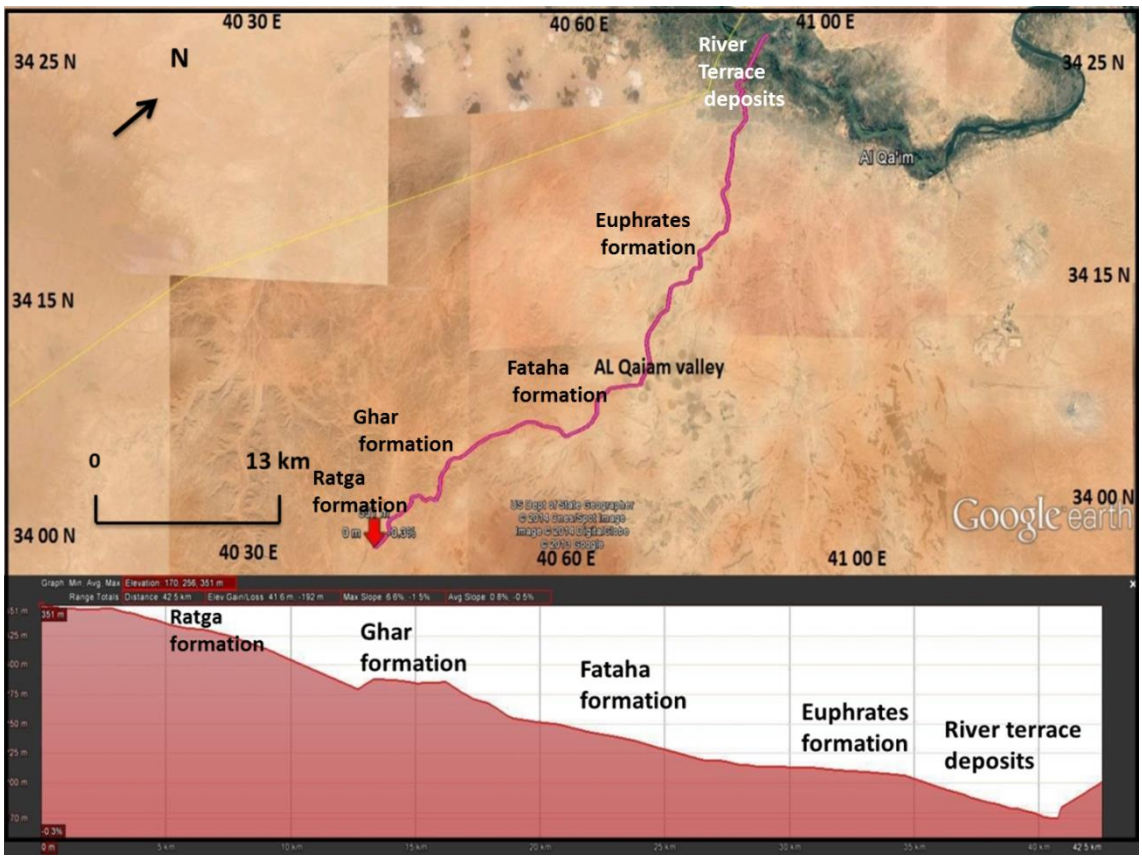
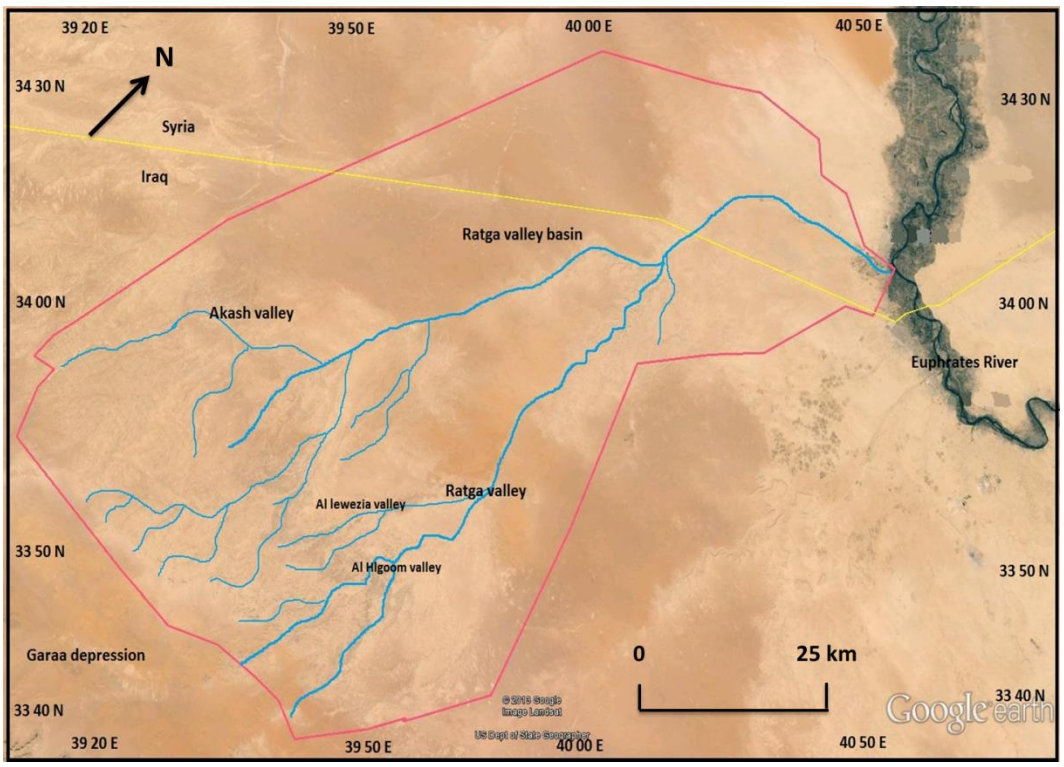


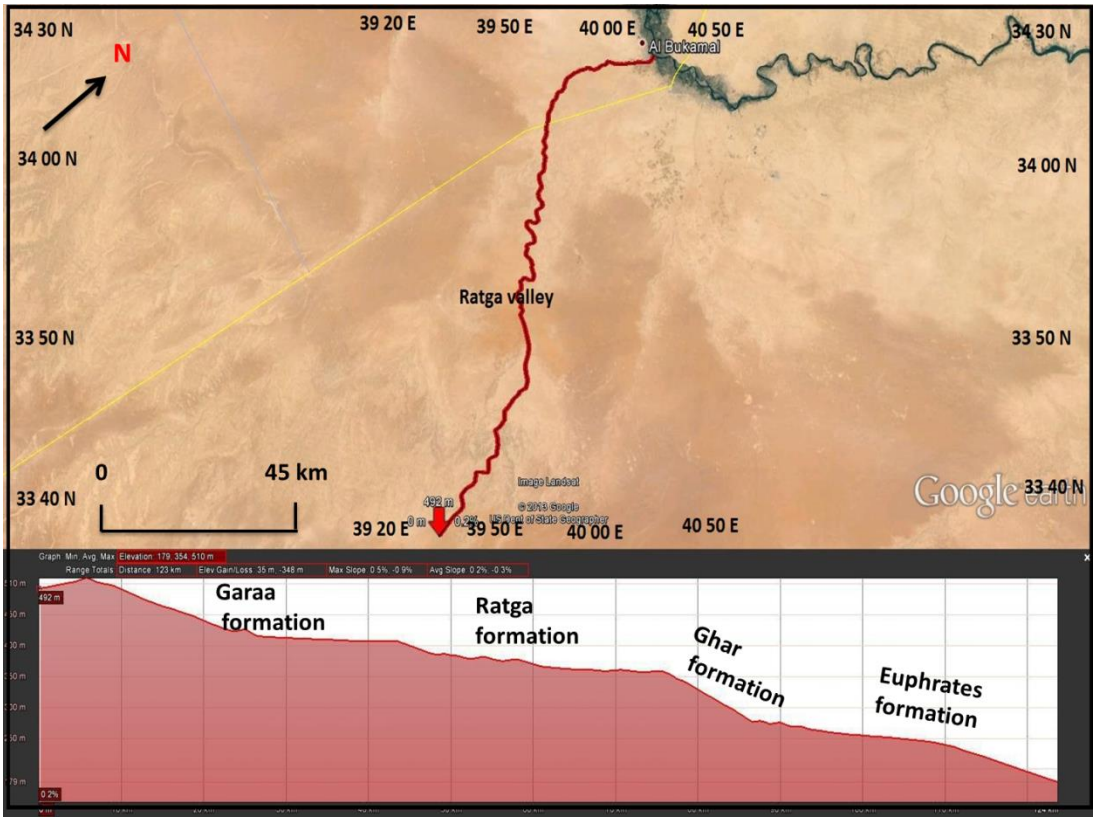
Figure 6.15: Al Qaiam valley length long section (for a general location map see figure 6.1) (Google Earth images).

6.4.3 Al Rataga Valley network

This valley lies to the north of the Garaa depression, and is formed by the confluence of Al Lewezia valley and Al Halgoom valleys (figure 6.16). This valley network is located between the basins of the Al Qaiam valley network and the Akash Valley network. This valley network collects water flowing out of the Garaa depression and runs northwest to join the Euphrates River at Al Bukamal inside Syria (Figure 6.16). The long section of this river is shown in (Figure 6.17).



Figuer 6.16: Al Ratga valley basin (for a general location map see figure 6.1) (Google Earth images).



Figuer 6.17: Al Ratga valley length long section (for a general location map see figure 6.1) (Google Earth images).

The shape of the longitudinal section is influenced by the bedrock, and the long section slope increases in the areas with strong rocks but flattens in the areas with soft rocks. The start of the Ratga valley has a simple with a linear element. But overall the Ratga valley has a steep upper section and convex profile. The steps in the profile are explained by harder rocks associated with the Ghar formation which Al Jumaily (1974) identified as a littoral sandstone facies of the first Miocene sedimentary cycle. Interestingly Al Jumaily (1974) recognized a horizon of conglomerate horizon on the right bank of Ratga valley capping the Ghar formation at Ratga valley in Muger Al Dheeb which Sissakan and Abdul Jabar (2001) considered as river terraces. Both Sissakan and Mohammed (2007) and field observations by the author would support this hypothesis.

6.4.4 Al Manai valleys network

The Al Manai catchment area under study is located in the Iraqi Western Desert between the latitudes 40° 00' to 40° 04' E and longitudes 33° 30' to 34° 23' N (Figure 6. 22). The area is now characterised by a water deficit in all months of the year which is highest in July (deficit of 335 mm) and lowest in January (deficit of 10.6 mm) (Al Khfaji, 2009). The geology is predominatly limestone covered by a thin sandy clay soil and there is very little vegetation.

The Al Manai river system derives water from a network of small ephemeral stream valleys to the northeast of the Garaa depression. The overall length of the Al Manai catchment is approximately 117 km; it has an area of 3,457 km^2 and the average slope along the main valley in 3.3m/ km.

The catchment lies between the catchments associated with the Al Fhada and Al Ratga valleys (Figure 6.18). The Al Manai ends in the exoreic Euphrates River. The long profile of the Al Manai is presented in Figure 6.19 which shows

a relatively linear profile until it reaches the edge of the Euphrates River where there is a significant increase in channel slope down on to the floodplain. The geomorphological features of this area are shown in Figure 6.23.

A stream ordering exercise was undertaken on the identifiable ephemeral stream valley network using the system derived by Strahler (1952). The result of this analysis was presented in table 6.2 which shows that the highest order stream, which enters the Euphrates River, is 5. There are also a high number of 1st order streams (959).

A number of cross-section were constructed for parts of the Al Manai main valley in order to gain a better understanding of the geomorphological development of the drainage network. The results of this phase of the investigation are exemplified by Figures 6.20 and 6.21. In Figure 6.20 the cross - section has been constructed in the lower steeper part of the catchment where the valley is through the Euphrates Formation. Here a typical ‘V’ shaped valley has formed indicating erosion is contemporary and active. In contrast Figure 6.21 is higher up in the catchments in the Fatha formation and the valley is clearly a misfit suggesting that erosion in the upper parts of the Al Manai catchment mainly occurred upper wetter palaeoclimatic conditions.

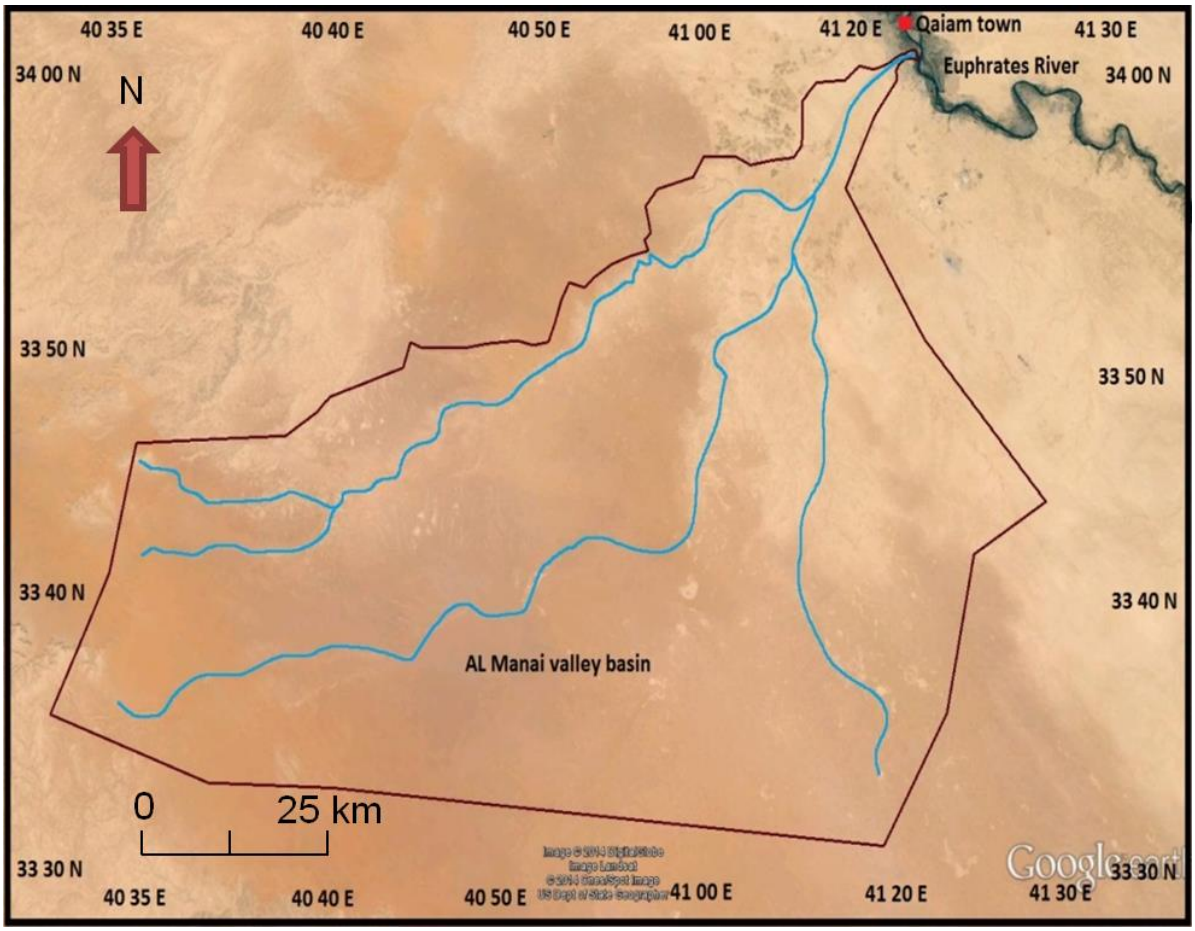
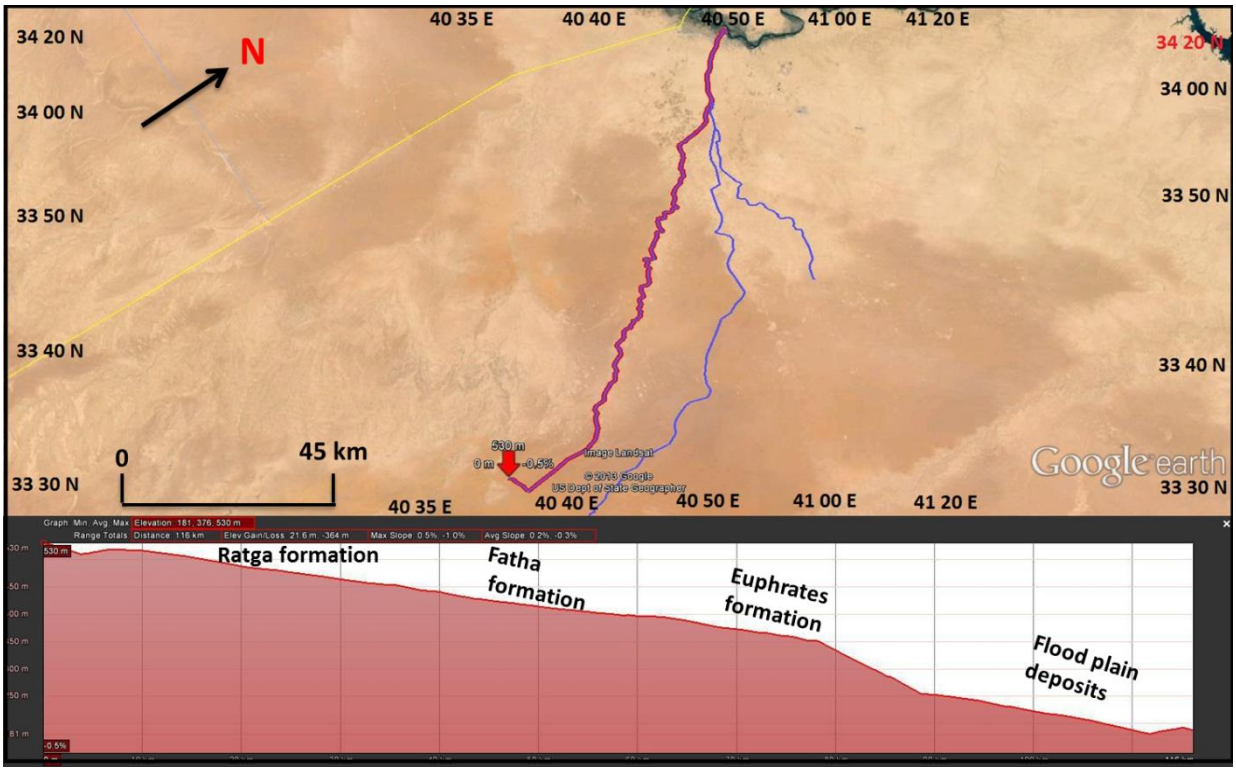


Figure 6.18: Al Manai valley basins (for a general location map see figure 6.1) (Google Earth images).



Figuer 6.19: Al Manai valley length cross section (for a general location map see figure 6.1) (Google Earth images).

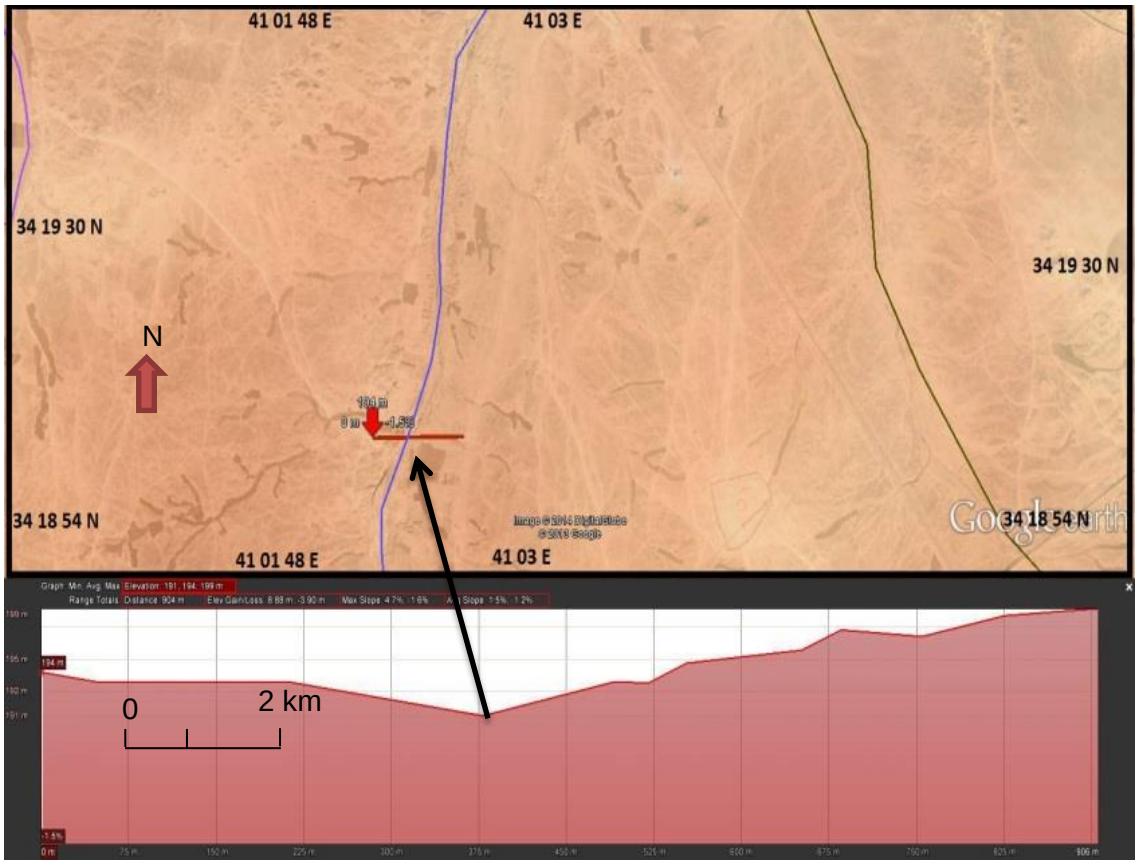


Figure 6.20: Al Manai valley cross section South town of Qaiam (for a general location map see figure 6.1) (Google Earth images).

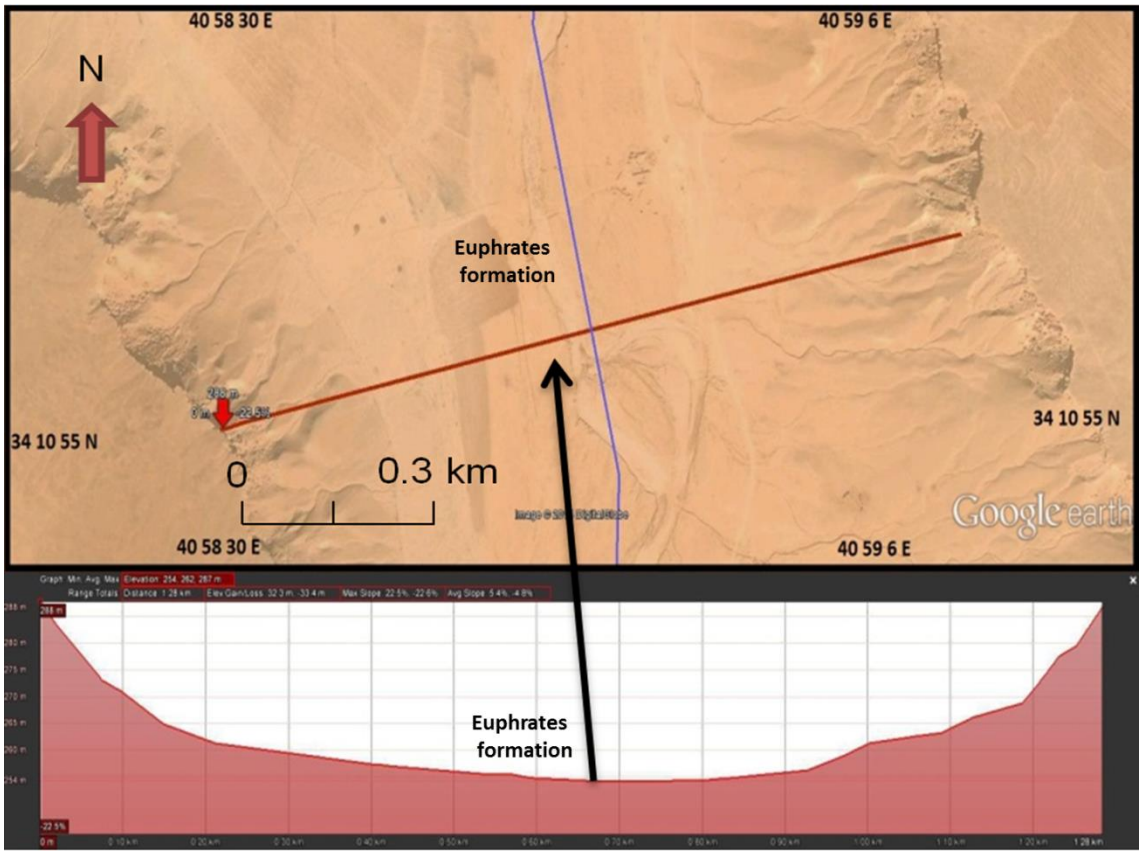


Figure 6.21: Al Manai valley cross section north Garaa depression (for a general location map see figure 6.1) (Google Earth images).

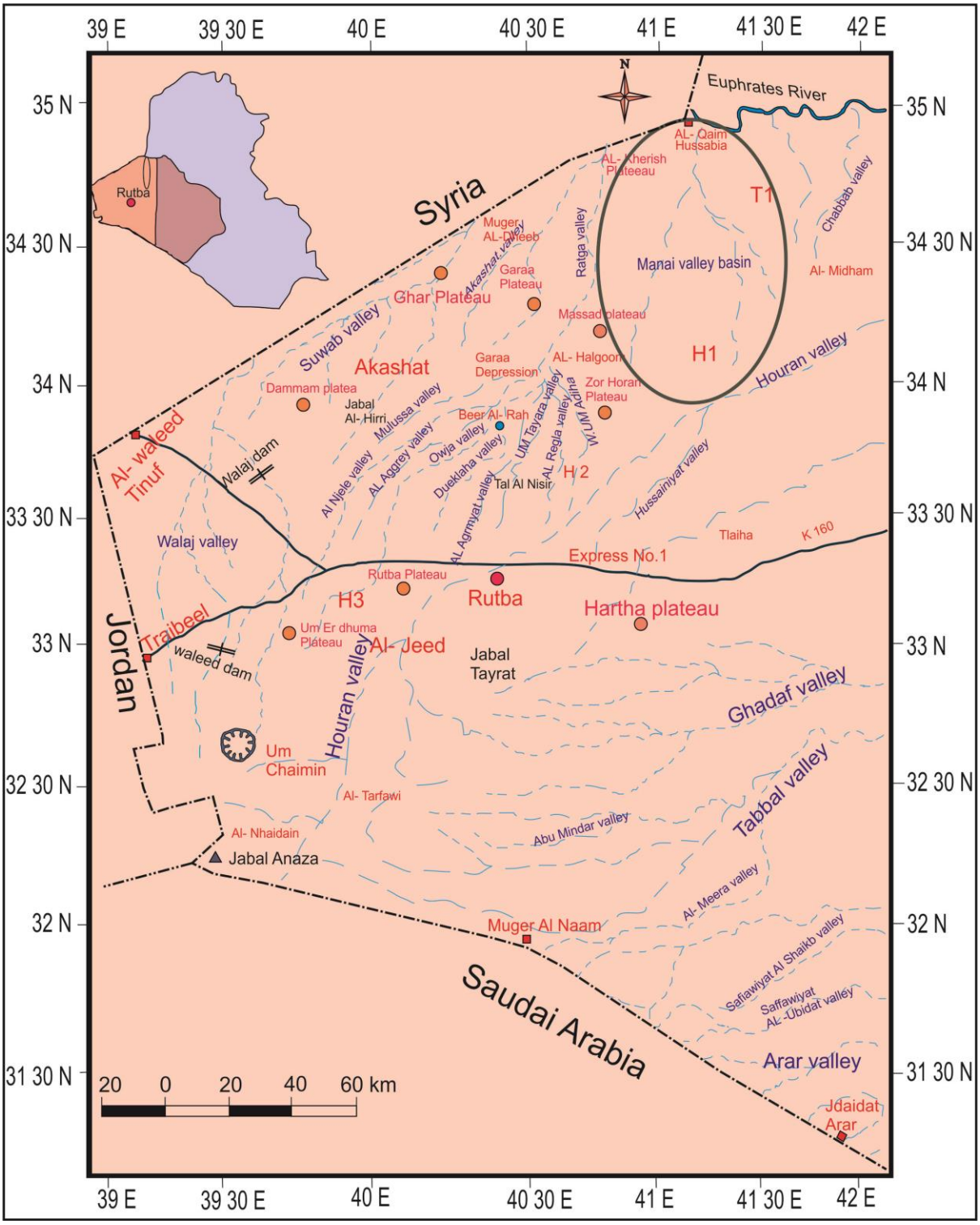


Figure 6.22: Manai valley located in Iraqi Western Desert.

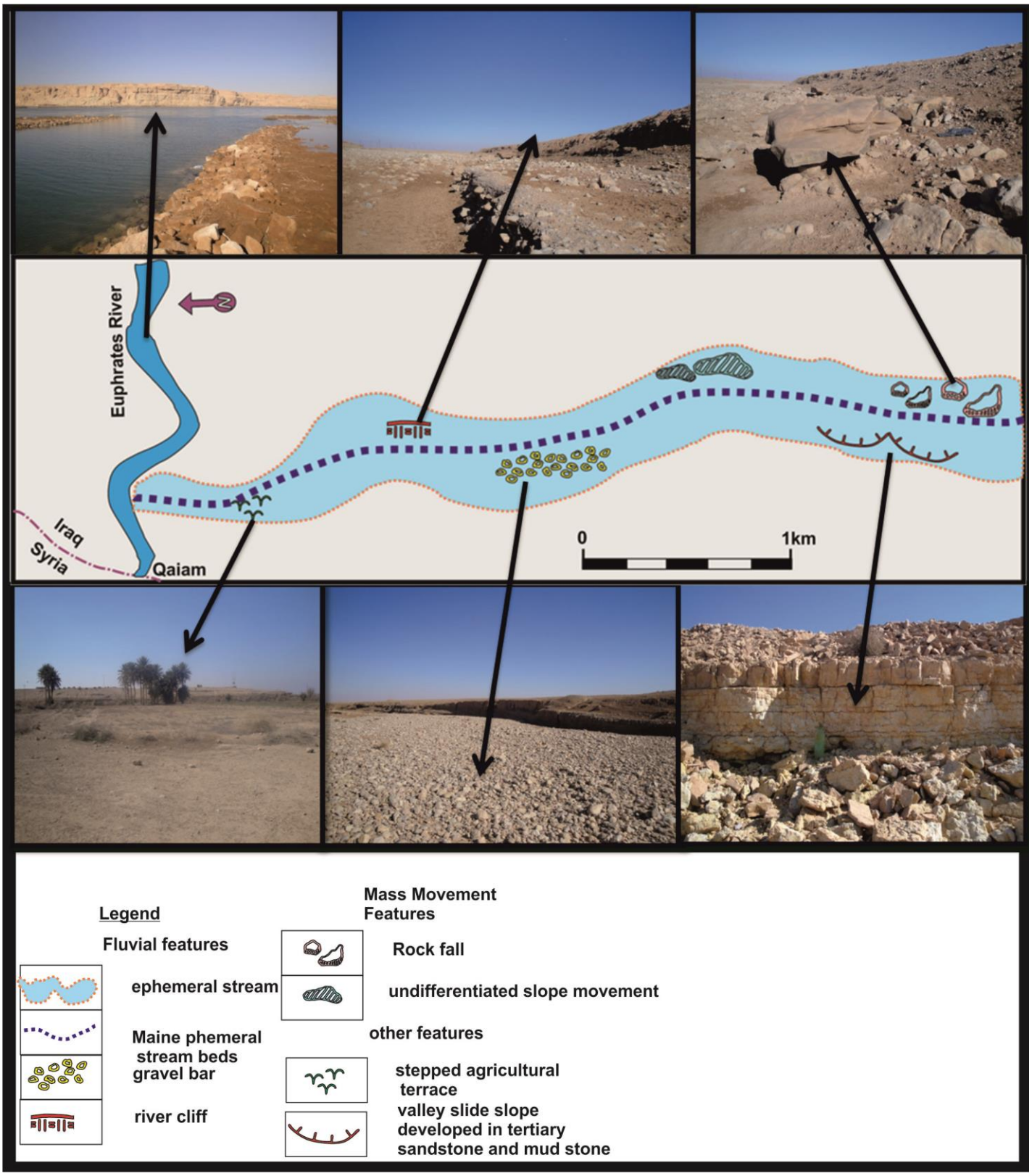


Figure 6.23: Al Manai valley, with geomorphological features shown, close to confluence with the River Euphrates (for a general location map see figure 6.1).

6.5 Endoreic drainage valley system

Whilst the Garaa depression does have an outlet into the Euphrates valley in the north-east, for the streams flowing into the southern limit of the depression this represents the local base level and therefore the drainage is effectively endoreic.

6.5.1 Example of an endoreic valley system into the southern Gaara depression.

The valleys that carry ephemeral streams in to the southern part of the Garaa depression comprise from west to east: Mulusa, Najili, Agri, Ojia, Dwakla, Agrmyat, and Tayrat, Reglia, and Um adia (Figure 6.24). There represent a predominantly internal (endoreic) drainage system with seasonal surface flow. The gross form of the valleys developed during the Quaternary period under wetter climate conditions and the streams now represent misfits under the prevailing desert environment. These valleys display many periods of river erosion and deposition as indicated by the sequence of terraces. For example the cross section in Al Agrai valleys near the Garaa depression shows some of these terraces (Figure 6.29).

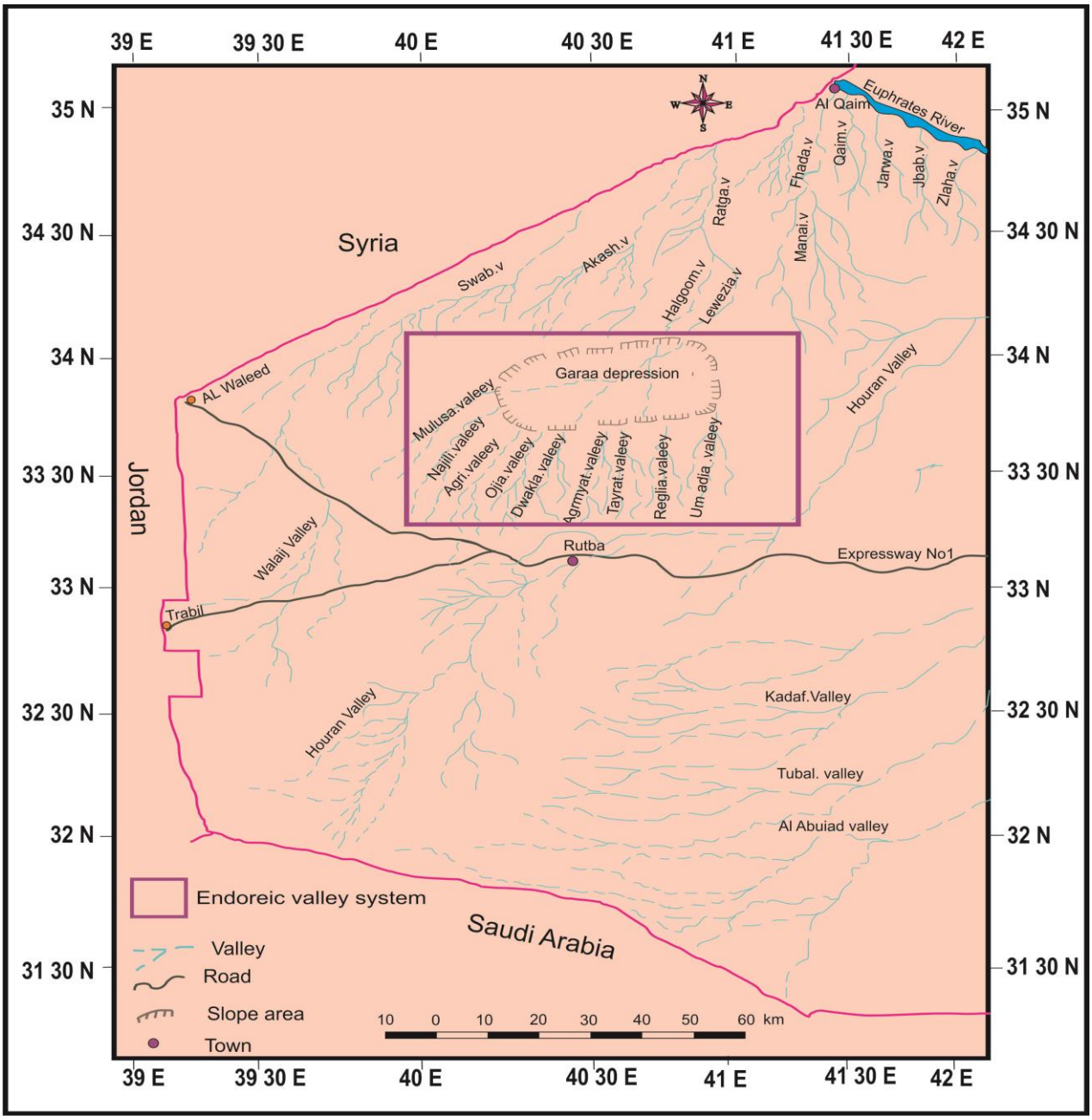


Figure 6.24: Endoreic valleys system for dry valleys in Iraqi Western Desert.

6.5.1.1 Al Mulusa valley

The Al Mulusa valley starts in the area located south of station H3. After about 10 km it takes a northerly direction passing the general road between H3 station and Al Rutba Town (Figure 6.25). From here it takes a path to the north east until Kbrat Al Mulusa and then enters the Garaa depression ending at north Al Raha village (Hamed, 2003).

6.5.1.2 Al Ojia valley

This valley consists of many small branches between the Al Nadhera area and Al ojia valleys. The branches combine in the north east flowing Al Ojia ephemeral stream which enters the Garaa depression south of Al Raha village and to the east of Abiran Hill (Figure 6.26).

6.5.1.3 Al Agrmyat valley

The valley ephemeral stream slopes down from north of Al Nsir Hill to wards and ends at the southern edge of Garaa depression near the Al afaif hills.

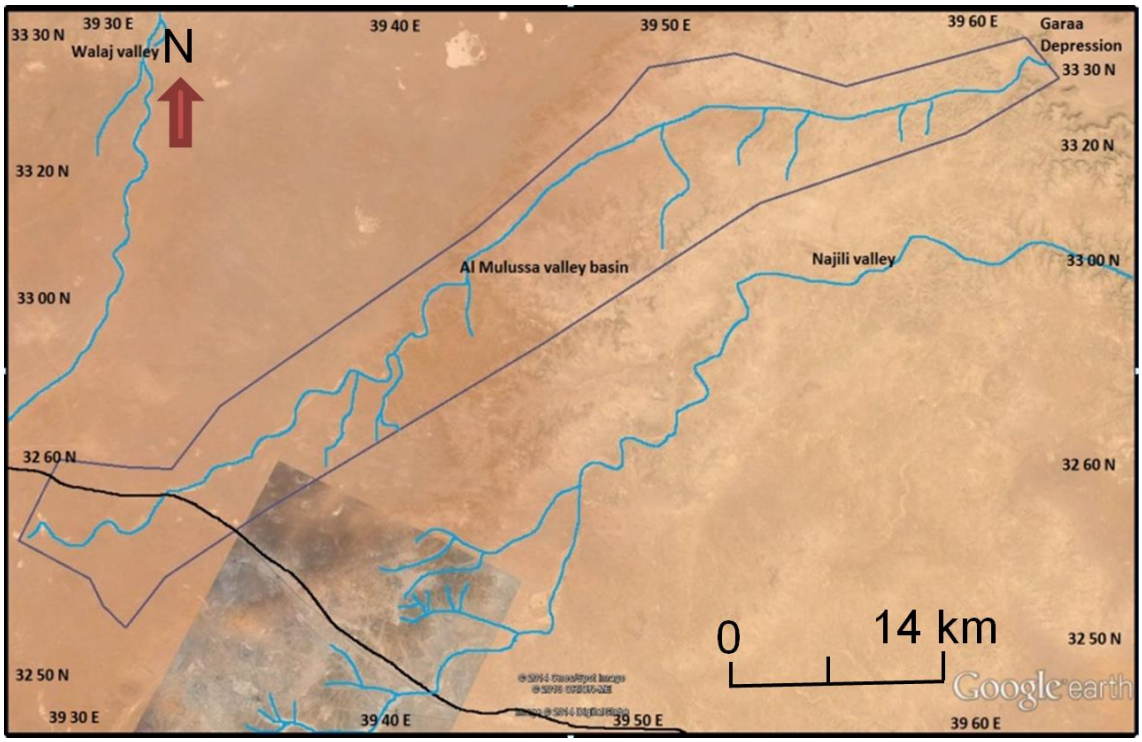


Figure 6.25: Mulussa valley basin (for a general location map see figure 6.1) (Google Earth images)

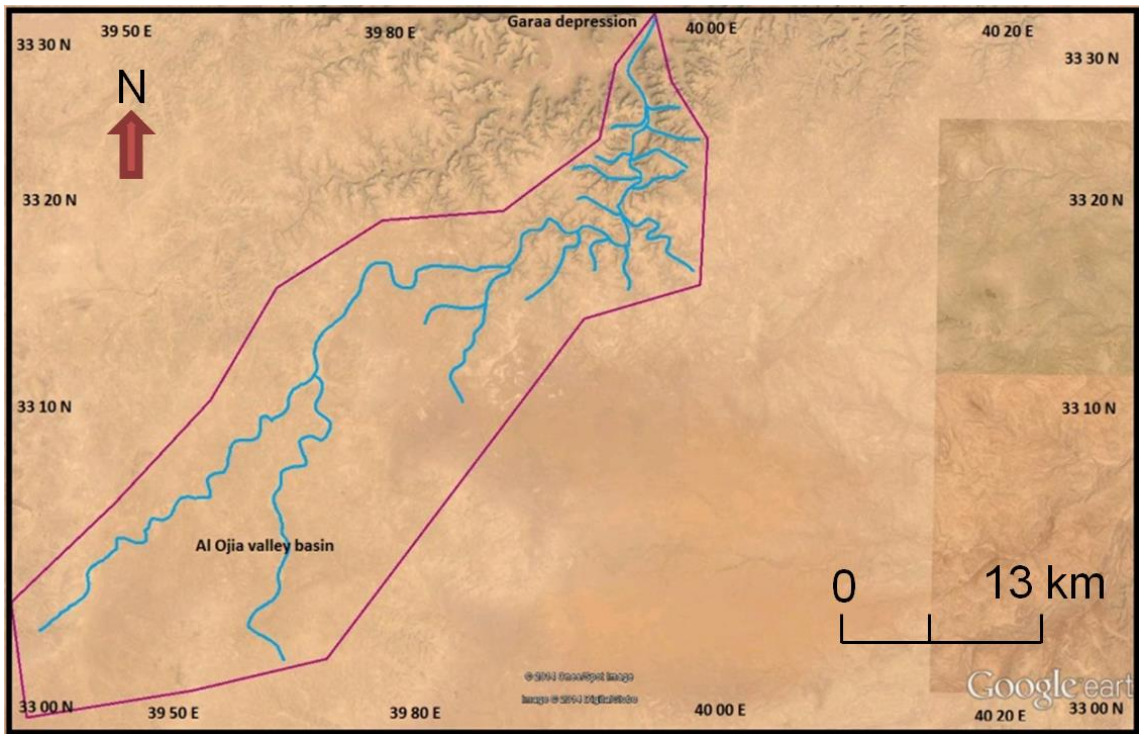


Figure 6.26: Al Ojia valley basin (for a general location map see figure 6.1) (Google Earth images).

6.5.1.4 Al Agrai valley

The Al Agrai valley is located in the Iraqi Western Desert to the north of Rutba Town (Figure 6.27) and it flows in to the southern part of the Garaa depression. The morphometric analysis of the Agrai valley basin involved examination of the areal extent, relief characteristics and the cross-sectional shape of valley at a number of locations. The Agrai valley is located in the Iraqi Western Desert between the latitude 39° 45' E to 40° 16' E and longitudes 32° 52'N to 33° 27'N. This area is characterized by a water deficit in all months of the year with the highest in July (deficit of 335 mm) and the lowest in January (deficit of 10.6 mm) (Al Khfaji, 2009). The geology is predominantly limestone covered by a sandy to sand-clay soil, and there is very little vegetation. The average slope in the Al Agrai valley basin along the long profile of the valley is 2.4 m / km. For more details for Agrai valley see Figure 6.27. Figure 6.28 shows the Agrai valley

basin, Figure 6.29 presents the long section of this valley, and the cross sections for the valley can be found in Figures 6.30 and 6.31. Figure 6.32 shows some morphological features for the Agrai valley. In a downstream direction the Agrai valley stream passes through four geological formations between south west of Rutba town and the Garaa depression, namely: the Ratga, Tayarat, Hartha, and Garaa formations, (Chapter 4). The long section (Figure 6.29) shows that in the Ratga formation the valley has a steady slope before flattering out over the Tayarat Formation. This broad flat area shows up in the cross-section (Figure 6.30). Over the Hartha formation the long profile reflects the variable lithologies of limestones, sandstones and siltstone with an undulating and uneven slope. At the significant tectonic feature of the Garaa depression the long profile steepens. Interestingly the cross section through the rock in this area (Figure 6.31) shows a wide but deep gorge. This suggests an important phase of river downcutting occurred but the contemporary ephemeral river is insufficient to have caused this, so this must be considered as further evidence of fluvial erosion taking place under wetter palaeoclimatic conditions

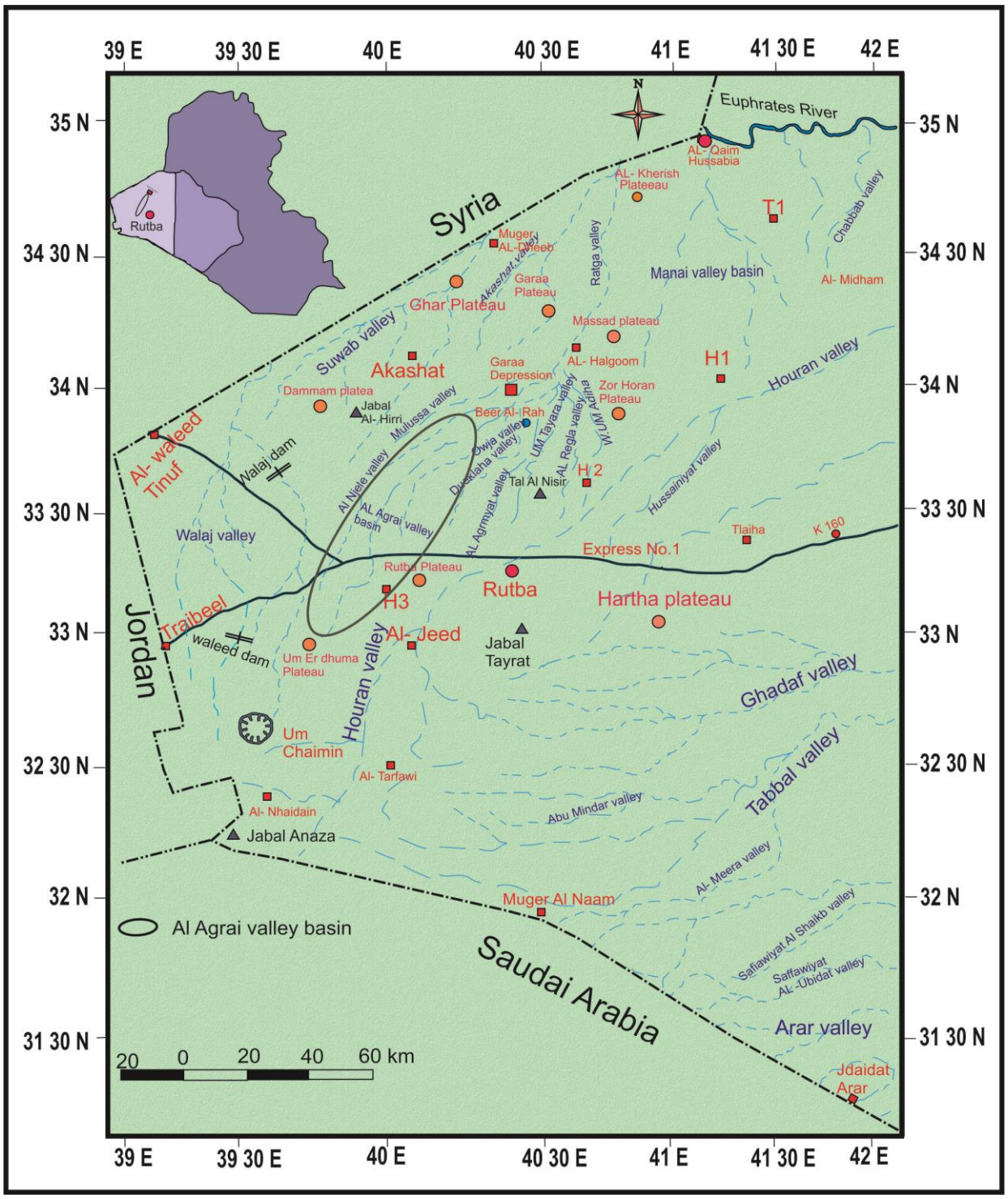


Figure 6.27: Al Agari valley located in Iraqi Western Desert.

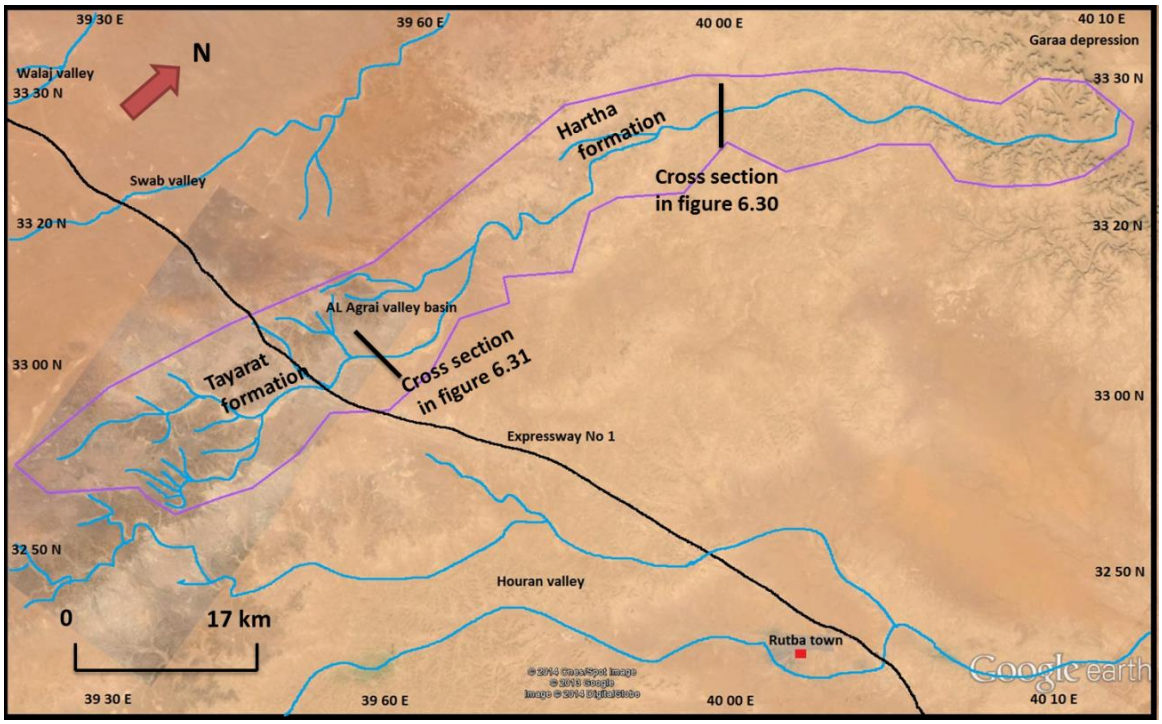


Figure 6.28: Al agrai valley basin (for a general location map see figure 6.1) (Google Earth images).

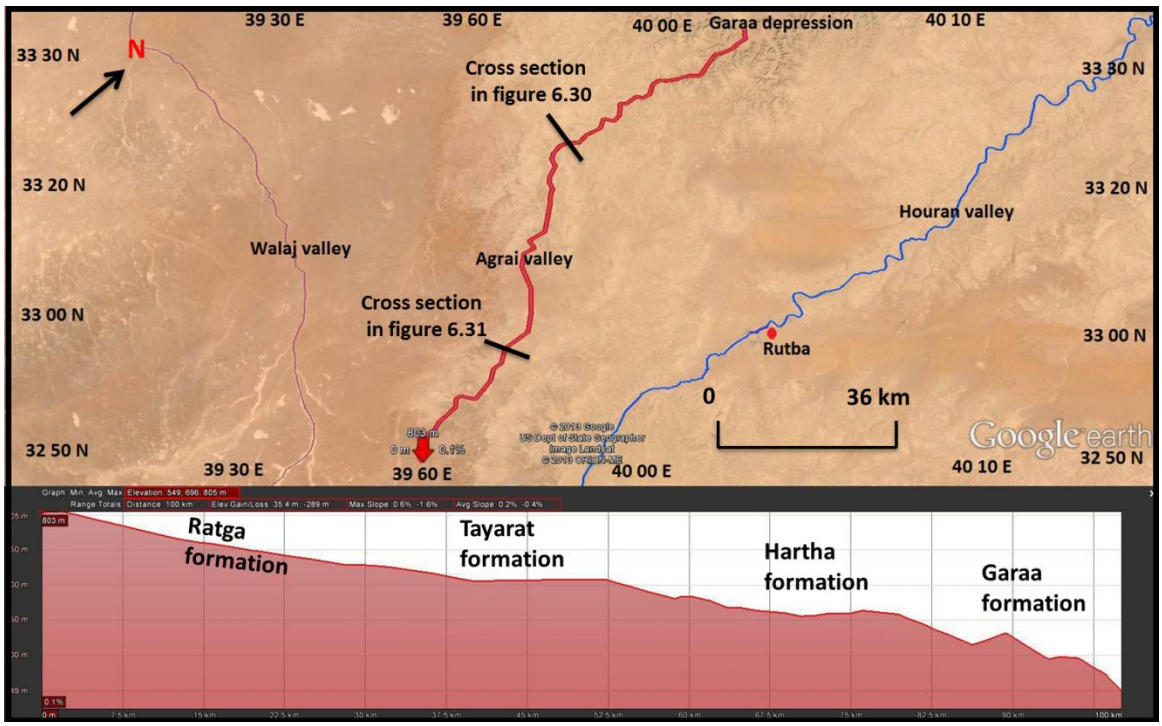
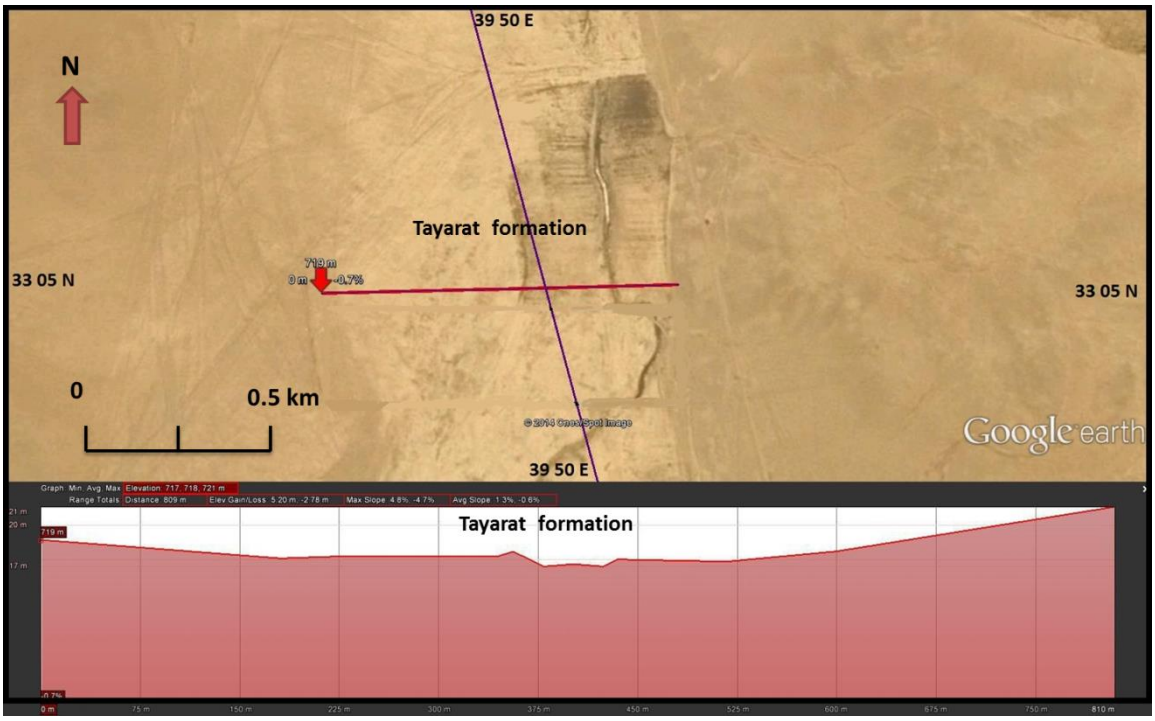
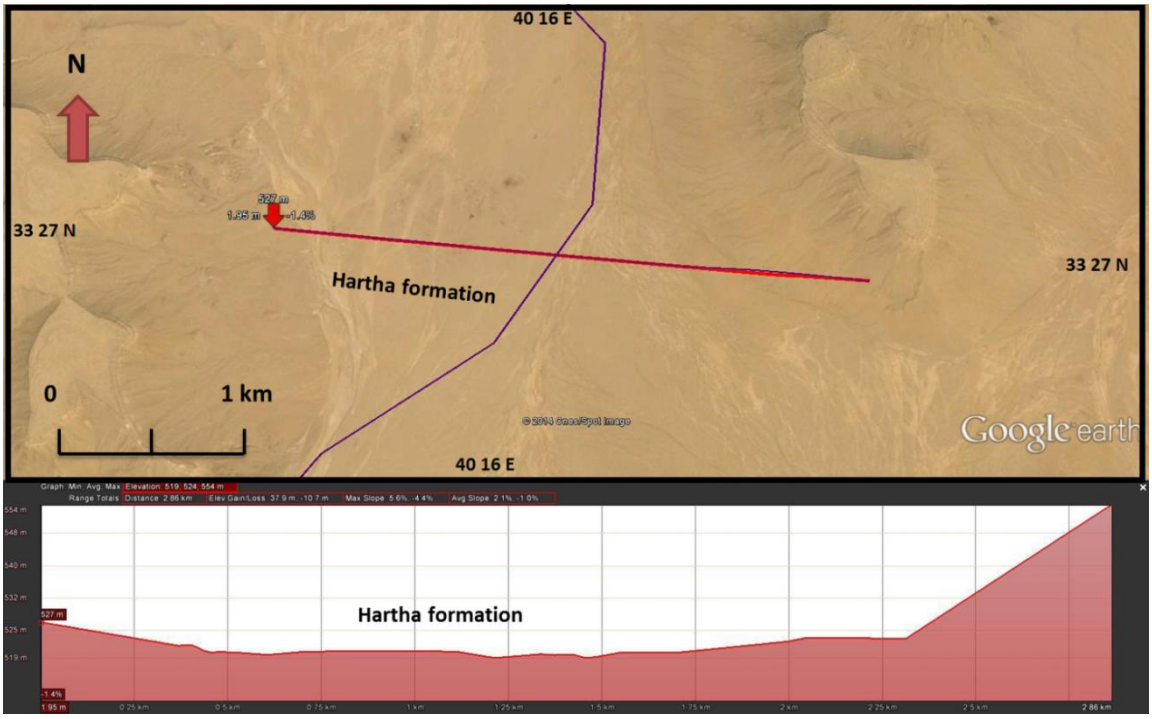


Figure 6.29: Al Agrai valley length section of the valley (for a general location map see figure 6.1) (Google Earth images).



Figuer 6.30: The Al Agrai valley cross section north west town of Rutba (for a general location map see figure 6.1) (Google Earth images).



Figuer 6.31: The Al Agrai valley cross section south of the Garaa depression (for a general location map see figure 6.1) (Google Earth images).

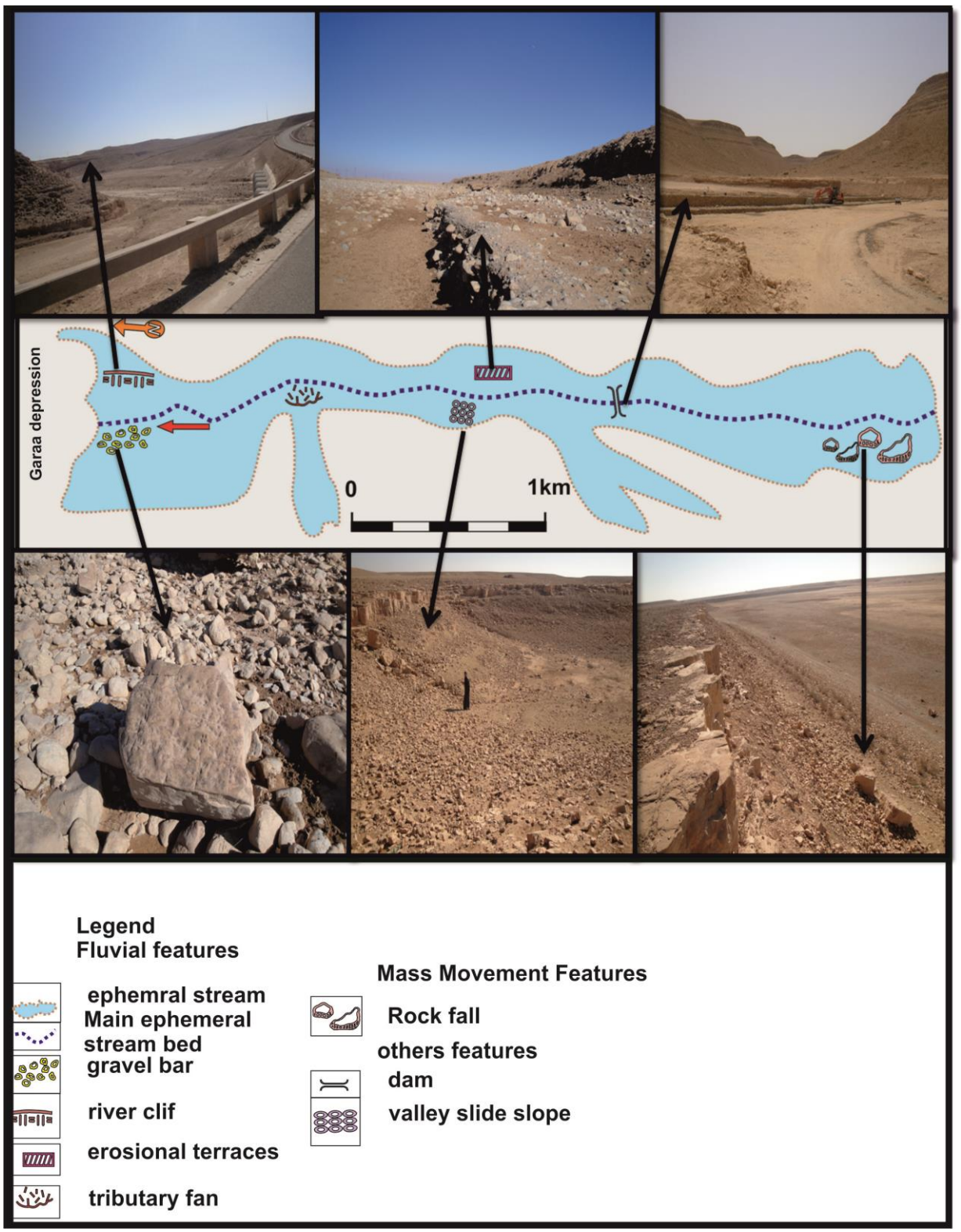


Figure 6.32: Al Agrai valley features (for a general location map see figure 6.1).

6.5.2 Characteristics of the endoreic valley systems

The morphological characteristics of nine of the endoreic misfit valley systems were described as part of this research and the data are presented in Tables 6.5 to 6.9. Table 6.5 provides the general topographic characteristic on the main river basins, and there range in size from 52.3 to 825 km^2. Hamed, 2003). The various morphometric characteristics are discussed below.

Table 6.5: Topographic characteristics for the endoreic dry valleys in Iraqi Western Desert that flow into the southern part of the Garaa depression

Basin name	Area km^2	Contour line highest	Contour line lowest	Main stream length km	Slope m/km
Mulusa valley	160	801	598	85.5	2.3
Najili valley	158	794	570	75.4	2.9
Agri valley	825	793	545	100	2.4
Ojia valley	115	737	509	55.7	4
Dwakla valley	89	708	534	55.5	3.1
Agrmyat valley	124	730	486	40.2	6
Tayrat valley	62	675	489	30.3	6.1
Reglia valley	52.3	646	491	25.9	5.9
Um adia valley	70.3	664	499	34.7	4.9

6.5.2.1 Bifurcation ratio

The bifurcation ratio emerges from on examination of stream ordering using the Strahler (1952) system. The number of streams of each order within the river catchments studied are presented in Table 6.6. The bifurcation ratio is calculated as the sum of the ratio between the number of streams in one order to those in the next higher order divided by the total sets of values. The higher the bifurcation ratio, the shorter the lag time is likely to be for a flood flow moving through the catchment and hence the higher the peak discharge. The

bifurcation ratio, therefore, is important for flood hazard studies and has a particular value in desert areas where actual flood flow data are often very rare. In addition steeper slopes provide more potential energy than slopes in more subdivided terrain, which will be a reflection of the strength of the underlying bedrock, and this also effects the bifurcation ratio (Gregory and walling, 1973). As an indication of the value of this ratio the effect of catchment shape, different stream ordering and the resultant bifurcation ratios, on potential sediment yield are illustrated in Figure 6.33 (Gregory and Walling, 1973).

Analysis of the stream orders in Table 6.6 allows us to calculate the bifurcation ratio:

1. The bifurcation ratio between the first order and second order in Agri valley basin in 2.2; the number of first order valleys is 81 and the second order is 36. In the Al Mulusa valley the ratio is 1.7. This is an interesting difference and is indicative of different rock lithologies affecting the drainage density (Gregory and Walling, 1973).

2. The bifurcation ratio for first order and second order in the Al Ojia valley is 1.9; 1.7 in the Dawkla basin; 1.6 in the Agrmyat basin; 1.8 in the Tayrat basin; 1.7 in the Reglia basin; and 2 in the Um adia and Najili river basin. This suggests the relief and rock type is very similar in these catchments.

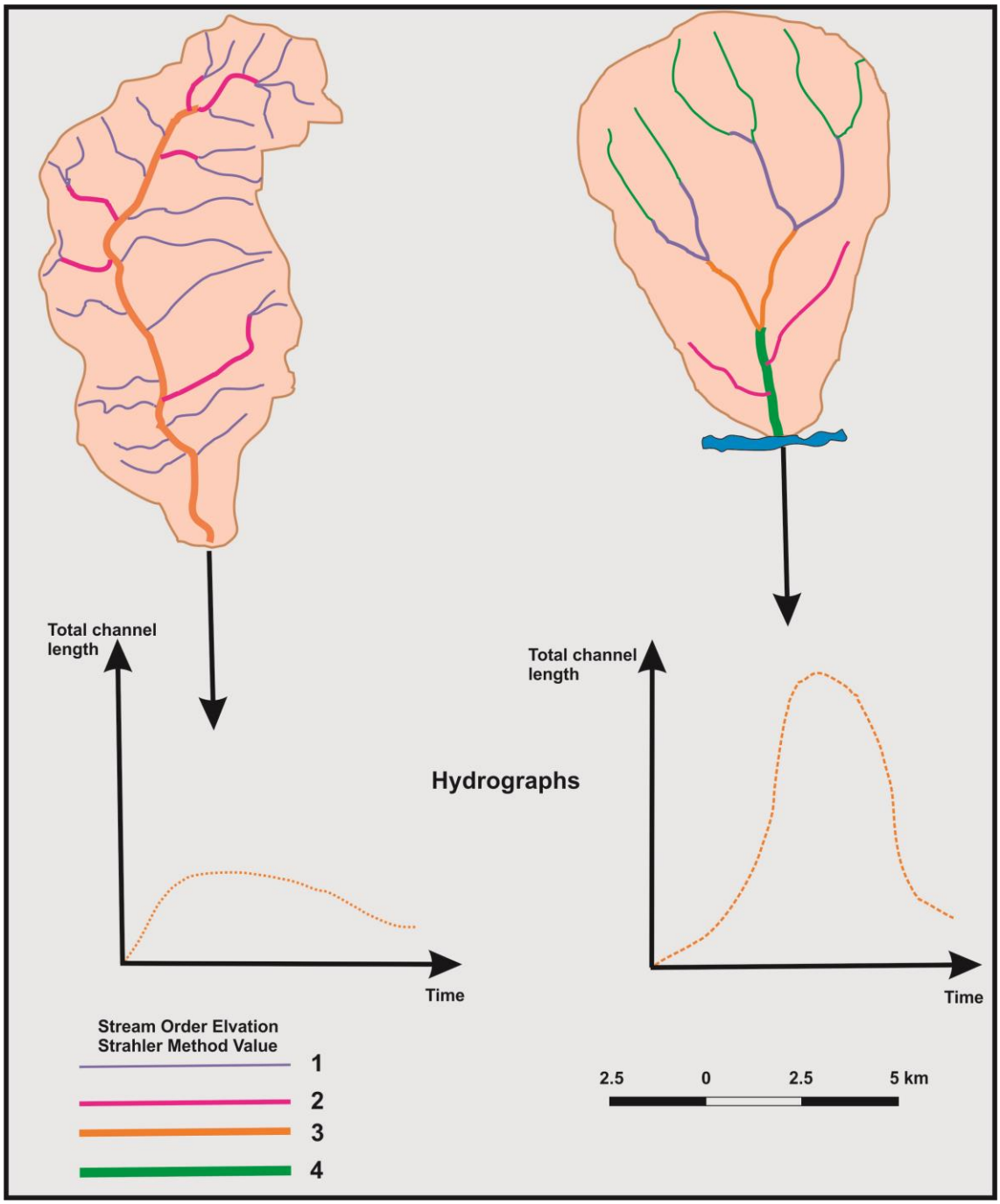


Figure 6.33: Basin relief and shape in relation to drainage basin process (modified after Gregory et al., 1973).

Table 6.6: Water drainage characteristics for valleys basins of Garaa depression.Bifurcation ratio = Number of streams in rank /Number of streams in rank after, Valleys length average = valleys length of the rank / valleys number of the same rank (km).

Ranked	Ranked 1				Ranked 2				Ranked 3				Ranked 4					Ranked 5			
Basin name	Valleys number	Valleys length total (km)	Bifurcation ratio (Ratio order1 to order2)	Valleys length average	Valleys number	Valleys length total (km)	Bifurcation ratio (Ratio order2 to order3)	Valleys length average	Valleys number	Valleys length total (km)	Bifurcation ratio (Ratio order3 to order4)	valleys length average	valleys number	Valleys length total (km)	bifurcation ratio (Ratio order4 to order5)	Valleys length average	Average Bifurcation Ratio	valleys number	Valleys length total (km)	Bifurcation ratio (Ratio order 5 to order 6)	Valleys length average
Mulusa valley	85	30	1.7	0.3	50	20	1.6	0.4	3	13	1.5	4.3	2	10	1	5	1.45	1	3	0	3
Najili valley	80	22	2	0.2	40	21	1.7	0.5	6	12	1.5	2	1	8	0	8	1.55	0	0	0	0
Agri valley	81	23	2.2	0.2	36	18	1.2	0.5	4	14	1.1	3.5	2	12	1	6	1.38	1	2	0	2
Ojia valley	75	20	1.9	0.2	38	21	0.9	0.5	4	15	2.1	3.7	1	7	0	7	1.22	0	0	0	0
Dwakla valley	72	21	1.7	0.2	42	15	1.4	0.3	5	10	1.2	2	1	8	0	8	1.3	0	0	0	0
Agrmyat valley	78	20	1.6	0.2	46	12	1.6	0.2	4	11	4	2.7	1	9	0	9	1.8	0	0	0	0
Tayrat valley	81	26	1.8	0.3	43	11	2.3	0.2	3	12	3	4	1	0	0	0	1.75	0	0	0	0
Reglia valley	83	22	1.7	0.2	48	15	1.4	0.3	4	13	4	3.2	1	0	0	0	1.75	0	0	0	0
Um adia valley	78	23	2	0.2	39	10	2.3	0.2	2	10	2	5	1	0	0	0	1.57	0	0	0	0

6.5.2.2 Drainage Density and other Basin Characteristics (Tables 6.7 and 6.8)

The drainage density of a catchment in calculated as the total length of the rivers (or in the case of ephemeral rivers, the valleys) divided by the catchment area. If the drainage density in high then any precipitation falling in the catchment will get through to the main streams quickly. Low drainage densities indicate that precipitation makes its way to stream more by overland flow, piping and through flow Low drainage density catchments with normally have a significant component of base flow in the downstream river hydrographs and are also likely to be sources of groundwater aquifers as they would normally be underlain by porous rocks. It should also noted that in desert catchments if river valleys are occupied by misfit ephemeral streams then the drainage density based as an analysis of river valleys may be indicator of flow conditions during wetter palaeoclimatic conditions. However, Carlston (1963) refers to the close relationship between mean annual flood discharges and drainage density in ephemeral stream valleys in the Iraqi Western Desert. This relationship does not appear to be affected by large differences among river basins when reviewing relief, valleys side slopes, stream slopes or the amount and intensity of precipitation. it is concluded that the drainage density is adjusted to the most efficient removal of flood runoff and that the mean annual of flood discharge is predominantly a function of the terrain in the river basin (Calstone,1963).

Drainage density, therefore, reflects the nature of the soils, bedrock, and topography and, where it occurs, the vegetation cover within a catchment (Lee, 2005). Within desert areas the range of drainage densities that have been observed can be extremely wide (Gregory, 1976). The values presented in Table 6.7 are at the lower end of these formed in dryland areas and suggest that elements of the endoreic drainage reflect contemporary precipitation

condition rather than paleoclimatic. This observation supports the work by Calstone (1963) referred to above. In Table 6.7 there are two other measures of catchment characteristics, the terrain ratio average and roughness (for definitions refer to Table 6.3). There measures are indicative of the relative relief and dissection within the catchments. The values are all quite low which reflects the generally subdued and flat nature of the terrain in the Iraqi Western Desert.

Table 6.7: Average Values of terrain ratio, roughness and Drainage density. (for definitions see Table 6.3).

Basin name	Terrain ratio average	Roughness value	Drainage density	
			Length density km /km^2	Numerical density valley/ km
Mulusa valley	2.3	0.03	0.9	0.87
Najili valley	2.8	0.04	1	0.80
Agri valley	2.4	0.03	0.81	0.14
Ojia valley	4	0.06	1.3	1.02
Dwakla valley	3.8	0.07	1.2	1.35
Agrmyat valley	6	0.14	1.9	1.04
Tayrat valley	6.1	0.12	2.6	2.06
Reglia valley	5.9	0.11	3.2	2.58
Um adia valley	4.7	0.10	2.2	1.69

Table 6.8: Drainage and numerical longitudinal density of the valleys of the study area.

Basin name	Valleys number	Valleys length total / km	Longitudinal density Km / km^2	Density of Valleys number / km^2
Mulusa valley	140	73	0.87	0.45
Najili valley	127	63	0.80	0.39
Agri valley	123	67	0.14	0.80
Ojia valley	118	63	1.02	0.54
Dwakla valley	121	54	0.64	0.60
Agrmyat valley	129	42	1.04	0.33
Tayrat valley	128	49	2.06	0.79
Reglia valley	135	50	2.58	0.95
Um adia valley	119	43	1.69	0.61

6.5.2.3 Deflection coefficient

The deflection coefficient for a catchment expresses the relationship between the actual length of valley for its source to outlet and the ideal length that is the shortest distance between these points. The measurement of this characteristic for the river drainage basins in the study area are presented in Table 6.9. This shows very little variation in the coefficient values which in probably a reflection of the narrow range of catchment areas and catchment length investigated. It is also possible that the nature of a centripetal drainage network has a bearing on this characteristic notably where the simple bedrock structure lends itself to the development of localised parallel drainage systems.

Table 6.9: Deflection coefficient for the valleys of the study area.

Basin name	Real Length km	Ideal length km	Deflection coefficient
Mulusa valley	85.5	76	1.12
Najili valley	75.4	70.33	1.07
Agri valley	100	84.95	1.17
Ojia valley	55.7	46.86	1.1
Dwakla valley	55.5	49.71	1.11
Agrmyat valley	40.2	34	1.18
Tayrat valley	30.3	26.85	1.12
Reglia valley	25.9	23.50	1.10
Um adia valley	34.7	30.62	1.13

6.5.2.4 Basin drainage form

The drainage basin form is one of the key morphometric characteristics of a river catchment. The measurement of river basin form enables quantitative relationships between the catchment characteristics and river hydrology. Two useful characteristics of the basin form are the area coherence ratio, and the circumference coherence ratio.

- Area coherence ratio = basin area km2 /circle area its circumference equals basin circumference
- Circumference coherence ratio = 1/ (area coherence ratio)

The area coherence ratio refers to how the basin form diverges from the circular shape. High values refer to a basin form that approaches a circular shape, whilst the low values reflect the opposite. The circumference coherence ratio is calculated by comparison with the basin circumference of an equivalent circular area. Calculating the area coherence ratio for Al Al Manai valley and Al Agari catchment the values are 3.6 and 3.8 in the two valley systems respectively. This indicates their basins have a generally circular to rectangular shape (Figures 6.19, 6.30). There are other river valley networks in the Western Desert with catchments nearer to a circular form, such as Al Qaiam valley with a 3.8 coherence ratio, and the Akash valley with a 3.6 coherence ratio. This is in contrast to the Swabe valley with a 2.6 coherence ratio. Higher values such as those in the Al Qaiam valley network indicate that precipitation will make its way quickly through the catchment as it all takes the shortest path to the outlet. With low values like the Swab valley, the catchment shape is more linear inform. Unless storms pass right along the centre line of the catchment normally flood flows would take longer to reach the outlet. However, if the storm does move

along the line of the catchment from its source to the out let then this is likely to result in very high magnitude floods, although there will be of very low frequency.

6.6 How has the drainage network evolved over time

Continental development of dry valleys in the Western Desert started after the marine regression caused by tectonic uplift during the Tertiary period. The elevation of the Eniza area (Jabal Enza) about 940m above sea level was caused by the tectonic movement associated with the Rutba Uplift. Remnants of the original uplift can be identified on the geomorphological map (Figure 5.18; appendix in thesis) as Plateau Level A. The sub-horizontal bedding of the sedimentary strata together with the prevailing climate did not allow high rates of erosion which was dominated by local rain-wash activity and deflation. This produced broad depressions and low angle slopes and escarpments (Buday and Hak, 1980). These landforms are the group shown on the geomorphological map (Figure 5. 18 appendix in thesis) as the features (mainly plateaux) that formed on the deposits related to the transgression of the lower Miocene Sea. The features are associated with a more humid climate and the related and denudational activity. This resulted in the development of the B levels plateaux group and two plains (B1 and B2) are preserved from this period. These Plateaux incorporate many sublevels recognized in the upper reaches of the Houran valley. Relicts of the old drainage pattern are indicated by the closed basins and dry lakes (Buday and Hak, 1980). During these times incision by the proto-Houran valley appears to have been significant in developing the present drainage pattern. Tectonic unrest caused the regression of the lower Miocene sea and tilting of the strata which increased the erosion potential. This, together with higher humidity with wetter conditions, is probably responsible for

the denudation of the upper Tayarat suite of rocks in the upper section of Houran valley drainage area. In the softer rocks of the lower Tayarat, and partly on the Digma formation a new drainage pattern originated including several 'C' plains separated by cliffs from the older plain. The older A and B plains were only slightly affected by this phase of erosion. Tectonic movements in Zagros caused moderate deformation of the sedimentary strata and changed conditions thuse enabling denudation and shaping of the older cliffs in the Rutba area. The large plains designated D on the geomorphological map originated during this period in the area around Tel Al Nisr Hill. In the next period denudation took place mainly in the Houran valley south of Al Nsir Hill. The plains of the east valley system probably correspond to the initial stage of the development of the Euphrates palaeo-valley terrace 1 (Tyracek 1980). Some tectonic effects in the Pliocene Euphrates valley cannot be excluded, given the development of the Q level terraces in the Western Desert.

6.7 Conclusion

1. There are two main types of valley natural in the Western Desert area, those with external drainage (exoreic) that flow unto the Euphrates River, and those with internal drainage that end inside the Western Desert (endoreic).

2. Because of the relatively homogenous rock formation the drainage pattern of most dry valleys in the Western Desert is dendritic.

3. Notwithstanding the above other patterns of drainage can be identified: dendritic, centripetal, radial and parallel

4. Centripetal drainage is formed around ephemeral lakes such as the dry lake in the Garaa depression

6. The main factor determining the present drainage pattern is the Late Tertiary tectonic compression associated with the Alpine Orogeny that led to the development of the anticlinorium of the Rutba Uplift. Antecedent drainage developed on this uplifting dome-like structure which produced the contemporary distribution of scarps and plateaux. This uplift continued throughout the Quaternary as indicated by various higher terraces in many of the river valleys and the River Euphrates. Throughout the Pleistocene the combination of climate fluctuation and continuing uplift of the Rutba 'dome' led to incision of the valley network where there was sufficient water avaliable for erosion. During the periods of water deficit it is more likely that deposition will have occured. These deposits now form part of the river terrace sequence visible in some of the river valleys and on the River Euphrates.

7. The contemporary nature of the river valleys of the Western Desert is a result of the wetter phases that may have prevailed in Iraq and wide areas of the Arabian Peninsula during parts of the Pleistocene period.

8. Although not established as part of this study, it is likely that there have been river capture events since the Late Tertiary adding to the complexity of drainage evolution in the Iraqi Western Desert. As this study has now established the nature of the drainage networks Figure 6.34, subsequent work will be able to explore this aspect of the geomorphology of the region.

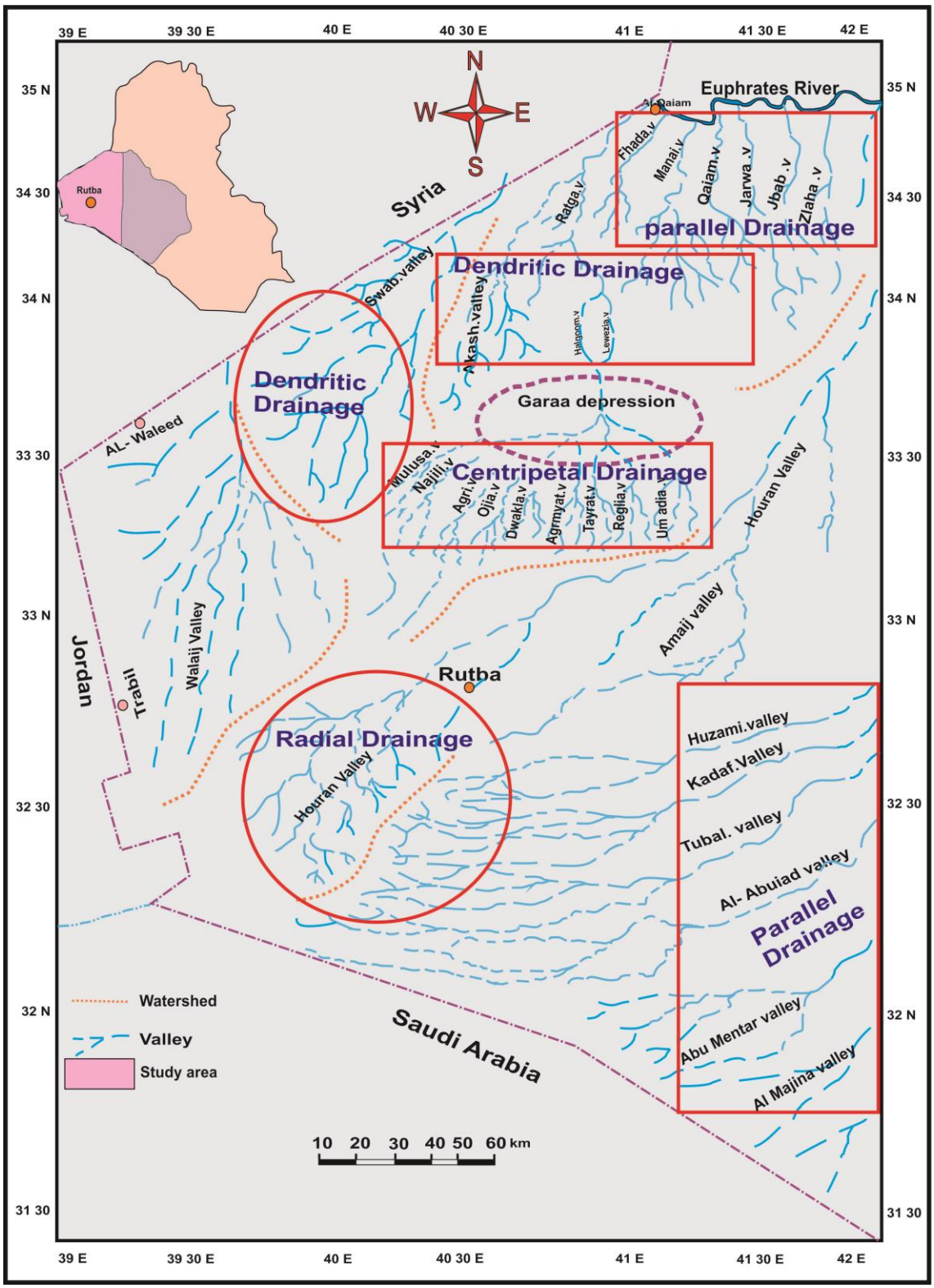


Figure 6.34: Patterns drainage for dry valleys in Iraqi Western Desert

Chapter 7

Discussion and Conclusion

7.1 Discussion

Based on the research carried out for the thesis it is possibble to evaluate the controls as the evolution of the drainage in the Iraqi Western Desert. Initially it is necessary to look at the geological history of the region. The dominating structural element of the Western Desert is the Rutba uplift. The Rutba uplift is a complex regional structure dominating the Syrian-Iraqi zone of the stable platform and is a part of a major regional north-south trending structure starting on the Hail arch on the north-east margins of the Arabian shield in Saudi Arabia and continuing up to the Mardin uplift in south Turkey. This huge basement block is dissected by younger movements forming individual parts components and there are mostly west east trending. The internal structure of the uplift is rather complex and reflects the complicated paleogeography and tectonic development of the Western Desert. The uplift axis is oriented north-south. A slight shifting of the axis towards the east can be observed in the surface geology. Differential uplift has lead to the creation of individual blocks within the overall anticline, thus it is better described as an anticlinorium. Local anticlines and synclines mostly trending southwest to north-east also occur on the southeast slope of the uplift. The dome of the uplift is in the area of the Garaa depression (Garaa block) and appears to be demarcated by the outcrops of late Palaeozoic sediments. The north slope is most probably the steepest and dips towards the deep upper Cretaceous Anah trough which lies outside the investigated area. The top of the uplift is thought to have been located further to the north or northwest during pre-Cretaceous periods. This may be demonstrated by the absence of pre-Cretaceous sediments along the north rim of the Garaa depression. It is probable that the Anha and Khleisia uplift (outside the investigated area) were all part of the same tectonic structure as the Rutba

uplift during the pre-Cretaceous (Budy and Hak, 1980). The other critical structural element of the Western Desert in the Houran anticlinorium the core of which lies to the south-southwest of Garaa Depression.

The east and south east limbs that form the uplift of the Houran anticlinorium are gentle, as demonstrated by the broad stripe of Triassic and Jurassic sediments. Their lithological development indicates that during the pre-Cretaceous period the uplift must have been extensive, often forming a coastline, notably during the Jurassic period. The west limb of the uplift is comparatively steep and is noted for the appearance of the Upper Cretaceous and Palaeogene sediments in the immediate neighbourhood of the top of the uplift along the west edge of the Garaa depression. It seems likely that the relatively steep western and northern lands resulted from late Cretaceous movements. This may also indicate that the uplift extended far more to the west during pre-Cretaceous periods (Budy and Hak, 1980). There are some structures of lower order relative to the first order Rutba uplift that are present mainly in the northern part of the investigated area, namely all the blocks demarcated by faults and gentle anticlines and synclines (is shown in Figure 4.6).

Throughout the generally gentle dipping structure shallower anticlines and synclines are relatively frequent and mainly formed during in the Triassic-Jurassic structural stage. Their amplitudes are rather small not exceeding a few tens of metre, but their lengths exceeds several tens up to more than a hundred kilometres. They are concentrated on the southeast slope of the Rutba uplift and continue under the area covered by Cretaceous sediments. Some smaller anticlines of similar trend occur in the southern part of the investigated area.

These may be of tectonic origin, but some of them might have resulted from the sediments conformably overlapping on reef bodies. Minor structures occur in some Palaeogene sediments, and are thought to have been caused directly or indirectly by the mobility of bodies of evaporates (i.e. diapiric structures). Their dimensions, however, are small and they cannot be traced on existing geological maps (Buday and Hak, 1980)

In general term the tectonic development of the Western Desert is not highly complex. The investigations for this thesis brought no new formation concerning the Precambrian and Palaeozoic development, but it does seems that the Western Desert was uplifted and eroded during the early Triassic period. The monotonous middle-upper Triassic transgression indicate a relatively flat surface and show, low energy sedimentation. Uplift movements started again at the end of the Triassic mainly in the northwest part of the Western Desert which then formed the shores of the transgressing Lower and Middle Jurassic seas. A general uplift of the whole Rutba-Khleisia block (Figure 4.3 and 4.4) took place after the deposition of the Middle Jurassic, and then the entire region was subjected to erosion (Budy and Hak 1980). New tectonic movements started in connection with the strong mid-Cretaceous orogenic activity and caused the tectonic rejuvenation of the platform (Ditmar et al. 1971, Buday, 1973). It seems that only the uppermost parts of the Rutba uplift connected at that time with the Khleisia uplift were preserved above the sea level. The structurally highest portions were situated in the north of the uplift and were subjected to further erosion. A new west-trending trough originated north of the Rutba uplift which, though it remained still relatively uplifted, was most probably partly flooded by the sea or might have formed only a small isolated island. The Rutba uplift then became separated from the Khleisia high and ever since it has formed an

independent structural unit. Movement during the periods of the Cretaceous-Palaeogene boundary are difficult to decipher but some differences in the regional development of the Palaeogene formations indicate that the Rutba uplift became more expressive than in the Cretaceous and formed at least a palaeographic boundary with a rough north-west south-east trend. Late Tertiary and probable Quaternary movements marked the paroxysmal phases of the Alpine orogeny and led to the rejuvenation of some old fault lines and to the general tilting of the whole block towards the east and northeast.

This geological history forms the background on which the drainage network of the Iraqi Western Desert has developed during the Cenozoic.

The regional topography of the Iraqi Western Desert is characterized by gradual increase in elevation from east to west. In general, the drainage is towards east and northeast. The Western Desert surface comprises carbonates, limestone, low (1-20°) towards the northeast and east, although in the west it is westwards (Al Jiburiand and Al Basraw, 2007). The Western Desert of Iraq land surface reflects the geology with a gradient of 10-20 m per kilometre from the Iraq, Jordan, Saudi Arabia border 975m elevation to the Euphrates River 100-200 m elevation. It is usually a plane surface mostly covered by desert pavement sediments but locally it is very rocky where dissected by valleys. There are four distinct drainage alignments:

1. The incised valleys are located in the south and southeast of Rutba city with a strongly incissed east-west valley system.

2. The incised northeast-south west trending Houran valley and its tributaries which are controlled by the strike of the Triassic and Jurassic sequences that

contain alternating softer clastics and relatively harder carbonate rock (Figure 6.13)

3. A less incised north-south trending drainage system west and southwest town of Rutba controlled by the north-south strike of Palaeogene strata (Figure 6.4 and 6.34)

4. A moderately incised north-northeast-south-southwest trending system north of the Garaa area flowing through Miocene outcrops to the Euphrates River

It is as the basin of this discussion on the geological controls of the drainage that some conclusions can be drawn

7.2 Conclusions

The study has given rise to the following conclusions

1. In very broad terms the Iraqi Western Desert is a plateau of 'rocky' desert located on a stable shelf which represent the northern part of the Arabian tectonic plate

2. The Iraqi Western Desert has comparatively thin Phanerozoic sediments over a Precambrian basement rock complex. The area lacks extensive Alpine Orogeny related compressional structures but has been subject to uplift and gentle folding.

3. The 'Alpine' Rutba Uplift has played major role in the historical geomorphology of the Iraqi Western Desert and since the Late Cretaceous the crest has remained as dry land. It was this uplift that enabled continental plateaux to develop on different geological formations. Uplift commenced in the late Permian and continued intermitently until the Palaeogene. The most significant structural feature created is the Cretaceous Garaa anticline and the Houran anticline. The top of the Rutba uplift is thought to have been

located further to the north or northwest during pre-Cretaceous periods. This may be demonstrated by the absence of pre-Cretaceous sediments along the northern rim of the Garaa depression.

4. Faulting associated with the Rutba Uplifit in seen as a major control on the orientation of dry valleys in Iraqi Western Desert. The most important faults are associated with the Houran anticlinorium, which is over 300 km long and consists of a series of northwest to southeast trending normal faults forming horsts, and the Garaa anticline which trends east-west and is a structure that extended into southeast Syria during the development of the Akashat anticline.
5. Continued but intermittent uplift of the major tectonic structures, namely the Houran anticlinorium and the Garaa anticline, occurred in Cenozoic Era. In general terms there appears to have been two distinct phases of landscape development during which a number of plateaux surfaces formed. The earliest phase covered the period from the Oligocene through to the Miocene (plateaux levels A-C on the geomorphological map Figure 5.18). The second occurred in the Pleo-Pleistocene.

6. It was the continuing uplift of the major tectonic structures, noted above, that created the antecedent drainage which are such a features of the geomorphological maps
7. The presence of river terraces on the Euphrates River and same its tributaries the effects of both tectonic uplift (isotactic) and the eustatic sea level changes that occurred during the Pleistocene.

8. The drainage network that developed during the late Cenozoic and notably during the Pleistocene is associated with river flow well in excess of those

associated with contemporary rivers. Thus many of the ephemeral rivers can be described as ‘misfits’ within the river valleys network.

9. Overall the Iraqi Western Desert now comprises extensive incised plateaux surfaces covered with gravel pavement. The most important topographic features are dry valleys, depressions, and plateaux.

7.3 Recommended additional work in the Iraqi Western Desert

The key additional work needed, now that the overall geomorphology of the Western Desert has been established by this thesis, will be:

1) Explore in more detail the nature and formation of the plateaux surface labelled A-E on the geomorphological map (Figure 5.18)
2) To examine the river terrace levels on the River Euphrates and those in the dry valleys in order to better understand the evolution of the drainage network during the Pleistocen. Linked to this work would be an examination of the role that river capture events might have in explaining the contemporary river network;
3) An assessment of contemporary flood hazard that exits even within misfit ephemeral streams as there is a lack of data on flood.

Not specifically related to the aims of this thesis a number of other items did emerge that need additional work:

1) It is suggested there is a need classify in more detail both the basal and the uppermost parts of the Garaa formation notably with respect to the investigation of macro and micro flora.
2) Obtain more data from all boreholes drilled in order to obtain more data on palaeontology, geology lithology, mineralogy geochemistry, etc. This is particularly important when studying older formations in the Iraqi Western Desert.

3) Take advantage of all climate stations in Iraqi Western Desert in order to collect all data regarding the changing conditions.
4) Increased instrumentation to in order to better provide new data to understand groundwater conditions.
5) Establishing gauging stations on dry valleys in order to record ephemeral run off, which will aid the evaluation of groundwater resources in the Iraqi Western Desert especially in the dry valleys near Al Rutba town.
6) Control of self-flowing wells within the discharge area along the Euphrates River between Al Qaiam to Heet city to preserve water, and prevent environmental pollution.

7.4 Final thoughts

The original intention for this research had been to undertake extensive field work in the Iraqi Western Desert to examine the fluvial deposits, log river terraces and produce detailed maps of a number of the main river valleys. The deteriorating security situation in Iraq made this impossible. Although time was spent in the field, the logistics of organizing passes, armed security and and guides meant this was very limited. However, as an Iraqi citizen this researcher was able to access data that have never been made available and were held in libraries, Government Ministries and University Departments. Most these data were unpublished, in Arabic, and available only as hard copy. Therefore, the form of the research was changed to place an emphasis on compiling, translating, scanning and digitising these data to enable a new evaluation of the geomorphology of the Iraqi Western Desert to be carried out. The data were put in to a GIS for the first time and outputs produced using CorelDraw. Thus a digital data set was compiled for future researchers to use. This researcher

used the complied data, supplemented with information gained by examining Google Earth images and the limited field observations to produce a new geomorphological map of the Western Desert. This unique product then formed the basis for the preliminary investigations of the drainage network and its evolution. It is recognised that the investigation is ongoing and much more work is possible on the interpretation of the geomorphology. But now, for the first time, researchers have a basis on which to work as a result of the material made available in this thesis.

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