

**SEDIMENTOLOGY AND RESERVOIR CHARACTERISTICS OF THE  
OLIGOCENE-EARLY MIOCENE CARBONATES (KIRKUK GROUP)  
OF SOUTHERN KURDISTAN**

By

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Thesis submitted for the degree of Doctor of Philosophy  
School of Earth and Ocean Sciences  
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This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other award.

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**Dedication:**

I dedicate this research to:

Heroes who gave their lives for Kurdistan freedom.

My father's soul, my mother, my brother and my sister.

My husband and my little son "Nali".

With love and respect

Ala

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## **Abstract:**

Kirkuk Group Formations (in addition to Avanah and Jaddala Formations) of southern Kurdistan were studied in order to determine biostratigraphy, chronostratigraphy and sequence stratigraphic relationships, in addition to major sediment producing environments and type of platform configuration. As well as to determine the paragenetic sequences with special attention to micrite diagenesis and its effect on microporosity.

Five biozones were identified in the study area in which two of them from Middle-Late Eocene: *Alveolina* biozone (AL) and *Discocyclina* biozone (DI) with three biozones from the Oligocene-Early Miocene of Kirkuk Group: *Nummulites fichteli* biozone (NF); *Praerhapydionina delicata* biozone (PD) and *Austrotrillina howchini* biozone (AH).

Twenty two microfacies were identified and interpreted as having been deposited in a ramp setting based on lateral variations of the microfacies; gradual deepening with no evidence of slope break or effective barrier. A depositional model has been generated from the overall palaeoenvironmental interpretations of the microfacies in which the analysed microfacies indicates palaeoenvironments ranging from terrestrial to open marine settings; nine major depositional environmental zones have been identified and correlated with the standard Cenozoic ramp model of Buxton and Pedley (1989). These zones distributed across the ramp setting dipping southwest, in which zone 1 is terrestrial deposit; zone 2, 3, 4 and 5 are belonging to inner ramp; zone 6, 7 and 8 are belong to middle ramp and zone 9 is belong to outer ramp and basinal settings.

A paragenetic sequence has been derived recording eleven diagenetic processes affecting the Kirkuk Group which are subdivided into an eogenetic, mesogenetic and telogenetic stages. Furthermore, micrite matrices were studied from both shallow and deeper marine settings using SEM, trace elements and carbon/oxygen isotopes; the result shows the different sources; inner-mid ramp muds have a hemi-pelagic source and could have been mostly sourced from high-Mg calcite benthic foraminifera and red algae, and possible partial aragonite dominating; in contrast, the outer ramp matrices, were sourced from plankton, are largely composed of low-Mg calcite, as they are mineralogically stable. Although the exact origin would be difficult to ascertain after diagenesis. From the above two different rock fabrics, two distinct pore systems were identified: (1) low microporosity inner-mid ramp microfacies, it was sourced from metastable precursors and were recrystallized and replaced under meteoric waters, undergoing loss of primary porosity; (2) higher microporosity outer ramp/basinal microfacies, composed of more stable low-Mg calcite that underwent less recrystallization and retained some primary porosity.

The Kirkuk Group succession comprises of two shallowing upward 4th order cycle within one 3rd order cycle located between two unconformable surfaces at lower and upper boundaries which can be correlated to the global regression of sea level. The first 4th order cycle is located at Rupelian and composed of only the Sheikh Alas Formation and the second 4th order cycle is located at Chattian-Early Aquitanian and composed of the Bajawan, Anah, Azkand and Ibrahim Formations. Two different depositional sequences with different thicknesses were developed due to the synsedimentary Khanaqin Basement Fault which cross-cuts the study area and was activate during deposition.

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# Chapter One

## Introduction:

### 1.1 Aims and objectives of the study:

Since the early twentieth century, the discovery of extractable oil and gas from the Kirkuk Group of the Kirkuk Oil Field has been a major focus of attention and it is the subject of numerous studies. This work concentrates on the Oligocene-Early Miocene of the Kirkuk Group which outcrops outside the Kirkuk field where there is a serious lack of research in south of the Kurdistan region with special attention to the Late Eocene formations in order to separate them with Kirkuk Group. The study will try to clarify the significance of the lithostratigraphic key surfaces, facies distribution and the depositional environments of the Oligocene-Early Miocene. Another aspect of this study is the porosity development of the Kirkuk Group carbonates in the studied area, evaluating the effects of the global sea level changes on the styles of deposition and reservoir potential.

### Specific objectives:

1. Proving the presence or absence of whole or partial of the Kirkuk Group formations (see Bellen, 1956; 1959 in section 1.3) in the study area with special attention to their lithostratigraphy, biostratigraphy, chronostratigraphy and sequence stratigraphic relationships.
2. To assure the age of the *Nummulites* rich layer which underlies Kirkuk Group is Late Eocene Avanah Formation not Early Oligocene Sheikh Alas Formation.

3. Establishing the chronostratigraphic framework for the studied units using index fossils, either macro or micro fossils, especially benthic foraminifera.
4. Select and utilize outcrops in the southern part of the Kurdistan region to identify sediment composition, strata geometries, major sediment producing environments (carbonate factories) and type of platform configuration for the Kirkuk Group interval (Figure 1.1).
5. To determine paragenetic sequences with careful attention to micrite diagenesis affecting microporosity that impacts upon reservoir quality in the study areas.
6. To determine and identify the main stratigraphic divisions and stages of major stratigraphic surfaces to develop regional sequence stratigraphic model.
7. To compare sequence stratigraphic interpretations with regional data sets in order to identify both regional and local controls on the depositional environment.

The hypotheses tested in this thesis include:

1. The Kirkuk Group depositional environment is on a ramp setting rather than reef.
2. That the Kirkuk Group age is not totally restricted to Oligocene age, and it may extend to early Miocene. Thus, the age of the *Nummulites* layer can include to either the Kirkuk Group or Avanah Formation.
3. New techniques can be used to determine the source of matrices in matrix rich limestones.

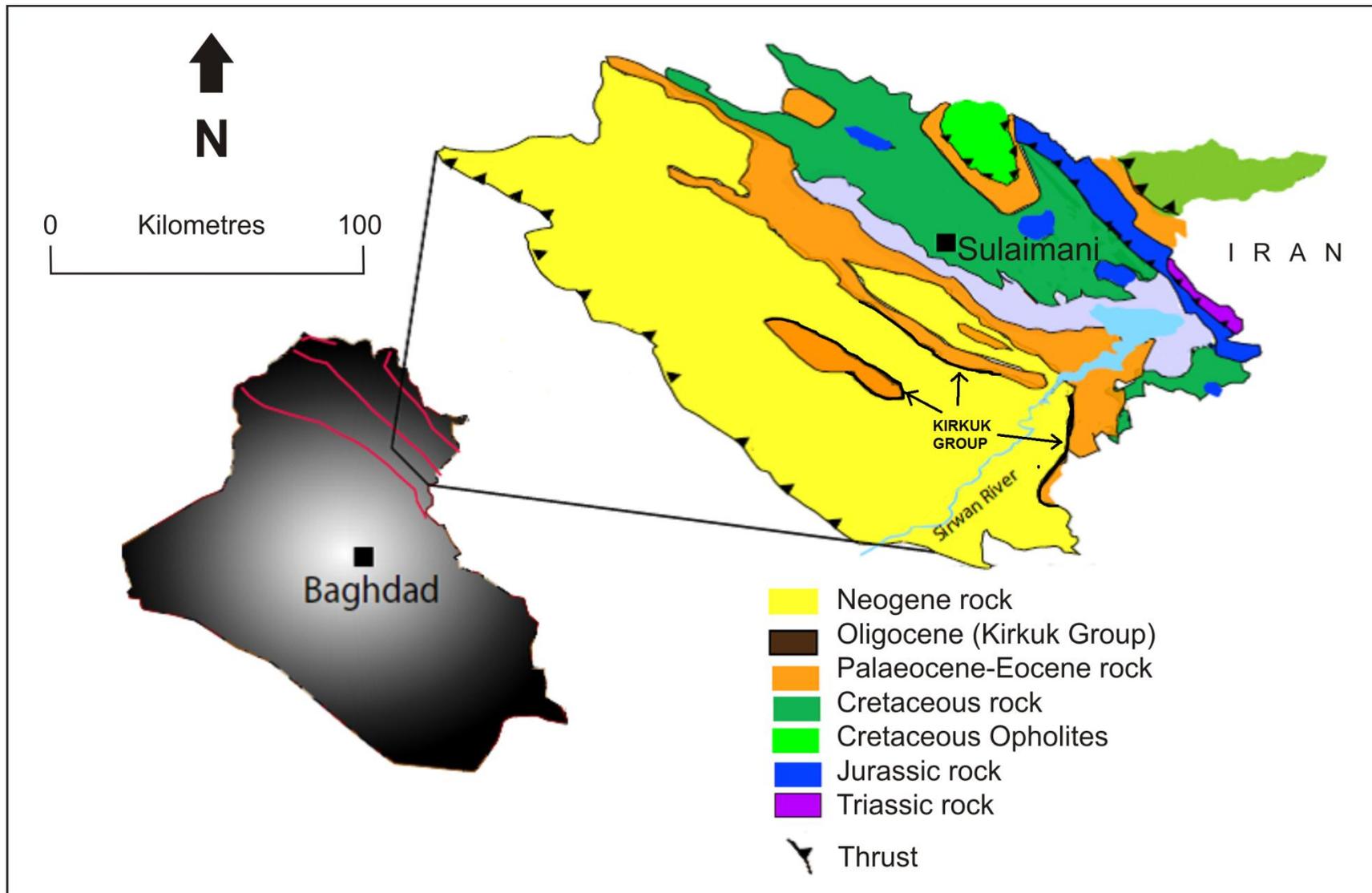


Figure 1.1: Geological map of the studied area located in the northeastern part of Iraq. Red lines are tectonic division lines of Kurdistan.

## **1.2 Introduction:**

The Kirkuk Group represents a major part of the “Main Limestone” (Middle-Upper Eocene and Oligocene). The term “Main Limestone” is an informal term introduced to indicate the first main oil pay zone of the Kirkuk structure. It consists of the Avanah and Jaddala Formations of Eocene age and those nine Oligocene formations of the Kirkuk Group (Figure 1.2) that occur in the Kirkuk structure (Bellen, 1956, Bellen et al, 1959 and Al-Naqib, 1960). The Early Miocene evaporite of the Fatha (formerly known as the Lower Fars) Formation (Burdigalian age ‘15.6-18.5 Ma’ according to Grabowski and Liu, 2009; 2010) acts as the cap rock for the reservoirs in the northern part of Iraq including the studied area.

The Kirkuk Group in the Low Folded Zone “LFZ” (for more detail see Chapter 2, section 2-1) is recognized as a complete set of nine formations (Shurau, Sheikh Alas, Palani, Baba, Bajawan, Tarjil, Anah, Azkand and Ibrahim) in one stratigraphic package. The absence of certain formations of the Kirkuk Group may reflect the palaeo-configuration of the basin (Majid and Veizer, 1986). However in the High Folded Zone “HFZ” (for more detail see Chapter 2, section 2-1) the Kirkuk Group formations are usually missing. Here conglomerates of variable thickness called the Basal Fars Conglomerate (BFC) are located between the Late Eocene (Pila Spi Formation) and Early Miocene (Fatha Formation) (Figure 1.3). The implication of the possible partial presence of Kirkuk Group members in the High Folded Zone will certainly increase the potential of hydrocarbons in the studied area.

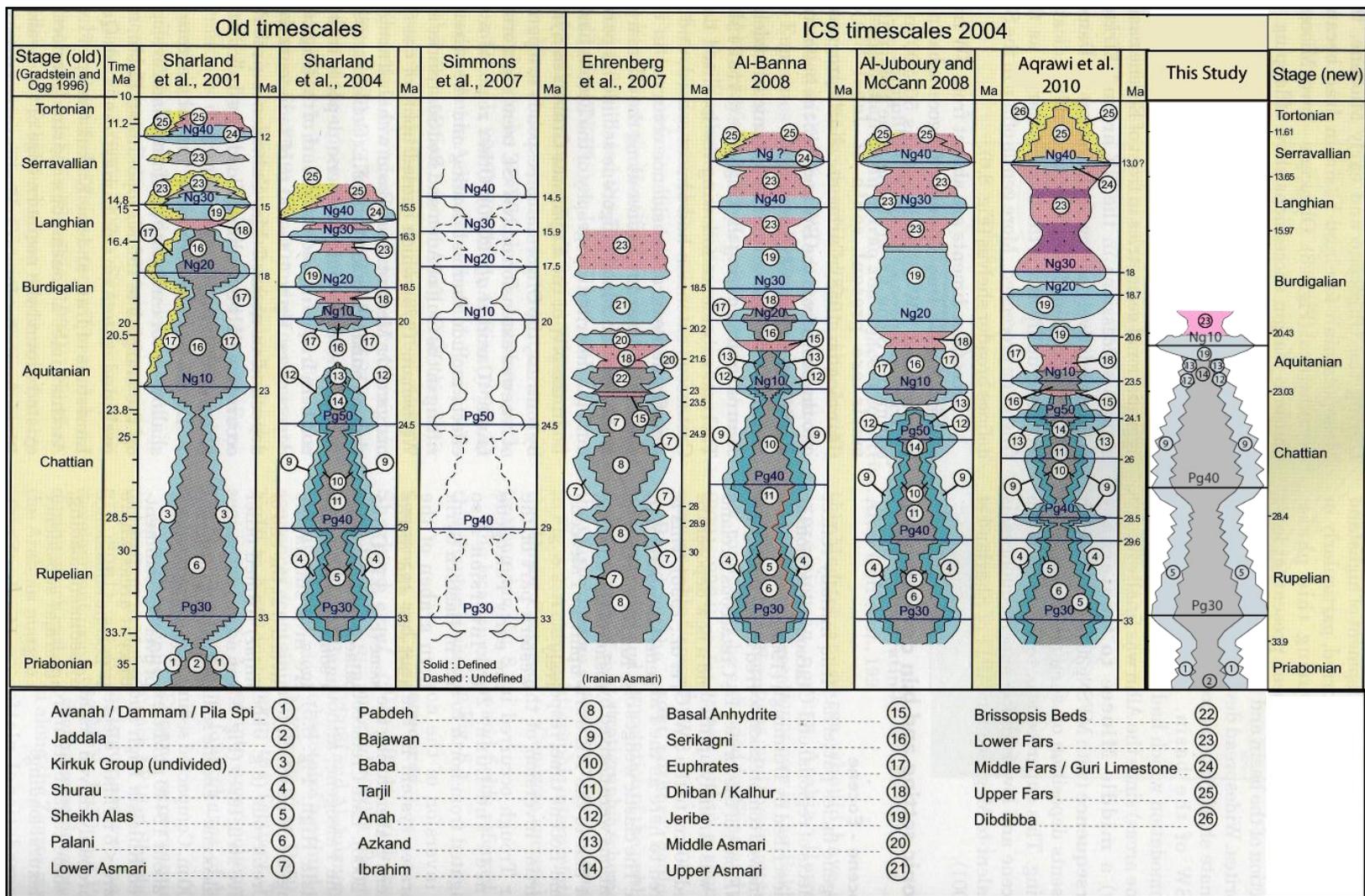


Figure 1.2: Comparison of the Kirkuk Group Formations and their regional equivalents with their sequence stratigraphic position (modified from Aqrawi et al., 2010).

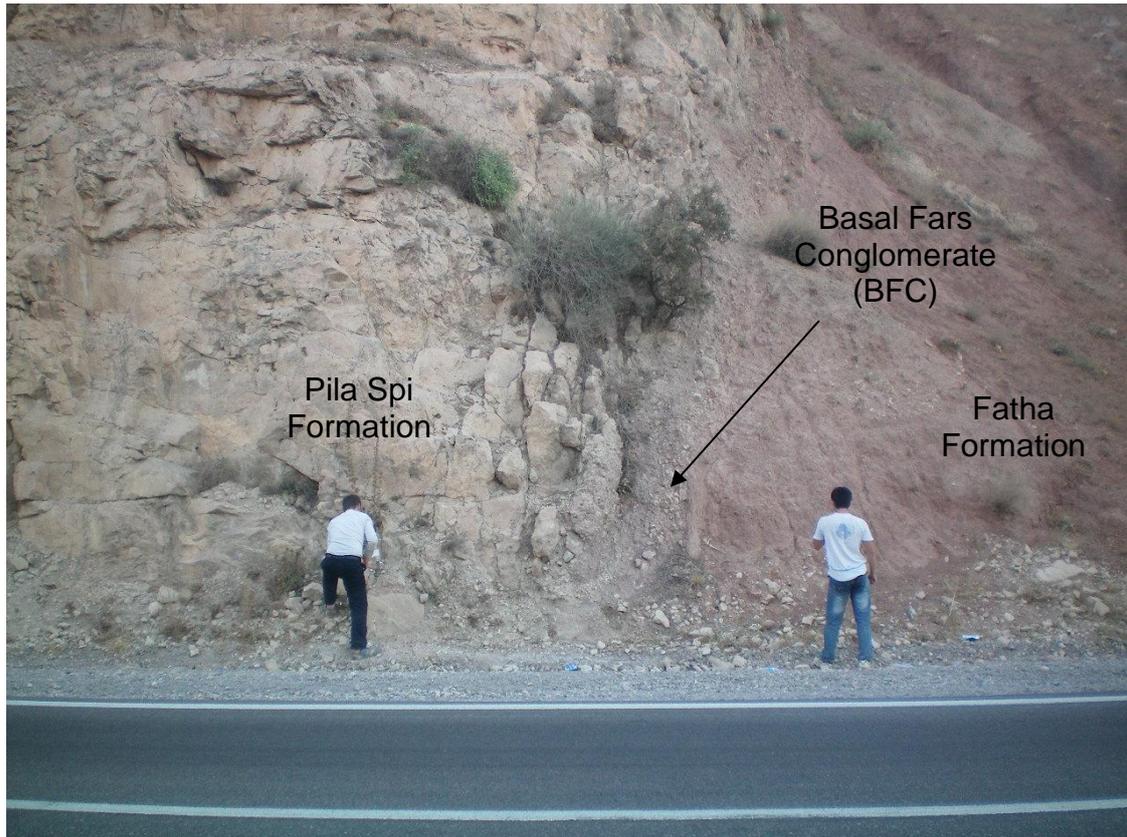


Figure 1.3: Late Eocene Pila Spi Formation separated from red claystone of Fatha Formation (Early Miocene) by the Basal Fars Conglomerate (BFC).

Jassim and Goff (2006) reported two belts of varying thickness ranging from the northwest to the southeast of the Oligocene successions (Fig.1.4). One belt lies in the southwest between the Iraq-Syria border, southwest of Al Qaim and Amara, and the other one from Mushorah in the northwest to the Iraq-Iran border in the southeast. The greatest thickness of the Oligocene succession is between the Kirkuk and Kor Mor structures and it is more than 370m. The recorded outcrops of the Oligocene formations in Iraq are in the Qara Chuq structure south of Erbil. This is situated in the Euphrates valley between Haditha and Anah, and other outcrops include Jabal Sinjar and Jabal Bamu, located along the Iraq-Iran border (Jassim and Goff, 2006).

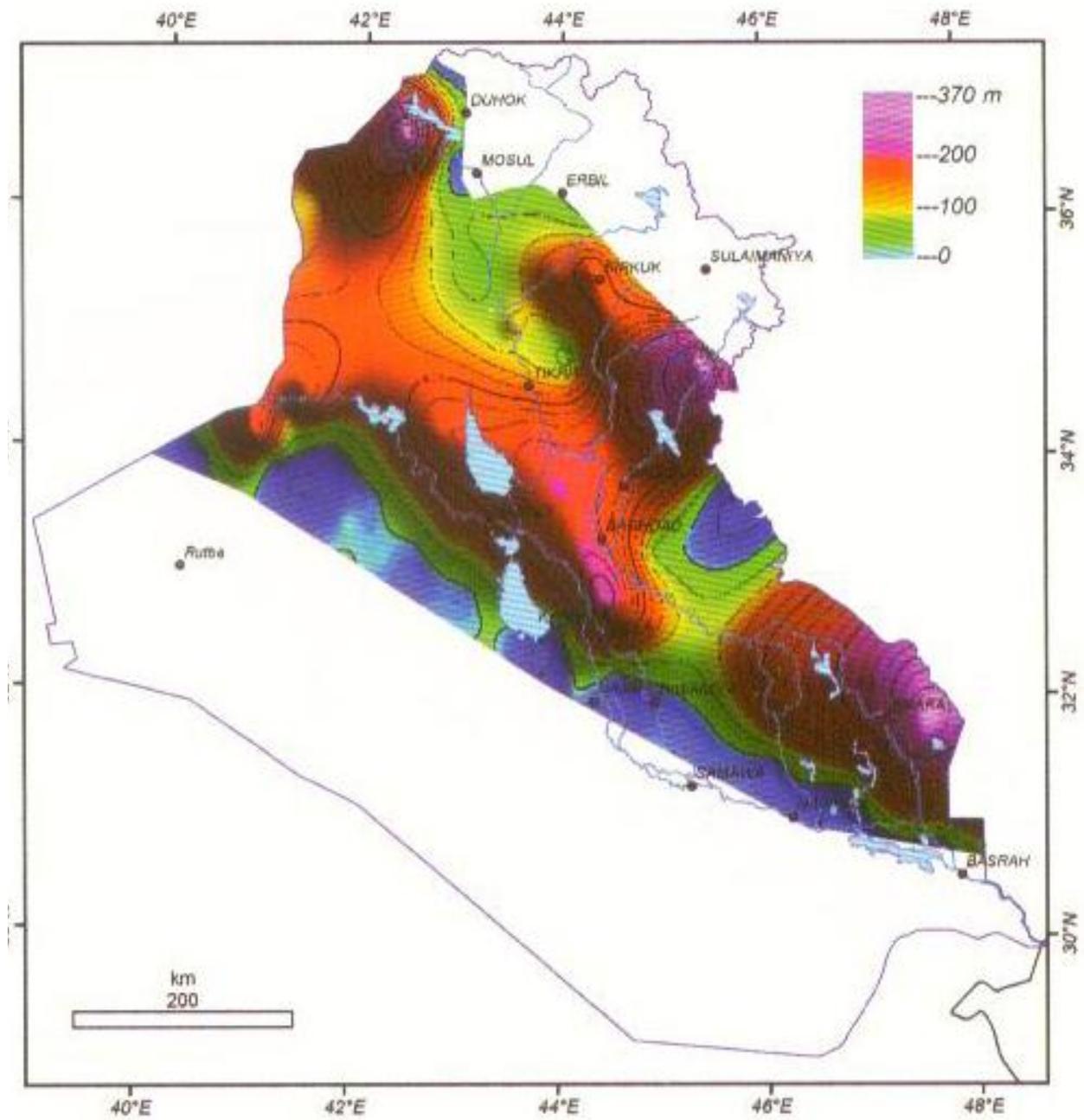


Figure 1.4: Thickness of the latest Eocene-Oligocene succession (Jassim and Goff, 2006). Note: dark areas are left without any explanation in Jassim and Goff (2006).

### **1.3 Previous studies:**

The Oligocene carbonate succession hosts major hydrocarbon reserves in Iraq. This is why investigations into Oligocene rock had started long time ago, especially for oil exploration. The first investigation well was drilled in 1902 in the Chia Surkh oil field, 90km south-east of Sulaimani city.

The general stratigraphy and reef concept of the Kirkuk Oil Field carbonates were established by Henson (1950a). He described the Kirkuk productive limestone as a reef-complex. The term “reef-complex” is applied to an aggregate of reef limestone with associated calcareous rocks, in which the back-reef, reef and fore-reef (basinward) can be differentiated by petrographic and micropaleontologic criteria. He also considered the integration zone between the reef-complex and basinward sediments to be favourable for the generation, migration and accumulation of oil, where the features of primary and secondary porosity and cementation in fore-reef limestones, if porous, may act as carrier beds and reservoirs.

Bellen (1956) described the stratigraphy as the “Main Limestone” of the Kirkuk, Bai Hassan and Qara Chauq Dagh structures in Northern Iraq. He presumed that the Main Limestone consisted of ?Paleocene, ?Lower, Middle and Upper Eocene and Lower, Middle and Upper Oligocene strata, of which the Paleocene and Eocene sequences were controlled by open shoal reefs, whereas the Oligocene successions were controlled by fringing reefs. He distinguished eight formations, with one unknown, which together form the ‘Kirkuk Group’. This group can be defined as a sequence of reef-controlled sediments of the Oligocene age, within which three separate reef ‘cycles’ can be identified as Lower (Shurau, Sheikh Alas and Palani formations), Middle

(Bajawan, Baba and Tarjil formations) and Upper (Anah, Azkand and “not known” formations) cycles; based on their relative stratigraphic positions, these sequences show lateral facies variations with backreef, reef and basinal facies. The “not known” was named “Ibrahim Formation” in 1959 by Bellen et al. as a basinal facies equivalent of the Anah and Azkand formations for the upper Oligocene cycle.

A revision of the foraminiferal genus *Austrotrillina* has been carried out by Adams (1968). He described, and compared the genus of *Austrotrillina* and discussed its geographical and stratigraphical distribution and concluded that the evolutionary changes observed in the *Austrotrillina* wall structure are of stratigraphic value also the age range of this genus is restricted to the Oligocene to Early Miocene. This study covers the Main Limestone of Kirkuk from numerous wells; *Austrotrillina paucialveolata* has been described in well K.14 for the first time. This species is located in the high Lower Oligocene or Middle Oligocene of the Shurau Formation with a thickness of 30 feet.

Ctyroky and Karim (1971a) studied the stratigraphy and paleontology of the Oligocene and Miocene strata near Anah, in the Euphrates valley, and defined the *Miogypsinoids complanata* as being from the late Oligocene age of the Anah Formation.

Ditmar et al. (1971) revised Bellen’s classification based on three cycles and instead divided the Oligocene sedimentary cycle into two sub-cycles, the Lower and Upper cycles. The lower cycle comprises the Sheikh Alas, Shurau, Palani and Tarjil Formations, and the upper cycle consists of the Anah, Azkand, Baba, Bajawan and Ibrahim Formations.

Cretaceous and Tertiary foraminifera were investigated by Grimsdale (1977) in the Middle East. Fifteen species have been described over the sequence from Senonian to Oligocene. The Oligocene species have been classified into:

1. Abundant *Heterillina hensoni* sp. nov. and *Austrorillina* (?) *paucisveolata* sp. nov. These two species are important additions to the fauna which was previously described by Henson (1950b), as the *Archaias operculiniformis*, *Peneoplis glynnjonesi* and *Praerhapydionina delicata*. These fauna occur in limestone, with abundant Miliolidae, in wells at Kirkuk, Iraq, in the Lower Oligocene age.
2. *Nummulites vascus* Joly and Leymerie var. *semiglobulus* (Doornink). This is associated with *Nummulites fichteli*, *N. intermedius* and *N. vascus* in the Oligocene of Kirkuk.
3. *Nummulites bouillei* de la Harpe which is known from the lowest beds of the Oligocene in Kirkuk.
4. *Lepidocyclina ephippioides* (Jones and Chapman). This species accompanies *Nummulites fichteli*, *N. intermedius* and *Lepidocyclina dilatata* (Michelotti) at Kirkuk.

Youkhana and Hradecky (1977) recorded the existence of some Oligocene formations (Shurau, Baba, Bajawan, Azkand and Anah formations) around the Bamu anticline. The thickness of the Oligocene in the recorded area is about 82m.

Behnam (1979) studied the stratigraphy and palaeontology of the Oligocene-Miocene strata in the Khanaqin area (northern Iraq) and described six

Oligocene formations (Shurau formation from the Early Oligocene, Tarjil, Baba and Bajawan formations from the Middle Oligocene, and Anah and Azkand formations from the Late Oligocene) for the first time from exposed rocks in the area.

Buday (1980), in recompiled work, argued that the Oligocene basin in Iraq represents a narrow basin that extends northwest to southeast, with basinal facies in its centre and reefal facies covering the shelves. He also confirmed the presence of nine formations in the Kirkuk Group succession.

Muhammad (1983) studied the biostratigraphy of the Kirkuk Group Formations in the Kirkuk and Bai Hassan area. This study complements previous research in its description of the micropaleontology of these formations, but in providing more detail to provide a clearer view of these formations. The paleoecology of the Kirkuk Group formations has been distinguished on the basis of the described sub-microfacies of these formations, and the age of these formations based on benthonic and planktonic foraminifera and red algae.

Al-Hashimi and Amer (1985) studied the Tertiary microfacies of Iraq. This study established petrographical texture, paleontological character, zonal recognition, facies types and depositional environments. It also analyzed fossil assemblages and lithostratigraphic units. The Tertiary sedimentary facies are represented by 159 illustrated plates which are arranged according to their stratigraphic order.

Majid and Veizer (1986) described the depositional and chemical diagenesis of Tertiary carbonates from the Kirkuk Oil Field. They classified the Oligocene strata as Early and Middle Oligocene. The Early Oligocene strata include a

backreef-reef Shurau formation, a forereef Sheikh Alas formation and a basinal Palani Formation, whereas the Middle Oligocene strata include a backreef-reef Bajawan formation, a forereef Baba formation and a basinal Tarjil formation. They also determined the main stratigraphic relationships of the Kirkuk Group, both vertically and laterally, with special attention paid to their depositional environments.

During a study of the hydrogeochemistry of the caves and springs in the Sangaw-Chemchemal area, Babashekh (2000) recorded the existence of an outcrop in a part of the Oligocene beds on the southern flank of the Aj Dagh Anticline in the Awa Spi valley. In this section the thickness of the Oligocene outcrop is between 2-7m and consists of grey, recrystallized (brecciated in part) limestone.

Lawa et al. (2000) studied the stratigraphy and hydrogeology of the Sulaimanyiah area and drew a geological map of the area under consideration and indicated that an Oligocene sequence may be present near the boundary between the High and Low Folded Zones.

Ziegler (2001) generated a palaeofacies map of the Arabian Plate from the Late Permian to the Holocene to reconstruct the depositional history of the Arabian Plate. This also included Oligocene palaeofacies spanning deposition of the Pebdeh-Chilo Formations (Palani Formation in Iraq) and their regional equivalents.

Lawa et al. (2001) recorded the Late Oligocene horizon from geological cross-section of Qaradagh - Karar basin.

Ghafor (2004), studied the evolutionary trend of large foraminifera using biometric analysis of Lepidocyclinids in the Kirkuk area from the Qara Chauq structure and the wells in the Kirkuk area.

In 2006, Al-Qayim studied the Oligocene basin of North-Central Iraq, which showed that the Oligocene sequence is developed in a relatively narrow, down-warping Sag-interior basin, which followed an interval of uplift and widespread regression. He also described the “Kirkuk Group” as a second-order sequence which is bounded by uneven surfaces upper and lower type 1 sequence boundaries.

Jassim and Goff (2006) rearranged the Oligocene deposits based on a sequence of stratigraphic principles into two main sequences: the Lower and Upper Sequences. The Lower sequence comprises the reefal Sheikh Alas and Shurau formations with basinal Palani and Tarjil Formations, while the Upper Sequence comprises the reef complex of the Baba, Bajawan, Azkand and Anah Formations with the basinal Ibrahim Formation.

Kharajiany (2008) described the sedimentary facies of Oligocene rock units at Ashdagh Mountain in Sangaw, north of Iraq. He ascertained the possibility of Oligocene strata at Ashdagh Mountain and classified them as Sheikh Alas and Shurau formations of Early Oligocene age, Baba, Bajawan and possible Tarjil Formations of Middle Oligocene age, and Anah Formation of Upper Oligocene age.

Al-Banna (2008) studied the Oligocene-Miocene boundary in northern Iraq and revised the previously assigned upper sub-cycle of the Late Oligocene age (Chattian) by Bellen et al. (1959) into the period of the Early Miocene age (Early Aquitanian).

Grabowski and Liu (2008) studied and sequenced the stratigraphy and depositional history of Eocene-Miocene carbonates and evaporates of the northern Mesopotamian Basin. They found that the Oligocene Kirkuk Group has two sets of pro-gradational shelf to shelf-margin limestones that pass laterally into basinal globigerinid limestones. They also mention that the tops of the shelf sequences were sub-aerially exposed and eroded, with pro-grading upward steepening shelf margins.

The lithostratigraphy of Late Oligocene-Early Miocene successions of Qaradagh-Kalawe Anticlines, south of Sulaimani, in the north of Iraq, was studied by Khanqa et al. (2009); they considered the conglomeritic sequence between the Pila Spi Formation and Lower Fars formation, which is known as Basal Fars conglomerates, to be equivalent in part to the Palani and Euphrates Formations.

#### 1.4 Study area:

The study area is located in the southern part of Kurdistan, northeastern Iraq, bounded by latitude 34° 45' to 35° 20' and longitude 45° 15' to 45° 50' (Table 1.1). The study area covers eight outcrops in four main structures; the Sagma, Aj-Dagh, Bamu and Sharwal-Dra anticlines in the south of the Sulaimani area (Figure 1.5). A basement fault separates the two former structures from the others called Khanaqin Fault.

Sections	Age	Latitudes North	Longitudes East	Elevation (A.S.L.)
1. Sagma	L. Eocene – E. Miocene	35° 18' 20"	45° 16' 55"	1307m
2. Zinana	L. Eocene - E. Miocene	35° 11' 30"	45° 16' 50"	822
3. Hazar Kani	L. Eocene - E. Miocene	35° 09' 06"	45° 17' 07"	779m
4. Core of Aj Dagh	L. Eocene - E. Miocene	35° 08' 38"	45° 17' 15"	720
5. Awa Spi	L. Eocene - E. Miocene	35° 08' 57"	45° 17' 02"	842m
6. Bamu	L. Eocene- E. Miocene	34° 55' 51"	45° 44' 06"	690m
7. Bellula	L. Eocene- E. Miocene	34° 52' 10"	45° 46' 28"	650
8. Sharwal Dra	L. Oligocene- E. Miocene	34° 47' 35"	45° 41' 12"	734

Table.1.1: Geographic coordinates of the eight selected sections of studied area.

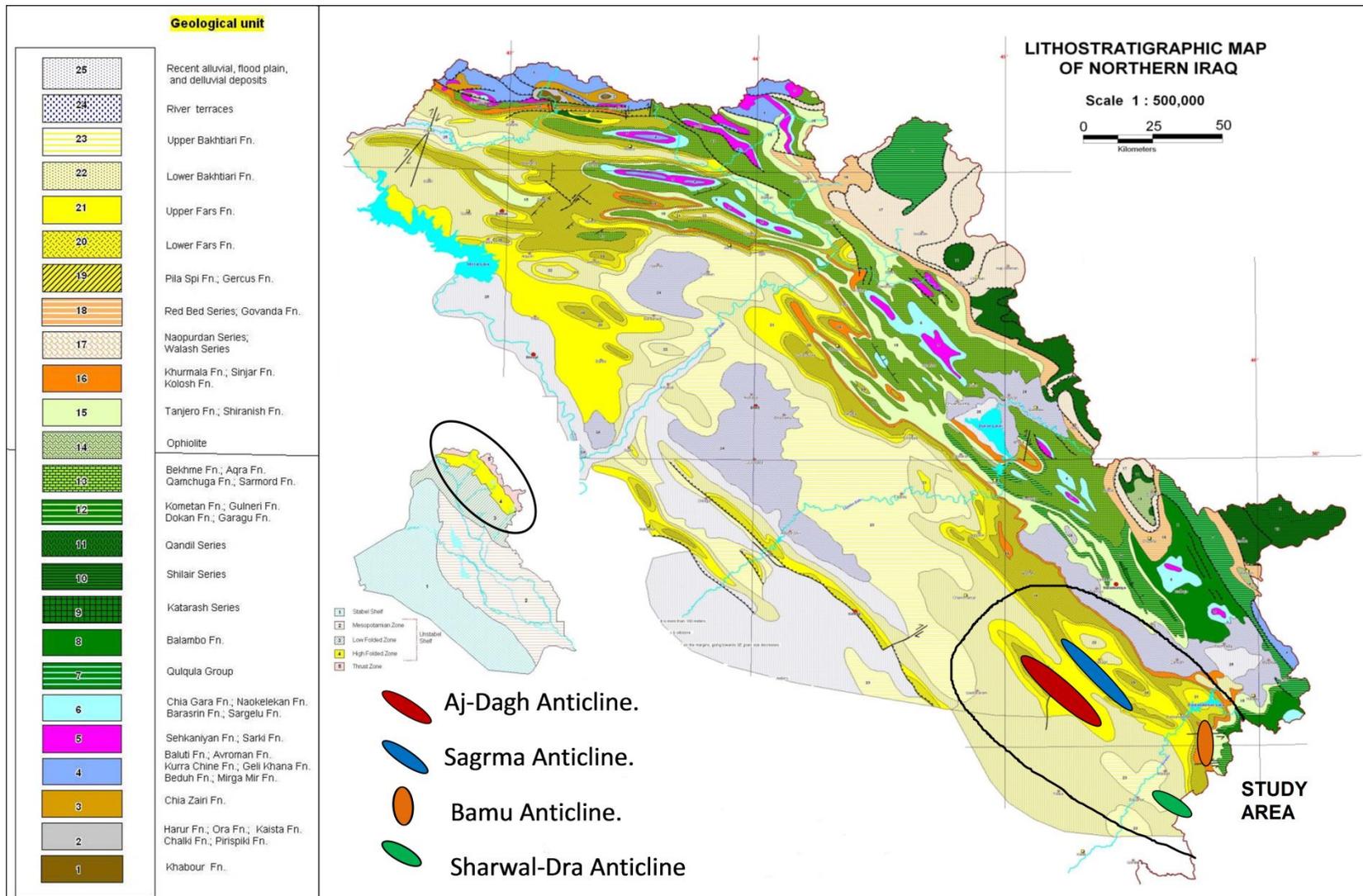


Figure 1.5: Geological map of the four structures in the studied area.

**Sagirma anticline:**

This structure is considered as one of the classical anticlines of the Western Zagros Fold thrust belt (Lawa, 2004), with major northwest - southeast trends extending in length for 50 km and 2-3 km in width. It forms a double plunging anticline with a north eastern limb which is steeper (even occasionally overturned) than the southwestern limb. The northeastern limb mostly consists of Late Eocene carbonates and is represented by the Avanah and Pila Spi Formations (Figure 1.6), while its core consists of Paleocene siliciclastic facies of the Kolosh Formation (Lawa, 2004). This fold represent the middle part between the Golan structures (southeast extension) while the Bazian structure represents its northwest continuation. One section has been logged at the southwestern limb of this structure named the Sagirma (SG) section (Figure 1.7).

**Aj Dagh anticline:**

The Aj-Dagh anticline represents the third structure in a range called the Ajdagh- Baski zabun and Khuweelen structures which consists of an enechelon series of anticlines trending predominantly northwest-southeast. The Aj Dagh anticline represents an asymmetric double plunging anticline, with a northeast limb gently dipping at about 25 degree, and a steeper southwest limb dipping at about 45 degree; the steeper limb is dissected by several reverse faults. A transverse fault, expressed on the surface by the Awa Spi river, mostly cuts across the southeast plunge of this structure, with five sulphureous springs with a discharge of more than 20 litres per second (Babashekh, 2000). Four outcrops have been logged; two of them located at

northeastern limb of Aj Dagh structure named Zinana (Z) and Hazar Kani (AS) sections (Figure 1.8, 1.9), the third outcrop is located at the core of Aj Dagh Anticline (CA) (Figure1.10) and finally the Awa Spi outcrop (AW) located at southwestern limb of this structure (Figure 1.11).



Figure 1.6: Northeastern limb of Sagma anticline comprised of Late Eocene Pila Spi Formation. Scale: 1cm=25m.



Figure 1.7: Selected section from southwestern limb of Sagma anticline. Scale: 1cm=10m.



Figure 1.8: Selected section of Zinana outcrop from northeastern limb of Aj Dagh Anticline.



Figure 1.9: Selected section of Hazar Kani outcrop from northeastern limb of Aj Dagh Anticline.



Figure 1.10: Selected section from core of Aj-Dagh anticline; person for scale marked in red colour.



Figure 1.11: Southwestern limb of Aj-Dagh anticline with a discharge of sulphureous water called Awa-Spi. Scale bar is 5 metres.

**Bamu anticline:**

This north-south trending structure deviate from the typical northwest-southeast Zagros trend is situated near the Iraqi–Iranian border. The eastern limb is comprised of horizontal strata (Figure 1.12), while the western limb is vertical to partly overturn with Mid. Eocene –Oligocene–Early Miocene Formations (Figure 1.13). The Kolosh Formation, of Paleocene age, is recorded from the core of this structure (Yokhana and Hradecky, 1978) and (Lawa, 2004). Both limbs are separated by a reverse fault with displacement of 150m. The length of structure is about 20 km and its average width is about 2.3 km. The Oligocene sequence was detected only from the western limb overlying thick Eocene carbonates (Bahnam, 1979). The deviation from a classical northwest-southeast trend toward north-south was also recognized by Lawa (2004) and interpreted as reflecting an earlier configuration of the Arabian plate boundary. Two outcrops have been logged at the western limb of this structure; the Bamu Gorge (BS) and Bellula Gorge (BL) outcrops.

**Sharwal Dra anticline:**

The Sharwal Dra anticline axis is oriented northwest-southeast and is located near the Iraqi-Irani border. The north eastern limb dips 10 degree, whereas the southwestern limb is more than 25 degree. Oligocene Formations are exposed in the in the core of the anticline which overlain by Fatha and Injana Formation of Early-Middle Miocene age, and covered unconformably by Upper Bakhtiari Formation of Pliocene age. Broad synclines separate this structure from the Bamu anticline, with their axes buried under thick Quaternary sediments.



Figure 1.12: Eastern limb of Bamu anticline with horizontal strata, mostly Eocene age.



Figure 1.13: Western limb of Bamu Anticline comprises of vertical strata from Eocene-Oligocene-Miocene age.

The southeastern plunge is mostly within Iranian territories, and only the northwestern plunge is found in the Iraqi Kurdistan region. Only one outcrop has been logged at the southwestern limb of this structure named Sharwal Dra (SD) (Figure 1.14), the researcher could not log more than 122 metres because of the nature of this outcrop which is located on the Iraqi-Iranian border. The Kirkuk Group may also occur on the northeastern limb of this structure, but because of an unexploded bomb in the soil of this area a relic of the Iraqi-Iranian war, any outcrop could not be logged (Figure 1.15).



Figure 1.14: Southwestern limb of the Sharwal Dra anticline.



Figure 1.15: Northeastern limb of Sharwal Dra Anticline. Field of view is 300 metres.

### 1.5 Data collection:

Eight sections were logged covering 673 metres of stratigraphy and 319 samples were collected from the south of Sulaimani area (Table 1.2). Sampling was designed to capture all major lithologies including changes in petro-physical properties.

No.	Sections	No. of samples	Total thickness (m)
1	Sagrna	33	50
2	Zinana	34	45
3	Hazar Kani	10	26
4	Core of Aj Dagh	52	84
5	Awa Spi	37	35
6	Bamu	30	125
7	Bellula	73	186
8	Sharwal Dra	50	122
	Total	319	673

Table 1.2: Total thickness and sample number from outcrops in the studied area.

## **Chapter Two:**

### **Geological Setting**

#### **2.1 Oligocene tectonics:**

The megasequence AP11 (34 Ma-Quaternary) (Figure 2.4) is subdivided by Jassim and Goff (2006) into three sequences of latest Eocene-Oligocene, Early-Middle Miocene, and Late Miocene-Recent age. This Megasequence is associated with the collision of Neo-Tethyan terrains along the north and east sides of the Arabian Plate (Figure 2.1), resulting in folding and thrusting of the Neo-Tethyan terrains. Co-incident was the opening of the Gulf of Aden and the Red Sea, accompanied by thermal uplift, flood basalts, and rifting on the south and west sides of the plate. The Gulf of Aden opened first during Oligocene time, followed by the Red Sea in the Early Miocene (Makris and Henke, 1992 and Hughes and Bydoun, 1992).

During the Upper Eocene, in Iraq, the signs of a new phase of Tertiary folding appeared. Basinal subsidence now strongly reduced or ceased altogether. The intensity of the folding and the subsequent uplift were increasing during the Oligocene and led to the complete uplift of most of the basin at the end of Oligocene (Numan, 2000).

There is more than one classification of tectonics in Iraq: according to Sharland et al., (2001) Iraq is divided tectonically into three different areas: Stable Shelf, Unstable Shelf and the Zagros Suture. The Stable Shelf consists of buried antiforms and arches, with no surface anticlines, subdivided into Ma'ania-Rutba Zone and Salman-Hadhar Zone. The Unstable Shelf, where surface anticlines are present, is subdivided into the High Folded Zone with

high amplitude of anticlines, the Foothill Zone with low amplitude of anticlines and the Mesopotamian Zone. The Zagros Suture; is composed of thrust sheets of radiolarian chert, igneous and metamorphic rocks, subdivided into the Shalair Zone, Eugeocyncline, Northern Thrust Zone and Miogeocyncline (Figure 2.2). The Stable Shelf trends north-south due to Palaeozoic tectonic movements, while, the Unstable Shelf and Zagros Suture trend northwest-southeast or east-west and reflects Cretaceous-Recent Alpine orogenesis. While, Muman (2000) divided Iraq into seven divisions rather than three

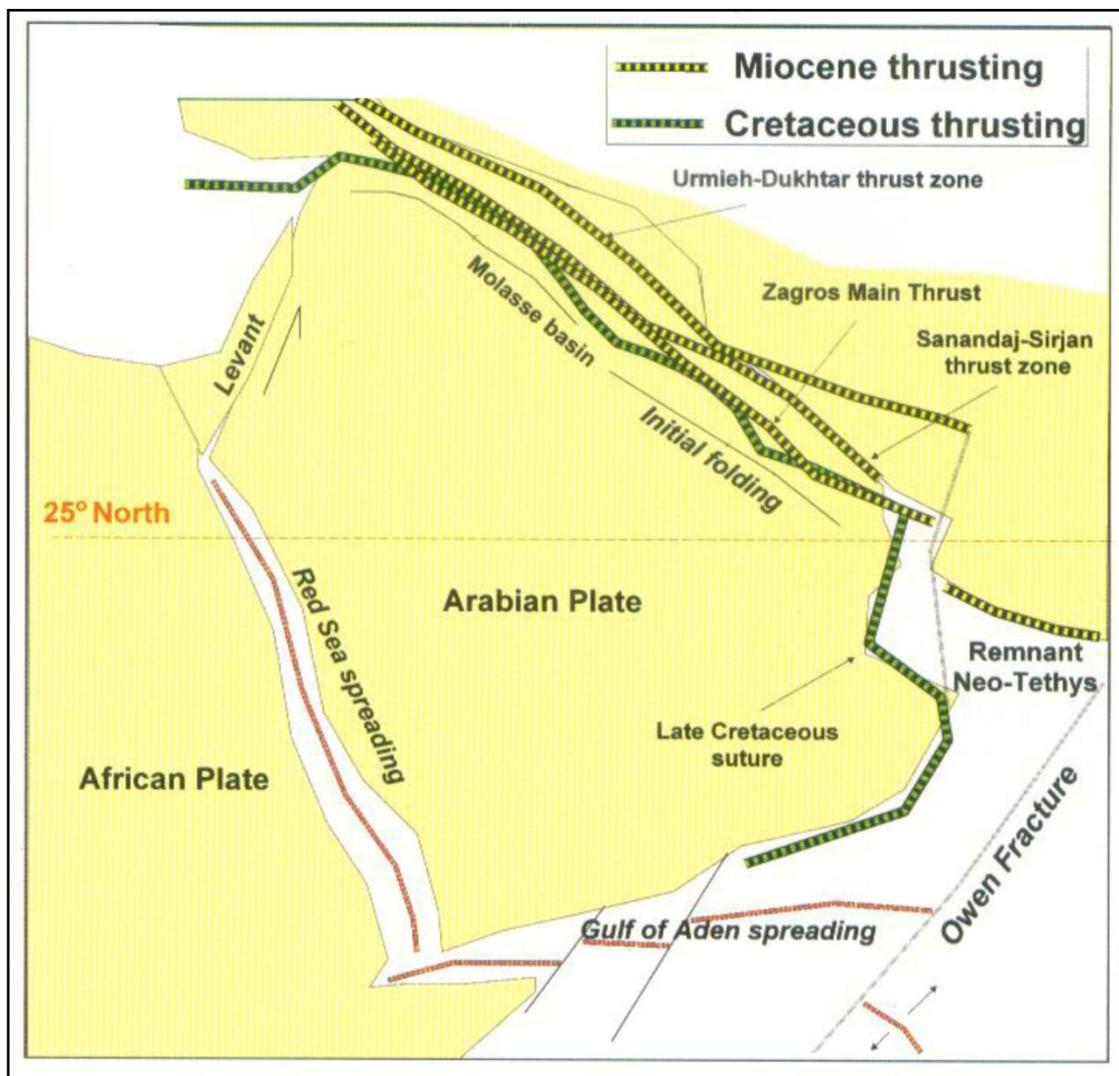


Figure 2.1: Oligocene-Recent geodynamic development of Arabian Plate showing closing of Neo-Tethys with the opening of Gulf of Aden and Red Sea (Jassim and Goff, 2006).

(Figure 2.3); subductional tectonic facies, zone of imbrication of the foreland basin, highly folded zone of the foreland basin, suspended basin, the sagged basin of the Mesopotamian zone, Salam zone and Rutba-Jazira zone. The first and second divisions are equivalent to the Zagros Suture; the third, fourth and fifth divisions are equivalent to the Unstable Zone, and the sixth and seventh are equivalent to Stable Zone.

Al-Qayim (2006) proposed that the Oligocene basin developed in a relatively narrow, down warping sag-interior basin following an interval of uplift and widespread regression. It is situated in the Mesopotamian Zone in the Unstable Shelf (Figure 2.2), in the Makhul-Hamrin Subzone of Foothill Zone of the Unstable Shelf, in the Jazira Subzone and on the north margin of the Rutba Subzone of the Stable Shelf (Jassim and Goff, 2006). Oligocene sediments are absent on the Butma-Chamchamal Subzone, High Folded Zone, over most of the southwest part of the Balambo-Tanjero Zone and in the Northern Thrust Zone in the northeast part of Iraq due to large uplift during Oligocene time. While, In the west of Iraq Oligocene sediments are absent over most of the Rutba Subzone, the Salman Zone and on the Zubair and Euphrates Subzone of the Mesopotamian Zone.

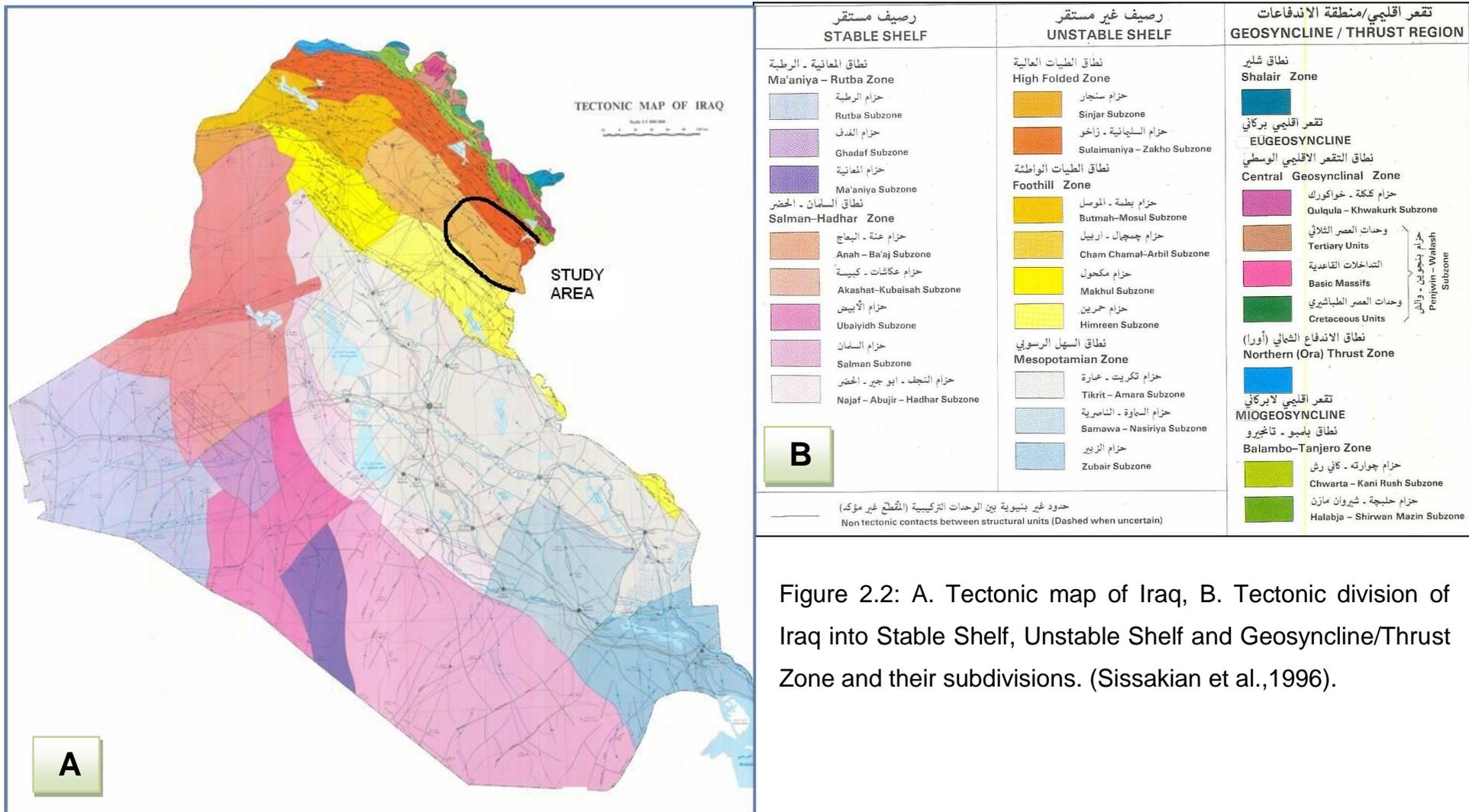


Figure 2.2: A. Tectonic map of Iraq, B. Tectonic division of Iraq into Stable Shelf, Unstable Shelf and Geosyncline/Thrust Zone and their subdivisions. (Sissakian et al.,1996).

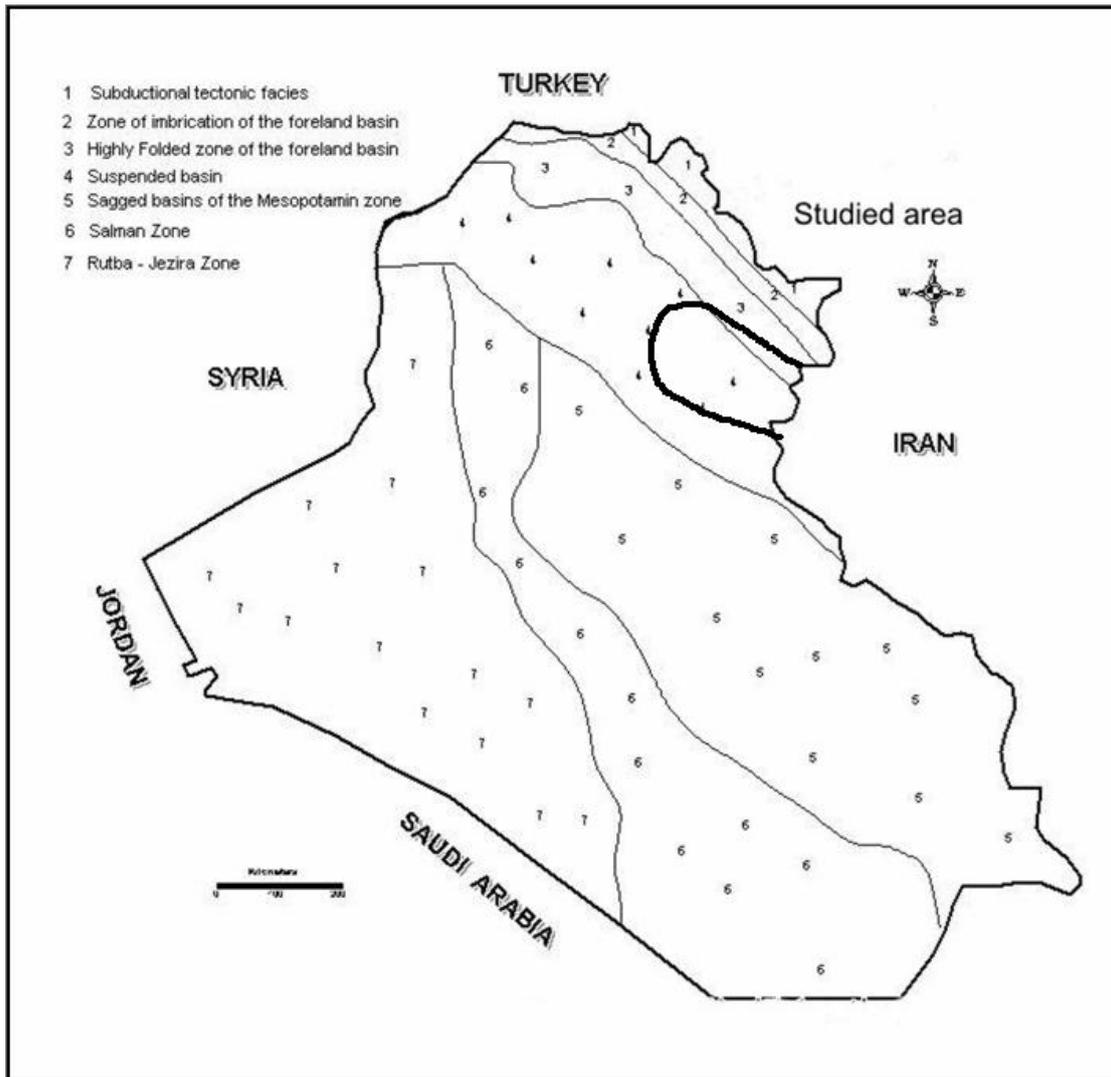


Figure 2.3: Tectonic division of Iraq (after Numan, 2000).

## **2.2 Palaeogeography of Oligocene:**

In general, the palaeogeography and depositional history of the Oligocene follows quite closely the pattern set in Middle-Late Eocene time. During the Middle-Late Eocene (49.0-33.7 Ma) interval the deposition of the Jaddala Formation (in Iraq and Syria), Dammam Formation (in Arabian Peninsula), Pebdah Formation (in Iran) took place with their regional equivalents (Figure 2.4) which represents the second-order depositional sequence within AP10 (Sharland et al., 2001). Global sea-levels were gradually falling (Haq et al., 1987), but it is possible that only a relatively small part of the Arabian Shield was exposed, at least at the beginning of the depositional sequence.

The Oligocene basin is located between northwest and northeastern shores of the Arabian Gulf in Mesopotamian Zone (for more detail see section 2.1). This is separated from thrust belt by comprising the High Folded Zone. It was a relatively narrow, weakly subsiding basin. Two northwest-southeast trending belts of thick sequences of fringing reefs were developed along western and eastern shorelines of the basin and thin marls were deposited in the centre of the basin which was starved of sediment supply (Figure 2.5).

Because Oligocene sediments were deposited after the gradual regression of sea level from the Eocene, almost the entire Arabian Plate was exposed. The Neo-Tethys sea was closing rapidly and the Zagros foreland basin along the northeastern plate margin once more became a narrow trench in which mainly limestones were deposited along its margins. In the central part of the basin Pebdah-type sedimentation (Palani Formation) continued with silty to sandy shales alternating with argillaceous limestone intercalation (Ziegler, 2001) (Figure 2.6).

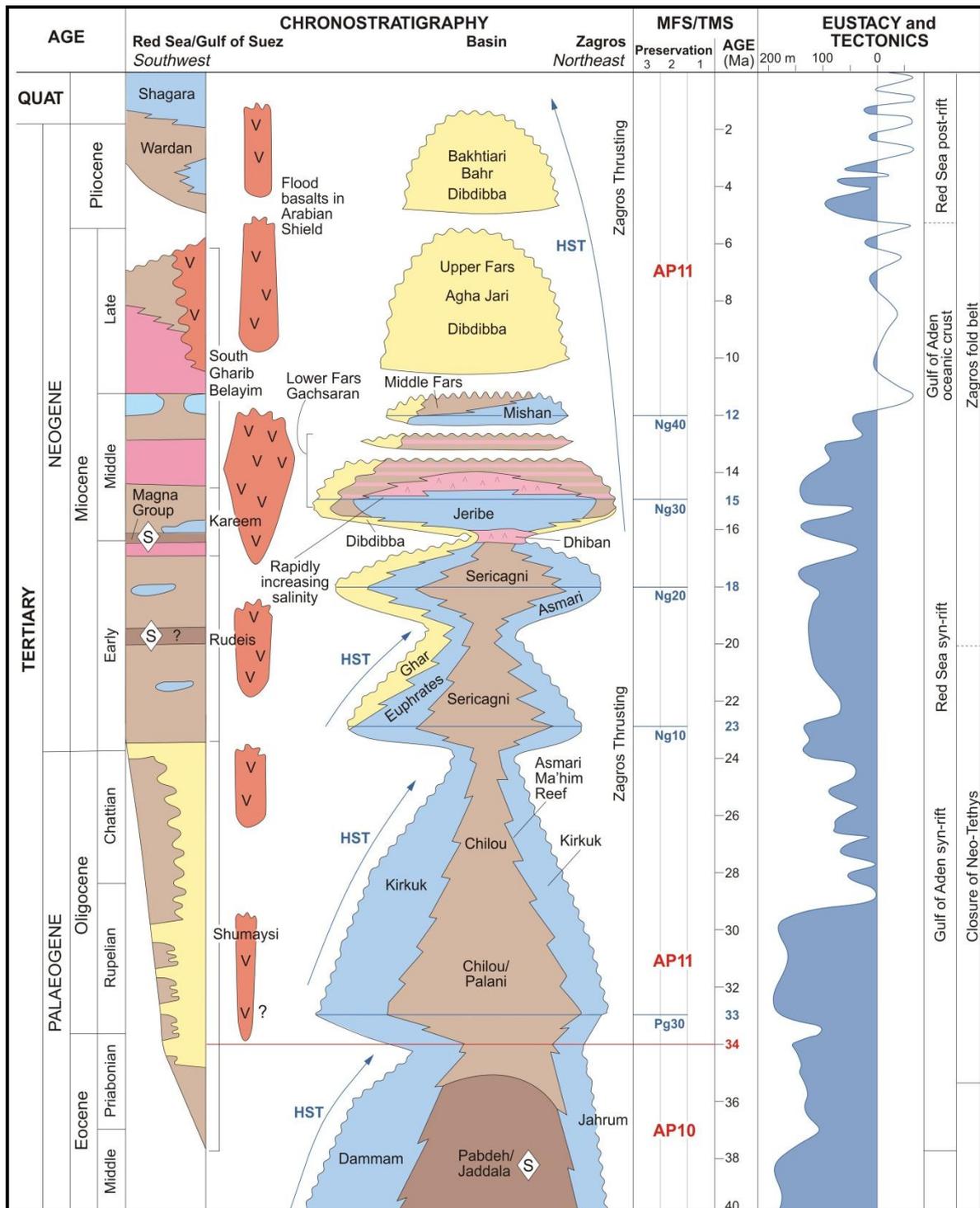


Figure 2.4: Chronostratigraphic section for Megasequence AP11 (34 Ma to present), derived from (Sharland et al., 2001).

Farther east toward the High Zagros the deposition of the variegated marly to silty, in part calcareous, Razak Formation indicated uplift and erosion of the

eastern plate margin. The flanking shelves of the Zagros foredeep are composed of light coloured, well jointed, micritic and foraminiferal limestones with *Nummulites* and miliolids that form the well-known reservoir rocks of Asmari Formation (Ziegler, 2001).

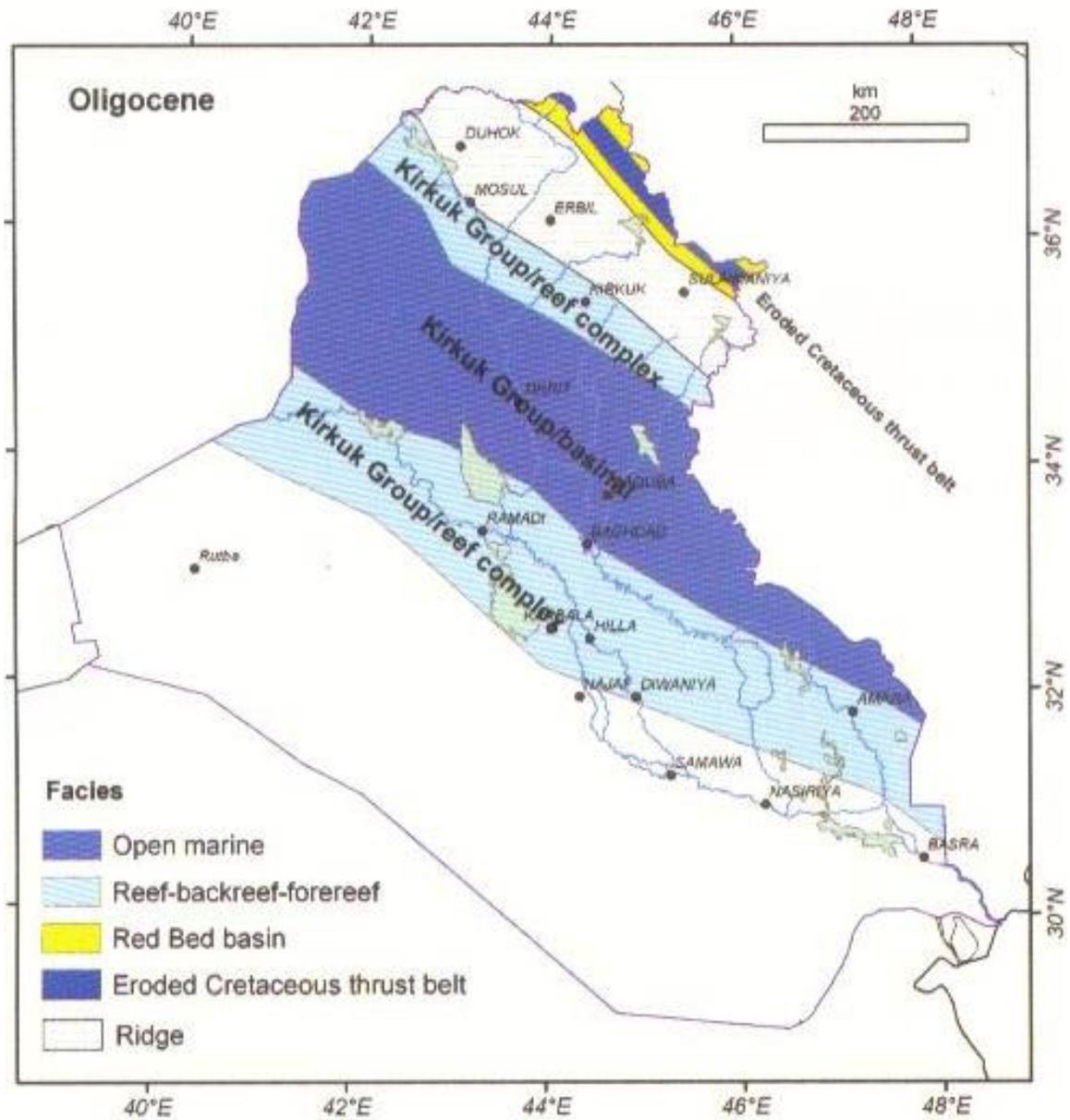


Figure 2.5: Palaeogeography and facies trend of Oligocene (Jassim and Goff, 2006).

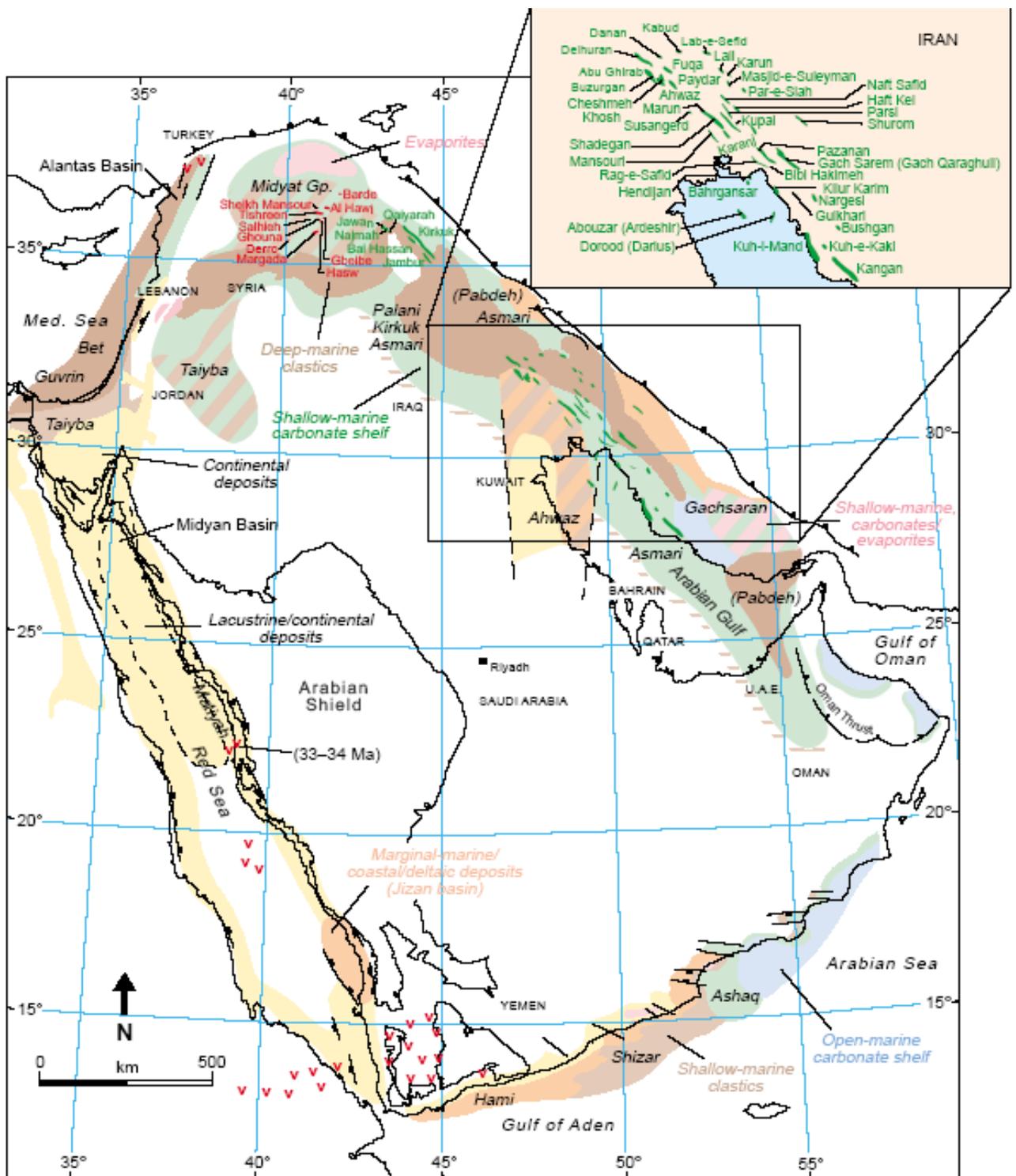


Figure 2.6: Oligocene facies deposition of the Palani, Kirkuk and Asmari Formations with their regional equivalents. ( Ziegler, 2001).

### **2.3 Introduction to the stratigraphic division of the Oligocene of Iraq:**

The Oligocene-Early Miocene succession in Iraq (Kirkuk Group) is composed of nine formations (Shurau, Sheikh Alas, Palani, Bajawan, Baba, Tarjil, Anah, Azkand and Ibrahim Formations) called the Kirkuk Group. Henson (1950a) established the original stratigraphy and the reef concept (backreef, reef, forereef and basin) for this group in the Kirkuk Oil Field.

It has been argued by Buday (1980) that the Oligocene succession is bounded by breaks and unconformities at both its lower and upper contacts. It would be located in the first sequence of Megasequence AP11 and Ng10 (Jassim and Goff, 2006) (Figure 2.4).

Bellen et al. (1959) divided the Oligocene section into three sequences of Early (Shurau, Sheikh Alas and Palani Formations), Middle (Bajawan, Baba and Tarjil Formations) and Late (Anah, Azkand and Ibrahim Formations) Oligocene age (as discussed in Chapter One section 1.3), based on their relative stratigraphic position rather than age diagnostic fossils. These sequences show lateral facies variations from basinal to reef and backreef facies (Table 2.1). Ditmar et al., (1971) modified Bellen's divisions into only two sequences rather than three based on lithological and well log correlation; they arranged the formations into two sequences: a lower sequence comprising the Palani, Sheikh Alas, Shurau and Tarjil Formations and an upper sequence comprising the Ibrahim, Anah, Azkand, Bajawan and Baba Formations (Table 2.2).

Depositional Envi. Oligocene	Backreef	Reef-Forereef	Basinal
Late Oligocene	Anah Formation	Azkand Formation	Ibrahim Formation
Middle Oligocene	Bajawan Formation	Baba Formation	Tarjil Formation
Early Oligocene	Shurau Formation	Sheikh Alas Formation	Palani Formation

Table 2.1: Oligocene stratigraphy and depositional environments (after Bellen et al., 1959).

Depositional Envi. Oligocene	Backreef	Reef-Forereef	Basinal
Upper Oligocene	Anah Formation, Bajawan Formation	Azkand Formation, Baba Formation	Ibrahim Formation
Lower Oligocene	Shurau Formation	Sheikh Alas Formation	Tarjil Formation, Palani Formation

Table 2.2: Oligocene stratigraphy and depositional environments (after Ditmar et al., 1971).

Ditmar et al. (1971) divided the Oligocene sequence into a Lower and an Upper sequence of carbonate strata, each sequence consists of back reef/reef, forereef, and basin facies .

### **2.3.1 Lower sequence:**

The lower sequence comprises the reefal Sheikh Alas and Shurau Formations and the basinal Palani and Tarjil Formations.

#### **2.3.1.1 Basinal (Palani and Tarjil Formations):**

##### **2.3.1.1.1 Palani Formation:**

The Palani Formation was first defined by Bellen (1956) from well Kirkuk-85 and recognized as a dolomitized globigerina limestone (Bellen et al., 1959), in the upper part composed of dolomitic, *Nummulites* rich soft limestone. There is only one surface exposure of the Palani Formation in the Qara Chauq structure.

There have been discussions about the age of the Formation, which was assumed to be Early Oligocene based on its stratigraphic position. However, Ditmar et al., (1971) reported the age of Palani Formation as Late Eocene. The Formation may extend from latest Eocene to Early Oligocene (Jassim and Goff, 2006).

The depositional environment of the globigerinal limestones in the Formation was interpreted as outer shelf to basinal (Majid and Veizer, 1986).

##### **2.3.1.1.2 Tarjil Formation:**

This Formation was defined by Bellen (1956) from well Kirkuk-85. It is composed of slightly dolomitized globigerina marly limestone; it is rich in foraminifera including *Nummulites intermedius* and *Lepidocyclina* (Bellen et al., 1959). According to Jassim and Goff (2006) these fossils indicate the

Formation was deposited in an outer shelf environment and *Nummulites intermedius* appears to be restricted to the Early Oligocene. While, Majid and Veizer, (1986) found that the lower part of the Tarjil Formation in the Kirkuk region was deposited in an open marine, and the upper part in a toe of slope environment.

Jassim and Goff (2006) recorded that the Tarjil Formation is crops out in Qara Chauq area and consists of 20 m of hard, yellowish grey limestone overlain by thick bedded limestone with fossils including: *Nummulites sp.*, *Lepidocyclina sp.*, *Rhapydionina sp.*, *Rotalia viennoti*, *Lenticulina sp.*, gastropods, echinoids, algae, bryozoa and bivalves.

### **2.3.1.2 Reef-backreef and forereef:**

#### **2.3.1.2.1 Sheikh Alas Formation:**

The Sheikh Alas Formation is characterized by buff, brownish grey to pinkish brown, dolomitized, porous and locally recrystallized Nummulitic limestone. It was defined by Bellen (1956) from an outcrop in the north dome of the Qara Chauq structure, it represents the forereef facies of the lower Oligocene cycle.

The Formation, in the type locality, contains only rare, poorly preserved *Nummulites fichteli* (Bellen et al., 1959), while in the Kirkuk area *Nummulites intermedius*, *Nummulites inceassatus*, *Operculina cf. complanata*, and *Rotalia viennoti* occur.

Majid and Veizer (1986) suggested that the lower part of this Formation was deposited in a foreslope environment, whereas the upper part represents a lagoonal environment, without any explanation why these two different facies occur next to each other.

#### **2.3.1.2.2 Shurau Formation:**

The Shurau Formation consists of two parts; a lower porous coralline limestone and upper grey and dense limestone which was first defined by Bellen (1956) in well K-109 in the Kirkuk structure. Fossils in the type locality are relatively rare.

In the Kirkuk area the lower part of the Formation was deposited in a reef, and the upper part in a tidal flat environment (Majid and Veizer, 1986). However, in the west of Iraq, the formation was deposited in a reef and partly in a backreef environment (Jassim et al., 1984). It represents the reef-back reef facies of the lower Oligocene reef cycle.

#### **2.3.2 Upper Sequence:**

The Upper Sequence comprises the reef complex of Baba, Bajawan, Azkand and Anah Formations and the basinal Ibrahim formation. These formations pass both vertically and horizontally into each other.

##### **2.3.2.1 Ibrahim Formation:**

The Ibrahim Formation is consists of globigerina marly limestones with traces of pyrite and occasional glauconite. It shows slight dolomitization (Bellen, et al, 1959) which was first defined by Bellen (1956) from well Ibrahim-1, in the Sheikh Ibrahim structure of the Foothill Zone, northwest of Mosul. The thickness of the formation at its type section is about 56m (Buday, 1980). This Formation was deposited in a basinal environment and represents the basinal equivalent of the upper Oligocene reef cycle.

### **2.3.2.2 Reef, backreef and forereef:**

#### **2.3.2.2.1 Baba Formation:**

The Baba Formation consists of porous, dolomitized fossiliferous limestone (Bellen, 1959) defined by Bellen (1956) from well Kirkuk-109.

Ctyroky and Karim (1971a) studied the outcrops of this formation in the Anah area west of Iraq and identified the following fauna: *Rotalia viennoti*, *Lepidocyclina cf. elephantiana*, *L. cf. dilatata*, *L. cf. morgani*, *Archaias sp.*, *Triloculina sp.*, *Quinqueloculina sp.*, *Robulus sp.*, *peneroplis sp.*, *praerhapydionina sp. (?)*, *Spiroclypeus cf. marginatus*, ostracods., gastropods, *Spirorbis sp. (?)*, *Chlamys sp. (?)*, corals and fish teeth. This fauna indicates a Middle Oligocene age. However, Bellen et al., (1959) dated the upper part of the Formation in the Anah area as early Late Oligocene.

Based on the fauna, the Formation was deposited in a fore-reef environment along both the northeast and southwest margins of the Oligocene basin (Majid and Veizer, 1986).

#### **2.3.2.2.2 Bajawan Formation:**

Bellen (1956) defined the Bajawan Formation from well Kirkuk-109. It consists of the alternation of tight miliolid limestone with more porous, patchily dolomitized coralline algal reef limestone, with relatively abundant coral fragments and thin argillaceous limestone beds (Bellen et al., 1959). The total thickness is about 40 m.

Based on the fossil content and the amount of porosity, this formation was subdivided to two parts as follows:

**A)** The upper dense unit:

This consists of dense miliolid limestone which is partly chalky or dolomitized. Its upper part is mostly brecciated; therefore it looks like the basal conglomerate of the overlying Fatha Formation.

**B) The lower porous unit:**

This consists of alternation of two types of rocks, one being similar to that of the dense unit of Bajwan with a moderately higher degree of recrystallization, dolomitization and porosity, and the second which consists of a porous and vuggy dolomitic limestone.

Two faunal zones were identified within Bajawan Formation (Bellen et al., 1959): a lower *Delicata* Zone characterized by *Praerhapydionina delicata* and an upper *Kirkukensis* Zone characterized by *Archais kirkukensis*, indicating the formation is probably of Late Oligocene age. Ditmar et al. (1971) claimed that there is no age difference between the Bajawan and Baba, Anah and Azkand Formations and that these four Formations belong to one sequence.

The lower part of the Bajawan Formation was deposited in a reef and partly backreef environment; the upper part was deposited on mud flats (Majid and Veizer, 1986).

**2.3.2.2.3 Azkand Formation:**

The Azkand Formation consists of massive, dolomitic and recrystallized limestone, generally with high porosity (Bellen et al., 1959) which was defined by Bellen (1956) in the Azkand area of Qara Chauq structure. The thickness is variable, but it is usually around 100m (Buday, 1980).

Fossils recorded from the formation include *Heterostegina cf. assilinoidea*, *Miogypsinoidea complanata* in the upper part, and in the lower part *Lepidocyclina spp.* (Bellen et al., 1959), the presence of *Heterostegina cf.*

*assilinoidea* indicates a Late Oligocene age, and the environment of deposition is represent the fore-reef environment.

#### **2.3.2.2.4 Anah Formation:**

Bellen in 1956 also defined the Anah Formation from the Euphrates valley about 15 km west of Al Nahiyah village near Anah. It is composed of grey, brecciated, recrystallized, detrital and coralline limestone, massive in the lower part and becoming thinner bedded upwards (Bellen et al., 1959). Jassim and Goff (2006) pointed out that the formation is mostly a reef deposit, alternating with backreef, miliolid facies.

Ctyroky and Karim, (1971a) studied outcrops of this Formation from the Euphrates valley, they reported: *Subterranopyllum thomasi*, *Archaias kirkukensis*, *Austrotrillina howchini*, *Rotalia viennoti*, miliolids, *Robulus* sp., *Bolivina* sp., *Textularina* sp., *Trioculina* cf. *gibba*, *Trioculina* sp., *Quinqueloculina* sp., *Peneroplis thomasi*, *P. evolutus*, *Operculina* cf. *complanata*, *Lepidocyclina* sp., *Miogypsinoides complanata*, *Hydrobia* sp. (in a reef?) Indet., *Cons* sp. Juv., *Scaphander* sp., *Acteonia* sp., *Nassa* sp., *Natica* sp., *Mitra* sp., *Cerithium* sp., *Pyramidella* sp. Juv., *Tympanotomus margaritaceus*, *Oliva* sp., *Chlamys* sp., *Euchilus* sp. Juv., bryozoa remains indet, *Heliastrea defrancei*, fish bones. According to Ctyroky and Karim, (1971a) the presence of *Miogypsinoides complanata* indicates a latest Oligocene age.

#### **2.4 Oligocene global climate change:**

During the 'Oligocene' 23.03 - 33.9 million years (Ma), Earth's climate changed significantly. About 34 million years ago, Earth's climate shifted from a relatively ice-free world to the glacial conditions on Antarctica characterized by huge ice sheets. The evidence for Northern Hemisphere polar ice evidence is controversial. The change in temperature of earth during this climate transition remains poorly understood. In Both hemispheres high-latitude (45 to 70 degrees) temperatures decreased on average by  $\sim 5^{\circ}\text{C}$ , where the original temperature before the cooling was  $\sim 20^{\circ}\text{C}$  (Liu et al., 2009).

The change in the palaeoclimate and palaeoenvironment can be seen easily during Oligocene time by the variation in fossil assemblages from Rupelian to Chattian (Lower and Upper Oligocene Stages). A strong contrast in foraminiferal assemblages was reported by Man and Simaey (2004) from the deeper marine cooler upper Rupelian assemblage to the shallower marine to restricted marine subtropical fauna at the base of Chattian. This suggests that the early Chattian transgression is genetically related to a widespread major warming pulse, known as the Late Oligocene Warming Event (Man and Simaey 2004, Zachos et al., 2001). The shallow marine microfacies from Kirkuk Group in the study area mostly precipitated during this Warming Event (Figure 2.7).

The global climate evolution during the Cenozoic Era includes gradual trends of warming and cooling driven by tectonic processes. The two glacial periods with Late Oligocene warming event (see above paragraph) was defined (Zachos et al., 1996; Zachos et al., 2001; Miller et al., 2008); the first glacial period is just above the Eocene/Oligocene boundary (34.0 Ma) (Figure 2.7). It

is a 400-ky-long glacial that initiated with the sudden appearance of large continental ice sheets on Antarctica. This transition, referred to as Oi-1. The second glacial one is the Oligocene/Miocene boundary (~23 Ma) and consists of a brief but deep (~200 ky) glacial maximum. This event, referred to as Mi-1. Both Oi-1 and Mi-1 were accompanied by accelerated rates of turnover and speciation in certain groups of biota. Of particular significance are; the rise of modern whales (i.e., baleen), the shift in continental floral communities at the E/O boundary and the extinction of Caribbean corals at the O/M boundary.

Investigations of Oligocene climate change in the equatorial Pacific were reported by Wade and Palike (2004) and Palike et al., (2006). The stable isotope records of Oligocene climate from the equatorial Pacific reveal a pronounced “heartbeat” in the global carbon cycle and periodicity of glaciations. This heartbeat consists of 405,000-, 127,000-, and 96,000-year eccentricity cycles and 1.2-million-year obliquity cycles in periodically recurring glacial and carbon cycle events (Palike et al., 2006).

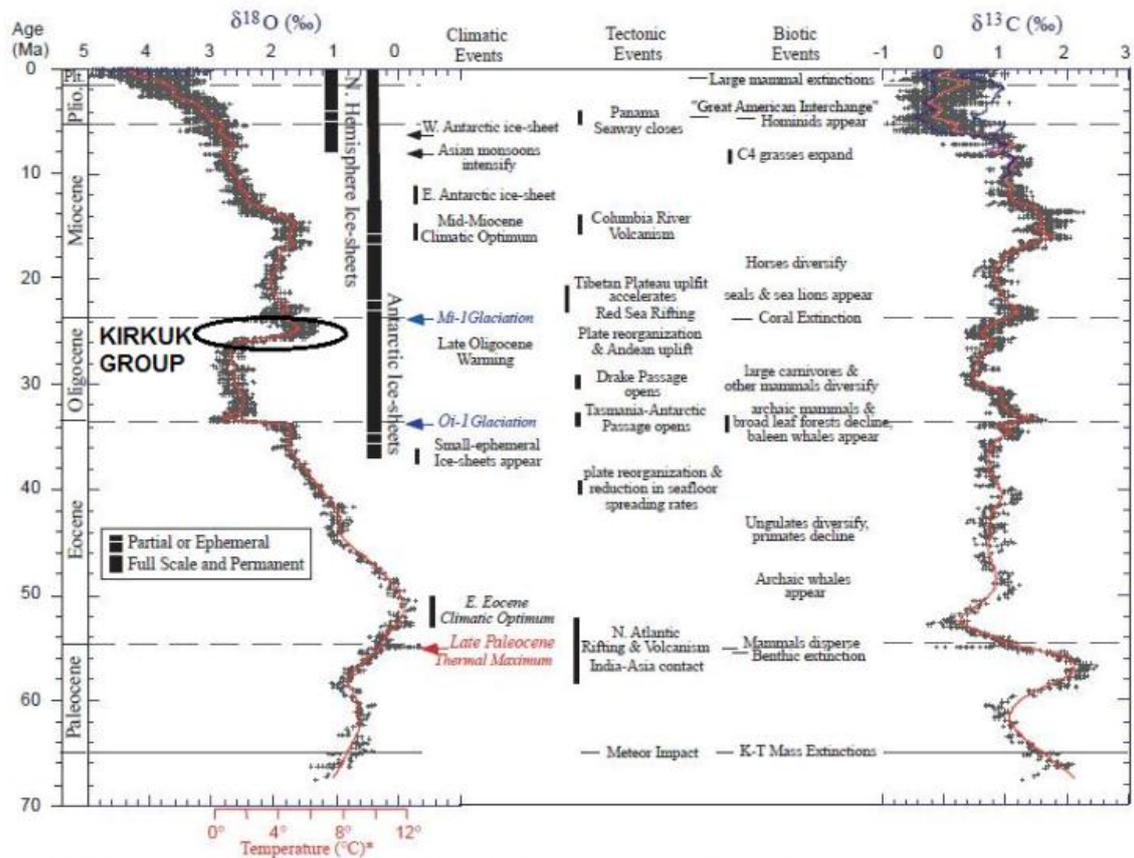


Figure 2.7: Oxygen-Carbon isotope showing the Oligocene (Oi-1) and Miocene (Mi-1) glaciations with Late Oligocene warming event (Zachos et al., 2001) including shallow microfacies of Kirkuk Group where deposited during Late Oligocene Warming.

## **Chapter Three:**

### **Biostratigraphy**

#### **3.1 Preface:**

A regional investigation of fossils from the Late Eocene as well as from Oligocene-Early Miocene Kirkuk Group has been carried out in northeast Iraq; the selected sections are characterized by being rich in fossils, mostly benthic foraminifera; occasional planktonic foraminiferal and macro fossils including bivalves, gastropods, echinoids fragments, red algae and coral bioherm are also present. Index fossils of benthic foraminifera have been used for the purpose of determining the age of the Kirkuk Group, because of their young age, wide geographical distribution and abundance in the selected sections.

For fossil recognition and zonation, a large number of sources have been used, the most important are: Henson, 1950b; Bellen, 1956; Bellen et al., 1959; Smout and Eames, 1958; Adams, 1967, 1968; Sampo, 1969; Grimsdale, 1977; Al-Qayim and Khaiwaka, 1980; Muhammed, 1983; Sharbazheri, 1983; Al Hashimi and Amer, 1985; Majid and Viezer, 1986; Sartorio and Venturini, 1988; Abid and Sayyab, 1989; Jones and Racey, 1994; Racey, 1994; Cahuzac and Poignant, 1997; Serra-Kiel et al., 1998; Bou Dagher-Fadel, 2008.

The facies/biofacies implications of the forams present are discussed in the next chapter.

### 3.2 Zonation:

The selected studied sections are subdivided into biostratigraphic units (zones) based preliminarily on the shallow benthic foraminifera zonation (SBZ) (Cahuzac and Poignant, 1997; Serra-Kiel et al., 1998). The planktonic foraminifera were carefully studied, but no index fossils were recognized that could be assigned to global planktonic foraminifera zones. The zones are also supported by their stratigraphic positions, the lateral and vertical relationships, especially the prominent criteria of continuity and discontinuity between different formations of the eight sections studied. The term zone is commonly used for a minor stratigraphic interval in any category of stratigraphic classification; there are many kinds of zones depending on the stratigraphic characters under consideration, e.g. lithozones, biozones, chronozones (Hedberg, 1976).

Biozonation has been carried out on the Kirkuk Group by several authors in the Kirkuk area. Bellen (1956) and Bellen et al. (1959) divided the Kirkuk Group into three main zones, Lower, Middle and Upper Oligocene biozones, each of these being divided into three main facies groups ranging from lower to upper: reef/back-reef Shurau Formation (*Dendrophyllum*, *Paucialveolata*), Bajawan Formation (*Kirkukensis*, *Delicata*) and Anah Formation (*Miogypsinoidea*); fore-reef Sheikh Alas Formation (*Nummulites*), Baba Formation (*Lepidocyclina*, *Lepidocyclina/Nummulites*) and Azkand Formation (*Miogypsinoidea*, *Miogypsinoidea/Lepidocyclina*); and finally offshore (*Globigerina*) Palani, Tarjil and Ibrahim Formations (see Table 3.1).

Al-Hashimi and Amer (1985) studied Cenozoic microfacies and their fossil assemblages in Iraq. They divided the biozones of the Kirkuk Group into three

zones: Early-Middle Oligocene Palani Formation (*Globigerina ampliapertura* zone), Middle Oligocene Tarjil Formation (*Globigerina ampliapertura* and *Globorotalia opima* zones: “upper part”) and the late Middle-Upper Oligocene Ibrahim Formation (*Globorotalia opima* and *Globigerina angulisuturalis* zones) (see Table 3.1).

Majid and Veizer (1986) classified the Kirkuk Group in the Kirkuk Oil Field into the Early and Middle Oligocene biozones, without referring to the units of Late Oligocene age. The biozone division for Early and Middle Oligocene is the same as Bellen’s classification (see Table 3.1).

The previous classifications were based on the fact that the Kirkuk Group Formations belong to the Oligocene Epoch, whereas there are revised classifications for the Kirkuk Group indicating that the upper part of this group also contains units of Early Miocene (Aquitania) age. More recent studies show that biotas of Anah, Azkand and Ibrahim Formations were deposited in the Early Miocene not Late Oligocene age as previously thought (Al-Banna, 1997; Al-Banna et al., 2002; and Al-Banna, 2008). This is based on a palaeontological study of the Oligocene-Miocene interval between the Tarjil and Ibrahim Formations in western Mosul-Iraq. Earlier, Youhanna (1983) and Al-Eisa (1992) also revised the previously assigned upper biozone of the Late Oligocene, which was suggested by Bellen (1956) and Bellen et al. (1959), into the Early Miocene age using the planktonic foraminifera genus *Globigerinoides* in the Kirkuk area.

Abid and Sayyab (1989) restudied the foraminifera of the Anah Formation, aiming to solve some of the taxonomic and chronology problems concerning

this formation; various genera and species were identified to ascertain that the age of this formation is Late Oligocene-Early Miocene.

This study supports the second group of author's opinion that the upper part of the Kirkuk Group, Anah; Azkand and Ibrahim Formations, were deposited in the early Miocene (Aquitanian) age. As the area of study is located close to

Age	Formation	Biozone Bellen (1956), Bellen et al. (1959)	Biozone Al-Hashimi and Amer (1985)	Biozone Majid and Viezer (1986)	Interpretation	
Oligocene	Late	Anah	<i>Miogypsinoides</i>		back reef-reef	
		Azkand	<i>Miogypsinoides</i> , <i>Miogypsinoides</i> / <i>Lepidocyclina</i>	<i>Globigerina angulisuturalis</i>	fore-reef	
		Ibrahim	<i>Globigerina</i>	<i>Globorotalia opima</i>	basin	
	Middle	Bajawan	<i>Kirkukensis</i> , <i>Delicata.</i>		<i>Kirkukensis</i> , <i>Delicata.</i>	back reef-reef
		Baba	<i>Lepidocyclina</i> , <i>Lepidocyclina</i> / <i>Nummulites.</i>	<i>Globorotalia opima</i> , <i>Globigerina ampliapertura</i>	<i>Lepidocyclina</i> , <i>Lepidocyclina</i> / <i>Nummulites.</i>	fore-reef
		Tarjil	<i>Globigerina</i>		<i>Globigerina</i>	basin
	Early	Shurau	<i>Paucialveolata</i> , <i>Dendrophyllum.</i>		<i>Paucialveolata</i> , <i>Dendrophyllum.</i>	back reef-reef
		Sheikh Alas	<i>Nummulites</i>	<i>Globigerina ampliapertura</i>	<i>Nummulites</i>	fore-reef
		Palani	<i>Globigerina</i>		<i>Globigerina</i>	basin

Table 3.1: Division of benthonic and planktonic foraminiferal biozones for the Kirkuk Group strata with environmental interpretation in the Kirkuk area. After Bewllen (1956); Bellen et al. (1959); Al-Hashimi and Amer (1985) and Majid and Veizer (1986).

the shoreline of the Oligocene basin, the Kirkuk Group succession is not complete as well as the biozones (see Table 3.2). The biozones identified have been correlated with global datasets of shallow benthic zones 'SBZ' of Cahuzac and Poignant (1997) and Serra-Kiel et al. (1998) (more detail is in Table 3.3).

### 3.3 Biozones:

The biozones in this study are composed of two Eocene biozones with three biozones from the Oligocene-Early Miocene of the Kirkuk Group (see Table 3.2); working from top to bottom, or from older to younger, these are:

3.3.1 *Alveolina* biozone (AL);

3.3.2 *Discocyclusina* biozone (DI);

3.3.3 *Nummulites fichteli* biozone (NF);

3.3.4 *Praerhapydionina delicata* biozone (PD);

3.3.5 *Austrotrillina howchini* biozone (AH).

Age		Formation	Biozones		
Cenozoic	Early Miocene	Anah	<i>Austrotrillina howchini</i> (AH)	Kirkuk Group	
	Oligocene	Late	Bajawan		<i>Praerhapydionina delicata</i> (PD)
		Early	Sheikh Alas		<i>Nummulites fichteli</i> (NF)
	M.-L. Eocene	Avanah		<i>Discocyclusina</i> (DI)	
				<i>Alveolina</i> (AL)	

Table 3.2: Biozone classification for the Kirkuk Group Formations at eight selected sections in the area studied.

Epoch		Age	SB Zones	This study SBZ	<i>Alveolina</i>	<i>Discocyclina</i>	<i>Nummulites fichteli</i>	<i>Praerhapydionina delicata</i>	<i>Austrorillina howchini</i>
Eocene	Middle	Bartonian	SBZ 17	<i>Alveolina</i> (AL)					
	Late		SBZ 18						
Oligocene	Early	Rupelian	SBZ 21	<i>Nummulites fichteli</i> (NF)					
			SBZ 22A						
	SBZ 22B								
	Late	Chattian	SBZ 23	<i>Praerhapydionina delicata</i> (PD)					
SBZ 20	<i>Praerhapydionina delicata</i> (PD)								
Miocene		Early	Aquitanian	SBZ 24	<i>Austrorillina howchini</i> (AH)				
	SBZ 19								

Table 3.3: The biozones used in this study are correlated with the global shallow benthic zones 'SBZ' of Cahuzac and Pognant (1997) and Serra-Kiel et al. (1998).

Starting with the oldest to the youngest biozones, the detailed descriptions are as below:

### **3.3.1 *Alveolina* biozone (AL):**

Age: Middle Eocene.

Locality: This biozone recorded only in the Avanah Formation of the Bamu Gorge section at the western limb of the Bamu Anticline (see Table 3.4).

Description: The AL biozone is defined by the presence of the Alveolinids (see Table 3.3 and Figure 3.1). The top of AL is the last occurrence of Alveolinids. This biozone has a predominance of both porcelaneous and hyaline larger benthic foraminifera such as: *Nummulites*; *Asterigerina* and *Orbitolites* with minor components of miliolids; *Biloculina*; *Triloculina*; *Quinqueloculina* and *Spirolina*.

The characteristic of the AL zone is the extinction of Alveolinids, which can be correlated with the upper boundary of the Shallow Benthic Zone<sup>17</sup> (SBZ<sup>17</sup>) in the zonation of Serra-Kiel et al. (1998) (see Table 3.3).

Sharbazheri (1983) described *Alveolina* bearing strata in the Duhok area of northern Iraq and considered these a part of the Avanah Formation, and the age of this layer has been determined as being the Middle Eocene age, as determined by the larger foraminiferal assemblage in this layer.

According to Hottinger (1960), Drobne (1977) and Nebelsick et al. (2005), the association of alveolinids with nummulitids, asterigerinids and small miliolids define the rocks of Middle Eocene age on the western and eastern Lessini Shelf.

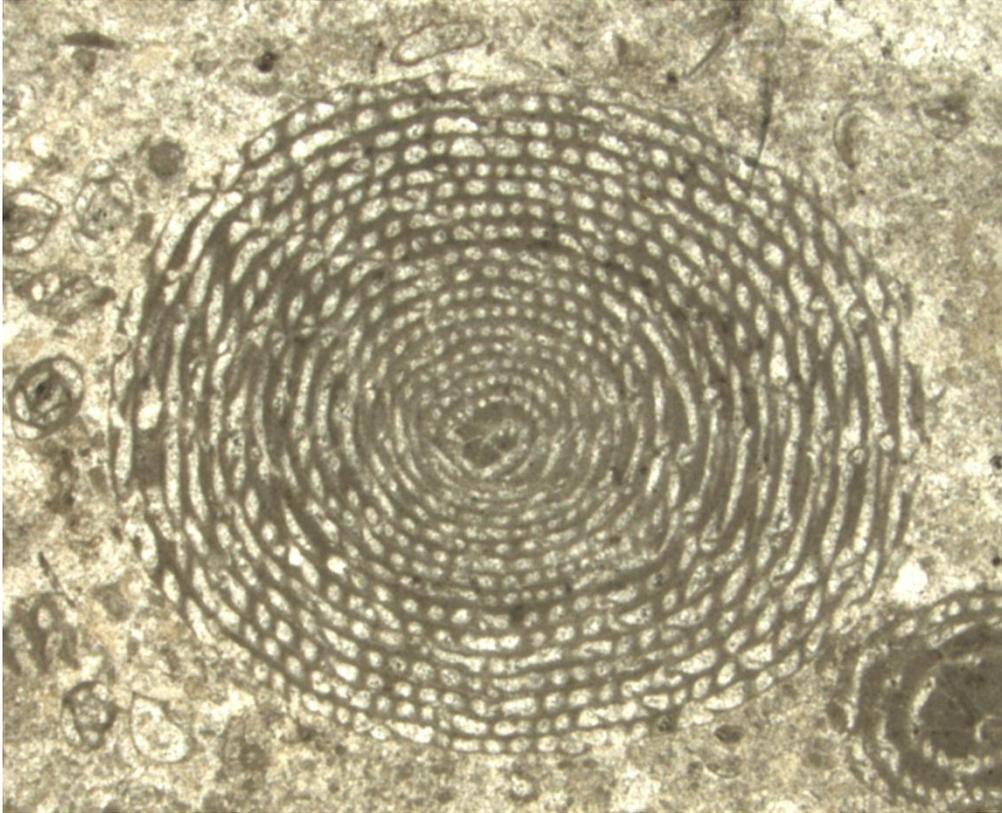


Figure 3.1: Photomicrograph of *Alveolina* in the Bamu Gorge. Unstained thin-section, sample number BS.1. Field of view is 5 mm.

### 3.3.2 *Discocyclina* biozone (DI):

Age: Late Eocene.

Locality: The *Discocyclina* biozone is recorded from the Avanah Formation at three localities: in the southwestern limb of the Aj Dagh Anticline at the Awa Spi locality, while at the northeastern limb and at the core of the Aj Dagh anticline it is absent. It is also present in the Bamu Gorge locality at the western limb of the Bamu Anticline and in the Bellula Gorge locality, at the western limb of the Bamu Anticline (see Tables 3.4, 3.5, 3.6).

Description: the DI biozone is defined by the occurrence of the Discocyclinids without Alveolinids (see Table 3.3 and Figure 3.2). The top of DI biozone is defined by the last occurrence of Discocyclinids. The *Discocyclina* is

associated with *Nummulites*, *Asterigerina* and with minor components of: miliolids; *Biloculina* *Triloculina*; *Quinqueloculina*; *Spirolina*; *Orbitolites*; *Operculina*; *Actinocyclus* and *Pellatispira*. The latter confirms the Late Eocene age for this biozone, because of its short age range which is located at the end of the Late Eocene (Sartorio and Venturini, 1988; Serra-Kiel et al., 1998).

The characteristic of the upper boundary of *Discocyclus* biozone is the extinction of Discocyclusids and this can be correlated with the upper boundary of Shallow Benthic Zone 20 in the zonation of Serra-Kiel et al. (1998) (see Table 3.3).

The larger foraminifera of the upper part of the Dammam Formation include assemblages of *Discocyclus*; *Nummulites* and *Pellatispira* are confirmed as being of the Late Eocene (Priabonian) age (Bokhary et al., 2005).



Figure 3.2: Photomicrograph of *Discocyclus* in Bellula Gorge. Unstained thin-section, sample number BL. 5.







### 3.3.3 *Nummulites fichteli* biozone (NF):

Age: Early-Late Oligocene.

Locality: This biozone defines the Sheikh Alas Formation and is present in the Bellula Gorge locality at the western limb of the Bamu Anticline (see Table 3.6).

Description: The NF biozone is defined by the first and last occurrence of *Nummulites fichteli* (see Table 3.3 and Figure 3.3). This is associated with *Nummulites vascus*.

The characteristic of the NF biozone is the range of *Nummulites fichteli*. The lower boundary of the NF biozone indicates the first appearance of Oligocene strata, and the upper boundary is in the Chattian, which may correlate with the shallow benthic zones SBZ 21, SBZ 22A and SBZ 22B, which were described by Cahuzac and Poignant (1997), Sirel (2003) and Gedik (2008) (see Table 3.3).

The NF biozone is similar to the *Nummulites* zone which was described by Bellen (1956), Bellen et al. (1959) and Majid and Veizer (1986) as one of the zones of the Kirkuk Group of the Early Oligocene which extends to the middle Oligocene in the Kirkuk area (see Table 3.1).

In the north-central Zagros Basin in Iran, Hakimzadeh and Seyrafian (2008); Laursen et al. (2009) and Seyrafian et al. (2011) used benthic foraminifera to determine the age of the Asmari Formation and they recorded the *Nummulites vascus-Nummulites fichteli* zone as being of Early Oligocene (Rupelian) age. However, Lackpour et al. (2008) studied the Asmari limestone of Iran and reported that the *Nummulites fichteli-intermedius* and *Nummulites vascus* belong in the Lower to Middle Oligocene.

Mukhopadhyay (2003) studied the foraminiferal assemblage from the Eocene-Oligocene boundary of the Cambay Basin in India; the first appearance of *Nummulites fichteli* has been correlated with the lower boundary of SBZ 21 of Serra-Kiel et al. (1998). Other records of *Nummulites fichteli* from India have been reported as being from the Early Oligocene age by Sengupta (2000, 2002). In 1986, Drooger and Laagland classified the larger foraminifera of the European-Mediterranean Oligocene into several sub-zones; the lowermost zone of the Oligocene was composed of *Nummulites*, these commonly consist of *Nummulites fichteli* and *Nummulites vascus* in widely varying abundance with a pronounced *Nummulites fichteli* zone.

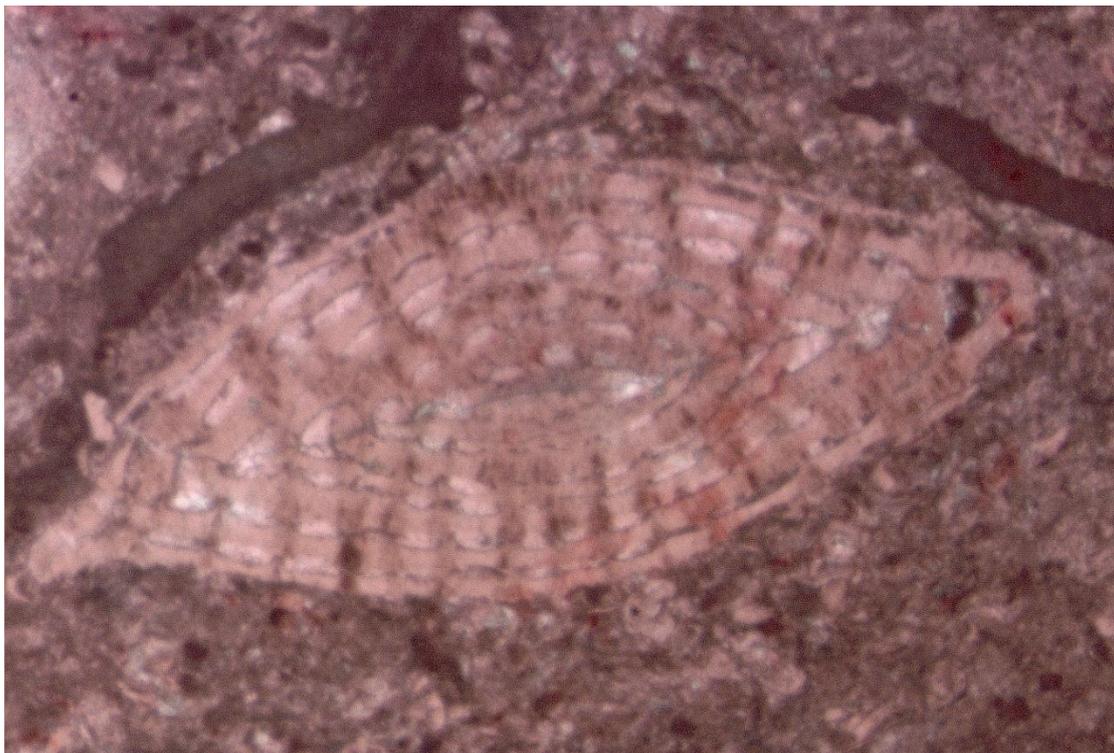


Figure 3.3: Photomicrograph of *Nummulites fichteli* in Bellula Gorge. Stained thin-section, sample number BL.56. Field of view is 1.5 mm.

### 3.3.4 *Praerhapydionina delicata* biozone (PD):

Age: ?Early-Late Oligocene.

Locality: A *Praerhapydionina delicata* zone defines the Bajawan Formation and it is present in three localities of the Aj Dagh Anticline in Zinana, in Hazar Kani, in the core of the Aj Dagh Anticline, and in the Bamu Gorge section in the Bamu Anticline (see Tables 3.4, 3.7, 3.8, 3.9).

Description: The PD biozone is characterized by the occurrence of *Praerhapydionina delicata* (see Table 3.3). The upper boundary is represented by last occurrence of *Praerhapydionina delicata* (Figure 3.4). It is associated with porcelaneous benthic foraminifera as: miliolids; *Peneroplis* sp.; *Peneroplis evolutus*; *Peneroplis thomasi*; *Austrotrillina* sp.; *Austrotrillina* ?*paucialveolata/asmariensis*; *Dendritina rangi*; *Archaias kirkukensis*; *Biloculina*; *Triloculina*; *Quinqueloculina* and rare *Spirolina*.

According to Henson (1950a), Adams (1970) and Abid and Sayyab (1989), the age of *Praerhapydionina delicata* is limited to the Oligocene age (Early and Late Oligocene). However, *Praerhapydionina delicata* was identified by Lackpour et al. (2008) in the lower part of the Asmari Formation as being of the Middle Oligocene age.

*Praerhapydionina delicata*, as a biozone, was first described by Bellen (1956) and Bellen et al. (1959) in the Kirkuk area as one of the two biozones of the Bajawan Formation (*kirkukensis* and *delicata*) of Middle Oligocene age (see Table 3.1) A similar biozone is also reported by Behnam (1979) in the Khanaqin area, in the northeast of Iraq.

In this study, the PD biozone is limited only to the Late Oligocene age. Furthermore, one of the associated fossils in this zone is *Dendritina rangi*,

which starts to appear from the Late Oligocene age (Henson, 1950b), thus confirming that the age limit of this biozone is the Late Oligocene. So the PD biozone correlates with the shallow benthic zones SBZ 22B and SBZ 23, according to Cahuzac and Poignant (1997).

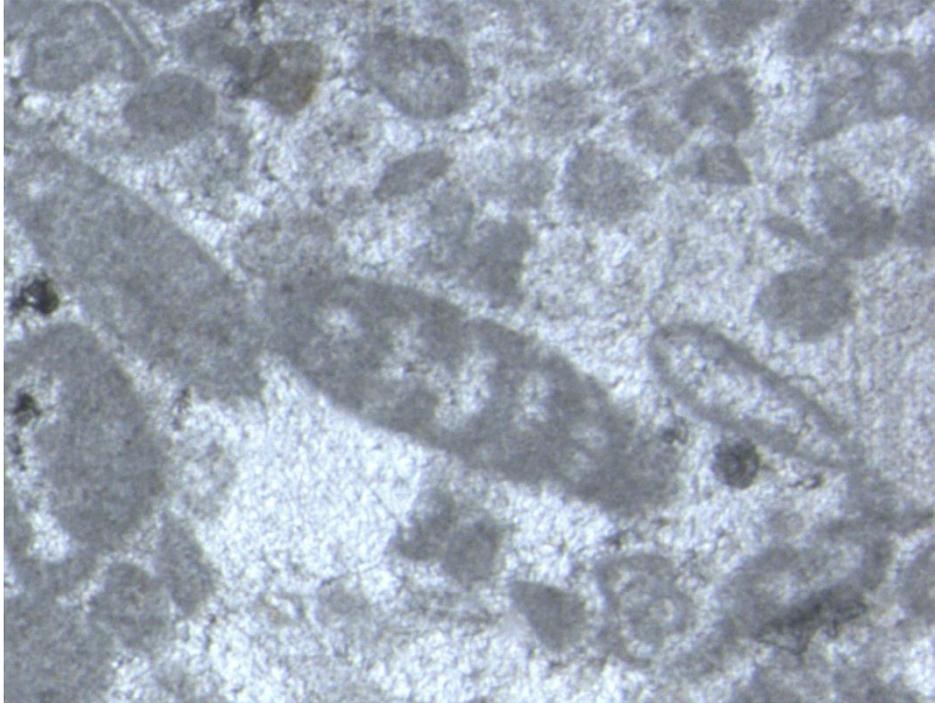


Figure 3.4: Photomicrograph of *Praerhapydionina delicata* in Hazar Kani area. Unstained thin-section, sample number AS.8. Field of view is 3 mm.



Age		Early Miocene		Late Oligocene		Late Eocene	
Formation	Faunal zone	Anah	Jeribi	Bejawan		Avanah	
sample number		AH		PD			
miliolids sp.							
Austrorillina sp.							
A. paucialveolata/asmaniensis							
Austrorillina howchini							
Peneroplis sp.							
Peneroplis evolutus							
Peneroplis thomasi							
Dendritina sp.							
Dendritina rangi							
Praerhapydionina delicata							
Archaias kirkukensis							
Spirolina sp.							
Triloculina sp.							
Rotalia sp.							
Nummulites sp.							
Operculina sp.							
Orbitolites complanatus							
Amphistegina sp.							
Asterigerina sp.							
Textularia sp.							
Colonial coral							
solitary coral							
Red algae							
Gastropods							
Bivalves							
Echinoids							

Table 3.8: Distribution chart of the Eocene-Miocene benthic foraminiferal biozones in the core of the Aj Dagh locality.

L.Eocene	Avanah	Unconform	AS.1	AS.2	AS.3	L. Oligocene				E. Miocene		Age	Formation	Faunal zone	sample number		
						Bajawan		PD		Annah	Jeribi						
										AS.4						miliolids sp.	
										AS.5							Austrotrillina sp.
										AS.6							A. paucialveolata/asmaniensis
										AS.7							Austrotrillina howchini
										AS.8							Peneroplis sp.
										AS.9							Peneroplis evolutus
										AS.10							Peneroplis thomasi
																	Spirolina sp.
																	Dendritina rangi
																	Praerhapydionina delicata
																	Archais kirkukensis
																	Triloculina sp.
																	Quinqueloculina sp.
																	Rotalia sp.
																	Colonial coral
																	Gastropods
																	Bivalves
																	Echinoids

Table 3.9: Distribution chart of the Eocene-Miocene benthic foraminiferal biozones in the Hazar Kani locality.

### 3.3.5 *Austrotrillina howchini* biozone (AH):

Age: Early Miocene.

Locality: This biozone defines the Anah Formation and is present in most of the sections in the study area in the Sagrama Anticline, in all of the localities of the Aj Dagh Anticline, and in the Bamu Anticline. It is absent only in the Bellula Gorge and Sharwal Dra localities (see Tables 3.4; 3.5; 3.6; 3.8; 3.9, 3.10).

Description: The AH biozone is characterized by the occurrence of the *Austrotrillina howchini* (see Table 3.3 and Figure 3.5). The lower boundary of

this biozone is represented by the first occurrence of *Austrotrillina howchini*. The associated porcelaneous benthic foraminifera are composed of: miliolids, *Austrotrillina sp.*, *Austrotrillina ?paucialveolata/asmariensis* *Peneroplis sp.*, *Peneroplis evolutus*, *Peneroplis thomasi*, *Dendritina rangi* and *Archaias kirkukensis*. Minor components of *Spirolina*; *Biloculina*, *Triloculina* and *Quinqueloculina* are also present.

Smout and Eames (1958) studied the Asmari Formation in Iran and found that the middle of the Asmari Limestone contains *Austrotrillina howchini*, which directly underlies beds of Burdigalian age in normal succession; they assessed the age of this fauna as Aquitanian, because it is definitely more closely related to a Burdigalian than to an Oligocene fauna. According to Adams (1968, 1970), the first appearance of *Austrotrillina howchini* is in the Early Miocene (Aquitanian).

As a result this biozone can be correlated with the shallow benthic zone SBZ 24 according to Cahuzac and Poignant's zonation (1997).

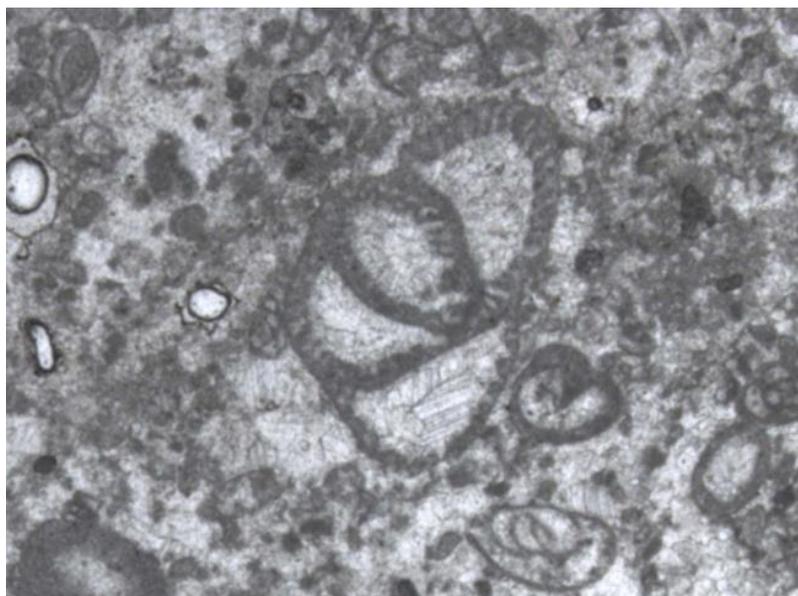


Figure 3.5: Photomicrograph of *Austrotrillina howchini* in the Zinana area. Unstained thin-section, sample number Z.28. Field of view is 3 mm.



### 3.4 Summary and conclusion:

This study reveals that the age of the Kirkuk Group in the northeast of Iraq corresponds to the Oligocene (Rupelian-Chattian) and Early Miocene (Aquitanian) stage. The most important species identified are *Nummulites fichteli*, *Nummulites vascus*, *Praerhapydionina delicata*, *Archaias kirkukensis*, *Austrotrillina howchini* and *Rotalia vienotti*. The following biozones based on benthonic foraminifera have been recognized: (1) *Austrotrillina howchini*; (2) *Praerhapydionina delicate*; (3) *Nummulites fichteli*; (4) *Discocyclusina* and (5) *Alveolina*. These biozones correlate to shallow benthic zones (SBZ) according to Cahuzac and Poignant (1997) and Serra-Kiel et al. (1998) (see Table 3.3).

## **Chapter Four:**

### **Sedimentology microfacies**

#### **4.1 Preface:**

Previous studies (Chapter 1, Section 1.3) have interpreted the Oligocene-Early Miocene Kirkuk Group as a back reef/reef – fore reef – basinal succession (Bellen, 1956; Bellen et al., 1959). It is bounded below by the Late Eocene Avana Formation in most of the sections in the area studied while; the upper boundary is either the Early Miocene Jeribe Formation (early Burdigalian (18.5-19.6 Ma) according to Grabowski and Liu, 2010) or the Early Miocene Fatha Formation (middle-late Burdigalian (15.6-18.5 Ma) according to Grabowski and Liu, 2010).

Despite the Kirkuk Group having been documented by several authors in different areas of Iraq, especially in the Kirkuk area, this study also consider the facies architecture of the Kirkuk Group, with most of the sections being studied for the first time, and based on studies of eight outcrops in southern Kurdistan and north-eastern Iraq (Chapter 1; Section 1-4). The total thickness of individual outcrops ranges between 26m to 186m in the areas studied (Chapter 1; Table 1-2 in Section 1-5), while the thickness of the Kirkuk Group only ranges between 4.5m to more than 122m (Table 4.1). The detailed sedimentary logs include: lithology, age, formation names, fossil content and facies; these are summarized in Appendix 3.

The main aims of this chapter are to document the different microfacies of this group, facies relationships, their environmental interpretations and depositional model, and to compare these with regional and global data.

Locations	Environmental interpretation	Description
Sagrma	Inner ramp	4.5 metres thick package of Anah Formation.
Zinana	Inner ramp	Thick limestone package of 17.5 metres of Bajawan and Anah Formations.
Hazar Kani	Inner-mid ramp	10 metres of massive to thick bedded limestone of Bajawan and Anah Formations.
Core of Aj Dagh	Inner-mid ramp	More than 15 metres, massive to thick package of Bajawan and Anah Formations.
Awa Spi	Inner ramp	Thick limestone package more than 11 metres of Bajawan and Anah Formations.
Bamu Gorge	Inner ramp	20 metres, massive limestone of Bajawan and Anah Formations.
Bellula Gorge	Mid ramp	More than 50 metres of massive limestone of Sheikh Alas Formation.
Sharwal Dra	Mid-outer ramp	More than 122 metres of massive to thick bedded of Azkand and Ibrahim Formations.

Table 4.1: Brief description with palaeo-environmental interpretations of the Kirkuk Group at the eight outcrops studied in northeastern Iraq.

Microfacies and their subdivisions are summarised in Table 4.2 based on stratigraphic position. Microfacies descriptions are summarised in Table 4.3, whilst the detailed microfacies characteristics are described in Section 4.2 and interpreted in Section 4.3. An integrated model has been generated in Section 4.4 and, finally, the summary and conclusions are in Section 4.5. The most widely used classification of carbonate rock is by Dunham (1962); this classification was modified by Embry and Klovan (1971) to include the reef textures. The classification was further revised by Wright (1992). In this study the latter classification scheme have been used for limestone classification. Moreover, the comparison charts after Baccelle and Boesellini (1965) have been used for estimating the percentage of each skeletal and non-skeletal grain in the microfacies.

Micro-facies	Sub-microfacies	Locations
FT	GY: Gypsum	BS, SG
	GM: Marl	BS, SG
	RC: Claystone	BS, BL, SG, Z, AS, CA, AW
JB	OG: Ooidal grainstone	CA
	PP: Peloidal packstone/grainstone	CA, AW, AS, Z
RR	Rotalids-Coralline red algae wackestone/packstone	SD
SP	SP-1: Skeletal packstone with brecciation	AS, AW
	SP-2: Skeletal packstone with <i>Austrotrillina howchini</i>	BS, SG, CA, Z
	SP-3: Skeletal grainstone with <i>Praerhapydionina delicata</i>	AS, CA, Z, BS
MP	MP-1: peloidal, bioclastic packstone/grainstone	Z, CA
	MP2: peloidal wackestone/calcimudstone	AS, AW, CA
CB	Coral bioherm	AS, CA, BL, SD
CG	Conglomerate	AS, AW
PS	Palaeosols	AW
PK	PK-1: peloidal packstone with planktonic foraminifera	AW
	PK-2: Planktonic foraminifera calcimudstone	BL, SD
	PK-3: Planktonic-benthonic foraminifera wackestone	BL
NR	NR-1: Coralline red algae- <i>Nummulites</i> wackestone	BL

	NR-2: Coralline red algae- <i>Nummulites-Discocyclus</i> packstone.	BS, AW, CA
	NR-3: <i>Nummulites-Discocyclus</i> packstone	BL, BS, AW
PG	Peloidal, skeletal grainstone.	BS,SG, Z, AS, CA, AW
NA	<i>Nummulites-Alveolina</i> packstone/grainstone.	BS

Table 4.2: Summary of the Microfacies divisions for the eight studied outcrops according to their stratigraphical position in the field. Location codes are: SG=Sagirma; Z=Zinana; AS=Hazar Kani; CA=Core of Aj Dagah; AW=Awa Spi; BS=Bamu Gorge; BL=Bellula Gorge and SD=Sharwal Dra.

#### 4.2 Microfacies descriptions:

Twenty-two different Microfacies have been recognized in the eight field areas studied. They have been differentiated based on lithology, bioclasts and diagenesis. Each Microfacies will be described separately, as detailed below; for all detailed percentages of all skeletal and non-skeletal grains including cement and matrix percentages see Table 4.3.

##### 4.2.1 Microfacies FT:

The FT microfacies is mainly divided into three sub-microfacies; GY, GM and RC. The successions of these three microfacies are formed from the Fatha (formerly named Lower Fars) Formation (Figure 4.1) of Early Miocene age (Burdigalian) which overlies unconformably the Kirkuk Group in the Sagirma (SG), Bamu Gorge (BS) and Bellula Gorge (BL) outcrops. While in the four outcrops of the Aj Dagah anticline (Zinana (Z), Hazar Kani (AS), core of Aj Dagah (CA) and Awa Spi (AW)), this formation rests on the top of the Early

Miocene Jeribe Formation. The following description focuses only on field appearance because of the well-known of this formation in the northern Iraq.

#### **4.2.1a Sub-microfacies GY:**

This microfacies is characterized in the field by white, thick to massive, bedded gypsum. It occurs only in the Sagrma and Bamu Gorge localities, the thickness ranges from 2 to 5 metres. It is interbedded with other two microfacies of the Fatha Formation (GM and RC) (Figure 4.1). The Chicken-wire structure can be recognized in the Bamu Gorge area (Figure 4.2). The microfacies appearance is limited to finely crystalline gypsum.

#### **4.2.1b Sub-microfacies GM:**

The GM microfacies is recognized in the field as greyish-green, thin-bedded, finely laminated to rarely low-angle laminated marl (Figure 4.3). Its thickness varies according to the location. This microfacies is present in only two localities; in the Bamu Gorge with a total thickness of 3.5 metres and in Sagrma with a total thickness of 4 metres. It is interbedded with GY and RC microfacies (Figure 4.1).

#### **4.2.1c Sub-microfacies RC:**

Microfacies RC is characterized in the field by red thin-bedded claystone (Figure 4.1). The thickness of this microfacies varies according to the locality; it occurs in seven localities within the study area. It is present in the Bamu and Bellula Gorges with a total thickness of tens of metres; in Sagrma at several metres; in the Aj Dagh Anticline (Zinana, Hazar Kani, core of Aj Dagh and Awa Spi) localities with thicknesses of tens to hundreds of metres, resting on JB microfacies of the Jeribe Formation. While in the three former localities it is located in the uppermost layer of the SP microfacies of the Kirkuk Group.

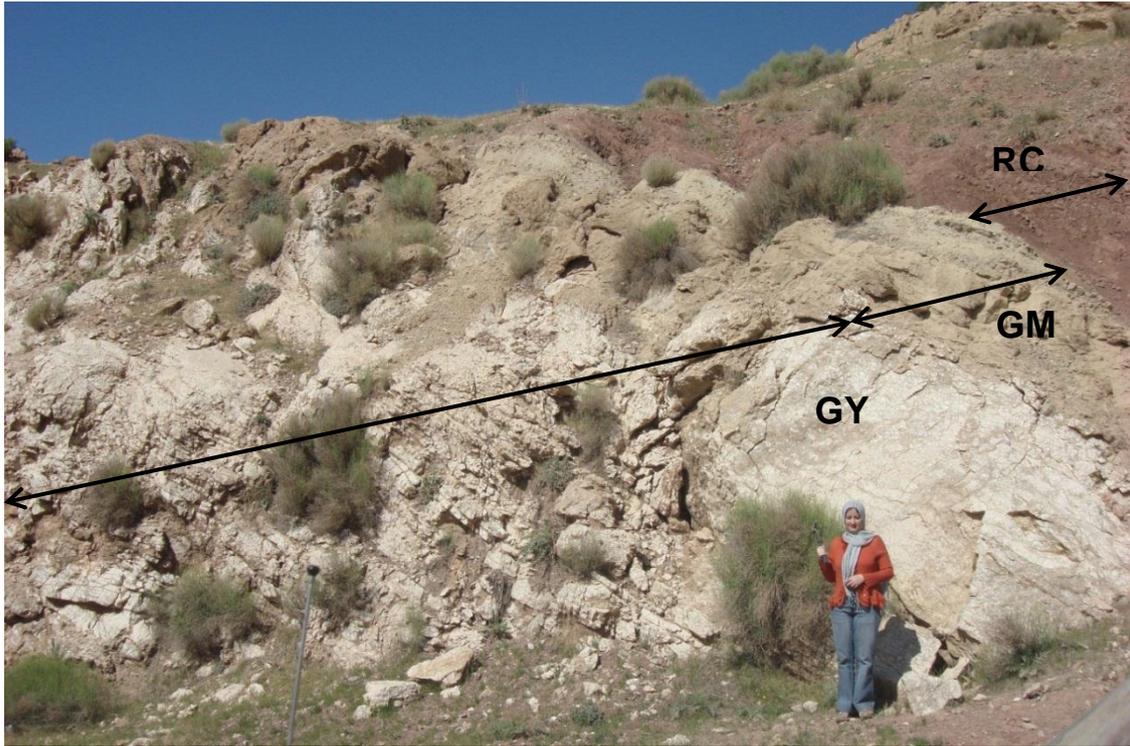


Figure 4.1: Field photograph for GY, GM and RC microfacies of Fatha Formation in the Bamu Gorge area.



Figure 4.2: Field photograph of gypsum (GY) microfacies with Chicken wire structure at Bamu Gorge locality.



Figure 4.3: Field photograph of fine lamination in GM microfacies located at Bamu Gorge locality. The scale bar is 15cm.

#### **4.2.2 Microfacies JB:**

Microfacies JB is subdivided into two main sub-microfacies, ooidal grainstone (OG) and peloidal packstone/grainstone (PP), and produces the Early Miocene Jeribe Formation. This microfacies is present only in the Aj Dagh Anticline localities, it overlies unconformably the SP microfacies of the Kirkuk Group.

##### **4.2.2a Sub-microfacies OG:**

Microfacies OG is characterized in the field by thin-bedded limestone. It overlies the PP microfacies. It occurs in only one locality of the Aj Dagh Anticline which is the core of the Aj Dagh Anticline outcrop; it has a total thickness of approximately one metre with no obvious sedimentary structures in this microfacies.

This microfacies composed of un-compacted ooidal grainstone. It is composed of medium sand grade sized ooids (average 35%), bioclasts (average 20%), peloids (average 7%) and calcite spar (average 38%).

Moreover, rare intraclasts are also present (Figure 4.4). There is no evidence of burrowing within this microfacies. The OG microfacies is moderately sorted to well sorted. A very limited biota has been found in the ooidal grainstone microfacies in the core of the Aj Dagh Anticline area. The most recognizable is bivalve debris consists of oysters or their fragments as ooid nuclei, with very rare forams (Figures 4.4 and 4.5).

The ooids in this microfacies are composed of high abundance; round and ellipsoidal shapes with a micritic/tangential structure. The cortex has inhomogeneous thickness (composed of both normal and superficial ooids). The nuclei of the ooids are comprised of elongated bivalve fragments, whose walls were replaced by ferroan calcite spar which produce the elongate/ellipsoid shape ooids; round, possibly from abraded forams and there are a few small sand grade sized, sub-rounded to sub-angular quartz grains which act as nuclei for ooids (Figure 4.5).

Only one peloid type has been found in OG microfacies, it is composed of small sand grade size, round-shaped peloids. In addition there are to very rare intraclasts, of round to sub-round, 1-3 mm, consisting of ooids-peloids grainstone (Figure 4.4). The diagenetic features inside the intraclasts are same as the whole texture of the rock.

Few diagenetic features are associated with this microfacies, such as cementation, dissolution and micritization in form of peloids and the cortex of ooids. Two types of cements have been recognized; early non-ferroan calcite spar filling intergranular pores, whereas the later cement is ferroan calcite spar, mostly found as nuclear of ooids and filling bivalve moulds (Figures 4.4 and 4.6).

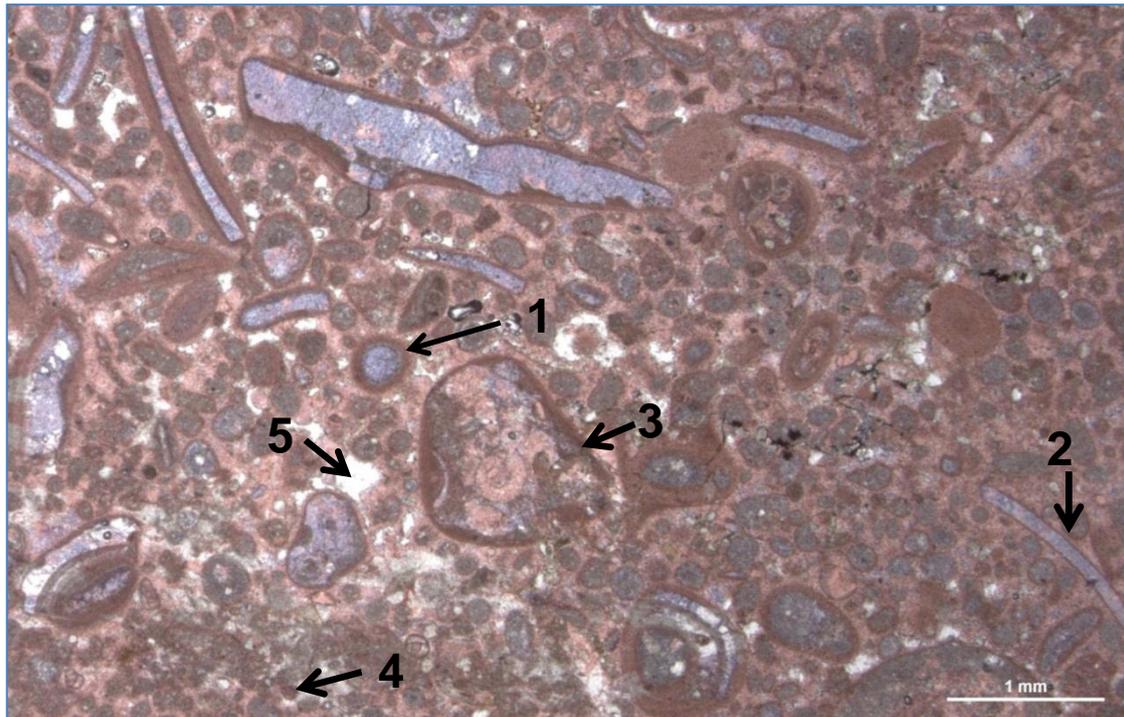


Figure 4.4: microfacies ooidal grainstone. (1) ooids, (2) former aragonitic bivalves, (3) sub-rounded intraclast, (4) peloids, (5) vugs. Photomicrograph of a stained thin-section from core of Aj Dagh Anticline (sample CA.32).

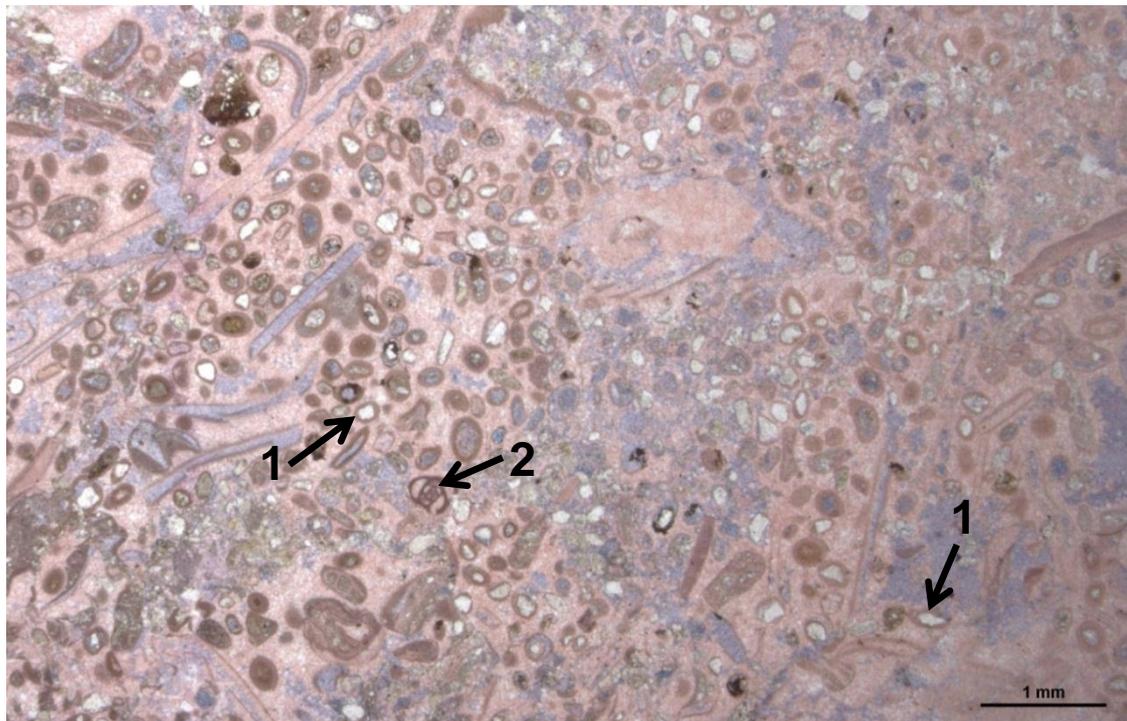


Figure 4.5: Sub-round to sub-angular quartz as nuclei for ooids (1), miliolid (2). Photomicrograph of microfacies OG, stained thin-section from core of Aj Dagh Anticline. (sample CA.33).

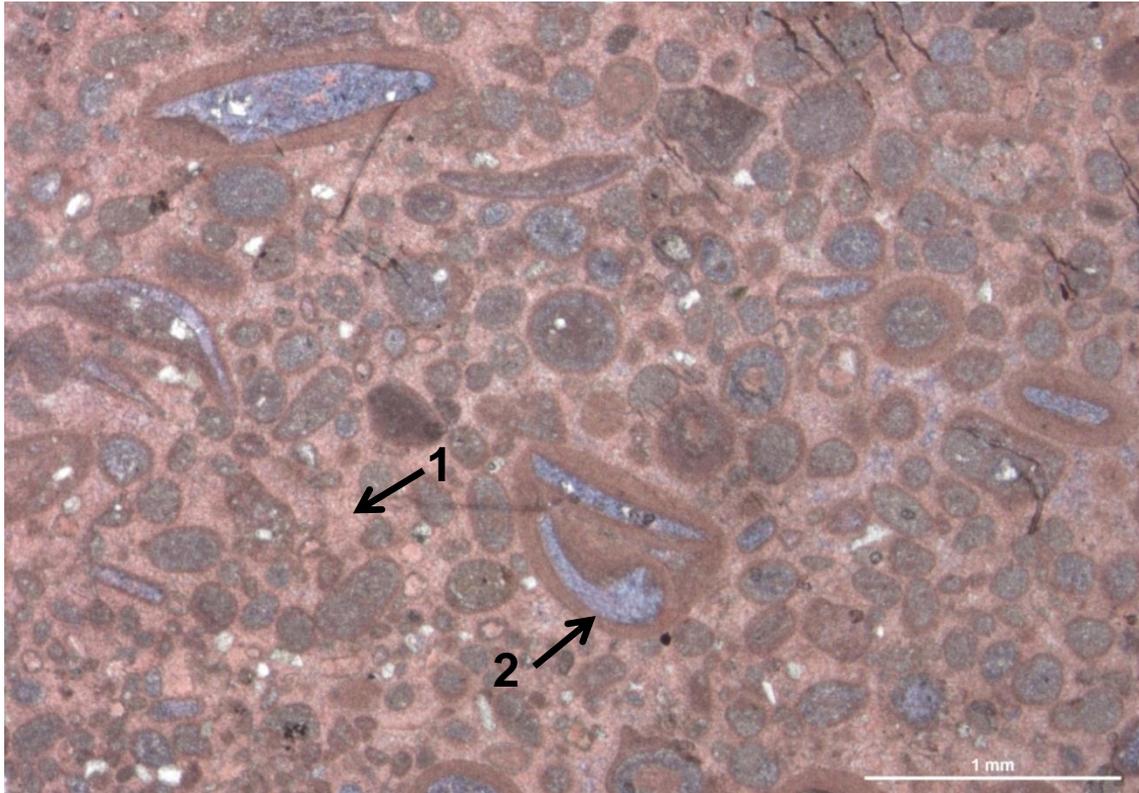


Figure 4.6: Non-ferroan intergranular calcite cement (1) and post aragonite dissolution moulds filled by ferroan calcite cement (2). Photomicrograph of microfacies OG. Thin-section is stained from core of Aj Dagh Anticline (sample CA.32).

#### 4.2.2b Sub-microfacies PP:

Microfacies PP is characterized in the field by thin-bedded irregularly laminated/bedded limestone (Figure 4.7). It rests unconformably on the top of the Kirkuk Group, on microfacies SP. It occurs in all localities of the Aj Dagh Anticline, in Zinana village, Hazar Kani Village, Awa Spi locality and the core of the Aj Dagh Anticline. The Zinana village outcrop has a total thickness of one metre; the Hazar Kani village outcrop has a total thickness of 1.5 metres, at Awa Spi locality has a total thickness of one metre and in the core of the Aj Dagh Anticline has a total thickness of less than one metre (70cm).

This microfacies comprises peloidal packstone (locally grainstone). It is composed of fine sand grade size peloids (average 30%); fine to very fine

grains of sub-angular quartz (average 30%); micrite matrix (average 33%); cements (average 5%) in addition to rare bioclasts (1-2%). There is evidence of horizontal burrowing on the bedding surface (Figure 4.8).

The biota is limited in this microfacies, consists of fragments of oysters and miliolids.

The recognizable peloids in the PP microfacies are composed of fine sand grade, round to ellipsoid shaped pellets (Figure 4.9). Quartz grains are common in this microfacies in all four localities; they are silt size, and sub-angular to sub-round in shape (Figure 4.9).

A thin molluscan rich-layer packstone, about 30cm, has been found only in the Zinana village locality which underlies this microfacies (Figure 4.10).

The main diagenetic features associated with peloidal packstone/grainstone microfacies include cementation in form of non-ferroan calcite cement; micritization; compaction and low amplitude stylolites (Figure 4.9); the other forms of diagenesis are not common.



Figure 4.7: Field photograph of irregular lamination/bedding in PP microfacies from Awa Spi locality. Field of view is 2m wide.



Figure 4.8: Field photograph of horizontal burrowing on the surface of PP microfacies from Core of Aj Dagh Anticline.

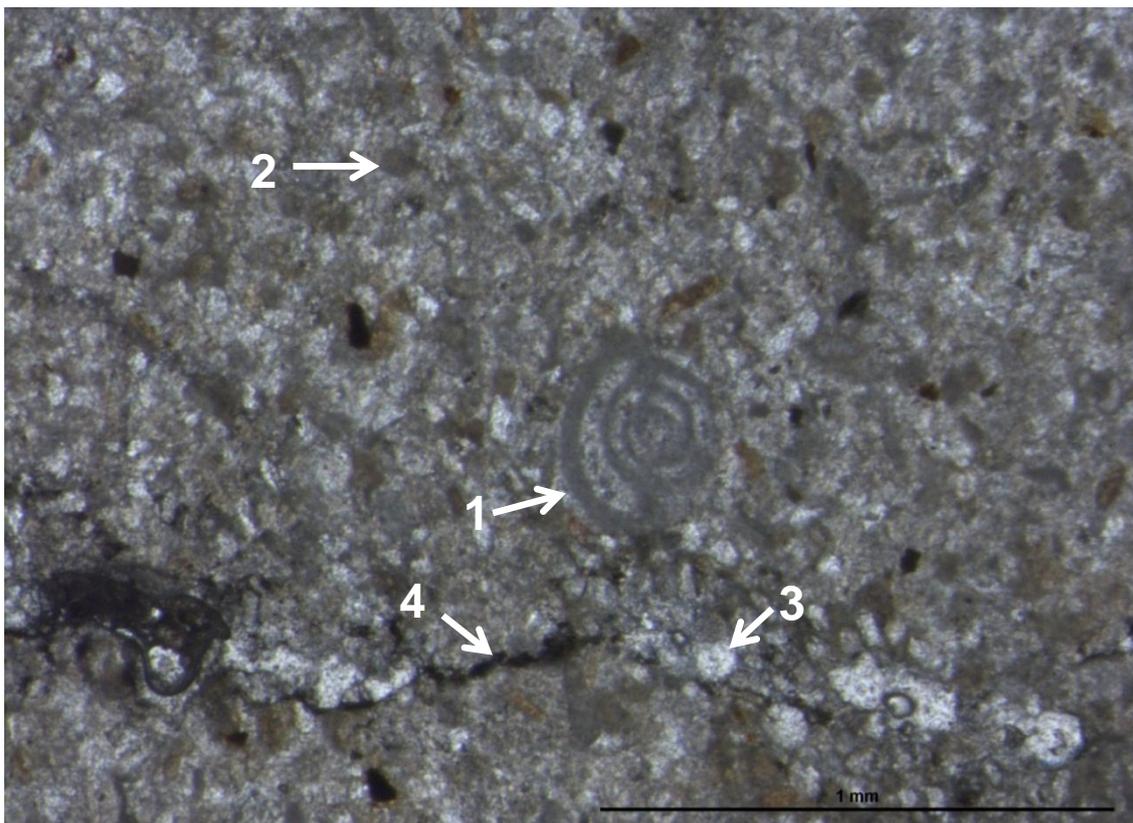


Figure 4.9: Photomicrograph of peloidal packstone microfacies. (1) miliolids, (2) peloids, (3) quartz, (4) stylolite. Unstained thin-section from Hazar Kani village (sample AS. 10).

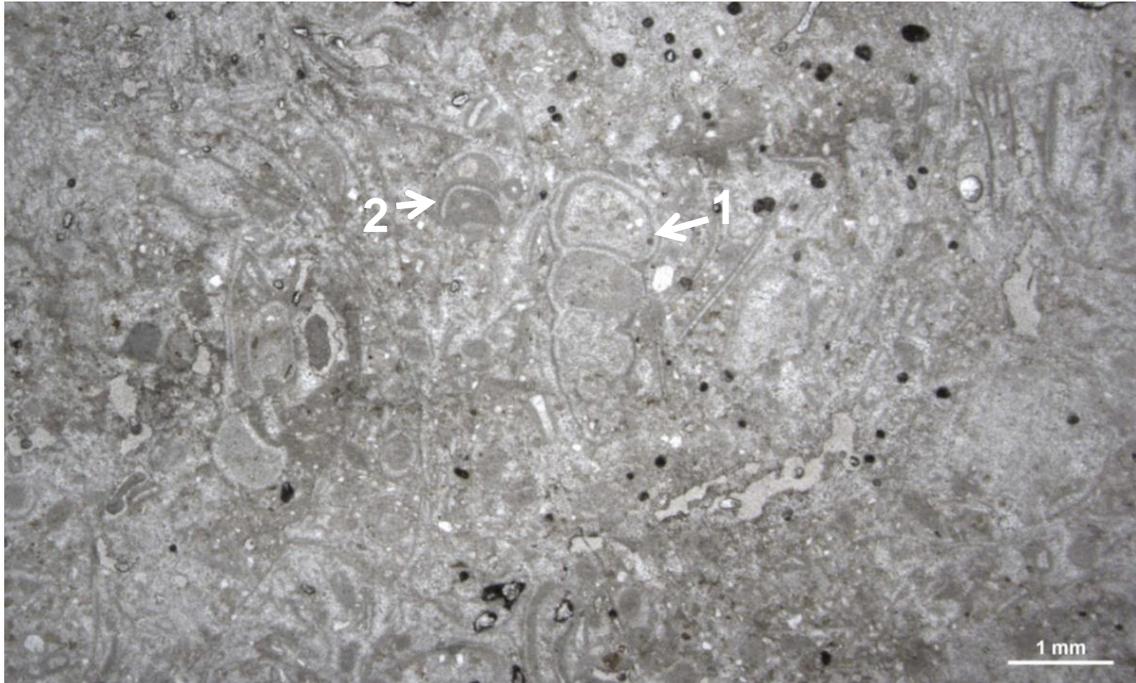


Figure 4.10: Photomicrograph of molluscan layer. (1) gastropod and (2) bivalve fragments with micritized envelope. Unstained thin-section from Zinana village area (sample Z. 31).

#### 4.2.3 Microfacies RR:

This microfacies is characterized in the field by thick to massive bedded limestone. It is identified in only one locality, on the southwestern limb of the Sharwal Dra Anticline (SD). The RR microfacies has an average thickness of 2-4 metres, it comprises one of the microfacies of the Kirkuk Group, is laterally extensive for tens to several hundreds of metres, and is interbedded with coral bioherm (CB) microfacies.

The microfacies comprises wackestone, locally packstone, and contains complete bioclasts (average 23%), with their fragments (average 15%), peloids (average <5%) and micrite (average 35%), in addition to rare dolomite (average 1%).

The identified bioclasts are generally: rotalids (usually 3-6%), while in some areas these reach 10%; red algae (average 5%); coral (5%); echinoid fragments (3-4%), *Nummulites* (1%), with rare miliolids, *Austrotrillina*, *Spirolina*, *Boriles* and bivalves (less than 1%) (as shown in Table 4.3). (Figure 4.11).

Diagenetic features associated with the RR microfacies include cementation and very rare dolomitization (Figures 4.12 and 4.13). Cementation, including syntaxial overgrowth of calcite cement on echinoid fragments is common. Moreover non-ferroan calcite cement filled fractures and finally dolomites are composed of scattered very fine of idiopic (euhedral) dolomite crystals.

#### **4.2.4 Microfacies SP:**

This microfacies of skeletal packstone, locally grainstone, is divided into three sub-microfacies, SP-1, SP-2 and SP-3, largely on the basis of variation in the larger benthic foraminifera species and their appearance as new species for the first time in the succession, and also by variations in physical properties and stratigraphic positions. The SP microfacies is one of the main microfacies of the Kirkuk Group, located at the upper part of this succession. The descriptions below of the fauna include detailed percentages of all skeletal grains.

The difference between SP-1 microfacies and SP-2 is mostly in the physical properties of the rocks, brecciation is present in SP-1, whereas both microfacies have a first appearance of *Austrotrillina howchini*, which is absent in SP-3. The microfacies SP-3 has other differences from the two previous ones because of the first appearance of *Praerhapydionina delicata* in this

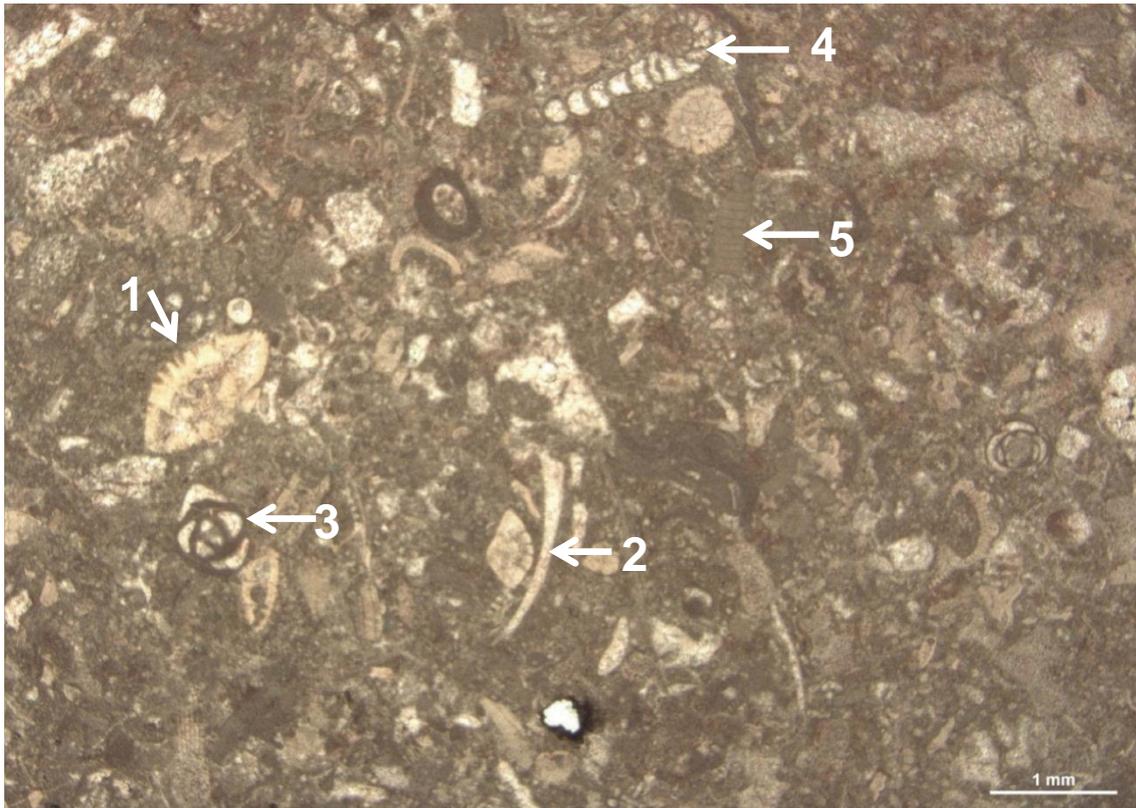


Figure 4.11: Photomicrograph of microfacies RR (1) *Rotalia*, (2) bivalve fragment, (3) miliolids, (4) *Spirolina*, (5) red algae. Stained thin-section from Sharwal-Dra locality (sample SD.29).

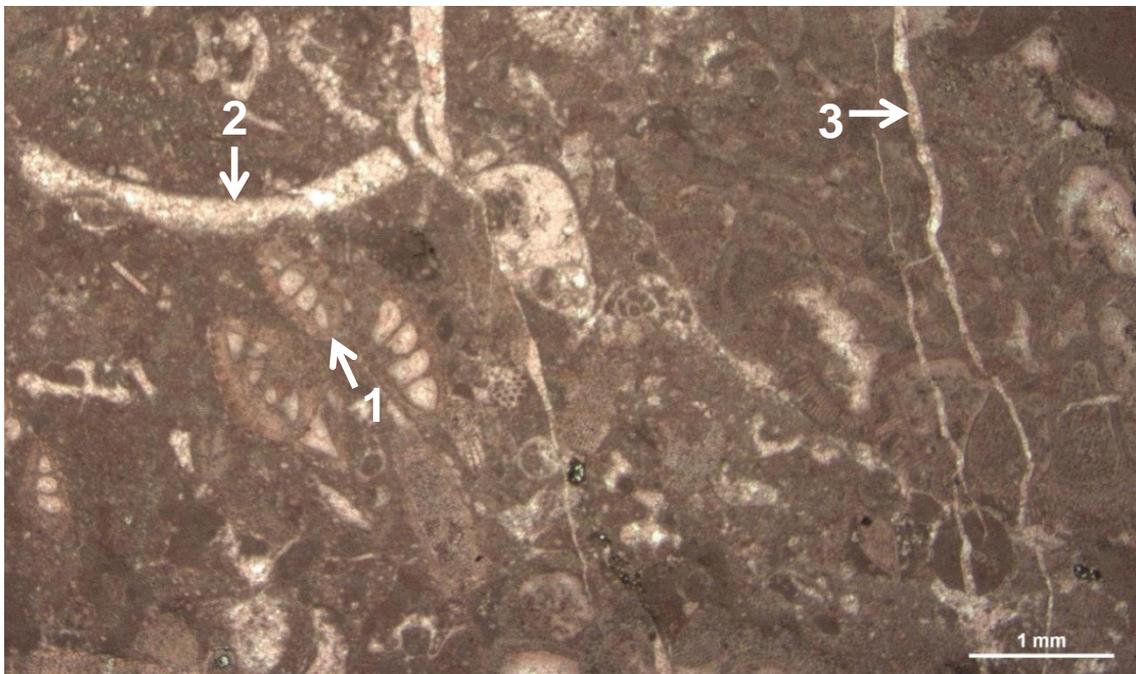


Figure 4.12: Photomicrograph of microfacies RR (1) *Rotalia*, (2) bivalve fragment filled with non-ferroan calcite cement, (3) fracture filled with non-ferroan calcite cement. Stained thin-section from Sharwal-Dra locality (sample SD.29).

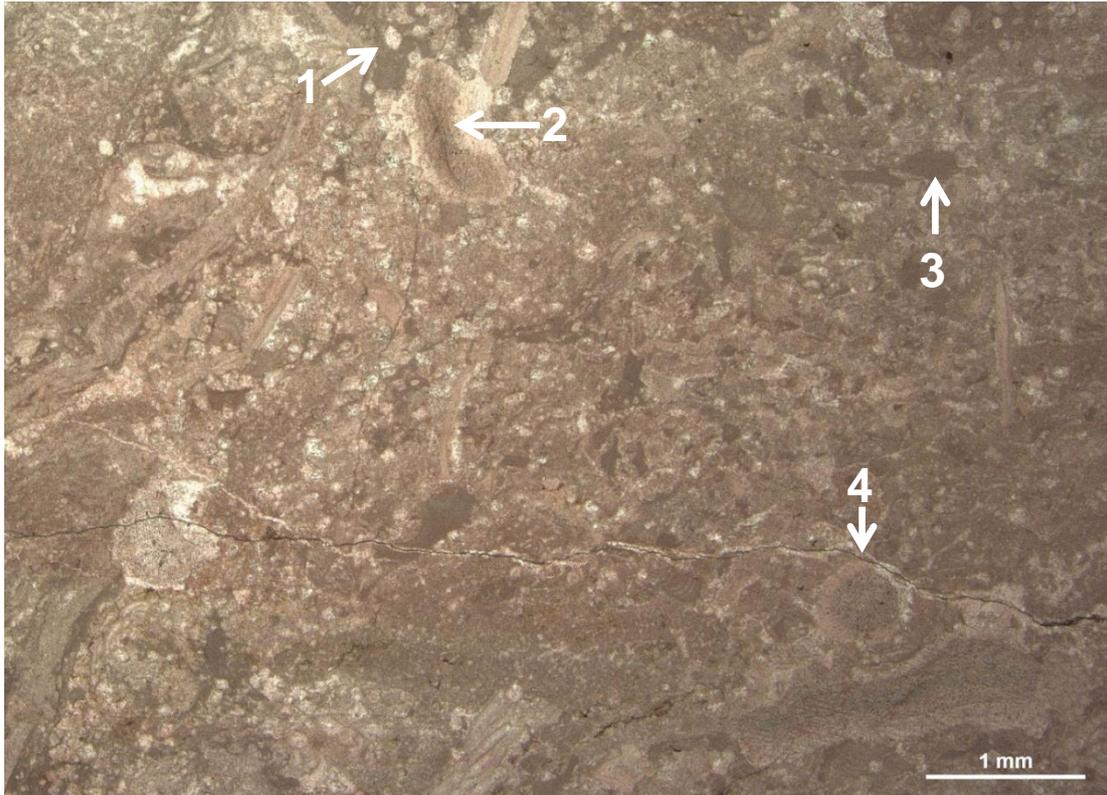


Figure 4.13: Photomicrograph of euhedral dolomite texture (1), echinoids fragment (2), red algae (3) fracture (4). Stained thin-section from Sharwal-Dra locality (sample SD.8).

microfacies. They also have different rock textures.

#### 4.2.4a Sub-microfacies SP-1:

Microfacies SP-1 is characterized in the field by generally indistinct bedded brecciated limestone (Figure 4.14). It occurs in two localities of the study area, both of them located at the Aj Dagh Anticline. It is present in Hazar Kani village, with a total thickness of 1 metre, and in the Awa Spi area, with a total thickness of 1.5 metres. The microfacies SP-1 extend laterally for tens of metres and occur in the uppermost levels of the Kirkuk Group at both localities; moreover, this microfacies is underlain by SP-3 and MP-2 in the Hazar Kani and Awa Spi localities, respectively (for more detail go to Appendix 3).

The microfacies is composed of medium to coarse sand grade sized packstone, with bioclasts (average 50%), matrix (average 40%) and peloids (average 10%).

This microfacies has a diverse biota. Most of the recognized fossils are benthonic foraminifera (average 40%), while macro-fauna includes echinoid fragments (3.5%), gastropods (3%) and bivalves (2.5%).

The porcellaneous-walled larger benthic foraminifera are composed of: miliolids (average 15%); *Austrorillina* (average 10%); *Peneroplis* (average 3.5%); *Dendritina* (average 2.5%); *Archaias* (average 2%); *Praerhapydionina* (average 2.5%); minor components include: *Biloculina* (1%); *Triloculina* (1%); *Quinqueloculina* (2%); and *Spirolina* (1%) (Figure 4.15).

Diagenetic features associated with this microfacies are cementation, including non-ferroan calcite cement and syntaxial overgrowth on echinoid fragments, micritization and compaction, including stylolite and clay seams along the brecciation area (Figures 4.15 and 4.16).

#### **4.2.4b Sub-microfacies SP-2:**

This microfacies is characterized in the field by mainly medium to thick bedding. It is identified in four localities of the study area (two of the localities are situated at the Aj Dagh Anticline with one locality in each of the Sagrma and Bamu Anticlines); in Zinana village, with a total thickness of 7 metres; in the core of the Aj-Dagh anticline with a total thickness of 4 metres; in the Sagrma area with a total thickness of 4.5 metres; and in the Bamnu Gorge with a total thickness of 5 metres. Evidence of both horizontal and vertical borrowing associated with hard ground is present on the uppermost layer of



Figure 4.14: Field photograph of SP-1 microfacies overlying the MP-2 microfacies in the Awa Spi locality.

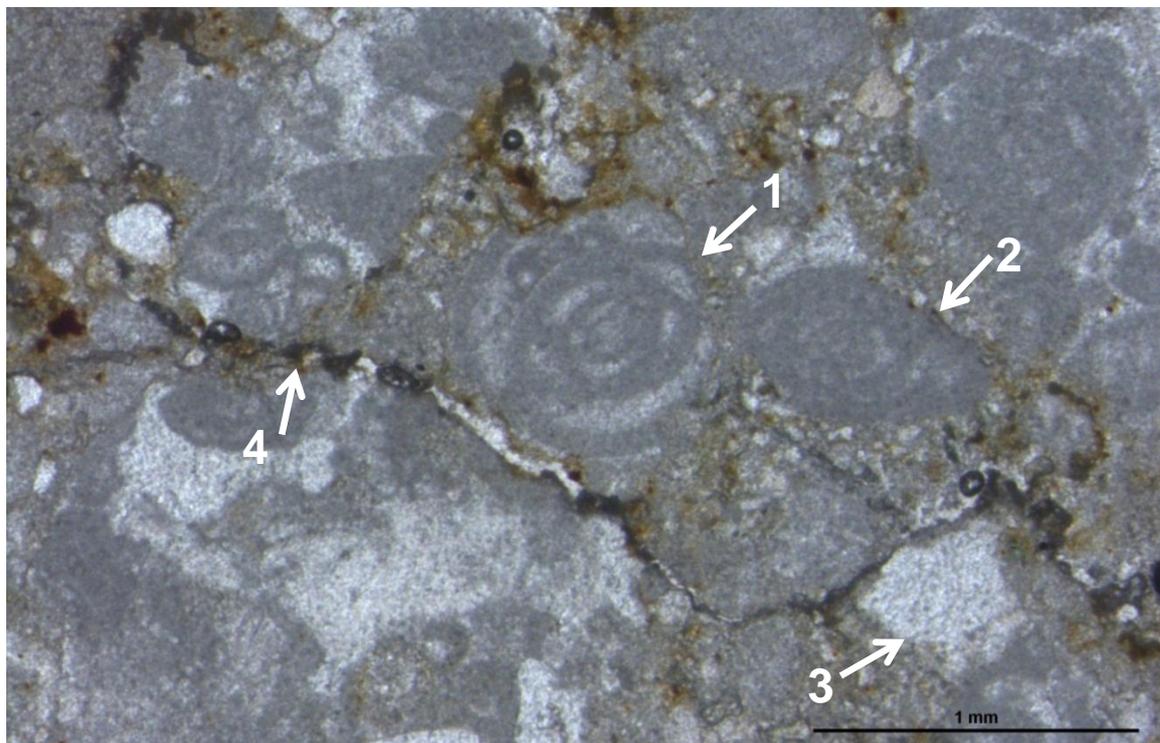


Figure 4.15: Photomicrograph of brecciated packstone (SP-1) with porcellaneous benthic foraminifera. (1) *Austrotrillina*, (2) *Archaias*, (3) echinoid fragments, (4) brecciation line filled with clay residue. Unstained thin-section from Awa Spi locality (sample DS.12).



Figure 4.16: Photomicrograph of brecciated packstone (SP-1 microfacies) with (1) *Triloculina*, (2) *Quinqueloculina*, (3) calcite filled fracture, (4) clay seams. Unstained thin-section from Hazar Kani village locality (sample AS.9).

this microfacies in the Bamu Gorge, with the presence of macrofossils such as gastropods (Figures 4.17 and 4.18).

This microfacies is laterally extensive, for tens of metres up to several hundreds of metres. It rests on SP-3 microfacies in most of the localities and comprises the uppermost unit of the Kirkuk Group.

The limestone comprises medium to coarse sand grade, skeletal packstone (partially grainstone), with bioclasts (average 49%), matrix (average 35%), peloids (average 10%) and cement (6%). The bioclasts in this microfacies are mostly composed of benthonic foraminifera (average 39%); other skeletal grains are: echinoid fragments (average 4.5%); bivalves (average 3%) and gastropods (average 2%) are also present.

The larger porcellaneous benthonic foraminifera are: miliolids (average 16.5%); *Peneroplis* (average 4%); *Austrotrillina* (average 7.5%); *Dendritina* (2-3%); *Archaias* (1.5%); *Praerhapydionina* (1-2%); minor components include *Biloculina* (1%); *Triloculina* (1%); *Quinqueloculina* (2%); *Spirolina* (1%) (Figure 4.19).

Diagenetic features associated with this microfacies are cementation by non-ferroan calcite cement and syntaxial overgrowths on echinoid fragments, as well as sparite filled fractures and vugs. Very rare chemical compaction as low amplitude stylolite is present. There is no evidence of dolomitization (Figure 4.20).



Figure 4.17: Field photograph of horizontal borrowing in the Sagrama locality.



Figure 4.18: Field photograph of macro fossil of gastropod in Sagrama locality.

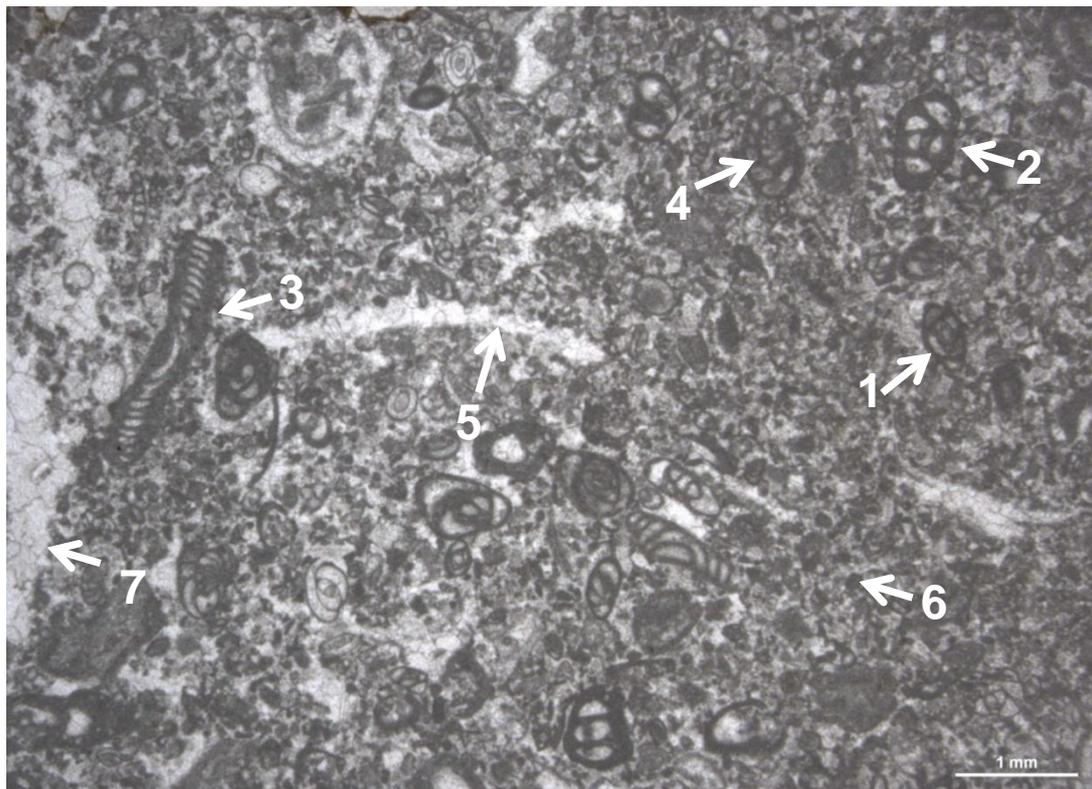


Figure 4.19: Photomicrograph of SP-2 microfossils (1) miliolids, (2) *Austrorillina*, (3) *Peneroplis*, (4) *Dendritina*, (5) bivalves, (6) peloids, (7) vugs filled with calcite cement. Unstained thin-section in the Zinana village locality (sample Z.28).

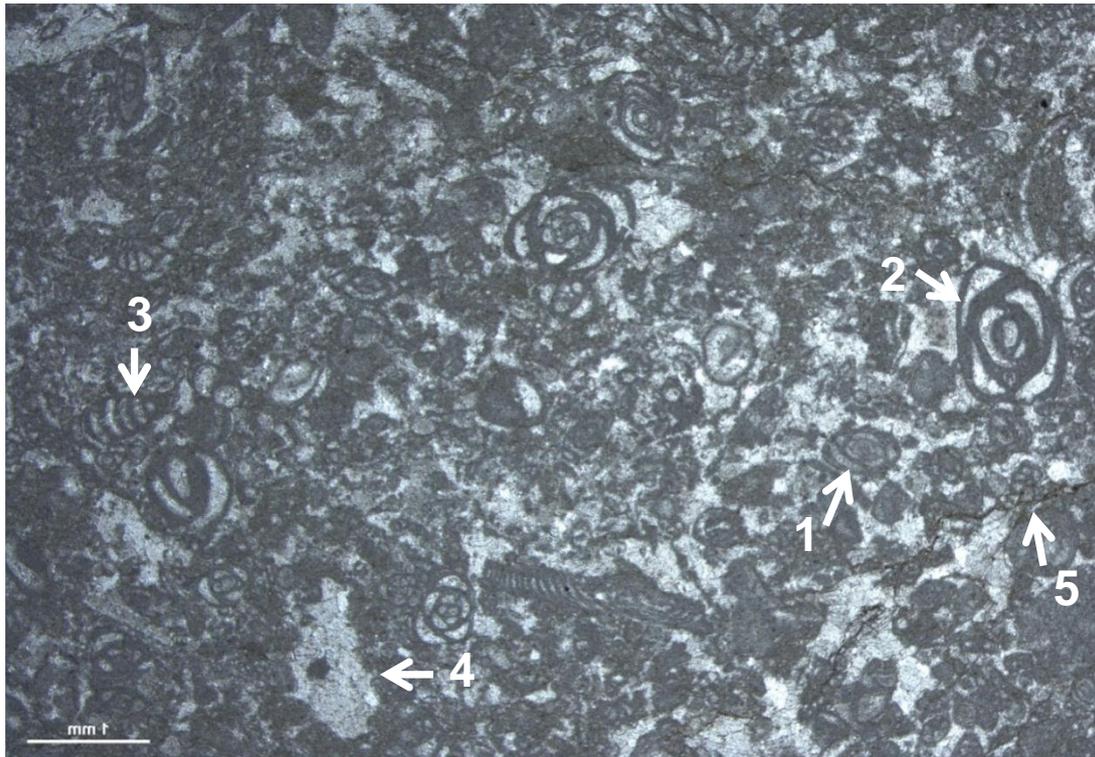


Figure 4.20: Photomicrograph of SP-2 microfacies with (1) miliolids, (2) *Austrotrillina*, (3) *Praerhapydionina*, (4) echinoid fragments, (5) low amplitude stylolites. Unstained thin-section from the Sagrama locality (sample SG.27).

#### 4.2.4c Sub-microfacies SP-3:

Microfacies SP-3 is characterized in the field by a mainly thick bedded limestone (Figure 4.21). It occurs in four localities of the study area (three of them are located at the Aj Dagh Anticline with one locality at the Bamu Anticline): in Zinana village, with total thickness of 17.5 metres; in the core of the Aj-Dagh anticline with a total thickness of 8 metres; in Hazar Kani village with a total thickness of 3.5 metres; and in the Bamnu Gorge with a total thickness of 15 metres. This microfacies extends laterally for tens to several hundreds of metres. It underlies SP-1 and SP-2 microfacies and is interbedded with both MP and CB microfacies.

This microfacies is composed of grainstone, locally packstone, and is dominated by: skeletal grains (average 44%); peloids (average 10%); micrite (average 10%); and cement (average 36%).

Skeletal grains consist mainly of benthic foraminifera (average 37%), whilst the macro-fauna present within this microfacies are: occasional echinoid fragments (3-4%); gastropods and bivalves (1-2%). Only in the Zinana village locality are bivalves common in the lower part of this microfacies unit.

The porcellaneous benthic foraminifers include: miliolids (average 14.5%); *Peneroplis* (average 4%); *Austrotrillina* (average 6%); *Dendritina* (average 2.5%); *Archaias* (average 3%); and *Praerhapydionina* (average 2%); minor elements are *Biloculina* (1.5%), *Triloculina* (1%), *Quinqueloculina* (2%) and *Spirolina* (1%), with very rare textularid and rotalid (<1%) (Figures 4.22 and 4.23).

The diagenetic features associated with this microfacies are cementation,



Figure 4.21: Field photograph of very thick bedded of skeletal grainstone in Zinana area. Scale bar is 25 cm.

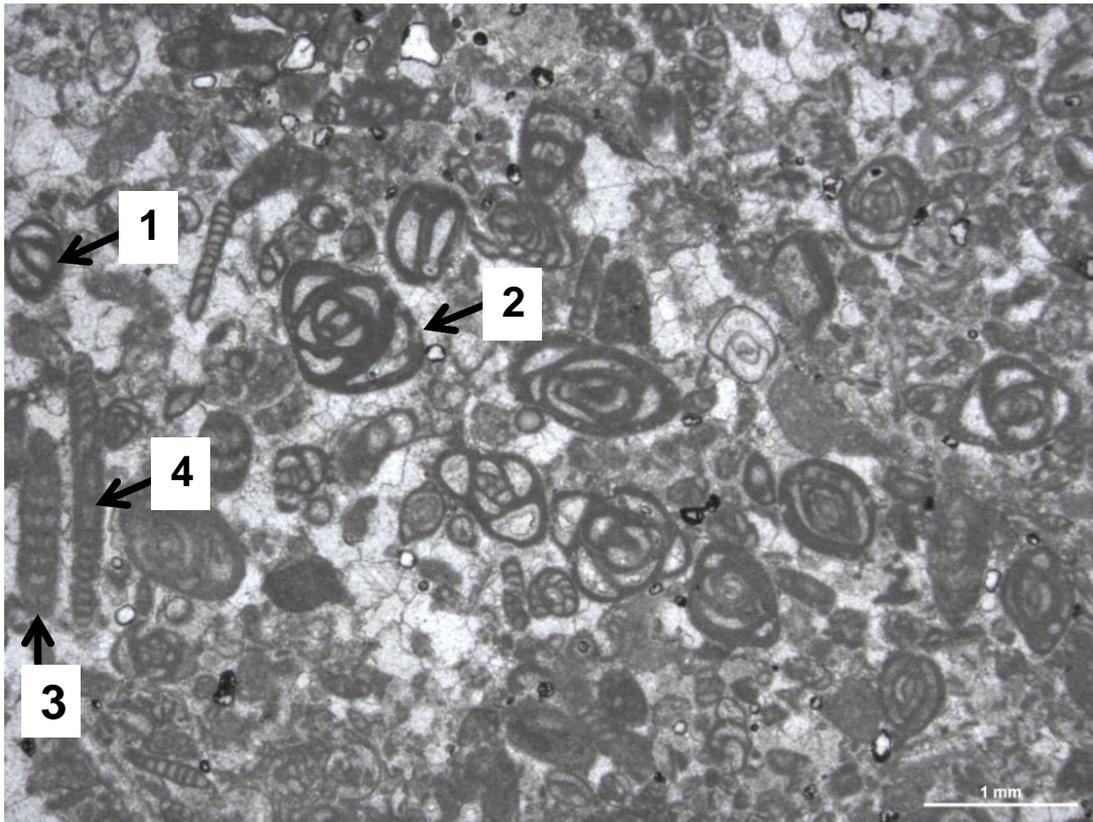


Figure 4.22: Photomicrograph of skeletal grainstone of SP-2 microfacies with (1) miliolids, (2) *Austrotrillina*, (3) *Praerhapydionina*, (4) *Peneroplis*. Unstained thin-section from the Zinana village locality (sample Z.18).

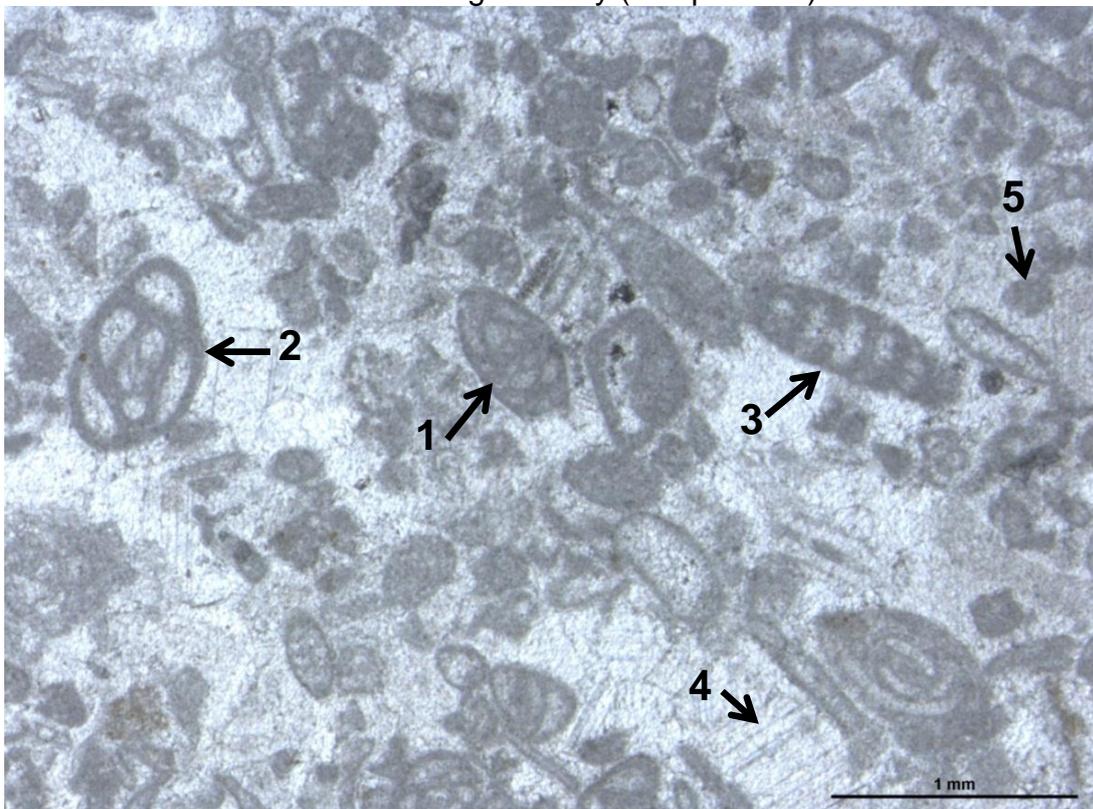


Figure 4.23: Photomicrograph of SP-3 microfacies with (1) *Dendritina*, (2) *Austrotrillina*, (3) *Praerhapydionina*, (4) echinoid fragments (5) peloids. Unstained thin-section in the Hazar Kani village locality (sample AS.8).

including syntaxial overgrowth of calcite cement around echinoid fragments, fracture and vug filled with non-ferroan blocky calcite cement. (Figure 4.24).

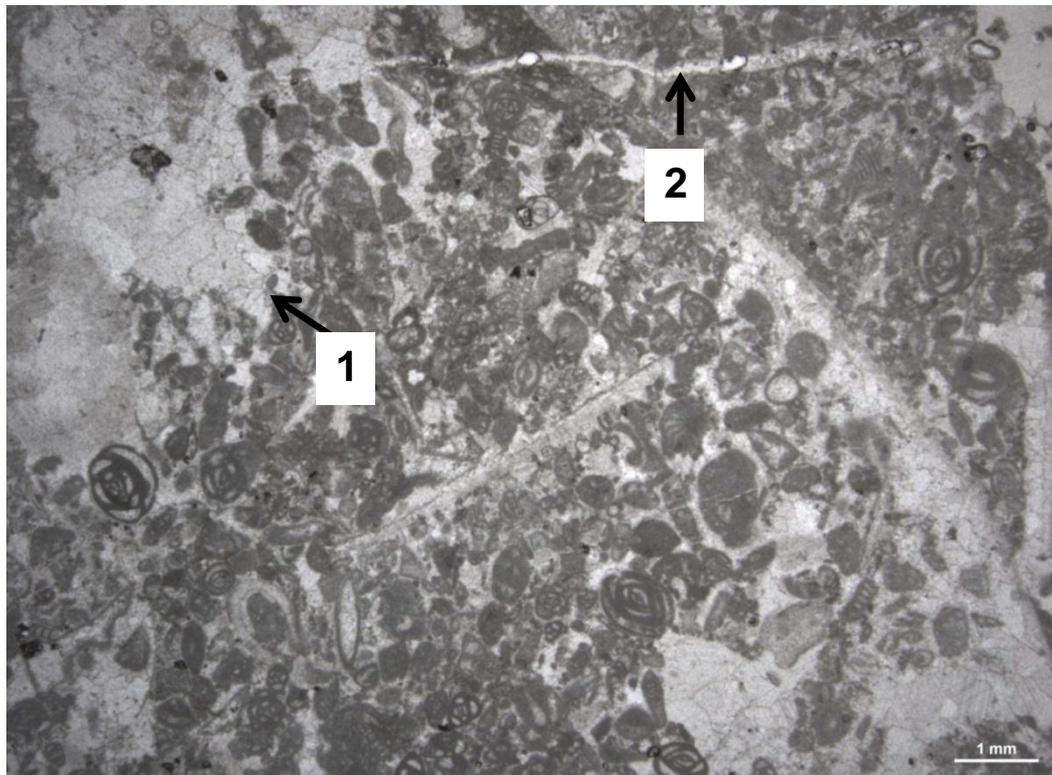


Figure 4.24: Photomicrograph of skeletal grainstone, partially packstone (1) dissolution filled with blocky calcite spar (2) calcite filled fracture. Unstained thin-section from the Zinana village locality (sample Z.21).

#### 4.2.5 Microfacies MP:

Microfacies MP is characterized by peloidal packstone/wackestone. The common skeletal grains are miliolids, *Austrorillina* and *Peneroplis*; it is divided into two sub-microfacies, MP-1 and MP-2 (as shown in Table 4.2), largely on the basis of variation in the proportions of larger benthic foraminifera, their degree of micritization and the texture of the rock. This microfacies is one of the main microfacies of the Kirkuk Group and is present in all the Aj Dagh Anticline localities (Zinana village, Hazar Kani village, the core of Aj Dagh and the Awa Spi area). The detailed description of the bioclasts, their composition and their percentages are provided below.

#### 4.2.5a Sub-microfacies MP-1:

This microfacies is typically characterized in the field by very thick to massive bedded limestone. It is identified in two localities, in Zinana village with a total thickness of 3 metres, and in the core of the Aj Dagh Anticline with a total thickness of 1 metre. It is laterally extensive for tens to several hundreds of metres and is interbedded with coral bioherms (CB) and skeletal grainstone (SP-3).

The microfacies MP-1 consists of packstone/grainstone, with bioclasts (average 35%), peloids (average 40%) and micrite (average 20%), in addition to cement (average 5%). Micritization of grains are uncommon.

The peloids in this microfacies appear as one form, they are composed of small- sand-grade sized round to ellipsoidal shaped pellets.

Laminoid type fenestrae with 1-2mm long and 0.2-0.5mm high, parallel to slightly sub-parallel to bedding planes is present (Grover and Read, 1978).

The common bioclasts are mostly porcellaneous benthic foraminifera: miliolids (average 11%); *Austrotrillina* (10-12%); *Peneroplis* (5%); *Praerhapydionina* (2%); minor skeletal grains of *Archaias*, *Dendritina*, *Spirolina*, *Biloculina*, *Triloculina*, *Quinqueloculina* and echinoid fragments (1%) (Figure 4.25).

Diagenesis features: cements, including in fenestrae, consist of non-ferroan calcite cement. Rare micritization is present (Figure 4.26).

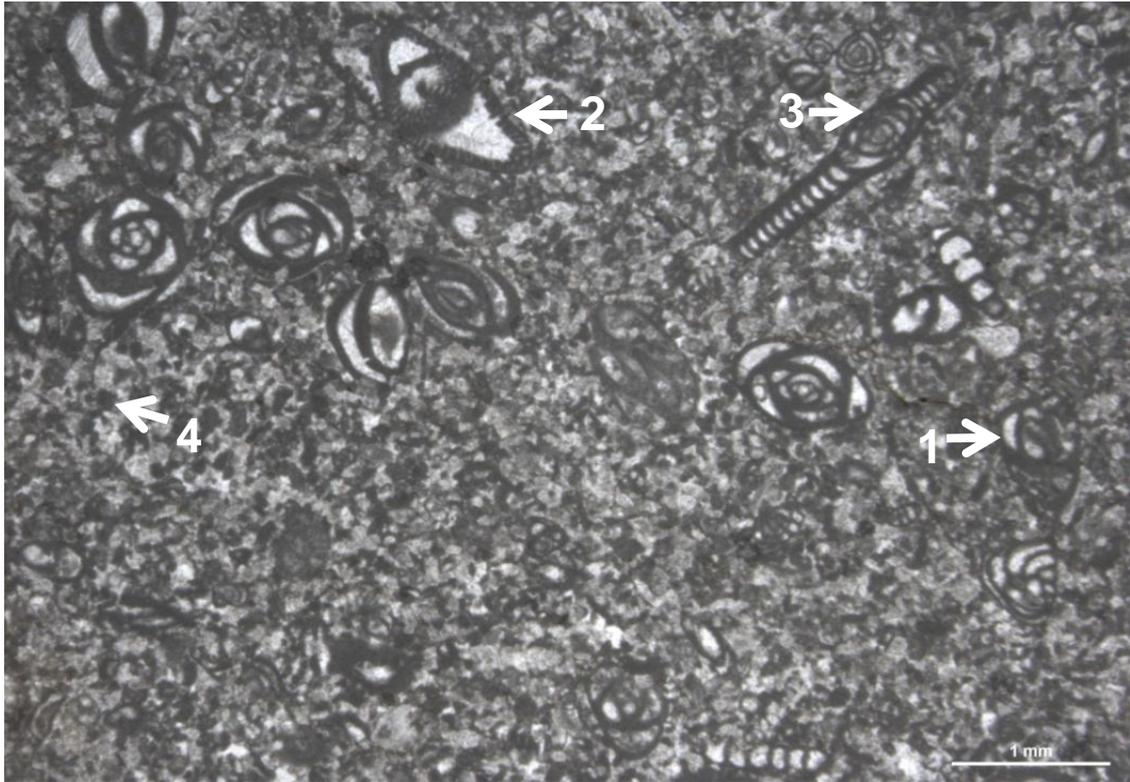


Figure 4.25: Photomicrograph of MP-1 microfossils (1) miliolids, (2) *Austrotrillina*, (3) *Peneroplis*, (4) peloids. Unstained thin-section from Zinana village section (sample Z.17).

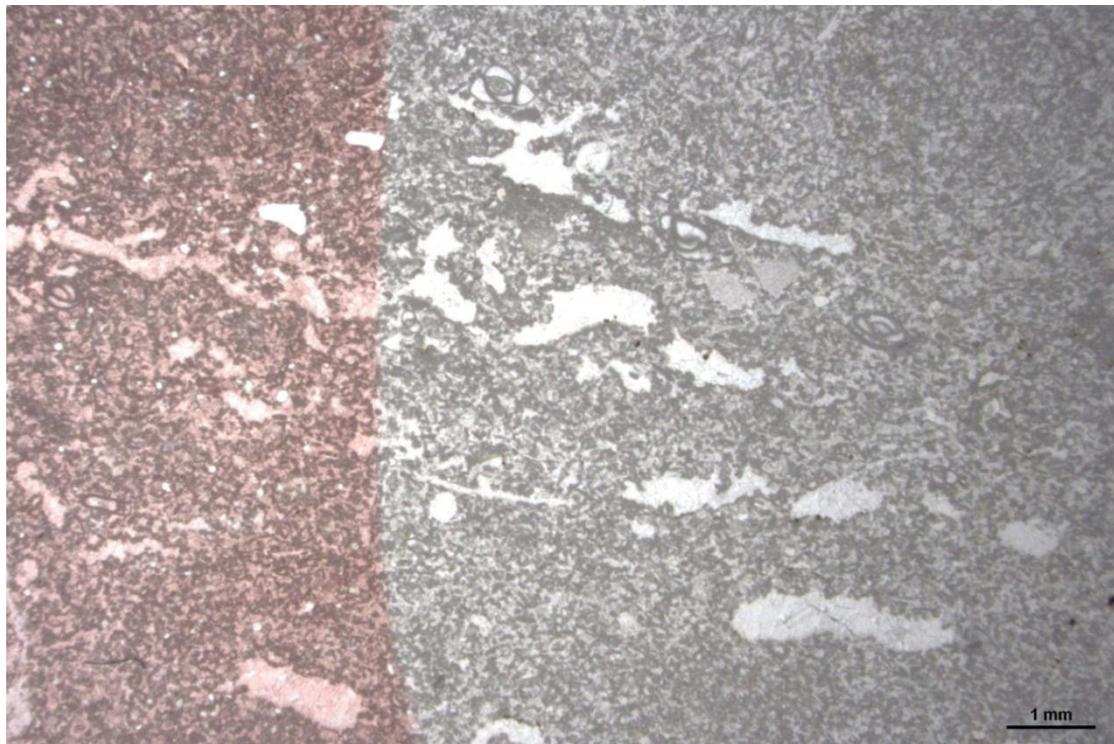


Figure 4.26: Photomicrograph of fenestral pores filled with non-ferroan calcite cement. The thin-section is half stained from the core of Aj Dagh Anticline (sample CA.16).

#### 4.2.5b Sub-microfacies MP-2:

This microfacies is characterized in the field by thick to massive bedded limestones. It is identified in three localities: in Hazar Kani village with a total thickness of 3.5 metres; in the core of the Aj Dagh Anticline with a total thickness of 1 metre; and in the Awa Spi area with a total thickness of 10 metres. It is laterally extensive for tens to several hundreds of metres, depending on the locality, and is interbedded with coral bioherms (CB) and skeletal grainstone (SP-3). In addition, the MP-2 microfacies overlie the conglomerate (CG) microfacies in Hazar Kani village and the Awa Spi area.

The microfacies MP-2 consists of peloidal wackestone-calcimudstone with bioclasts (average 17%), peloids (average 25%) and micrite (average 54%), and with poorly sorted, sub-angular quartz grains (less than 4%) are also present. There is extensive micritization of the grains in this microfacies. Fine to very fine sand-sized, sub-angular to rounded quartz grains are present in the lower part of this microfacies in the Hazar Kani and Awa Spi localities, in which this microfacies overlies a massive layer of conglomerate (Figure 4.27).

The major observed bioclasts are: miliolids (average 5%); *Austrotrillina* (average 3%); *Peneroplis* (3%); *Dendritina* (2%); with rare *Praerhapydionina*, *Archaias*, *Biloculina* and echinoid fragments (less than 1%) (Figures 4.28 and 4.29).

The diagenetic features present in this microfacies are cementation, only non-ferroan calcite cement, micritization and uncommon clay seams are also present (Figure 4.28).



Figure 4.27: Field photograph of MP-2 microfacies overlying the CG microfacies, note the quartz pebble at the lower part of MP-2 microfacies selected by arrow. Location is Awa Spi area. Field of view is 50cm wide.

#### 4.2.6 Microfacies CB:

The CB microfacies is characterized in the field by mostly massive bedded limestone. It occurs in four localities of the study area: in Hazar Kani village with a total thickness of 1.5 metres; in the core of the Aj-Dagh anticline with a total thickness of 1.5 metres; in the Bellula Gorge with a total thickness of 31 metres; and in the Sharwal Dra locality with a total thickness of 60 metres (Figure 4.30). This microfacies is interbedded with skeletal grainstone with *Praerhapydionina delicata* (SP-3) microfacies in the two former sections.

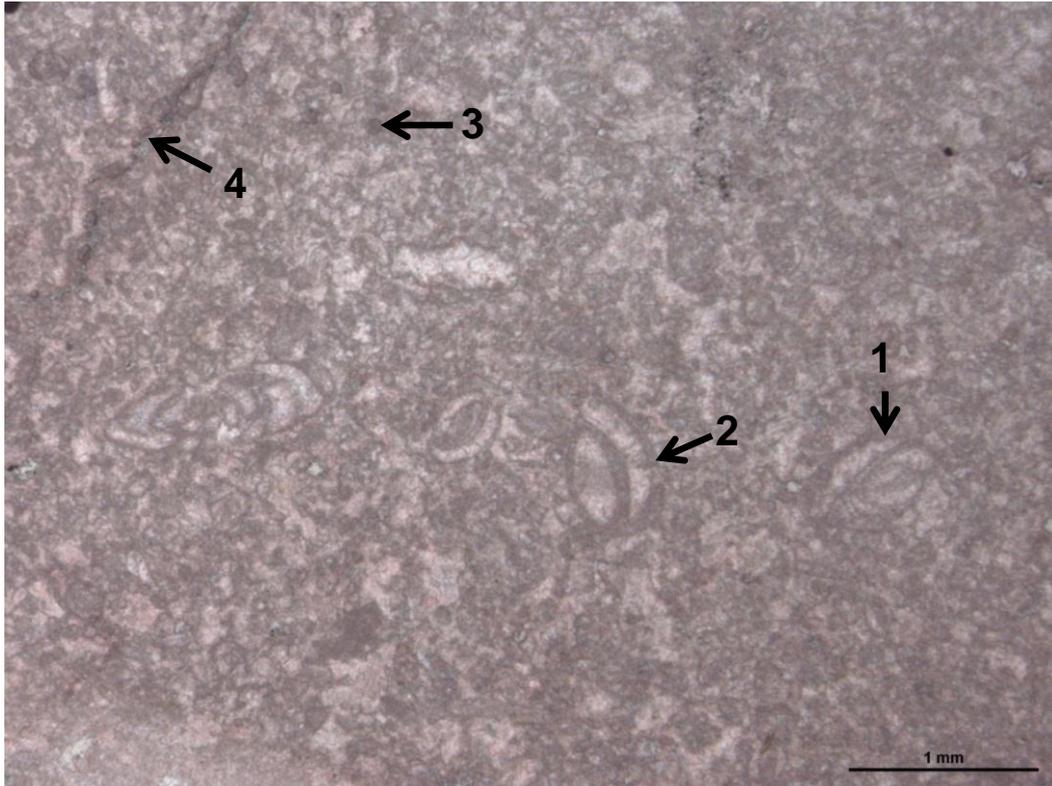


Figure 4.28: Photomicrograph of peloidal wackestone of MP-2. (1) miliolids, (2) *Austrotrillina*, (3) peloids, (4) clay seam. Stained thin-section of core of Aj Dagh Anticline (sample CA.18).

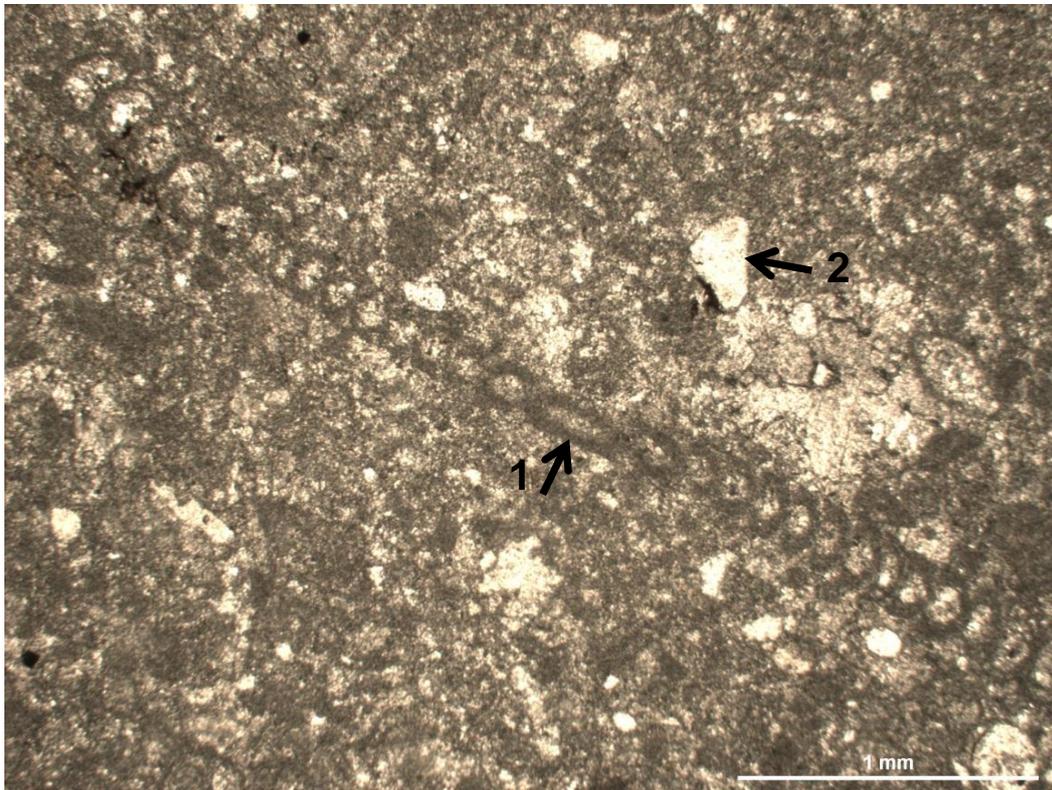


Figure 4.29: Photomicrograph of peloidal calcimudstone of MP-2. (1) peneroplids, (2) quartz grain. Un-stained thin-section of core of Awa Spi locality (sample DS.8).

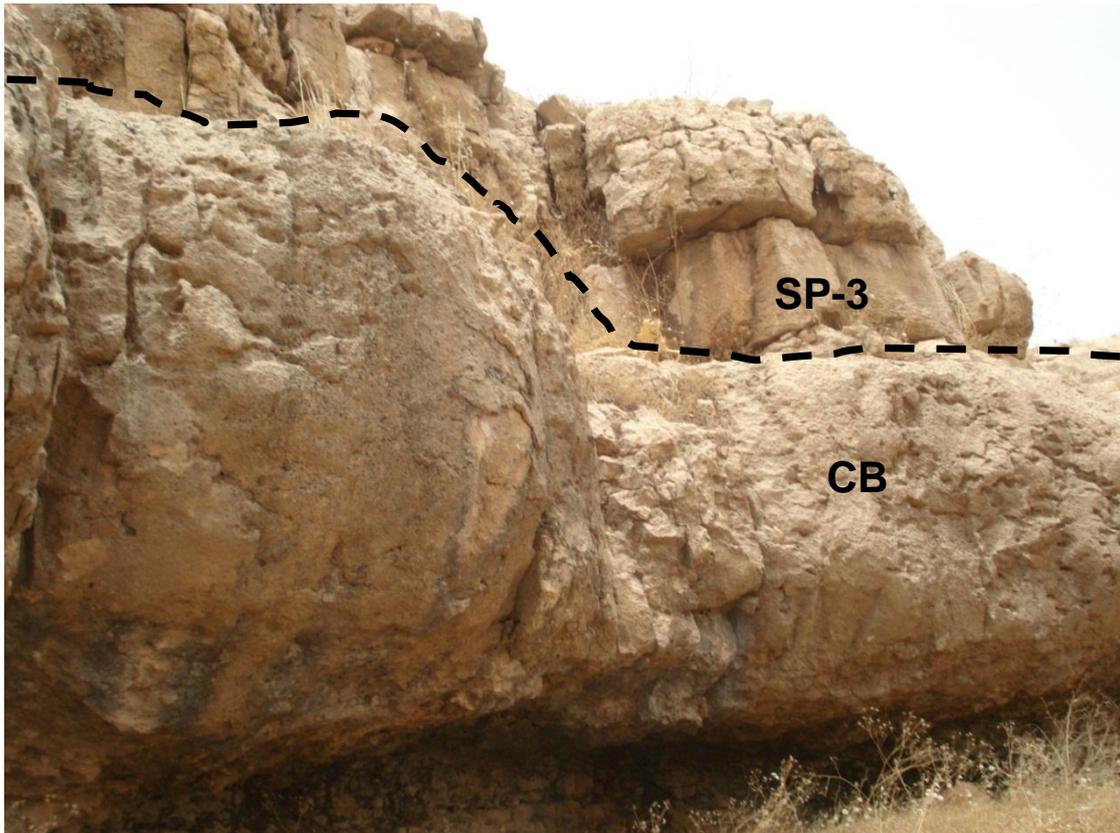


Figure 4.30: Field photo of CB microfacies overlain by SP-3 at core of Aj Dagh Anticline. Field of view is 3 metres wide.

Meanwhile, the two latter sections are interbedded with coralline red algae-*Nummulites* wackestone (NR-1) and rotalids-coralline red algae wackestone/packstone (RR), respectively. The lateral extent of this microfacies varies with geographical location; at Hazar-Kani village and Bellula Gorge, it is laterally extensive for tens of metres, whilst in the core of Aj-Dagh and Sharwal-Dra it may laterally extensive for hundreds of metres.

Microfacies CB is also one of the main microfacies of the Kirkuk Group in the area studied composed of coral boundstone which is predominantly composed of colonial coral, with aragonite replaced by non-ferroan calcite cement and the outer surface infested by micritization (Figures 4.31 and 4.32). From the outcrop photo you can notice that lots of detail is missing as there is

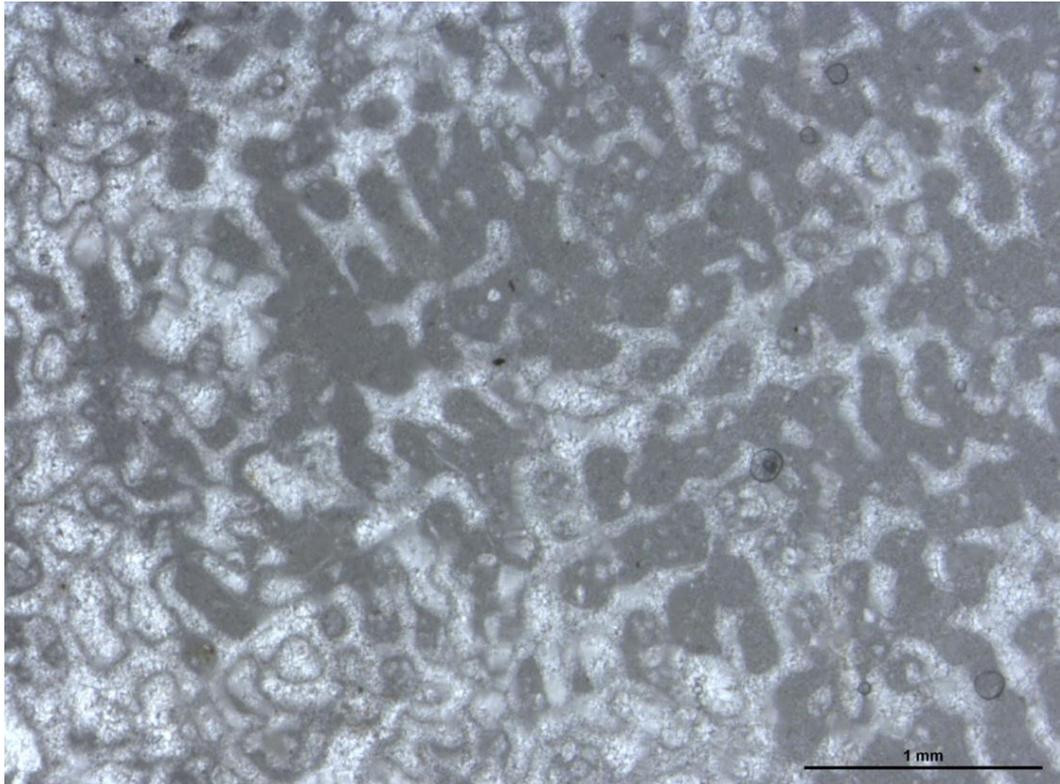


Figure 4.31: Photomicrograph of colonial coral, with aragonite replaced by non-ferroan calcite cement, the intra-skeletal pores filled by micrite. Unstained thin-section of Hazar Kani village (sample AS.6).

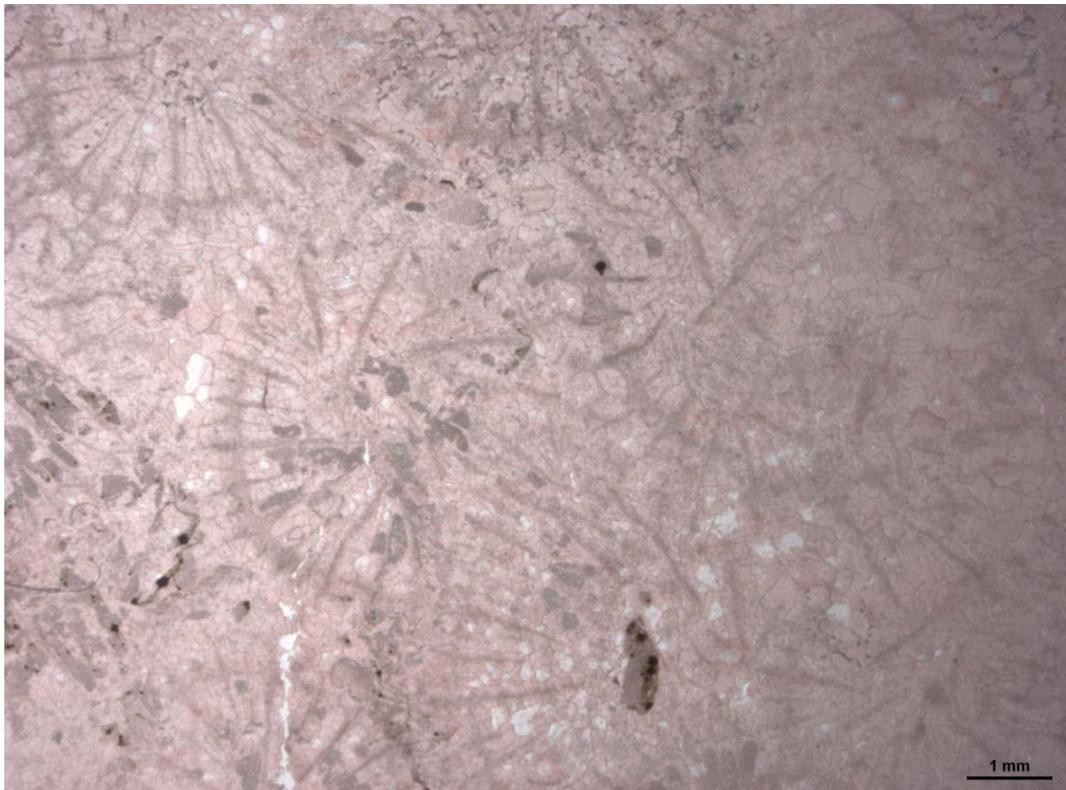


Figure 4.32: Photomicrograph of colonial coral replaced by non-ferroan calcite cement. Stained thin-section of core of Aj Dagh locality (sample CA.19).

no clear shape of the coral heads. Any observed coral heads were in growth position. The dominant diagenetic features of this microfacies are cementation including non-ferroan calcite and micritization.

#### **4.2.7 Microfacies CG:**

The CG microfacies is characterized in the field by a massive conglomerate layer. It is present in only two localities, in Hazar Kani village with a total thickness of 4.5 metres, and in the Awa Spi area with a total thickness of approximately 4 metres, with variation in thickness laterally (Figures 4.33 and 4.34). The conglomerate layer is overlain by peloidal wackestone/calcimudstone (MP-2) microfacies. There are no clear sedimentary structures.

The body is composed of single storey, clast supported, exotic clast conglomerate. The clasts are poorly sorted, sub-rounded to rounded chert pebbles, cobbles and sand size approximately 85%, with 15% of clay matrix (Figure 4.35).

According to the classification of Prothero and Schwab (2004), the rock is an oligomict, orthoconglomerate, extraformational conglomerate. Oligomict as the grains are composed of a limited variety of rocks and minerals; orthoconglomerate as it is grain supported and extraformational as the clasts are from outside the depositional basin.

#### **4.2.8 Microfacies PS:**

Paleosols are formed by the accumulation of calcium carbonate within unconsolidated carbonate-rich soils in terrestrial, subaerially exposed settings. Calcrete is present in only one locality, in the Awa Spi area with a thickness of

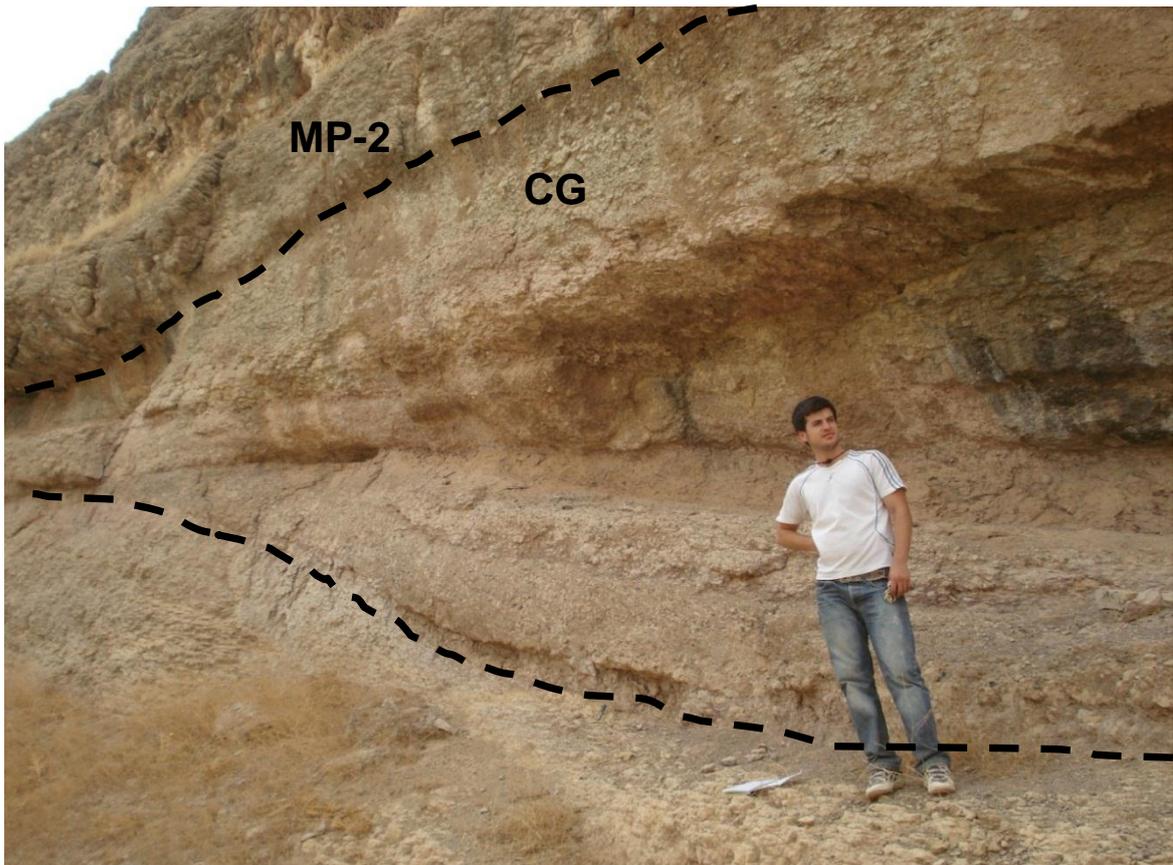


Figure 4.33: Field photo of CG microfacies at Awa Spi locality, note the thinning at the margin of this unit.



Figure 4.34: Field photo of CG microfacies at Hazar Kani village.

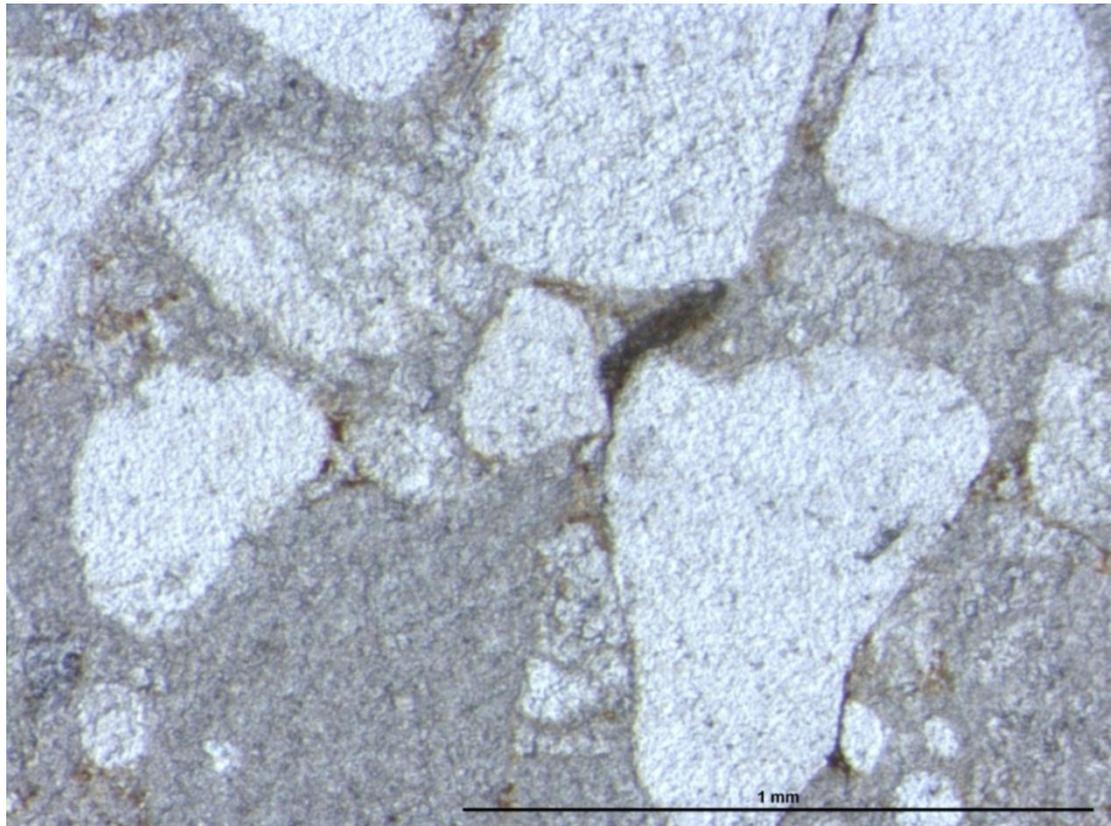


Figure 4.35: Photomicrograph of CG microfacies composed of sub-round to sub-angular quartz clasts in clay matrix. Unstained thin-section. Hazar Kai village (Sample AS.2).

30cm, located between PK-1 at the lower boundary and CG at the upper boundary (Figure 4.36).

The calcretes are composed of Alpha type, according to Wright and Tucker (1991) classification. They are composed of a dense micritic ground mass with features such as crystallaria including circumgranular cracks with floating quartz grains (Figure 4.37). They consist of irregular shaped nodular carbonate calcrete. According to Wright (1982b) they are composed of type 2 nodules, these nodules are characterized by having sharp margins that differ from type 1 which has diffuse margins.

Many nodules, which are surrounded by veins (crystallaria), show evidence of having formed circumgranular cracks (Ward, 1975) where these cracks are filled by calcite spar.

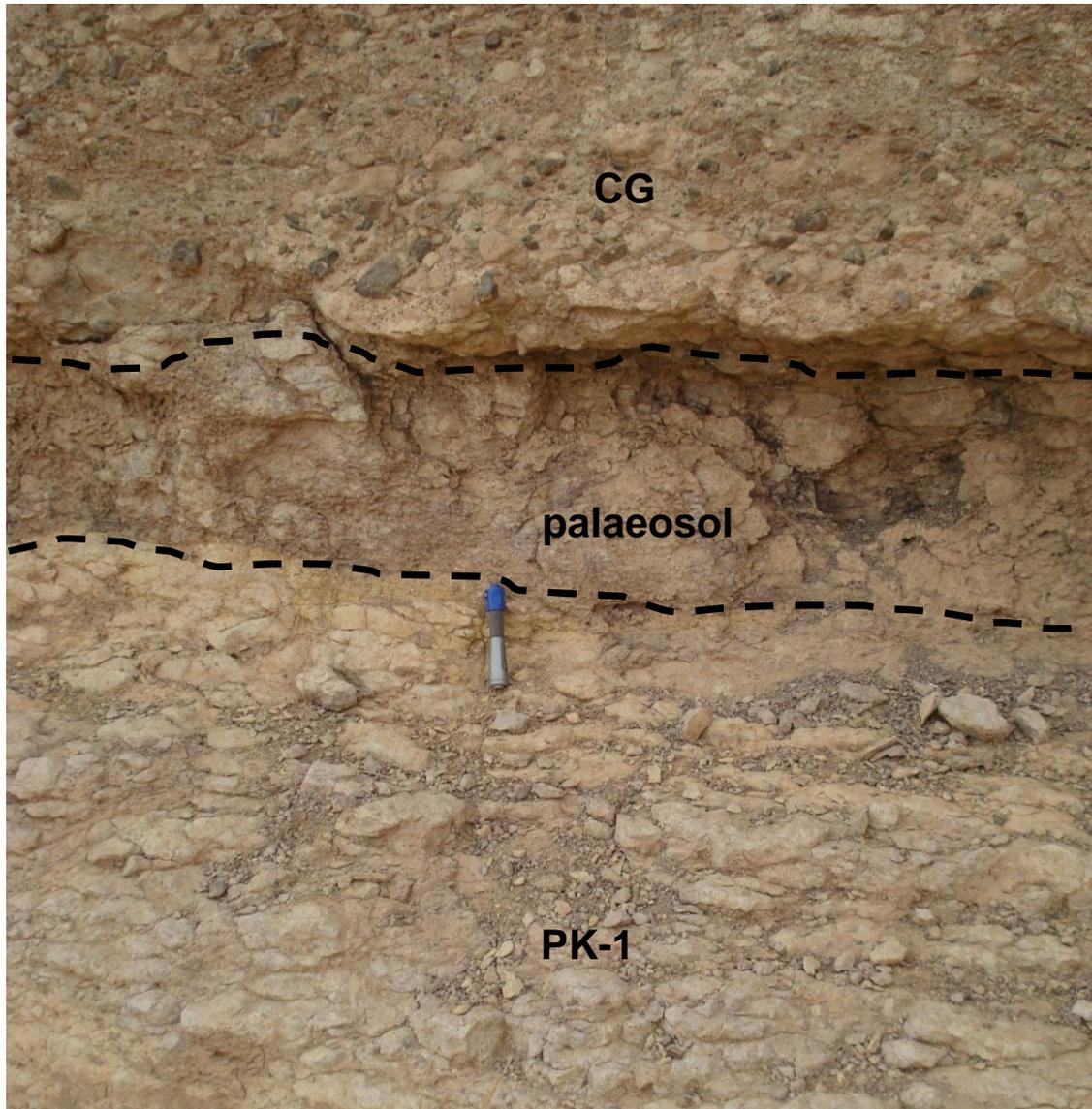


Figure 4.36: Field photo of paleosols underlies by PK-1 microfacies and overlies by CG microfacies at Awa Spi locality.

#### 4.2.9 Microfacies PK:

The PK microfacies is recognized by the presence of planktonic Foraminifera. It is divided into three different sub-microfacies, PK-1, PK-2 and PK-3 (see Table 2-4), on the basis of different kinds of planktonic Foraminifera in each

microfacies, the presence or absence of benthonic foraminifera, and also different rock textures. This microfacies is present in the Sharwal Dra; Awa Spi, and Bellula Gorge localities; the former locality belong to the Kirkuk Group, whereas the two latter are belongs to the Late Eocene Jaddala Formation.

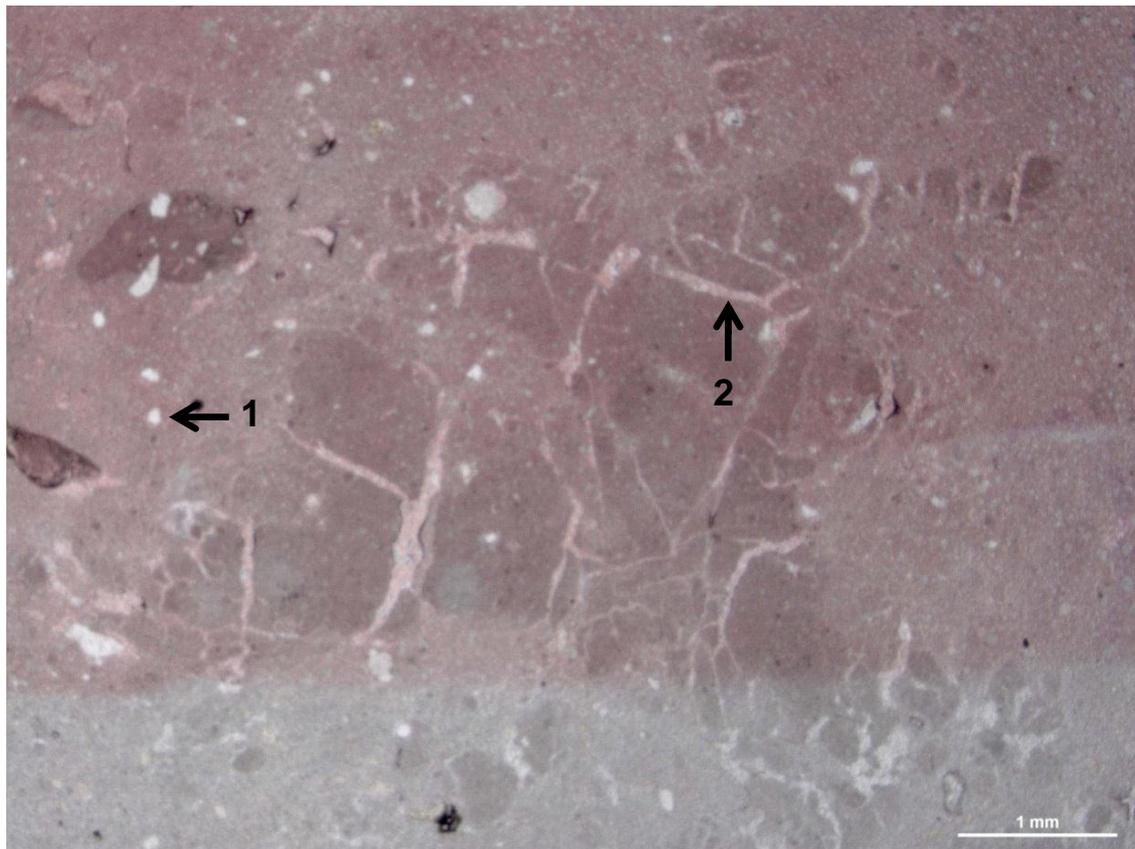


Figure 4.37: Photomicrograph of paleosols. (1) floating quartz, (2) fine irregular fractures some circumgranular cracks. The thin-section is half stained. Awa Spi locality (sample AW.18).

#### **4.2.9a Sub-microfacies PK-1:**

The PK-1 microfacies is characterized in the field by thin bedded limestones. It is identified in only one locality in the Aj Dagh Anticline, in the Awa Spi area with a total thickness of 1 metre, and is laterally extensive for tens of metres.

This microfacies is overlain by a very thin palaeosol and then followed by a thick conglomerate layer of CG microfacies (Figure 4.36).

This microfacies comprises thin bedded, very fine grained peloidal packstone. The rock is composed of bioclasts of ostracods (average 3%) and planktonic foraminifera (less than 2%); peloids (40%) and micrite matrix (average 55%) (Figure 4.38).

The diagenetic features in PK-1 microfacies are cementation and compaction, including low-amplitude stylolites, and clay seams are also present (Figure 4.38).

#### **4.2.9b Sub-microfacies PK-2:**

PK-2 microfacies is characterized in the field by thin bedded limestone. It is identified in two localities, in the Sharwal Dra area with a total thickness of 1 metre and at Bellula Gorge with a total thickness of 80 metres, laterally extensive for tens to hundreds of metres, according to the location; it is interbedded with PK-3 microfacies.

The PK-2 microfacies is composed of calcimudstone (partially wackestone) with bioclasts of planktonic foraminifera (average 12%), *Discocyclus* (average 2%), *Nummulites* (average 1%), rare *Pellatispira* (less than 1%), unrecognizable fragments (average 4%), peloids (average 12%) and micrite matrix (average 69%) (Figure 4.39).

The diagenetic features in this microfacies are cementation (non-ferroan calcite cement) including cement filled fracture and clay seams are also present (Figures 4.40 and 4.41).

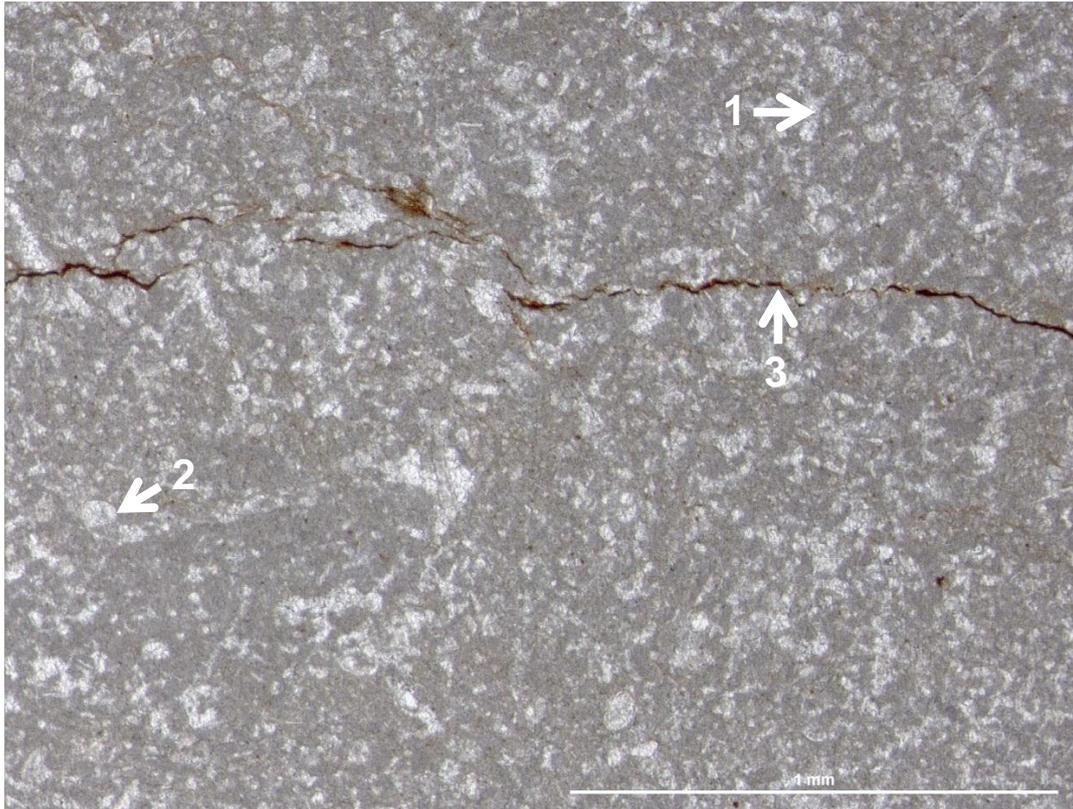


Figure 4.38: Photomicrograph of peloidal packstone. (1) peloids, (2) planktonic foraminifera, (3) low-amplitude stylolites. Unstained thin-section from Awa Spi area (sample AW.16).

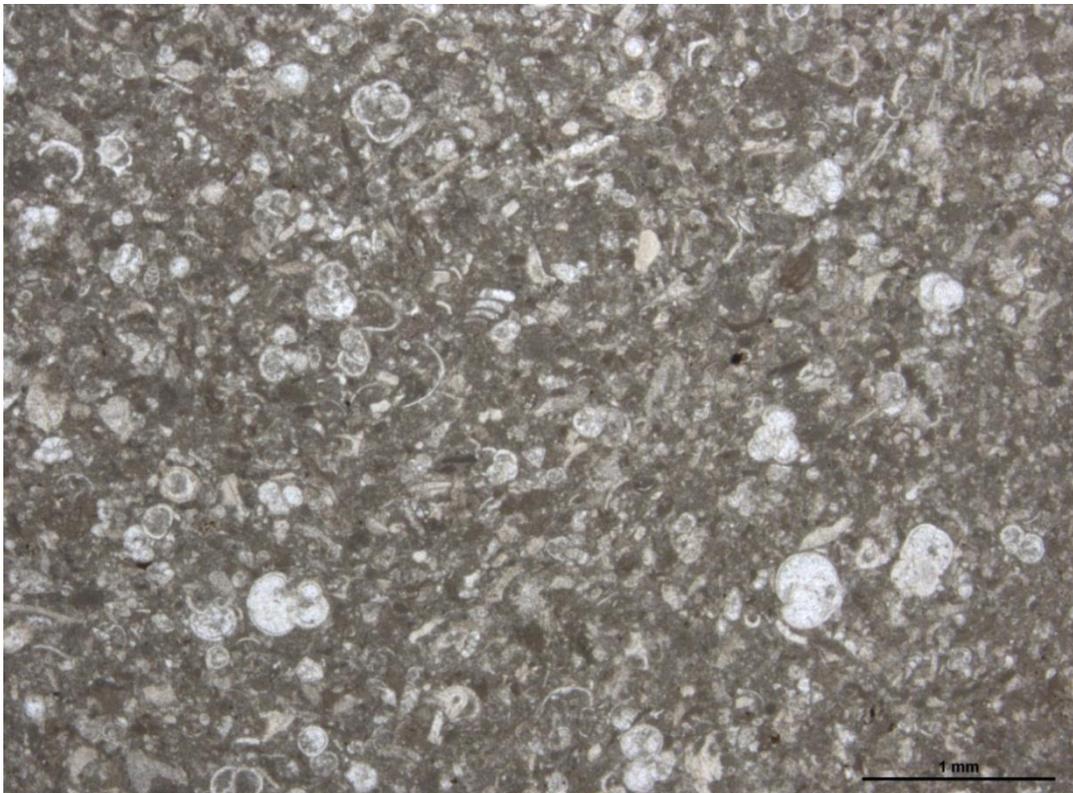


Figure 4.39: Photomicrograph of wackestone with planktonic foraminifera. Unstained thin-section from Bellula Gorge locality (sample BL.26).

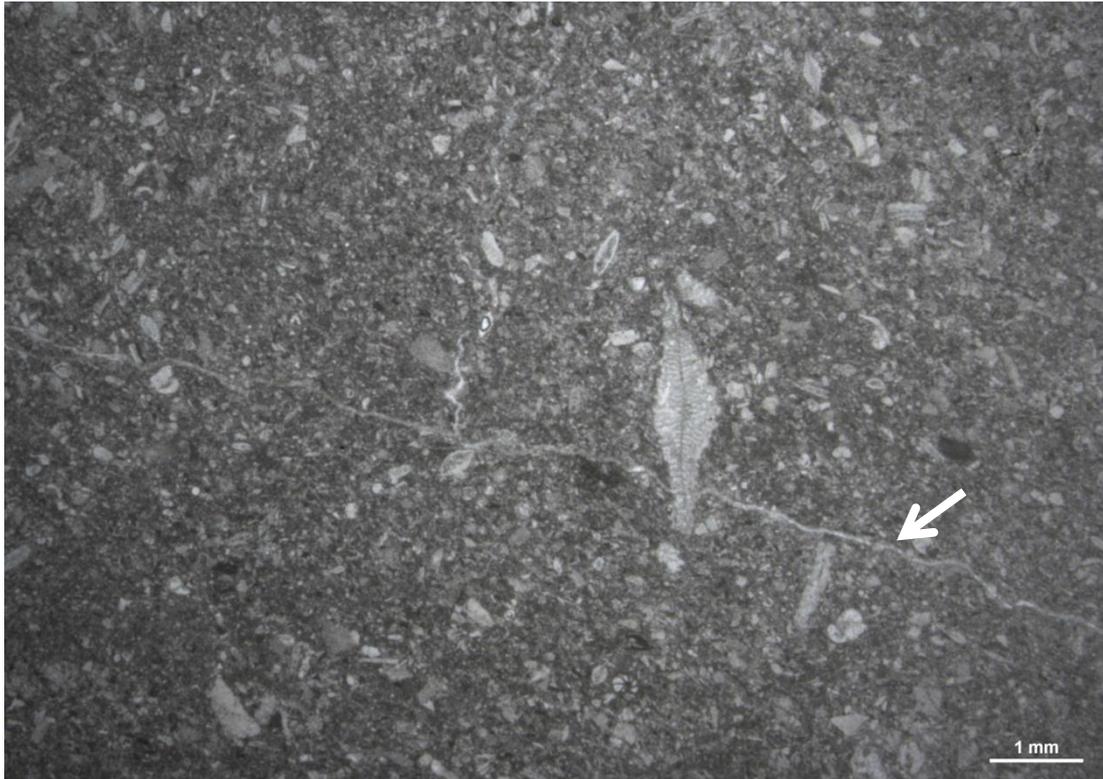


Figure 4.40: Photomicrograph of PK-2 with presence of calcite filled fracture (arrowed). Unstained thin-section from Bellula Gorge locality (sample BL. 43).



Figure 4.41: Photomicrograph of PK-2 with clay seams (arrowed). Unstained thin-section at Bellula Gorge locality (sample BL.32).

#### **4.2.9c Sub-microfacies PK-3:**

The microfacies PK-3 is characterized in the field by thin to medium bedded limestones. It is identified in only one locality, in Bellula Gorge with a total thickness of 32.5 metres, laterally extensive for tens of metres.

This microfacies is interbedded with PK-2 microfacies. It is composed of wackestone with bioclasts (average 25%), unrecognizable fragments (average 20%) and peloids (average 4%). In addition is micrite matrix (average 51%).

The bioclasts are composed of a mixture of planktonic foraminifera (average 11%), and benthonic foraminifera including *Discocyclina* (average 8%) and *Nummulites* (average 5%). Minor components include echinoid fragments, textularids and *Pellatispira* (less than 1%) (Figure 4.42).

The diagenetic features in this microfacies are cementation, non-ferroan calcite cement filled fractures and compaction including clay seams and stylolites (Figure 4.43).

#### **4.2.10 Microfacies NR:**

The microfacies NR is composed of skeletal wackestone to packstone, divided into three sub-microfacies, NR-1, NR-2 and NR-3, largely on the basis of variations in the larger benthic foraminifera, rock texture and their stratigraphical positions.

The difference between NR-1 microfacies, and NR-2 and NR-3 microfacies is that the former microfacies has a different rock texture and stratigraphic position. Whereas the difference between NR-2 and NR-3 microfacies is in the variation of the type of larger benthic foraminifera (the detail is in 4.2.10a, b and c). The NR-1 microfacies is one of the dominant microfacies of the Kirkuk

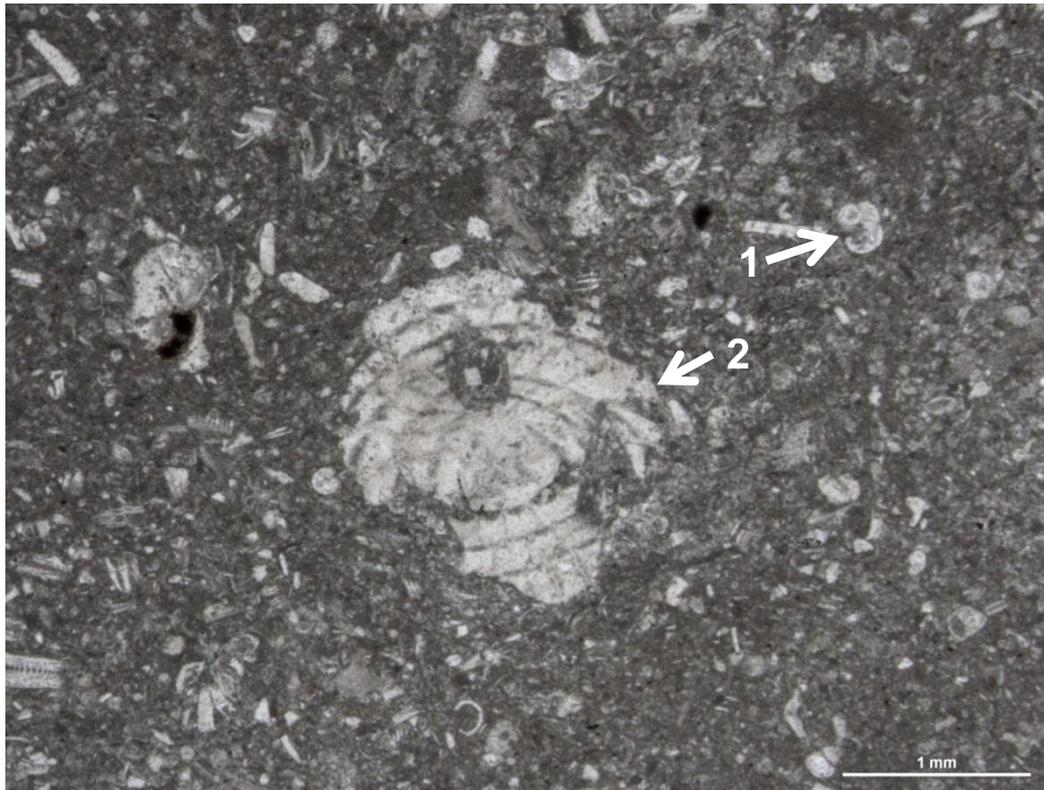


Figure 4.42: Photomicrograph of PK-3. (1) planktonic foraminifera, (2) broken *Nummulites*, Unstained thin-section from Bellula Gorge locality (sample BL.51).

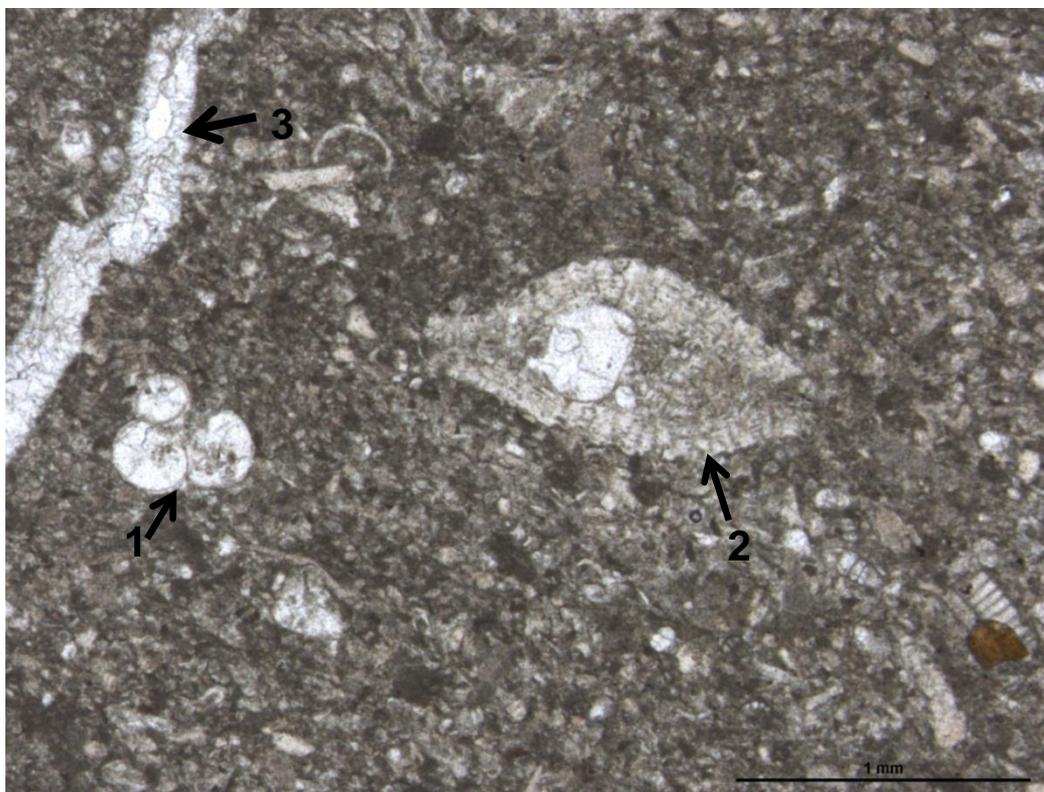


Figure 4.43: Photomicrograph of PK-3. (1) planktonic foraminifera, (2) *Discocyclina*, (3) calcite filled fracture. Unstained thin-section at Bellula Gorge locality (sample BL.31).

Group, located at the lower part of the succession, whilst the NR-2 and NR-3 belong to the Late Eocene Avana Formation and directly underlie the Kirkuk Group succession.

#### **4.2.10a Sub-microfacies NR-1:**

The microfacies NR-1 is characterized in the field by massive bedded limestones. It is identified in only one locality, in the Bellula Gorge with a total thickness of 16 metres. It is laterally extensive for tens of metres, overlying PK-2 microfacies and underlying coral bioherm (CB) microfacies.

This microfacies comprises fine to coarse, sand grade, grained coralline red algae- *Nummulites* wackestone. The rock is composed of bioclasts (average 18%); peloids (average 5%); micrite matrix (average 72%) and cements (average 5%).

The recognizable bioclasts of this microfacies are: *Nummulites* (average 5%); *Asterigerina* (2%); red algae (average 8%); rare *Victorella* (1%); and corals (average 2%) (Figure 4.44).

The diagenetic features in the NR-1 microfacies are includes cementation in only one form of cement which is early non-ferroan calcite cement with cement filled fractures with no evidence of chemical and mechanical compaction (Figure 4.45).

#### **4.2.10b Sub-microfacies NR-2:**

The microfacies NR-2 is predominantly characterized in the field by massive bedded limestone. It is identified in three localities, at Bamu Gorge with a total thickness of 10 meters, at Awa Spi locality with a total thickness of 9 metres,



Figure 4.44: Photomicrograph of NR-1. (1) *Nummulites*, (2) red algae. Stained thin-section at Bellula Gorge locality (sample BL.56).

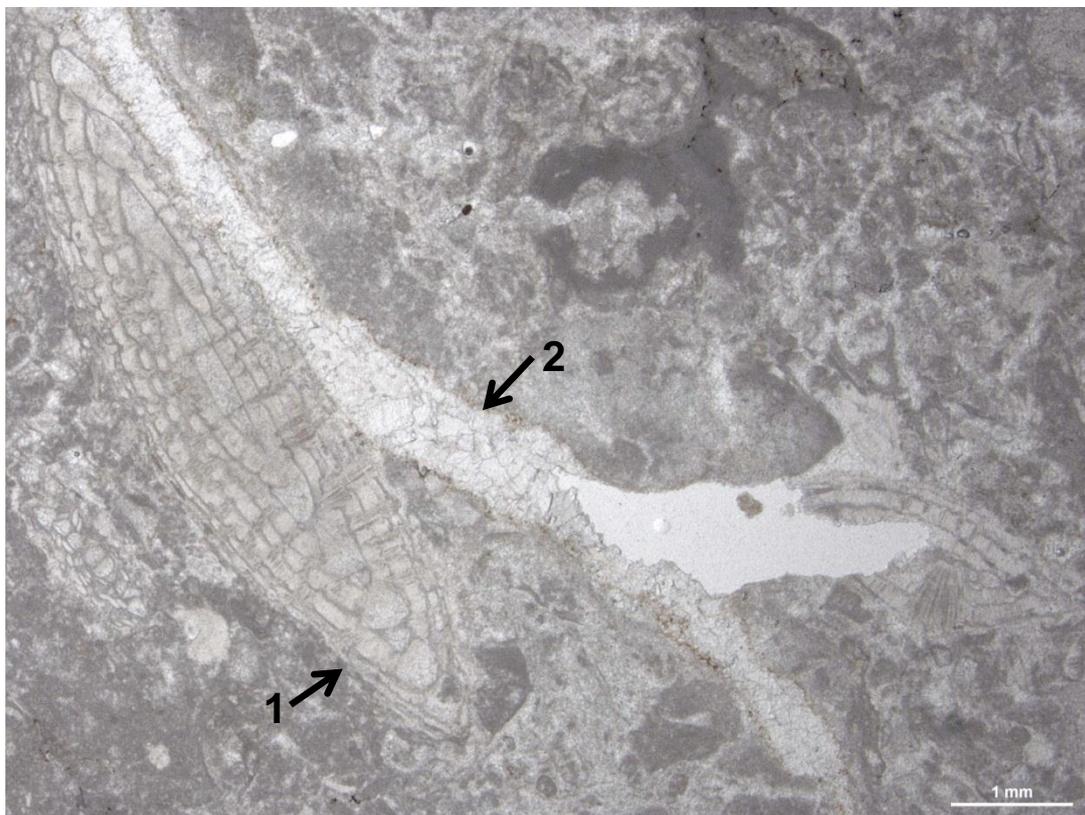


Figure 4.45: Photomicrograph of NR-1. (1) *Nummulites*, (2) calcite filled fracture. Unstained thin-section at Bellula Gorge locality (sample BL.59).

and at the core of the Aj Dagh Anticline with a total thickness of 11 metres. It is laterally extensive from tens of metres to hundreds of metres, according to location. The NR-2 microfacies in Bamu Gorge underlie the SP-3 microfacies and is interbedded with NR-3 microfacies; at the Awa Spi locality it overlies the MG microfacies and underlies the PK-1 microfacies; at the core of the Aj Dagh Anticline It is interbedded with MG microfacies (Figure 4.46).

The microfacies NR-2 comprise peloidal, skeletal packstone (locally wackestone). Grains are dominantly fine to coarse sand grades. The rock consists of matrix (46% average), peloids (20% average) and bioclasts (29% average). In addition there are some cements (5% average) (Figures 4.47, 4.48 and 4.49). The most common recognized bioclasts of this microfacies are: *Nummulites* (average 10%); *Asterigerina* (4%); red algae (average 4%); *Operculina* (average 2%); *Discocyclusina* (2%); *Textularia* (1%); echinoid fragments (average 4%). The minor components are miliolids, *Victorella* and *Pellatispira* (less than 1%).

The diagenetic features associated with this microfacies include the non-ferroan calcite cement, calcite-filled fractures, in addition to dissolution (Figures 4.46 and 4.49).

#### **4.2.10c Sub-microfacies NR-3:**

The NR-3 microfacies is characterized in the field by massively bedded limestones (Figure 4.50). It is identified in three locations, at Awa Spi locality with a total thickness of 1 metre, at Bamu Gorge with a total thickness of 10 meters, and at Bellula Gorge with a total thickness of 2.5 metres. It is laterally extensive for tens to hundreds of metres, according to locality. The NR-3

microfacies in Awa Spi is located at the lower part of the section and is overlain by the MG microfacies; in the Bamu Gorge it is interbedded with NR-2 microfacies, and in the Bellula Gorge this microfacies is located at the lower part of this section and is overlain by PK-3 microfacies.



Figure 4.46: Field photograph of NR-2 microfacies at the Awa Spi locality with the presence of a cavity. The height of outcrop is 8m.

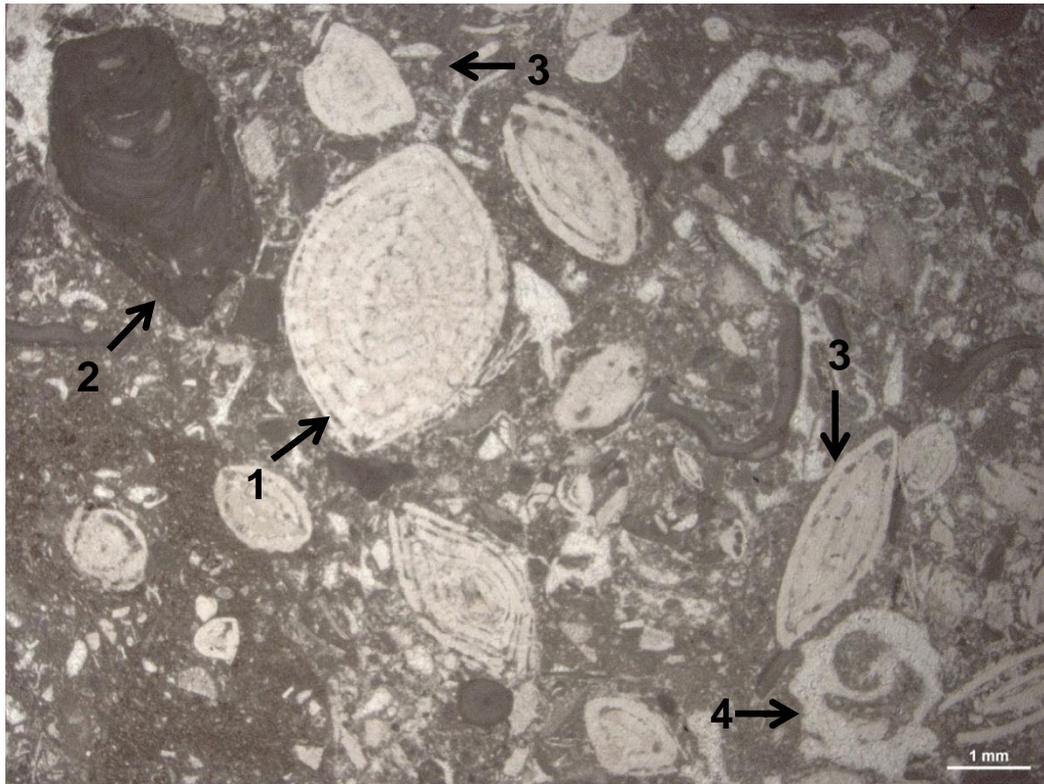


Figure 4.47 Photomicrograph of NR-2. (1) *Nummulites*, (2) red algae (3) *Asterigerina*, (4) gastropod. Unstained thin-section of microfacies NR-2 from Awa Spi locality (sample AW.10).

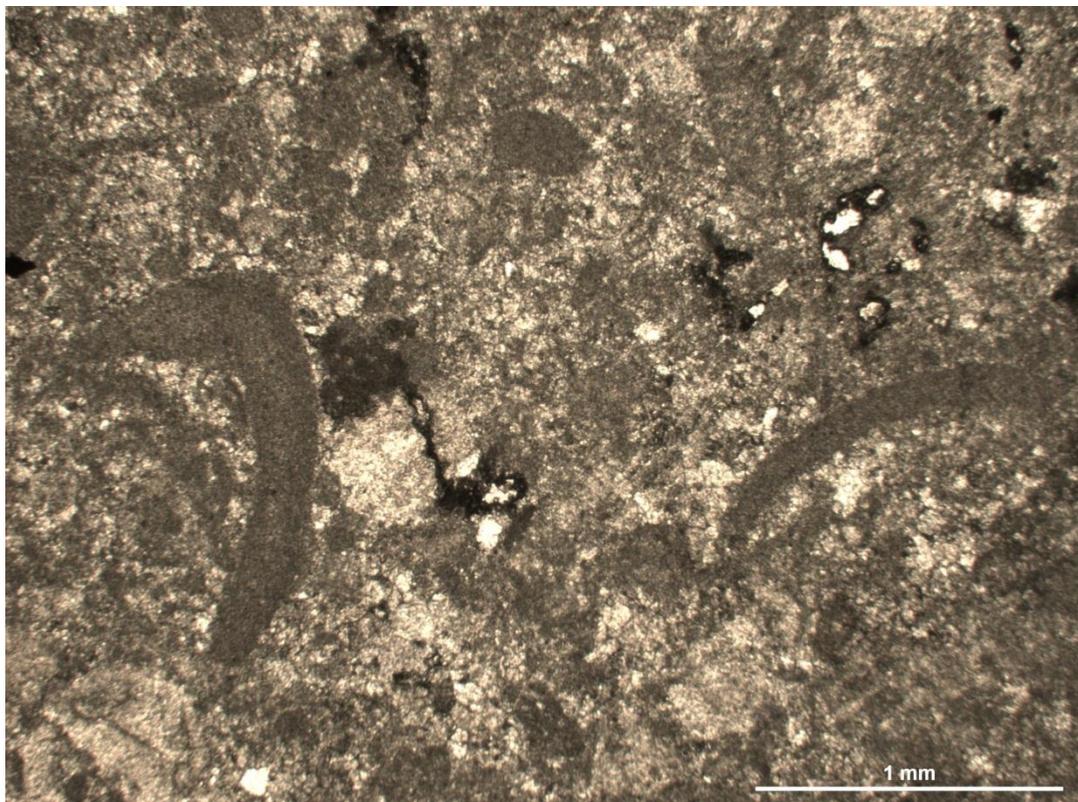


Figure 4.48 Photomicrograph of NR-2 microfacies. Showing red algae with hooked structure. Unstained thin-section from Awa Spi locality (sample AW.12).

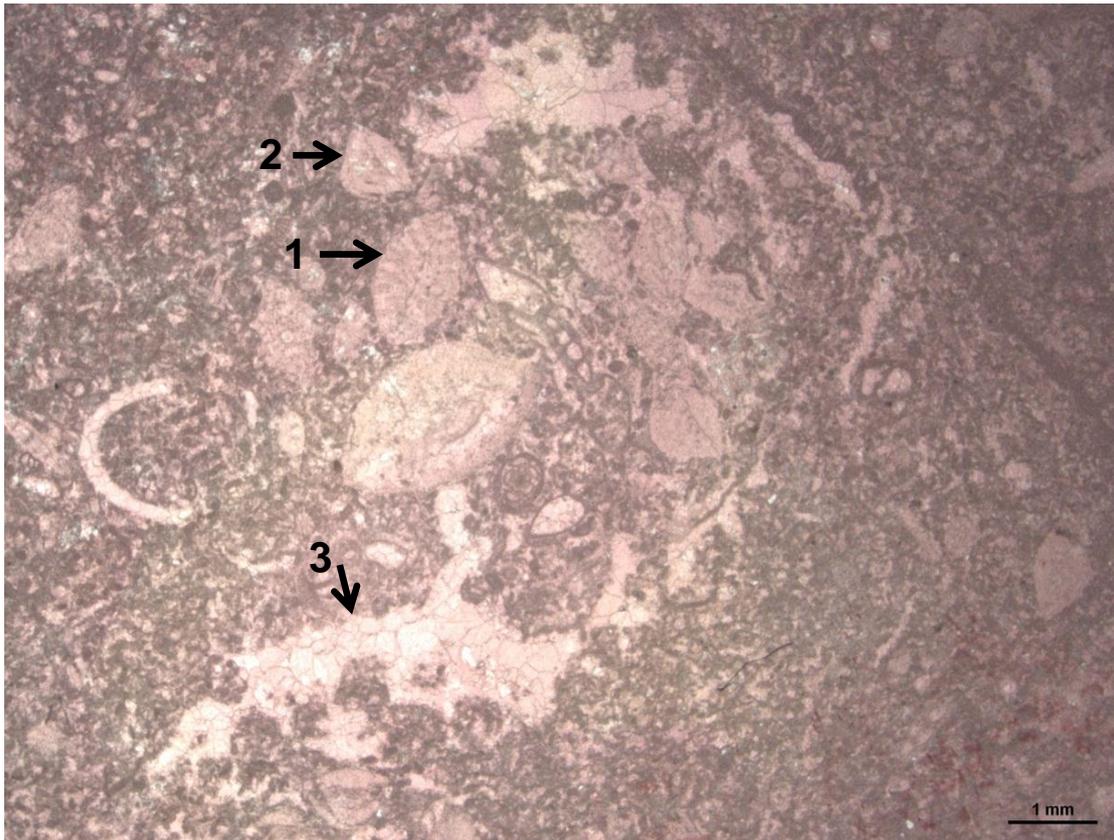


Figure 4.49: Photomicrograph of NR-2. (1) *Nummulites*, (2) *Asterigerina*, (3) vug filled with non-ferroan calcite cement. Stained thin-section from core of Aj Dagh Anticline (sample CA.10).

This microfacies is composed of massive skeletal packstone (Figures 4.50 and 4.51). Grains are medium to very coarse grained of sand grade, locally reaching rudstone size, and occasionally forming a fitted fabric packstone. The limestone is composed of bioclasts (average 56%); peloids (average 7%) in addition to micrite matrix (average 36%). Moreover, uncommon dolomites (average 1%) are only present in Bellula Gorge section.

The most common recognized bioclasts are benthic foraminifera including *Nummulites* (average 30%); *Discocyclina* (average 15%); *Asterigerina* (average 3-4%); *Operculina* (average 2%) and *Textularia* (less than 1%). Moreover, red algae (1%) and echinoid fragments (3-4%) are also present (Figures 4.52, 4.53 and 4.54).

There are diagenetic features associated with NR-3 microfacies, such as cementation, and including: syntaxial overgrowths on echinoid fragments; non-ferroan calcite-filled fractures and compaction, including mechanical and



Figure 4.50: Field photograph of NR-3 microfacies at Bellula Gorge locality.

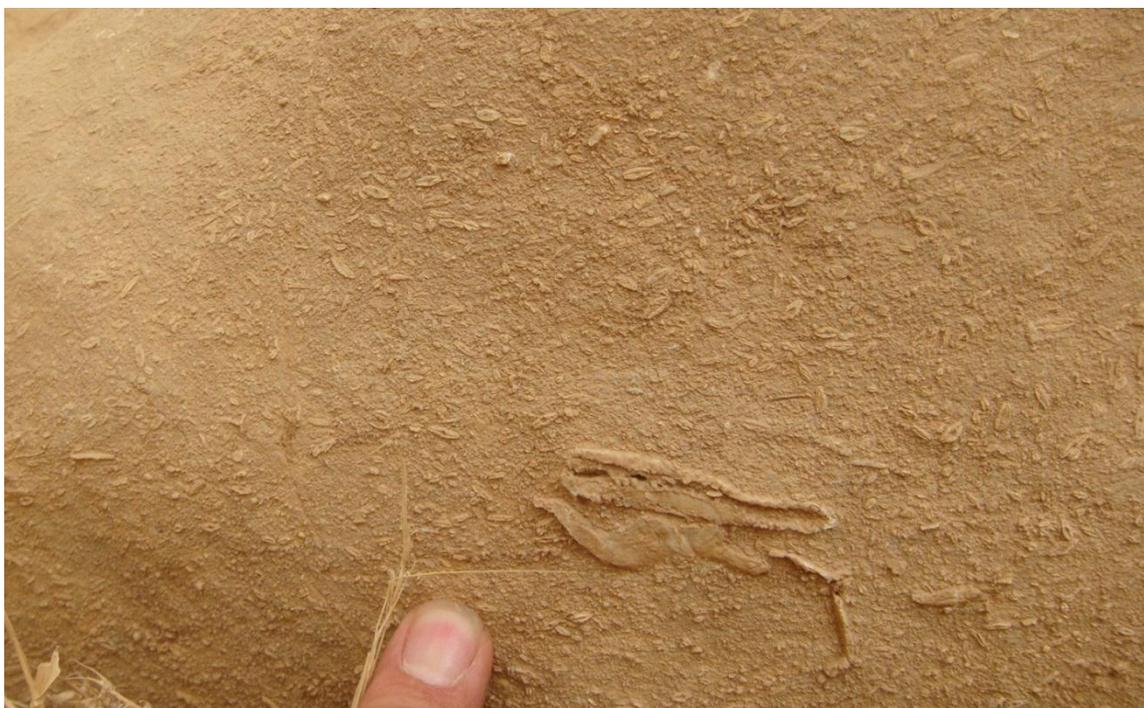


Figure 4.51: Field photograph of skeletal packstone of NR-3 microfacies from Bellula Gorge locality.



Figure 4.52: Photomicrograph of sutured contact between grains (marked by arrow), left is *Discocyclus* and right is *Nummulite*. Unstained thin-section of NR-3 microfacies from Bellula Gorge locality (sample BL.3).

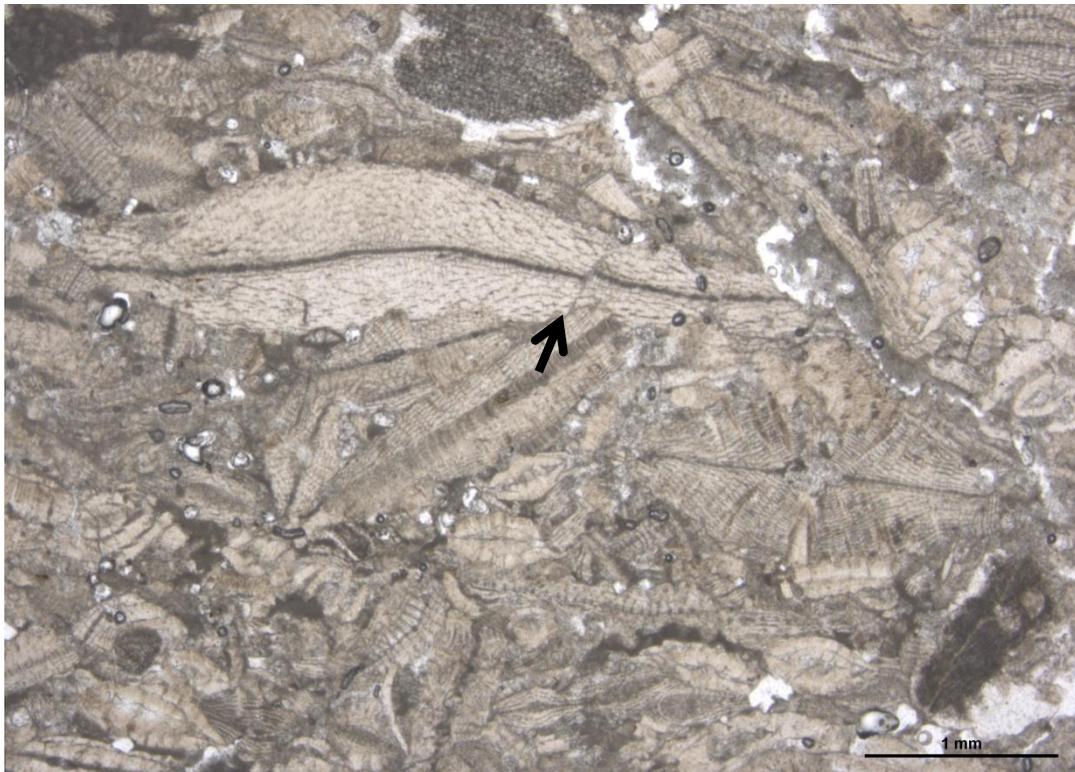


Figure 4.53: Photomicrograph of mechanical compaction inside *Discocyclus* (marked by arrow) in NR-3 microfacies. Unstained thin-section from Bellula Gorge locality (sample BL.2).

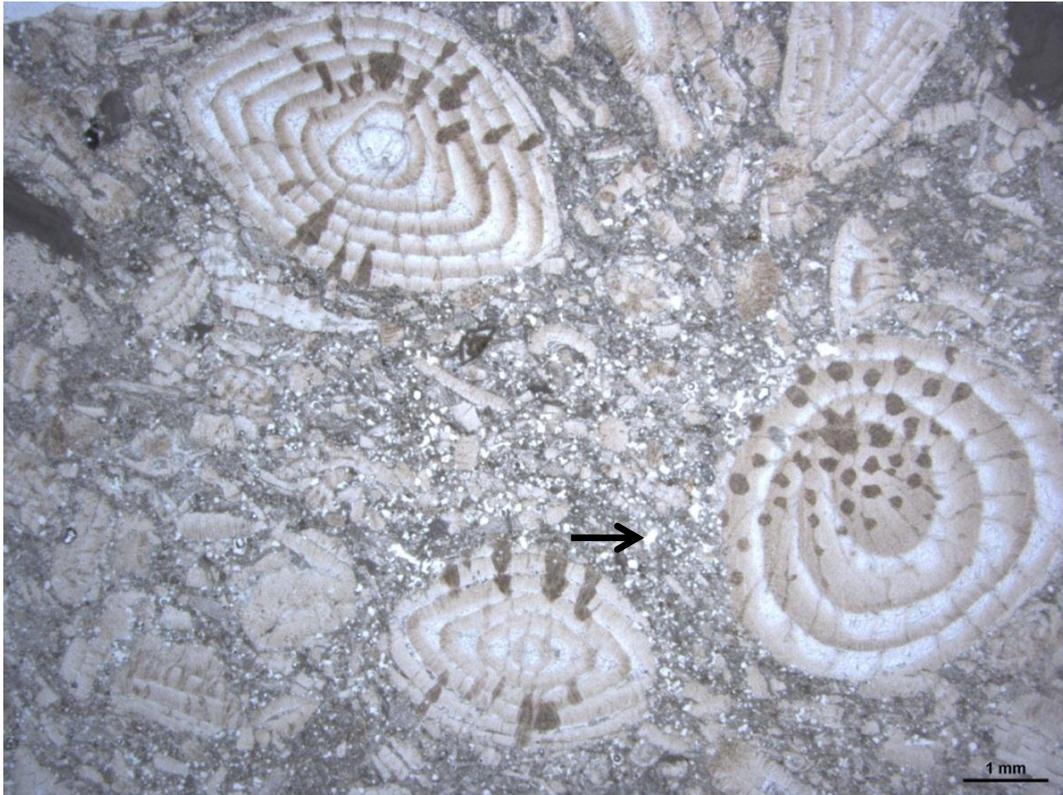


Figure 4.54: Photomicrograph of idiotopic dolomite rhombs (marked by arrow) in NR-3 microfacies. Unstained thin section from Bellula Gorge locality (sample BL.5).

chemical compactions such as concavo-convex and suture contacts between grains. Dolomites are presence as scattered, very fine crystals of idiotopic (euhedral) dolomite crystals (Figures 4.52, 4.53 and 4.54).

#### **4.2.11 Microfacies PG:**

The microfacies PG is characterized in the field by massive bedded limestones. It is identified in six localities: at Bamu Gorge with a total thickness of 5 meters; at Sagrama locality with a total thickness of 25.3 metres; at Zinana village locality with a total thickness of 10.5 metres; at Hazar Kani village locality with a total thickness of 3 metres; at the core of the Aj Dagh Anticline with a total thickness of 12.7 metres; and at Awa Spi locality with a

total thickness of 4.3 metres (Figure 4.55). This microfacies is one of the microfacies of Late Eocene Avanah Formation which is laterally extensive varying from tens of metres to hundreds of metres according to the location. It has nodular or discontinuously bedded of diagenetic silica (chert) and/or borrows filled with silica (Figure 4.56). The PG microfacies in Bamu Gorge is located between NA and NR-2, at the lower and upper parts respectively; in the Sagma area, the PG is located at the lower part of this section and overlain and separated from the SP-2 microfacies by a hardground surface; at Zinana village, this microfacies is located at the lower part of the succession and overlain by SP-3 microfacies; at Hazar Kani village also, this microfacies is located at the lower part of this section and overlain by CG microfacies; at the core of the Aj Dagh Anticline, the MG microfacies underlies the MP-1 microfacies, while at the lower part it is interbedded with NR-2 microfacies, and finally, at Awa Spi locality, it is interbedded with NR-3 and NR-2 microfacies.

This microfacies is composed of peloidal, skeletal grainstone. Grains are fine to medium grained. The rock is composed of bioclasts (average 34%) and peloids (average 35%), in addition to cement (average 30%). Moreover, reworked superficial ooids (>1%) are present. The most common bioclasts are: miliolids (average 15%); *Orbitolites* (average 4%); ?*Dendritina* (average 2%); *Quinqueloculina* (average 2%); echinoid fragments (8%); in addition to rare skeletal grains are *Biloculina*, *Triloculina*, *Textularia* and green algae (less than 1%) (Figure 4.57).

The non-skeletal components in this microfacies are peloids, they are dominantly composed of small-sized sand grade, round to ovate peloids or

sometimes irregular shape, and another component is superficial ooids, which are only present in the Hazar Kani village locality with few millimetres thick. Those ooids comprise very fine sand grade, round to sub-round shapes, the nuclear of the ooids are mostly composed of quartz grains (Figure 4.58). The most recognizable diagenetic features which are present in this microfacies include micritization, cementation as non-ferroan calcite cement



Figure 4.55: Field photograph of PG microfacies from Sagrama locality.



Figure 4.56: Field photograph of borrows filled with silica (arrowed) in PG microfacies from Awa Spi locality.

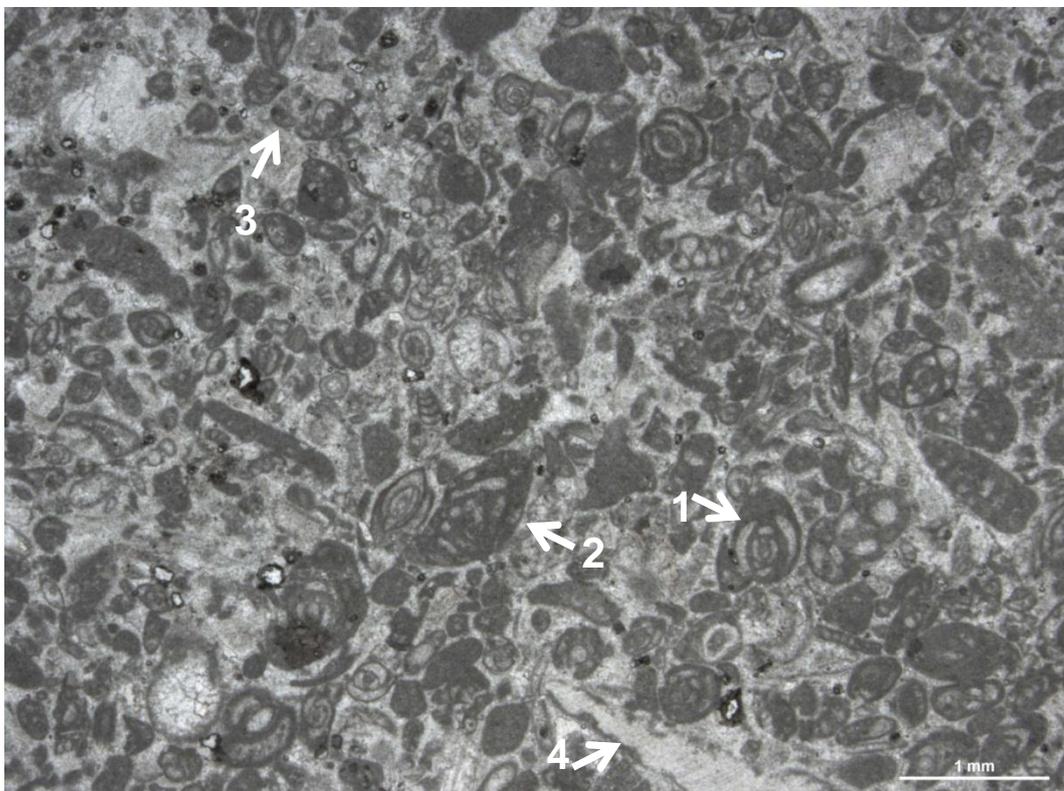


Figure 4.57: Photomicrograph of peloidal, skeletal grainstone (PG) microfacies. (1) miliolids, (2) ?*Dendritina*, (3) peloids, (4) echinoid fragments. Unstained thin-section from Zinana village locality (sample Z.7).

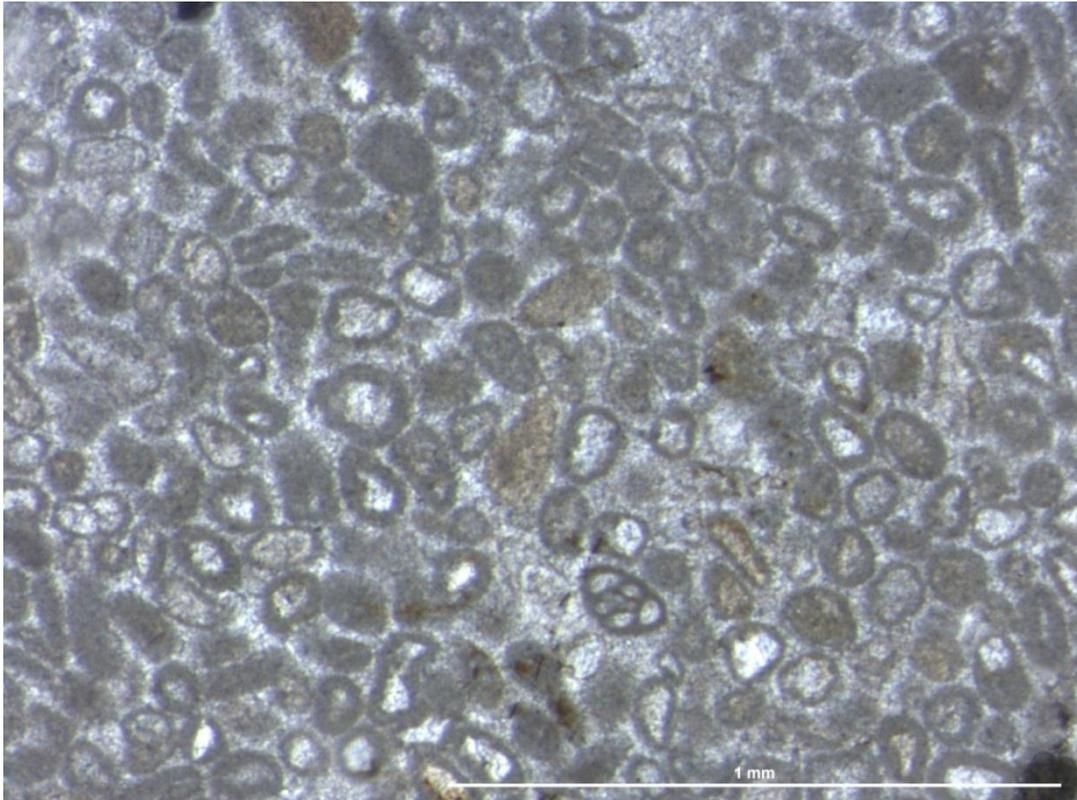


Figure 4.58: Photomicrograph of very fine sand grade superficial ooids in PG microfacies. Unstained thin-section from Hazar Kani village locality (AS.1).

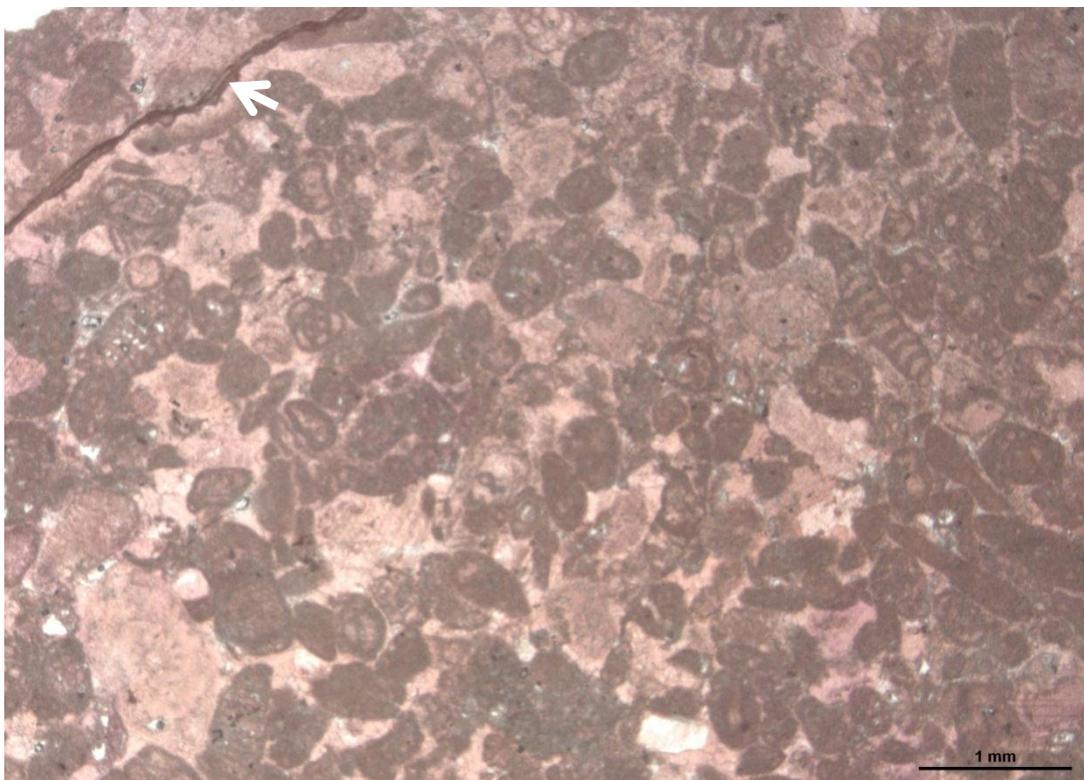


Figure 4.59: Photomicrograph of low amplitude stylolites (arrowed) present in PG microfacies. Stained thin-section from core of Aj Dagah Anticline locality (sample CA.5).

with presence of syntaxial overgrowths on echinoid fragments; compaction with low-amplitude stylolites and silicification as nodules or discontinuous beds/borrows are also present (Figures 4.56 and 4.59).

#### **4.2.12 Microfacies NA:**

NA Microfacies in the field is mainly characterized by very massively bedded limestone. It occurs in only one locality in the study area. It is present in Bamu Gorge with a total thickness of 100 metres. This microfacies is located at the lower part of the Bamu Gorge section which is overlain by PG microfacies. It occurs in the Middle Eocene Avana Formation which is laterally extensive for tens of metres (Figures 4.60).

Microfacies NA comprise larger benthic foraminiferal packstone/grainstone (Figure 4.61). The grains are composed of medium to very coarse grains of sand grade, to a rudstone size, and burrows are present (Figure 4.62). The limestone comprises of matrix (average 20%), bioclasts (average 25%), peloids (average 25%), dolomite (average 25%), in addition to cement (5%).

The bioclasts in this microfacies are composed of: *Nummulites* (average 5%); *Alveolina* (average 8%); *Orbitolites* (average 3%); miliolids (average 2%); *Asterigerina* (average 2%); echinoid fragments (2%). In addition to minor skeletal components include *Biloculina*, *Triloculina* and *Quinqueloculina* (1%) and the non-skeletal component is peloids (average 25%) (Figure 4.63).

Dolomites in this microfacies are common and composed of non-ferroan, tightly packed, idiotopic (euhedral) and hyoidiotopic (subhedral) crystals. Some units are totally dolomitized; while the others are over 80% have been dolomitized (Figure 4.64).



Figure 4.60: Field photograph of NA microfacies from Bamu Gorge locality.



Figure 4.61: Field photograph of skeletal packstone/rudstone of NA microfacies from Bamu Gorge locality.



Figure 4.62: Field photograph of burrowing (arrowed) on the surface of the bed of NA microfacies, from Bamu Gorge locality.

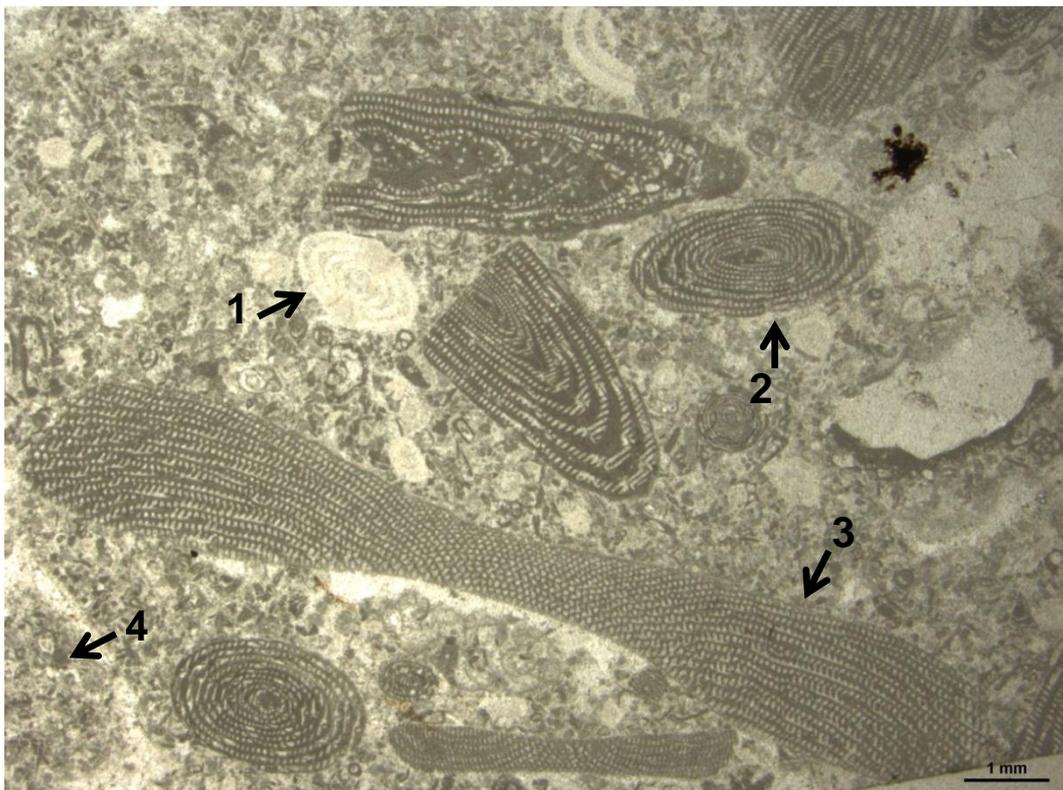


Figure 4.63: Photomicrograph of peloidal, skeletal packstone/rudstone.(1) *Nummulites*, (2) *Alveolina*, (3) *Orbitolites*, (4) peloids. Unstained thin-section of microfacies NA from Bamu Gorge locality (sample BS.8).

Other diagenetic features associated with the AN microfacies is cementation including non-ferroan calcite cement and calcite filled fractures.

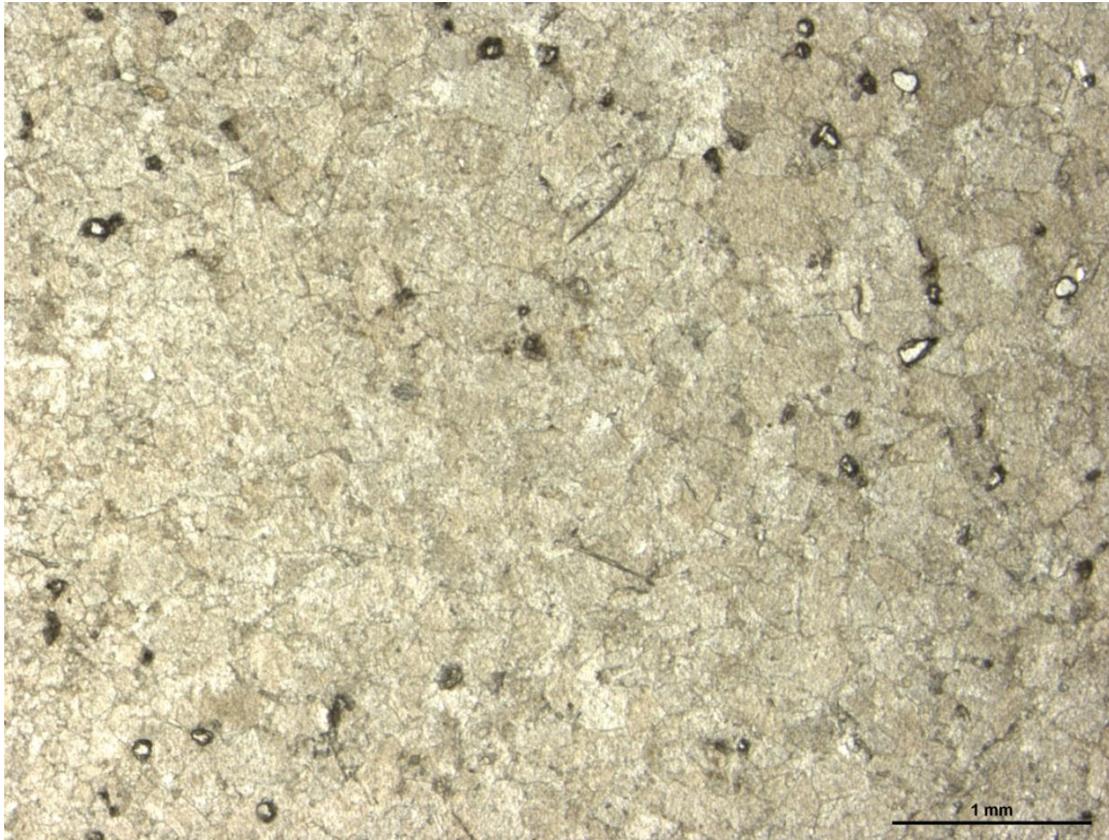


Figure 4.64: Photomicrograph of idiotopic dolomite in NA microfacies. Stained thin-section from Bamu Gorge locality (sample BS.2).

Microfacies name	Microfacies descriptions:	Figures
<u>FT: Fatha microfacies:</u>	<p><u>GY: Gypsum:</u></p> <p>This microfacies is recognized by white, thick to massive bedded gypsum with chicken-wire structure, the total thickness is 5 metres thick.</p> <p><u>GM: Marl:</u></p> <p>The GM microfacies is characterized by greyish green, thin bedded, rarely fine laminated marl, the total thickness is several of metres according to the location.</p> <p><u>RC: Claystone:</u></p> <p>RC microfacies is composed of red, thin bedded claystone, the thickness of this microfacies varies according to the locality, the total thickness several metres to tens of metres.</p>	Figure (4.1, 4.2 & 4.3)
<u>JB: Jeribe microfacies:</u>	<p><u>OG: Ooidal grainstone:</u></p> <p>OG microfacies is characterized by thin bedded, fine laminated ooidal (average 35%) grainstone with bivalve fragments (20), peloids (7%). it has an average thickness of 1 metre.</p> <p><u>PP: Peloidal packstone/grainstone:</u></p> <p>This microfacies is composed of thin bedded, fine laminated of (1) fine grain peloids (30%); (2) silt size, sub-angular to sub-round quartz (30%); (3) rare miliolids and bivalves (1-2%). It is approximately one metre thick.</p>	Figure (4.4, 4.5, 4.6, 4.7, 4.8 & 4.9)
<u>RR: Rotalids-Coralline red algae wackestone/packstone:</u>	<p>Microfacies RR has average thickness of 2-4 metres, composed of: (1) rotalids (average 4%) up to (10%); (2) red algae (average 5%); (3) echinoid fragment is (3-4%); (4) coral (5%); (5) rare miliolids, <i>Austrotrillina</i>, <i>Spirolina</i>, <i>Alveolina</i>; (6) un-recognizable fragments (average 15%).</p>	Figure (4.10, 4.11, 4.12 & 4.13)

<p><u>SP: Skeletal packstone/ grainstone:</u></p>	<p><u>SP-1: Skeletal packstone with brecciation:</u></p> <p>SP-1 microfacies has maximum thickness of 1.5 metres, composed of porcellaneous wall larger benthic foraminifera: (1) miliolids (average 15%); (2) <i>Austrorillina</i> (average 10%); (3) <i>Peneroplis</i> (average 3.5%); (4) <i>Dendritina</i> (average 2.5%); (5) <i>Archaias</i> (average 2%); (6) <i>Praerhapydionina</i> (average 2.5%); (7) minor component include: <i>Biloculina</i> (1%); <i>Triloculina</i> (1%); <i>Quinqueloculina</i> (2%); and <i>Spirolina</i> is (1%). Common macrofaunal community are: (1) echinoid fragment (3.5%); (2) gastropods (3%); (3) bivalves (2.5%). Peloids (approximately 10%).</p> <p><u>SP-2: Skeletal packstone with <i>Austrorillina howchini</i>:</u></p> <p>The skeletal packstone of SP-2 microfacies is composed of 5 metres thick (average thickness), it has maximum thickness of 7 metres, contains porcellaneous larger benthic foraminifera, include: (1) miliolids (average 16.5%); (2) <i>Peneroplis</i> (average 4%); (3) <i>Austrorillina</i> (average 7.5%); (4) <i>Dendritina</i> (average 2.5%); (5) <i>Archaias</i> (average 1.5%); (6) <i>Praerhapydionina</i> (average 2%); (7) minor component include: <i>Biloculina</i> (1.5%); <i>Triloculina</i> (1%); <i>Quinqueloculina</i> (2%) and <i>Spirolina</i> is (1%). A diverse macrofaunal community are: (1) echinoid fragment (average 4.5%); (2) gastropods (2%); (3) bivalves (3%). Peloids (average 10%).</p> <p><u>SP-3: Skeletal grainstone with <i>Praerhapydionina delicata</i>:</u></p> <p>SP-3 microfacies is grainstone, locally packstone, it has the average thickness of 11 metres with maximum thickness of 17.5 metres. Bioclasts are largely composed of larger benthic foraminifera, include; (1) miliolids (average 14.7%); (2) <i>Peneroplis</i> (average 4%); (3) <i>Austrorillina</i> (average 6%); (4) <i>Dendritina</i>, <i>Archaias</i> and <i>Praerhapydionina</i> (2-3%); (5) <i>Biloculina</i> (2%); (6) <i>Triloculina</i> (1%); (7) <i>Quinqueloculina</i> (2%); (8) <i>Spirolina</i> is (1%); (9) minor component include: <i>Rotalia</i> and <i>Textularia</i> (less than 1%); (10) Other</p>	<p>Figure (4.14, 4.15 &amp; 4.16)</p> <p>Figure (4.17, 4.18, 4.19 &amp; 4.20)</p> <p>Figure (4.21, 4.22, 4.23 &amp; 4.24)</p>
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	skeletal grain are; echinoid fragments (3-4%) with gastropods and bivalves (1-2%).	
<u>MP: miliolids-Austrotrillina-Peneroplis packstone/wackstone:</u>	<p><u>MP-1: peloidal, bioclastic packstone/grainstone:</u></p> <p>This microfacies is 1-3 metres thick, contains: (1) peloids (40%); (2) miliolids (average 11%), (3) <i>Austrotrillina</i> (10-12%); (4) <i>Peneroplis</i> (5%); (5) <i>Dendritina</i> (1-2%); (6) <i>Praerhapydionina</i> (2%); (7) <i>Archaias</i> (1-2%); (8) minor skeletal grains are: <i>Spirolina</i>, <i>Biloculina</i>, <i>Triloculina</i>, <i>Quinqueloculina</i> and echinoid fragments (1%).</p> <p><u>MP-2: peloidal wackestone/calcimudstone:</u></p> <p>The maximum thickness of MP-2 microfacies is 10 metres. The skeletal grains are micritized, include: (1) peloids (average 25%); (2) miliolids (average 5%), (3) <i>Austrotrillina</i> (2-4%); (4) <i>Peneroplis</i> (3%); (5) <i>Dendritina</i> (2%); (6) rare <i>Praerhapydionina</i>, <i>Archaias</i>, <i>Biloculina</i> and echinoid fragments (less than 1%).</p>	<p>Figure (4.25 &amp; 4.26)</p> <p>Figure (4.27, 4.28 &amp; 4.29)</p>
<u>CB: Coral bioherm:</u>	The coral bioherm microfacies have various thicknesses; it has maximum thickness of 31 metres thick, and composed of colonial coral replaced by calcite spar (aragonite in origin).	Figure (4.30, 4.31 & 4.32)
<u>CG: Conglomerate:</u>	The CG microfacies is composed of massive, channelized conglomerate layer, the thickness laterally various between one to five metres, The average thickness is 3.5 metres comprises of sub-round shape, mixture of coble, pebble, very coarse to fine grains.	Figure (4. 33, 4.34 & 4.35)
<u>PS: Palaeosols:</u>	The palaeosols (calcretes) of this microfacies are composed of Alpha type, composed of dense micritic ground mass with features such as crystallaria	Figure (4.36 & 4.37)

	including circumgranular cracks with floating quartz grains.	
<u>PK: Planktonic foraminifera wackstone/calcite mudstone:</u>	<p><u>PK-1: Peloidal packstone with planktonic foraminifera:</u></p> <p>This microfacies is composed of thin bedded peloidal packstone. It has total thickness of 1 metre, the bioclasts in this microfacies: (1) Planktonic foraminifera (2%) and (2) ostracods (average 3%); (3) the non-skeletal component is peloids (average 40%).</p> <p><u>PK-2: Planktonic foraminifera calci-mudstone:</u></p> <p>The PK-2 microfacies is composed of thin bedded wackstone, locally calcimudstone. It has the total thickness of 80 metres, contains: (1) Planktonic foraminifera (average 12%); (2) <i>Dicocyclina</i> (2%); (3) <i>Nummulites</i> (1%); (4) rare <i>Pellatispira</i> less than 1%; (5) peloids (average 12%).</p> <p><u>PK-3: Planktonic-benthonic foraminifera wackstone:</u></p> <p>Microfacies PK-3 is medium to thin bedded wackstone, with total thickness of 32.5 metres, composed of: (1) <i>Nummulites</i> (average 5%); (2) <i>Dicocyclina</i> (8%); (3) planktonic foraminifera (average 11%); (4) unrecognizable fragments (average 20%); (5) rare echinoid fragments, <i>Pellatispira</i> and <i>Textularia</i> (less than 1%); (6) peloids (average 4%).</p>	<p>Figure (4.38)</p> <p>Figure (4.39, 4.40 &amp; 4.41)</p> <p>Figure (4.42 &amp; 4.43)</p>
<u>NR: <i>Nummulites</i>-red algae-<i>Dicocyclina</i> packstone/wackstone:</u>	<p><u>NR-1: <i>Coralline</i> red algae-<i>Nummulites</i> wackstone:</u></p> <p>The NR-1 microfacies comprises of wackstone with <i>Nummulites</i> and red algae, it has thickness of 16 metres, bioclasts include; (1) <i>Nummulites</i> (average 5%); (2) <i>Asterigerina</i> (2%); (3) red algae (average 8%); (4) coral (1-2%) and (5) <i>Victorella</i> (1%).</p>	<p>Figure (4.44 &amp; 4.45)</p>

	<p><u>NR-2: Coralline red algae-<i>Nummulites-Discocyclus</i> packstone:</u></p> <p>NR-2 microfacies is massively bedded, average thickness is between 6-9 metres thick. This most common recognizable bioclasts of this microfacies are: (1) <i>Nummulites</i> (average 10%); (2) <i>Asterigerina</i> (4%); (3) red algae (3-6%); (5) <i>Discocyclus</i> (1-2%); (6) <i>Operculina</i> (2%); (7) <i>Textularia</i> (1%); (8) echinoid fragments (3-4%); (9) minor components are: miliolids, <i>Victorella</i>, <i>Pellatispira</i> (less than 1%), (10) peloids and micritized grains and fragments approximately (18-22%).</p> <p><u>NR-3: <i>Nummulites-Dicocyclus</i> packstone:</u></p> <p>Microfacies NR-3 is also massively bedded, the maximum thickness is 10 metres, bioclasts are dominantly composed of benthic foraminifera: (1) <i>Nummulites</i> (average 30%); (2) <i>Dicocyclus</i> (average 15%); (3) <i>Asterigerina</i> (3-4%); (5) <i>Operculina</i> (2%); (6) <i>Textularia</i> (less than 1%). Other components are (7) echinoid fragments (3-4%); (8) red algae (1%); (9) echinoid fragments (average 3.5%) and (10) peloids (average 7%).</p>	<p>Figure (4.46, 4.47, 4.48 &amp; 4.49)</p> <p>Figure (4.50, 4.51, 4.52, 4.53 &amp; 4.54)</p>
<p><u>PG: Peloidal, skeletal grainstone:</u></p>	<p>The peloidal, skeletal grainstone microfacies has varied thickness according to the locality, the maximum thickness is 25.3 metres, the rock is composed of peloidal, skeletal grainstone comprises of: (1) miliolids (average 15%); (2) <i>Orbitolites</i> (average 4%); (3) <i>Dendritina</i> (average 2%); <i>Quniquiloculina</i> (average 2%); (4) echinoid fragments (8%); (5) Rare skeletal grains are: <i>Biloculina</i>, <i>Triloculina</i>, <i>Textularia</i> and green algae (less than 1%) and (6) The non-skeletal grains include peloids (average 35%) and uncommon superficial ooids (1%) only in Hazar Kani village locality.</p>	<p>Figure (4.55, 4.56, 4.57, 4.58 &amp; 4.59)</p>
<p><u>NA: <i>Nummulites-Alveolina</i> packstone/grainstone:</u></p>	<p>This microfacies is approximately 100 metre thick, composed of: (1) <i>Nummulites</i> (average 5%); (2) <i>Alveolina</i> (8%); (3) <i>Orbitolites</i> (3%); (4) miliolids (2%); (5) <i>Asterigerina</i> (2%); (6) echinoid fragments (2%); (7) minor</p>	<p>Figure (4.60, 4.61, 4.62, 4.63 &amp; 4.64).</p>

	skeletal components are: <i>Biloculina</i> , <i>Triloculina</i> and <i>Quinqueloculina</i> (1%) and (8) the non-skeletal components are peloids and micritized grains (average 25%).	
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Table 4.3: Microfacies names with brief microfacies descriptions including percentage of each of skeletal and non-skeletal grains with number of figures.

### 4.3 Microfacies interpretation:

Interpretation for each microfacies is mainly based on the distribution of foraminifera; planktonic faunas dominate the deeper, open marine segments, whereas the intervening shallower segments are characterized by an abundance of benthonic foraminifers. The microfacies analysis indicates palaeoenvironments ranging from terrestrial to open marine settings (down-ramp) in nine microfacies zones (Table 4.4). Buxton and Pedley's (1989) model for Cenozoic carbonate ramps (Figure 4.65) strongly correlates with the current study's pattern of microfacies, based on the distribution of foraminiferal associations across the ramp setting over time (Figures 4.66 and 4.67).

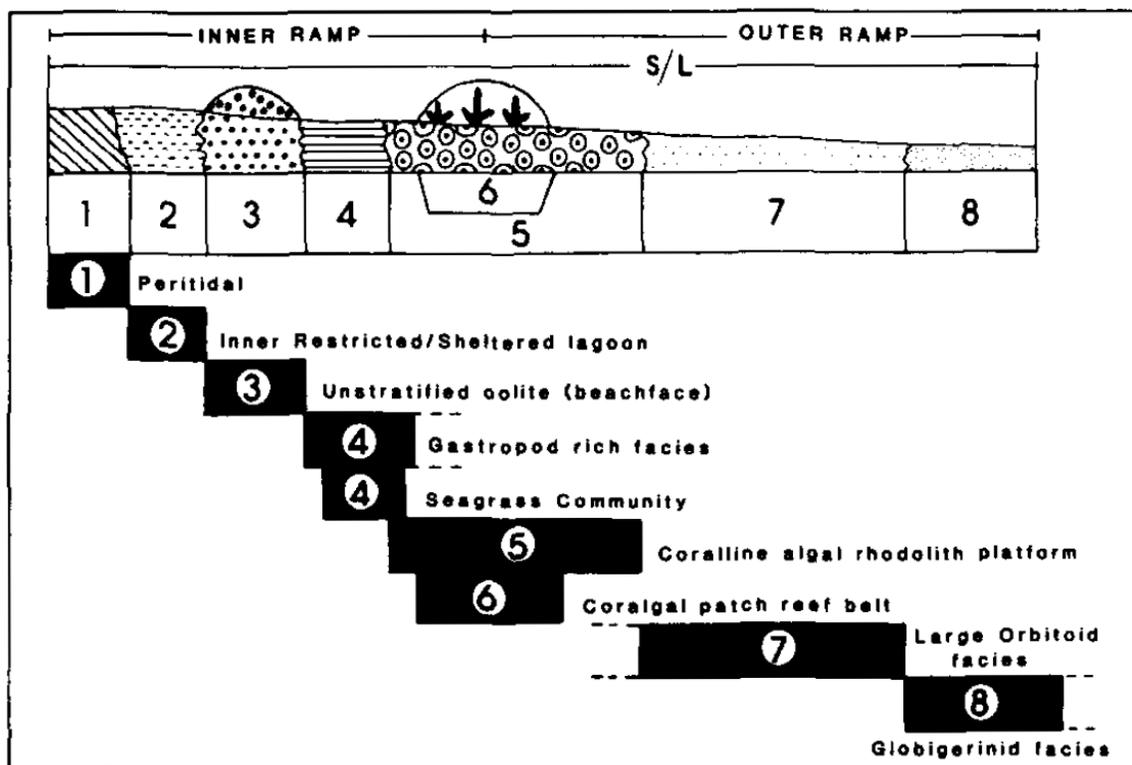


Figure 4.65: Profile of standard Cenozoic ramp model showing down-ramp facies distribution (Buxton and Pedley, 1989).

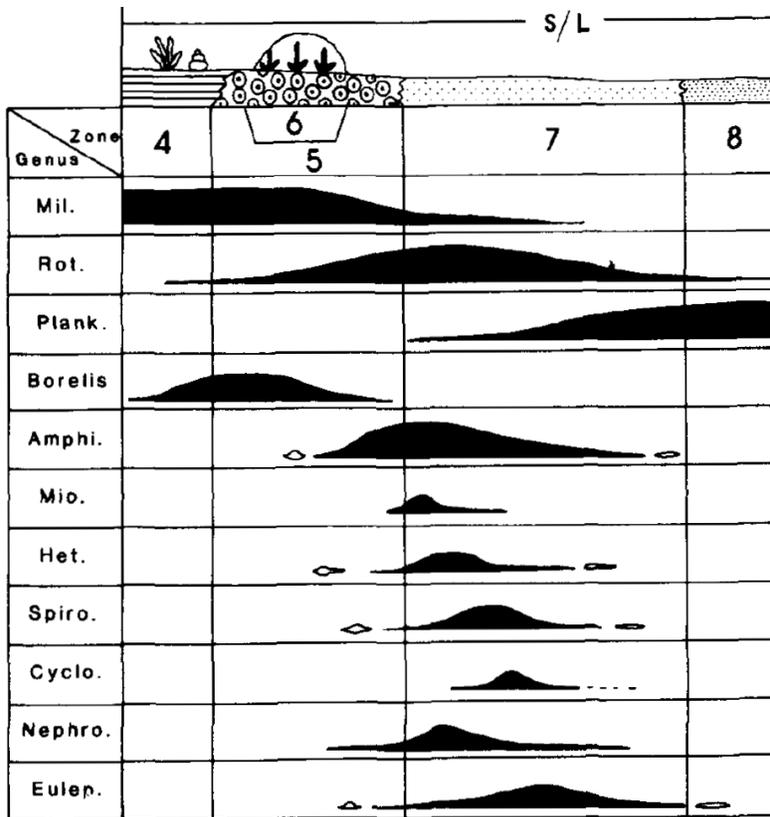


Figure 4.66: Foraminiferal distribution of Middle-Upper Oligocene Tethyan ramps (Buxton and Pedley, 1989). Mil: Miliolids; Rot: Rotaliids; Plank: Planktonic foraminifera; Amphi: *Amphistegina*; Mio: *Miogypsinoidea*; Het: *Heterostegina*; Cyclo: *Cycloclypeus*; Nephro: *Nephrolepidina* and Eulep: *Eulepidina*.

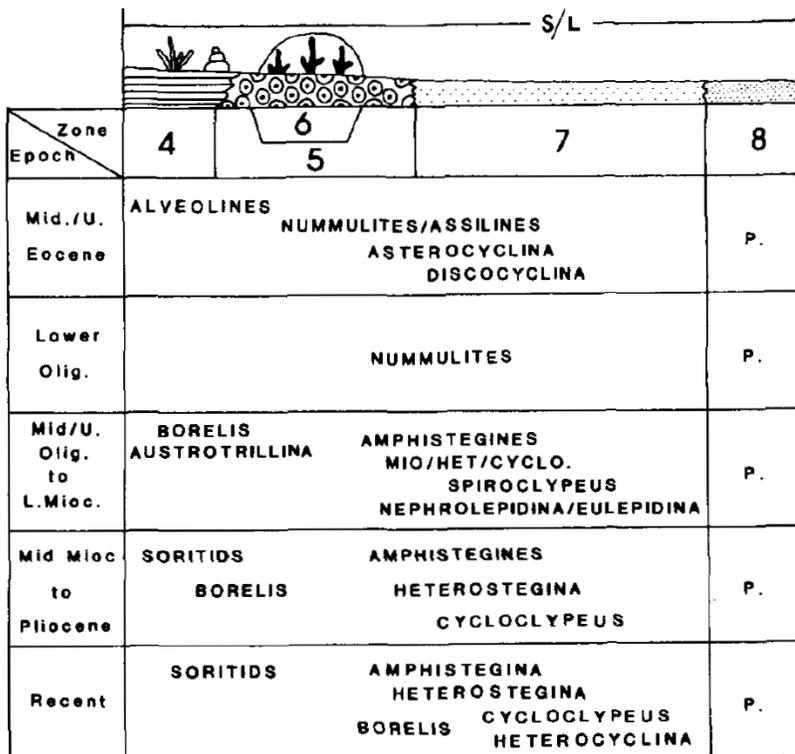


Figure 4.67: Distribution and evolution of Tethyan foraminiferal associations over time (Buxton and Pedley, 1989). P: Planktonic foraminifera.

Ramp zones	Micro-facies	Sub-microfacies	Buxton and Pedley's (1989) facies distribution
1	FT	Gypsum/Marl/Claystone	-
	CG	Conglomerate	
	PS	Palaeosol	
2	MP	MP-1: peloidal, bioclastic packstone/grainstone	1
3		MP-2: peloidal wackestone/calcimudstone	2
	PG	Peloidal, skeletal grainstone	
	JB	PP: Peloidal packstone/grainstone	
4	JB	OG: Ooidal grainstone	3
5	SP	SP-1: Skeletal packstone with brecciation	4
		SP-2: Skeletal packstone with <i>Austrotrillina howchini</i>	
		SP-3: Skeletal grainstone with <i>Praerhapydionina delicata</i>	
	NA	<i>Nummulites-Alveolina</i> packstone/grainstone	
6	CB	Coral bioherm	6
7	RR	Rotalids-coralline red algae wackestone/packstone	5
	NR	NR-1: Coralline red algae- <i>Nummulites</i> wackestone	
		NR-2: Coralline red algae- <i>Nummulites-Discocyclusina</i> packstone	
8		NR-3: <i>Nummulites-Discocyclusina</i> packstone	7

9	PK	PK-1: peloidal packstone with planktonic foraminifera	8
		PK-2: Planktonic foraminifera calcimudstone	
		PK-3: Planktonic-benthonic foraminifera wackestone	

Table 4.4: Distribution of the depositional environment zones by comparison to Buxton and Pedley's (1989) ramp model.

Although foraminifera are one of the main components for the interpretation of microfacies, texture of the rock with presence and absence of micrite matrix is also a major consideration. Detailed interpretations for each ramp zone are listed below:

#### **4.3.1 Zone 1:**

##### **4.3.1a FT Microfacies interpretation:**

The gypsum layer is one of the main microfacies of the Lower Fars (Fatha) Formation. The Fatha Formation was studied in many localities in Iraq, Syria and Iran (Bellen, 1959; Ctyrocky and Karim, 1971; Behnam, 1975, 1977; Ponikarov et al., 1967; James and Wynd, 1965), but only a few of them discussed the depositional environment. In Syria this formation was deposited in a littoral environment (Ponikarov et al., 1967). In Iraq, in Jazera and Duhok-Ain Zalah area it was deposited in shallow near shore lagoons or coastal lagoons of tropical to subtropical waters, where lagoons periodically isolated from sea water (Behnam, 1975; 1977). Jassim and Goff (2006) interpreted the Fatha Formation as deposited in a rapidly subsiding sag basin that periodically became evaporitic

with formation of sabkhas and salinas. The presence of chicken-wire structure suggests displacive growth as in such supratidal sabkha environment.

#### **4.3.1b CG Microfacies interpretation:**

The conglomerate layer is composed of a single story unit with complex internal geometry. It comprises of a central thick conglomerate body, thinning at the edges with lateral extent of few tens of metres, which suggests an incised valley. The detrital mineralogy of the valley fill exhibits a different composition and provenance to the surrounding strata suggesting the clasts were reworked from different origin. Furthermore, poorly sorted, subround-round shape clasts refer to transport from the source moderately. No marine faunas were been found in the matrix suggesting a non-marine, probably alluvial environment.

#### **4.3.1c PS microfacies interpretation:**

Calcretes result from the progressive calcification of the soil due to the precipitation of calcite within the soil profile (Wright and Tucker, 1991). The nodular carbonate textures in paleosols are referred to as glaebular textures. The disorthic type nodules described by Wieder and Yaalon (1974) are similar to the type 2 nodules because of the sharp contacts separating them from the surrounding matrix suggesting possible shrinkage and swelling of the soil matrix. The presence of circum-granular cracks suggests the cracking of the soil, including the wetting and drying (Brewer, 1964).

### **4.3.2 Zone 2:**

#### **4.3.2a MP-1 microfacies interpretation:**

The nature of bioclasts in MP-1 microfacies suggests very shallow marine water. The low diversity of bioclasts in this microfacies, such as miliolids, *Austrotrillina* and *Peneroplis* with few other porcellaneous foraminifera (Figure 4.25), is indicative of restricted, very shallow marine environment (Geel, 2000) (for details see 4.3.5a). Furthermore, the depositional environment of the packstone/grainstone texture suggests a relatively moderate to high energy regime, probably influenced by waves and currents.

The origin of peloids is commonly uncertain, although many appear to be highly abraded, totally micritized ?miliolids. However a few may be ?faecal pellets, based on their shape and aggregate nature (Pusey, 1975). In a modern shallow marine environment, faecal pellets are produced in large quantities, especially by worms and gastropods; faecal pellets account for most soft pellets within muddier low energy areas such as the south Florida Shelf (Enos, 1977).

Fenestrae indicate subsequent exposure in a tidal flat environment, while the evidence of exposure is generally absent (Hardie, 1977).

The cements, including cement filled fenestrae, are composed of non-ferroan calcite cement (figure 4.26) with no trace of ferroan calcite to indicate burial diagenesis.

This microfacies is analogous to standard microfacies 1 peritidal of the Cenozoic carbonate ramps of Buxton and Pedley (1989). The microfacies MP-1 is also similar to standard microfacies SMF21 of Flügel (2004).

The overall characteristics suggest a very shallow marine setting above a fair-weather wave-base in a relatively high energy intertidal environment receiving skeletal grains from a somewhat restricted setting.

### **4.3.3 Zone 3:**

#### **4.3.3a MP-2 microfacies interpretation:**

The nature of the bioclasts of MP-2 represents a very shallow marine setting. They are mostly the same as MP-1 but with lower diversity of miliolids, peneroplids and *Austrotrillina* (for more details see 4.2.5b and 4.3.5a). Low diversity of organisms suggest restricted lagoonal environment (Tucker and Wright, 1990). Partial micritization in the skeletal grains mostly in benthic foraminifera represents shallow marine environment, according to Perry (1998) the highest degree of grain infestation occurs within shallow (less than 18 metres), low energy environment and one of the most susceptible grains for infestation are foraminifera. The occurrence of matrix in wackestone/calcmudstone beds indicates lower energy conditions with no effect of waves or currents. Furthermore, a low energy regime is indicated by the presence of poorly sorted sub-angular quartz which comes from the erosion of underlying conglomerate bed.

The cements are composed of non-ferroan calcite with no evidence of burial cements.

This microfacies is analogous to standard microfacies 2, restricted lagoonal, of the Cenozoic carbonate ramps of Buxton and Pedley (1989).

Majid and Veizer (1986) described similar facies in the Kirkuk Group in the Kirkuk Oil Field in northern Iraq. They proposed a tidal flat/mud flat as the environment of depositional. Subsequently, Bassi and Nebelsick (2010) logged similar microfacies in Upper Oligocene shallow water carbonates in the Venice area, north-east Italy and interpreted as a proximal inner ramp environment.

The overall characteristics suggest a very shallow, restricted lagoonal environment in inner ramp setting.

#### **4.3.3b PG Microfacies interpretation:**

The bioclasts of PG microfacies comprises of mostly porcellaneous benthic foraminifera suggesting a shallow water marine setting. Shallow water depth is supported by the abundance of miliolids which are found in lagoonal environment (Geel, 2000), when miliolids are abundant indicates a connection to the open ocean (Chassefiere et al., 1969). *Orbitolites* lives in ranges of environments, it has interpreted as restricted environments between *Nummulites* banks and the shoreline by Serra-Kiel and Reguant (1984); shallow inner ramp by Racey (1994) and “well-flushed” back-reefs and other carbonate facies free of mud in less than 40 metres water depth by Geel (2000).

The dominant grainstone texture of this microfacies with un-common superficial ooids indicates deposition in a relatively high energy environment under the action of waves and currents. The grainstone texture may suggest wave winnowing in shallow, broad lagoon by Kendall and Skipwith, (1969). Colby and Boardman (1989) described the windward, high-energy lagoon in Graham’s

Harbor, Bahams and they presumed that the packstone/grainstone texture is one of these facies which receive the greatest wave energy in the lagoon.

This microfacies may be analogous to standard microfacies 2, lagoonal facies of Buxton and Pedley (1989). Furthermore, the faunal association of this microfacies may be correlated with the shallowest faunal association of Eocene carbonate ramp which were described by Beavington-Penny and Racey, (2004).

The overall characteristics suggest a restricted biota with wave winnowing in a very shallow, broad lagoon.

#### **4.3.3c PP Microfacies interpretation:**

The nature grains in the PP microfacies suggest a very shallow restricted lagoonal environment. The abundant peloids indicate that the depositional environment was very shallow water setting as lagoon (Tucker and Wright, 1990). The presence of a micrite matrix and packstone texture suggests a low energy regime, not affected by waves or currents. Furthermore, a low energy environment may also be inferred from the presence of sub-angular/angular poorly sorted quartz that comes from aeolian. The fine irregular lamination/bedding suggests lack of bioturbation (Tucker and Wright, 1990). Micritization and micrite envelopes are indicators for shallow marine environments less than 18 metres (Perry, 1998). In addition the presence of very few bioclast is indicative of a restricted environment.

Non-ferroan calcite cement is evidence that cementation occurred before burial in an oxygenated diagenetic fluid. Subsequently, compaction includes stylolites formed during burial diagenesis (Flügel, 2004).

This microfacies is analogous to standard microfacies 2, inner restricted lagoon of the Cenozoic carbonate ramps of Buxton and Pedley (1989).

The overall characteristics suggest low energy, very shallow water restricted lagoonal in an inner ramp setting.

#### **4.3.4 Zone 4:**

##### **4.3.4a OG Microfacies interpretation:**

Ooids are the main components of this microfacies, which are found in very shallow settings, in areas where tidal wave/foreshore processes retain the grains in the environment. Although ooids are capable of being transported by storms and sediment gravity flows into deeper waters, the absence of these features suggests that these oolitic grainstones are effectively *in situ*. The dominant grainstone texture and the absence of fine micrite matrix indicate deposition in a high energy, well-winnowed environment under the effect of waves and currents. High energy setting may be inferred from the well-sorted grains as well.

The cement is composed of both ferroan and non-ferroan calcite, which is evidence that cementation continued during burial. Most of the interparticle cements are non-ferroan, while the dominant ferroan cement is restricted to ooid nuclei, mostly from bivalve fragments. The cement in the intraclasts looks similar to the rest of the rock.

The absence of a range of sedimentary structures allowing a more specific flow regime to be identified prevents further interpretation.

This microfacies can be correlated with standard microfacies 3 of Buxton and Pedley (1989), and also standard microfacies RMF 29 of Flügel (2004), it is common in bank and sand shoal environments.

Ooid skeletal grainstones in the Qom Formation in Iran were interpreted as a shoal environment (Shakeri et al., 2007). Also, similar microfacies were recorded in the Rupelian, Umm Ad Dahiy Formation in South Sirte Basin, Libya by Imam and Galmed (2000).

The overall characteristics suggests high energy, very shallow marine shoal environment.

#### **4.3.5 Zone 5:**

##### **4.3.5a SP-1 Microfacies interpretation:**

The nature of the bioclasts of SP-1 suggests a shallow water environment, this deduced from the abundance of porcellaneous benthic foraminifera (for details see 4.2.4a). Peneroplids are estimated to inhabit water shallower than 30 metres deep (Beavington-Penney and Racey, 2004) and they prefer a relatively low energy water environment (Brasier, 1975a) and they are common in lagoon setting, it is believed that the foraminifera do not normally live on the sediment surface in these environments but their dead remains were transported some distance prior to burial (Murray, 1965, 1966).

Furthermore, a shallow depth of water is supported by the abundance of miliolids, which live in a variety of very shallow water environments, from subsaline to hypersaline, preferably in low turbulence water in lagoonal and/or backreef environments (Geel, 2000). *Praerhapydionina* is another component of this microfacies, largely found with lime-mudstone in a very shallow water platform interior accompanied by abundant miliolids, and may indicate a sheltered low energy backreef environment. In contrast, *Austrotrillina*, generally associated with miliolids, lived under somewhat higher environmental energy conditions compared with *Praerhapydionina*, in very shallow water less than 30m deep in a platform interior (Geel, 2000). Furthermore, the shallowest part of the photic zone, in the inner ramp, is characterized by *Austrotrillina* and *Archaias* (Bassi et al., 2007). The presence of a large number of porcellaneous foraminiferal tests may point to the depositional environment being slightly hypersaline (Vaziri-Moghaddam, 2006; Brandano et al., 2009).

The dominant packstone texture of this microfacies indicates deposition in a relatively low energy environment, with the effect of waves or currents not being obvious.

Cementation occurred before burial and is composed of non-ferroan calcite cement.

Chemical compaction, including stylolites and organic-rich seams along the brecciation lines, formed during burial diagenesis (Flügel, 2004). The presence of common irregular fractures within this microfacies gives the rock a brecciated appearance; tectonic may cause this brecciation.

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as being a protected embayment in a shallow subtidal ramp (microfacies 4). It represents lagoonal environment in the standard microfacies types described by Wilson (1975) and Flügel (1982, 2004).

The overall characteristics represent shallow water protected environment, in shallow subtidal zone.

#### **4.3.5b SP-2 Microfacies interpretation:**

The nature of the bioclasts of SP-2 suggests shallow water setting. This assemblage is mostly composed of porcellaneous benthic foraminifera, miliolids; *Peneroplis*; *Austrotrillina*; *Praerhapydionina*, *Dendritina* are the most commons (for bioclasts interpretations see 4.3.5a). The occurrence of large numbers of imperforate foraminifera in wackestone-packstone-grainstone represents restricted shallow sub-tidal environments with relatively low current energy (Geel, 2000; Romero et al., 2002). The dominant packstone texture suggests deposition in a low energy environment, although, the partial grainstone texture indicates a relatively higher energy environment than SP-1 microfacies.

Both horizontal and vertical burrowing creates an extensive burrow network which represents a wide variety of environments.

Cements are precipitated in an oxic fluid before burial and are composed of non-ferroan calcite. Rare chemical compaction represents burial diagenesis (Flügel, 2004).

In accordance with the standard microfacies type in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as microfacies 4, protected embayment in a shallow subtidal ramp.

A similar microfacies described as shelf lagoon environment by Okhravi and Amini (1998) from Miocene in Central Basin, Iran; by Vaziri-Moghaddam et al. (2006) at Oligocene-Miocene Asmari Formation in south-west Iran and by Brandano et al. (2009) at the Late Oligocene Attard Member in Malta.

The overall characteristics represent a shallow protected environment above the normal fair-weather wave base in an inner ramp setting.

#### **4.3.5c SP-3 Microfacies interpretation:**

The nature of the bioclasts of SP-3 suggests a shallow water marine setting. It comprises shallow marine biota with abundant porcellaneous benthic foraminifera as miliolids, peneroplids, *Austrotrillina*, *Praerhapydionina*, *Dendritina* and *Archaias* are dominant (for bioclasts interpretations see 4.3.5a).

The grainstone texture suggests deposition in a high energy environment with the depositional setting being influenced by waves and currents. In addition, the partial packstone texture indicates intervals with a relatively low energy. Overall, this microfacies is higher energy than SP-1 and SP-2 microfacies.

The open, uncompacted texture is characteristic of rocks that were substantially cemented in early diagenesis (Adams and MacKenzie, 1998), with non-ferroan calcite cement formed before significant burial.

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as being a microfacies 4, protected embayment in a shallow subtidal ramp. This microfacies is analogous to the standard microfacies SMF18 of Flügel (2004).

Similar microfacies were described by Vaziri-Moghaddam et al. (2006) from Oligocene-Miocene Asmari Formation in south-west Iran as a lagoon close to nearby tidal flat.

The overall characteristics represent shallow environments above the normal fair-weather wave base in an inner ramp.

#### **4.3.5d NA Microfacies interpretation:**

The nature of bioclasts of NA suggests a shallow marine setting. Alveolinids are one of the more abundant components and have been found in a variety of shallow subtidal environments down to approximately 80m water depth, although their maximum abundance occurs in depths of less than 35m (Reichel, 1964; Bandy, 1964; Hottinger, 1973). Moreover, *Orbitolites* is common down to 40 metres (Geel, 2000). *Nummulites* is another component, the shape and size of which can be used as an environmental indicator. The shape and thickness of test of the larger foraminifera is strongly influenced by water turbulence and light. The species which live in either more turbulent environments or higher level of light produce thicker tests than specimens from less turbulent environments and lower light levels (Hallock, 1979, 1983; Kuile and Erez, 1984; Hallock and Glenn,

1986). Furthermore, the modern amphisteginids from the Gulf of Aqaba shows that interspecific changes in diameter to thickness (D/T) ratio of some species may be related to the level of incoming light (Larsen, 1976), a general tendency towards increasing D/T ratio with depth was observed. In addition to Beavington-Penney and Racey, (2004) interpretation of foraminiferal test shape, *Nummulites*, for example, that have ovate tests with thick wall are produced in shallow water, while the flatter tests with thinner walls are produced with increasing water depth (for more detail of *Nummulites* environment interpretation see 4.3.7b).

*Nummulites* in this microfacies are composed of small to medium size lens shaped forms, which; according to above interpretations suggest growth in shallow water environment, in relatively medium-high level of light.

The co-occurrence of hyaline, perforate benthic foraminifera from normal marine and imperforates one suggests that sedimentation took place in lagoon with no effective barrier to separate lagoon from normal marine (Geel, 2000; Romero et al., 2002).

The Micrite matrix with a packstone texture is evidence that the deposition was took place in relatively low energy condition.

The cement in this microfacies is composed of non-ferroan calcite cement without any evidence of burial one.

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as being a protected embayment in a shallow subtidal ramp (microfacies 4). It is similar to the ramp microfacies type RMF14 of Flügel (2004)

which was interpreted as restricted to open marine environments. Moreover, the faunal association of this microfacies may be correlated to the *Nummulites-Alveolina-Assilina* faunal association of Eocene carbonate ramp which were described by Beavington-Penney and Racey, (2004).

The overall characteristics suggest shallow marine environment in an open lagoon setting with no effective barrier.

#### **4.3.6 Zone 6:**

##### **4.3.6a CB Microfacies interpretation:**

This microfacies, representing in-situ coral reef bioherm. It is present as a patch reefs which are common in open (non-restricted) lagoons and/or barrier reef which separated the open marine from a restricted lagoon (Tucker and Wright, 1990).

Individual coral heads are difficult to see in the field due to the massive nature of the outcrop and to recrystallization (Figure 4.30) and it is interbedded with skeletal grainstone (SP-3), coralline red algae-*Nummulites* wackestone (NR-1) and rotalids-coralline red algae wackestone/packstone (RR) with almost metre scale (for more detail see 4.2.6), that suggest a patch reef rather than a reef environment.

The main component of CB microfacies comprises different coral genera with different shapes, together with a muddy matrix. The corals were originally composed of aragonite which was completely dissolved and replaced by sparite

cements, but the morphology has been conserved by micritization of the outer surface.

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as being a microfacies 6, coralgal patch-reef belt (shallow ramp build-up).

Similar microfacies have been reported by Amirshahkarami et al. (2007) as in-situ organisms of organic reefs of mid ramp origin in the Asmari Formation-southwest Iran. Furthermore, the coral boundstone in the Qom Formation (central Iran) generates both barrier reef and patch reefs (Shakeri et al., 2007).

According to the lateral distribution of facies in the Lower Oligocene Gornji Gard Beds (Slovenia), the coral facies lived in a deeper marine environment relative to foraminiferal-coralline algal facies (Nebelsick et al., 2000).

The overall characteristics suggest in-situ coral reef bioherm in the form patch reef belt in middle ramp setting.

#### **4.3.7 Zone 7:**

##### **4.3.7a RR Microfacies interpretation:**

The nature of the bioclasts in the RR microfacies suggests a shallow open marine setting. One type of bioclast is composed of non-articulated, fruticose with few crustose coralline red algae, with rare “hooked” form or curved shape (improper hooked structure), which may provide evidence of the growth of sea grasses in vegetated environments (Beavington-Penney et al., 2004) (Figure

4.47 and 4.48). Fossil seagrasses are rarely found in the geological record, yet it has been suggested that seagrasses first appeared in the Tethyan region during the Late Cretaceous and became wide spread during Eocene (DenHartog, 1970; Brasier, 1975d; Eva, 1980). Furthermore, during Late Eocene when many larger benthic foraminifera became distinct, numerous seagrass-dwellers disappeared and seagrass meadows became uncommon in the Oligocene. Therefore, it is difficult to suggest that the distribution of seagrass communities may have been present during the Oligocene. Although, in Bembridge, Isle of Wight, *Cymodocea* has been recorded during Oligocene times (Chesters et al., 1967).

Wolf and Conolly (1965) pointed out that algae are generally good indicators for shallow water because photosynthesis is depth controlled. Rotalids are another component that represents shallow turbulent water of 0-40 m water depth in the shore zone, on reefs and inter-reef areas (Geel, 2000).

The packstone and wackestone textures suggest a low energy regime, in a depositional environment not influenced by waves or currents. Moreover, the matrix is indicative of deposition within low water energy conditions. The cements in this microfacies are non-ferroan calcite precipitated in an oxic fluid before burial.

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as microfacies 5, rhodolith platform facies.

A similar microfacies is found in the Qom Formation in central Iran, it has been interpreted as indicating a proximal open marine environment (Shakeri et al.,

2007). Moreover, Amirshahkarami et al. (2007) reported the same microfacies in the Asmari Formation, south-west Iran, as indicating a shallow open marine environment or being near fair weather wave base on the proximal side of a mid-ramp environment.

The overall characteristics suggest a shallow open marine setting, just below a fair-weather wave-base.

#### **4.3.7b NR-1 Microfacies interpretation:**

*Nummulites* and coralline red algae are the most common bioclasts in NR-1 microfacies which suggest an open marine setting. The depositional environment of *Nummulites* is clearly related to size and form, but it is difficult to interpret, because authors draw different conclusions as it has been interpreted from shallow nearshore, inner ramp shore face to mid and outer ramp or shelf within 30-60 metres water depth (Moody, 1987; Aigner, 1983; Racey, 1994; Bassi, 1998; Gilham and Bristow, 1998; Sinclair et al., 1998; Loucks et al., 1998; Luterbacher, 1998; Nebelsick et al, 2000; Racey, 2001). Moreover, Racey (2001) concluded that *Nummulites* occupied a broad range of open marine environments, on both ramps and shelves, where restricted water is absent. In addition, Geel (2000) concluded that *Nummulites* could live in various environments, except for very restricted areas, and that they could form banks on swells. He mentioned that large flat *Nummulites* proliferated on the seaward side of the shallow shelf and the upper part of the deeper shelf at 50-80m water

depth, but the small and medium-sized lens shaped *Nummulites* lived in a platform interior (for more detail on *Nummulites* shape see 4.3.5d).

Another component is red algae, mostly composed of *Lithothamnium* (for more detail on red algae see 4.3.7a). Pomar (2001) concluded the presence of larger foraminifera with red algae indicated a distally steepened ramp platform.

According to these interpretations of the environment, *Nummulites* can be interpreted as characteristic of a shallow open marine setting; because of the lens shape, coarse sand sized *Nummulites* are accompanied by abundant coralline red algae.

The matrix in wackestone beds suggests a low energy condition, so the environment was not influenced by waves or currents. The open uncompacted texture suggests that cementation began during early diagenesis, before any compaction (Adams and MacKenzie, 1998). The only form of cement present is non-ferroan calcite, with no evidence of burial cement.

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as microfacies 5, rhodolith platform facies.

The overall characteristics suggest a shallow open marine setting, just below the fairweather wave base in a proximal part of the mid-ramp.

#### **4.3.7c NR-2 Microfacies interpretation:**

The nature of bioclasts of NR-2 suggests an open marine setting. They are composed of *Nummulites*, and red algae with uncommon *Discocyclusina* (more

detail on *Discocyclusina* is in 4.3.8a). The bioclasts are more diverse and relatively deeper than NR-1 microfacies. The medium to large lens-shaped *Nummulites*, in addition to its association with *Discocyclusina*, are indicative of an open marine setting (more detail is in 4.3.5d and 4.3.7b) relatively deeper than NR-1. *Operculina* is another component of this microfacies which can live in environments with water depths of 15-150m (Geel, 2000).

The texture of packstone with the presence of micrite matrix is evidence that the deposition was in low energy conditions without the effect of waves or currents. The cement in this microfacies is only non-ferroan calcite, without evidence of burial cement. The cement can be described as early cement because the grains are open-packed.

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as being a microfacies 5, rhodolith platform facies. A similar microfacies is reported in an open marine environment in Middle Eocene-Early Oligocene shallow water carbonate by Nebelsick et al. (2005). Furthermore, *Nummulites* from same microfacies in Aj Dagh Anticline were described by Aqrabi et al. (2010) as Early Oligocene *Nummulites vascus* “with question mark” of Sheikh Alas Formation, but they also mentioned that no *Lepidocyclusina* were found which is indicative of an Early Oligocene age. Whereas, this study reveals that these *Nummulites* occur in the Late Eocene Avanah Formation, because they are associated with *Discocyclusina* and *Pellatispira* which are indicative of a Late Eocene age.

The overall characteristics suggest an open marine setting above the storm wave base in a mid-ramp setting.

## **Zone 8:**

### **4.3.8a NR-3 Microfacies interpretation:**

The bioclasts of NR-3 represent an open marine setting deeper than NR-1 and NR-2. The dominant bioclasts are *Nummulites* and *Discocyclusina*. *Nummulites* are mostly large flat shaped *Nummulites* which are associated with *Discocyclusina*; the environment of deposition can be described as a distal part of the shallow shelf and the upper part of a deeper shelf at water depths of 50-80m according to Geel's (2000) conclusion.

*Discocyclusina* is one of the most common components of this microfacies. Numerous studies have interpreted *Discocyclusina* as having lived in a broad spectrum of environments within the photic zone, including shallow fore-reef/fore-shoal environments (Henson, 1950a; Racz, 1979; Anketell and Mriheel, 2000) and deeper outer ramps (Racey, 1994; Gilham and Bristow, 1998). Meanwhile Ghose (1977) studied *Discocyclusina* from the Palaeogene of north-east India and concluded that *Discocyclusina* had lived in both fore-reef and back-reef environments. Both Loucks et al. (1998) and Sinclair et al. (1998) concluded that the ovate form can be found in shallow marine settings above fair-weather wave base in inner ramps, while the flattened form below fair-weather wave base in mid to outer ramp settings. According to Geel (2000), *Discocyclusina* is an indicator of normal marine water and can be found down to water depths of 100m. In NR-3

microfacies, the *Discocyclusina* is more likely to be large and flat in shape and can be assigned to nearby outer ramp settings.

The texture of packstone is evidence of low energy conditions and the effects of waves and currents are not present. Only non-ferroan calcite cement is present, while both chemical and mechanical compactions are obvious. The chemical compaction is clear between grains as grain-to-grain contact, concave-convex contact and suture contact which indicate burial diagenesis, while the mechanical compaction is indicative of a lack of early cement in this microfacies (Figures 4.51 and 4.52).

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as being a microfacies 7, large foraminifera 'orbitoid' facies.

Similar microfacies were reported as an open marine by Amirshahkarami et al. (2007) in the Asmari Formation in south-west Iran.

The overall characteristics suggest low energy; open marine setting in the proximal part of deeper marine.

#### **4.3.9 Zone 9:**

##### **4.3.9a PK-1 Microfacies interpretation:**

The bioclasts in PK-1 microfacies suggest an open marine outer ramp/basinal environment. The bioclasts are composed of rare planktonic foraminifers with small fragments of ostracods. Planktonic foraminifers live in open marine water and their abundance increases seaward. Where larger benthic foraminifers are

absent, the water depth is assumed to have been more than 200m in slope and basin environments (Geel, 2000). Furthermore, open marine deposition is suggested by the presence of pelagic foraminifera.

The occurrence of matrix in packstone beds indicates a low energy regime, thus suggesting deposition in an environment not affected by waves or currents. This indicates a deposition below the normal wave base (Wilson, 1975; Flügel, 1982, 2004).

The cements comprise non-ferroan calcite with no evidence of burial cementation. Meanwhile, the clay seams and low amplitude stylolites are indicative of burial diagenesis.

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as being a microfacies 8, planktonic foraminiferal facies. It represents the standard microfacies SMF2 deep sea of Flügel (2004). It is the deepest deposit in the succession.

Similar microfacies have been described by Amirshahkarami et al. (2007) in the Asmari Formation in south-west Iran and have been interpreted as an outer ramp facies.

The overall characteristics suggest an open marine environment below the storm wave base in the outer ramp towards basinal setting.

#### **4.3.9b PK-2 Microfacies interpretation:**

The nature of bioclasts of PK-2 suggests an open marine setting. The lack of benthonic foraminifera and the abundance of planktonics suggest an open marine setting down to more than 200m of slopes and a basinal environment (Geel, 2000).

The absence of any micritization of the bioclasts indicates deposition at depth more than 18 metres, and below fair-weather wave-base (Perry, 1998). Furthermore, the matrix-rich texture of calcimudstone is indicative of a lower energy regime without influence of waves or currents. The low energy hydrodynamic regime indicates deposition below the normal wave base (Wilson, 1975; Flügel, 1982, 2004).

Only non-ferroan calcite cement is precipitated in this microfacies, with no burial cement, while the presence of clay seams indicates burial diagenesis.

The microfacies PK-2 is equivalent to the 'facies (8) planktonic foraminifera' in the standard model of the Cenozoic carbonate ramp generated by Buxton and Pedley (1989), and to the standard microfacies SMF3, deep water basin of Flügel (2004); the deposition environment is interpreted as being a slope and basin setting. A similar microfacies was reported on the outer slope toward a basin environment in the Oligocene-Miocene Asmari Formation in south-west Iran by Vaziri-Moghaddam et al. (2006).

The overall characteristics represent an open deep marine setting on the outer ramp to a basinal environment.

#### **4.3.9c PK-3 Microfacies interpretation:**

The nature of bioclasts of PK-3 suggests an open marine setting. The presence of both allocthonous benthonic and autochthonous planktonic foraminifera suggests transition from a shallow to a deep marine environment above 200m of water depth. So, it can be interpreted as a shallower microfacies relatively to PK-1 and PK-2.

The absence of the micritization of bioclasts indicates deposition at a depth of more than 18 metres, below fair-weather wave-base (Perry, 1998). Moreover, the matrix-rich texture of wackestone indicates a lower energy condition and deposition in an environment not influenced by waves or currents, below normal wave base (Wilson, 1975; Flügel, 1982, 2004). However high energy is indicated by the abundance of larger benthic foraminiferal debris, including fragments of *Nummulites* and *Discocyclusina*. This may suggest this debris was driven from a different environmental setting during a storm event or by geostrophic currents. There is no evidence of sediment gravity (slope-related) flows.

The only cement precipitated is non-ferroan calcite cement, with no evidence of burial cement, while the presence of stylolites and clay seams indicates burial diagenesis.

In accordance with the standard microfacies types in a Cenozoic carbonate ramp which were described by Buxton and Pedley (1989), this microfacies is interpreted as microfacies 8, planktonic foraminiferal facies.

A similar microfacies was interpreted as an outer slope environment by Pedley (1996) on the Maltese Tortonian ramp, and also by Vaziri-Moghaddam et al. (2006) in the Asmari Formation in southwest Iran.

The overall characteristics suggest an open marine setting below the storm wave base in an outer ramp setting nearby basin.

#### **4.4 integrated depositional model:**

Shallow marine carbonate sediments can occur in three different settings: platforms, shelves and ramps (Tucker, 1985). Platforms regionally composed of extensive environments of shallow subtidal and intertidal sedimentation; shelves have relatively narrow depositional environments, recognized by a distinct break of slope at the shelf margin, while ramps are composed of gentle slope from intertidal to basinal depths, with no major change in facies gradient. This study considers that deposition took place on a carbonate ramp, because of lateral variations in microfacies; gradual deepening with no evidence of steep slope suggest that there was no effective barrier or slopes break, and only minor patch reefs have been detected. The distribution of foraminiferal assemblages allows the ramp to be divided into three parts: inner ramp; middle ramp and outer ramp (Burchette and Wright, 1992).

The depositional model has been generated from the overall palaeoenvironmental interpretations of the microfacies. Nine major depositional environmental zones have been identified from the twenty two different microfacies and have been correlated to the standard Cenozoic ramp model of Buxton and Pedley (1989) (more detail is in Table 4.4). These zones distributed across the ramp setting, dipping southwest, zone 1 is terrestrial deposit; zones 2, 3, 4 and 5 are located in inner ramp; zones 6, 7 and 8 are located in middle ramp and zone 9 is located in outer ramp and basinal settings. In addition to the evolution and changes in associated foraminifera across the ramp has been

separated into two time intervals, Late Eocene foraminiferal association and Oligocene-Early Miocene foraminiferal association (see Figure 4.68).

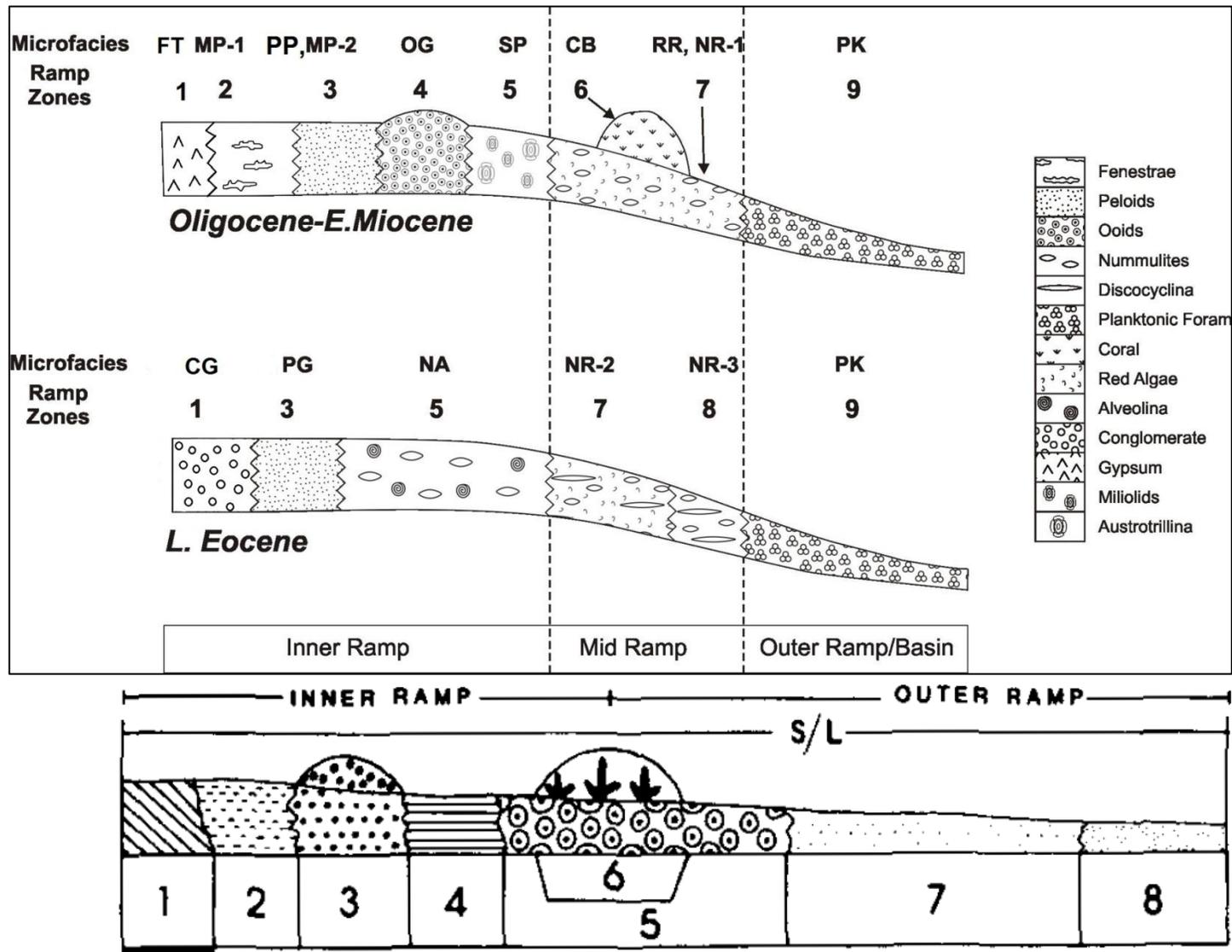


Figure 4.68: A. Depositional model and microfacies change across the ramp during Late Eocene and Oligocene-Early Miocene in the study area. B. Standard Cenozoic ramp model by Buxton and Pedley (1989) (see Figure 4.65).

#### 4.5 Summary and conclusion:

Although the previous study (Henson, 1950a) established the depositional environment of the Kirkuk Group as reefal, this study considers that deposition took place on a carbonate ramp. The previous interpretations (see section 4.3) show that the depositional environment represents ramp setting as the lateral facies changes gradually with depth, and also there is no evidence of rimmed shelf and steep slope.

According to the distribution of foraminiferal associations, nine depositional environment zones were determined ranging from terrestrial to open marine settings distributed across inner, middle and outer ramp settings (see Figure 4.68) where the microfacies gypsum/marl/claystone (FT), conglomerate (CG) and palaeosol (PS) are located in ramp zone one; microfacies peloidal, bioclastic packstone/grainstone (MP-1) is in ramp zone two; microfacies peloidal wackestone/calcmudstone (MP-2), peloidal, skeletal grainstone (PG) and peloidal packstone/grainstone (PP) are in ramp zone three; microfacies ooidal grainstone (OG) is located in ramp zone four; microfacies skeletal packstone with brecciation (SP-1), skeletal packstone with *Austrorillina howchini* (SP-2), skeletal grainstone with *Praerhapydionina delicata* (SP-3) and *Nummulites-Alveolina* packstone/grainstone (NA) are in ramp zone five. These five ramp zones are attributed to an inner ramp setting. Microfacies coral bioherm (CB) is in ramp zone six; microfacies rotalids-coralline red algae wackestone/packstone (RR), coralline red algae-*Nummulites* wackestone (NR-1) and coralline red algae-*Nummulites-Discocyclus* packstone (NR-2) are in ramp zone seven; microfacies *Nummulites-Discocyclus* packstone is in ramp zone eight. The ramp zones six to eight are attributed to deposition in a

middle ramp setting. In addition to microfacies peloidal packstone with planktonic foraminifera (PK-1), planktonic foraminifera calcimudstone (PK-2) and planktonic-benthonic foraminifera wackestone (PK-3) are located in ramp zone nine. This zone occurs in outer ramp to basinal setting (see Figure 4.68).

This study's microfacies can be correlated to the Cenozoic ramp facies which were described by Buxton and Pedley (1989) where the Late Eocene foraminiferal association is dominated by *Alveolina*, *Nummulites* and *Discocyclina*; the Early Oligocene foraminiferal association is dominated by *Nummulites*; finally during the Late Oligocene to Early Miocene the foraminiferal association changed to dominance in miliolids, *Austrotrillina*, *Peneroplis*, *Praerhapydionina* and *Dendritina*.

## **Chapter Five:**

### **Diagenesis**

#### **5.1 Aim:**

The aim of this chapter is to review the main diagenetic processes which have affected different microfacies, to generate the paragenetic sequence in the studied area, and to assess if it is possible to differentiate the origins of the fine carbonate matrices in different microfacies types using their diagenetic signatures.

#### **5.2 Techniques:**

To determine different diagenetic stages and produce a paragenetic sequence, several techniques were used:

Thin sections were stained using the standard technique (Dickson, 1965, 1966) in order to differentiate different types of calcite and dolomite (for more details see Appendix 2.1). This technique was used for over 300 thin sections.

For scanning electron microscopy (SEM) studies thirty mudstone-packstone textured limestone blocks were selected and polished (for more details see Appendix 2.2), cleaned with distilled water and then etched in acetic acid for 20 seconds. The etched solutions were filtered through a millipore filter in order to collect any material falling from the limestone block during the etching process. All the polished limestone blocks and the millipore filter were coated with gold, and then examined with a scanning electron microscope (ESEM) and back scatter (BSEM). Furthermore, electron back-scattered diffraction (EBSD) was used for clay cages and a few micrite and microspar crystals.

Thermo X Series2 ICP-MS coupled to a New Wave Research UP213 UV laser were used to analyse the geochemistry of carbonate grains and matrices. Numerous thin sections were bombarded by a laser beam to analyse 100µm diameter sections. Helium gas was used for ablation and initial transport from the laser cell (for full details of the procedure see Appendix 2.3). Furthermore, Plasmalab software was used for initial data reduction with post-processing in Excel.

Oxygen/carbon stable isotope analysis were conducted based on sampling using both hand-drilling and micro-drilling on a polished surface limestone block in order to have a micrite matrix powder. Hand-drilling was used for coarse-grained rock, while micro-drilling was used for fine-grained rock. The powder was weighed and analysed oxygen and carbon isotopes for both shallow marine and deep marine micrite matrices in an isotope laboratory (for full procedure see Appendix 2.4).

### **5.3 Diagenetic process:**

Diagenesis includes all the processes which sediments undergo directly after deposition, during burial and any subsequent uplift. Several diagenetic processes have been recognized during petrographic studies of stained thin sections as well as SEM. These processes are classified into eogenetic, mesogenetic and telogenetic stages, according to Choquette and Pray's (1970) classification. The eogenetic stage represents those diagenetic processes which took place at the time of deposition on the surface down to depths where processes related to the surface become ineffective; the mesogenetic stage represents those diagenetic processes which occur during

burial and lie below the major influences of processes operating at the surface; and finally, the telogenetic stage represents those diagenetic processes occurring after uplift, from the erosion surface to depths at which major surface-related erosional processes become ineffective (see Figure 5.1).

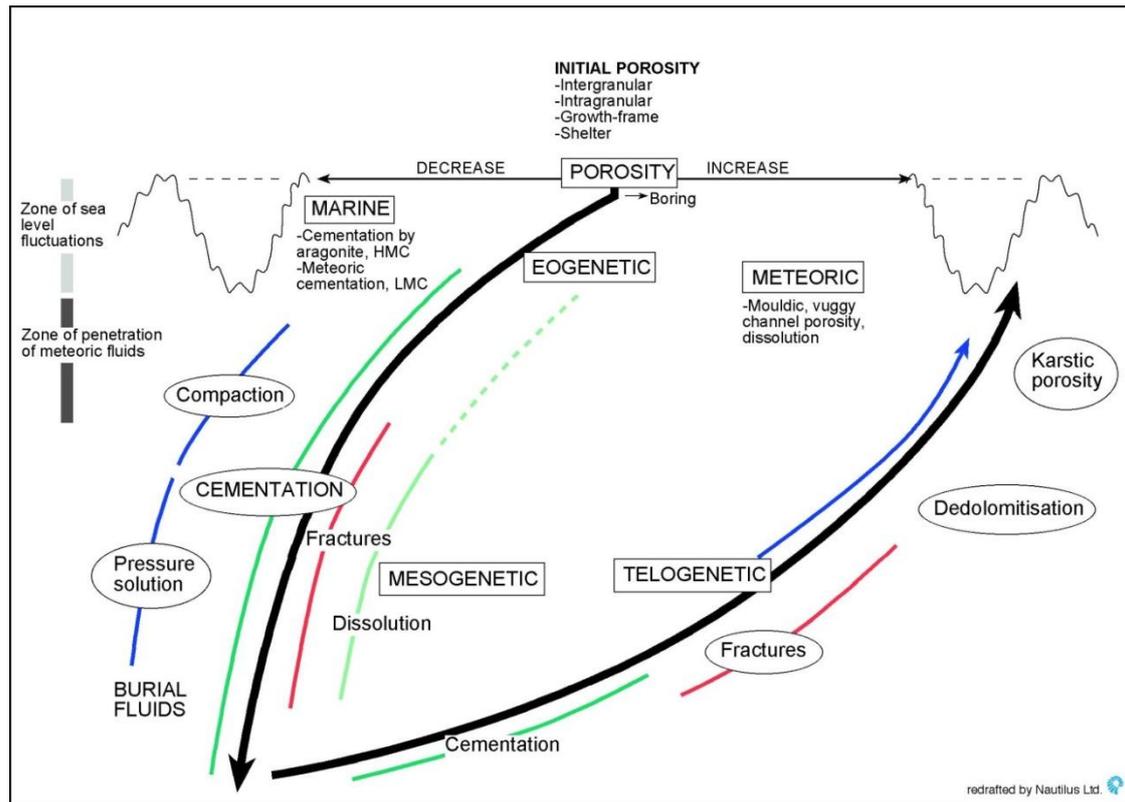


Figure 5.1: Schematic diagram showing the diagenetic processes during eogenetic, mesogenetic and telogenetic stages (Wright, 2006).

This study's diagenetic effects are classified into: an eogenetic stage including micritization, peloidal marine cement, aragonite replacement, neomorphism, dolomitization and non-ferroan calcite cementation; a mesogenetic stage including ferroan calcite cementation, fracture and compaction; and finally a telogenetic stage including dissolution. The diagenetic processes of each realm are listed below (see Table 5.1).

Process	Stage	Eogenetic	Mesogenetic	Telogenetic
Micritization		—————		
Peloidal cement		—————		
Aragonite replacement		—————		
Neomorphism		—————		
Non-ferroan calcite cement		—————		
Dolomitization		—————		
Ferroan calcite cement			—————	
Mechanical compaction			—————	
Chemical compaction			—————	
Fractures		—————	—————	—————
Dissolution				—————

Table 5.1: Timing of diagenetic processes in the study area.

### **5.3.1: Eogenetic stage:**

This stage includes all those diagenetic processes which occur in the early stages of diagenesis after deposition near the surface. The processes seen in the study material are described below:

- **Micritization:**

Micritization is identified as an early stage of the diagenetic process which can be found in almost all inner-ramp microfacies in the study area such as MP, SP, OG, PP, PG and CB microfacies in the form of total or partial micritization, peloids and micritized envelopes. The most common grains in which micritization occur are skeletal grains; in some cases extreme micritization can lead to complete alteration of the original grains and produce peloids (Figure 5.1). This may cause some benthic foraminifera to be difficult to recognize as it is present in SP microfacies; furthermore, micritization occurs in the ooid cortices of OG microfacies (see Figure 5.2). In some cases, a micritized envelope is the only way to recognize skeletal grains; the grains were originally of aragonite composition which later dissolved to be replaced by calcite cement during the stabilization of aragonite to calcite, the micrite envelopes retain the outline of the shells of bivalves and gastropods (see Figure 5.1).

Micritization occurs when the original carbonate grain or its margins are replaced by micrite, at or just below the sediment/water interface, as a result of fungal, algal, cyanobacterial and bacterial attacks on the outside of the grain by these organisms boring small holes in them which are filled later with

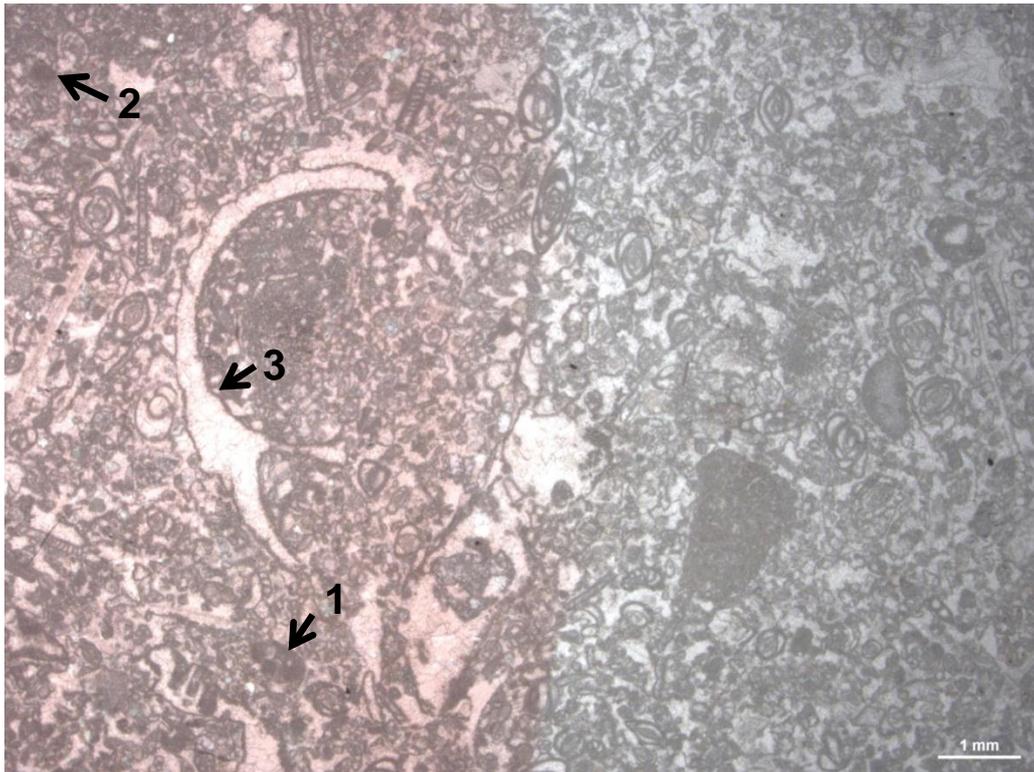


Figure 5.1: Skeletal grainstone with three forms of micritization (1) partial micritization possibly in miliolids, (2) fully micritized grains as peloids and (3) micritized envelope in gastropod shell fragment. Half stained thin-section from Core of Aj Dagh (sample CA.17).

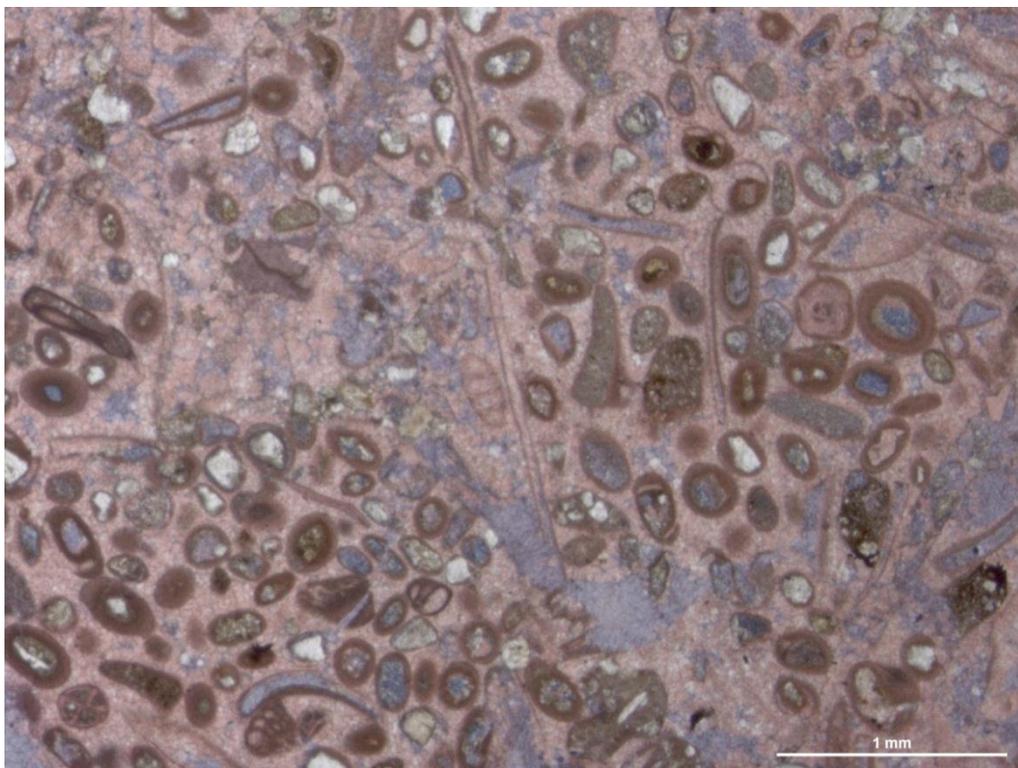


Figure 5.2: Photomicrograph of ooidal grainstone with micritization in the cortices of ooids. Stained thin-section from Core of Aj Dagh (sample CA.33).

micrite cement (Tucker and Wright, 1990; Adams and MacKenzie, 1998). The advantage of this feature is that it is a very good indicator of the palaeo-environment; it indicates shallow water environments of less than 18 m depth (Perry, 1998).

- **Marine peloidal cementation:**

Peloidal cement is another form of early diagenesis recognized only in the SP-1 microfacies in the Awa Spi locality, south-western limb of Aj Dagħ Anticline, and it composed of small spherical peloids, associated with micrite, which fill the space around grains and the intraskeletal cavities of the bioclasts (see Figures 5.3, 5.4 and 5.5). It was difficult to distinguish between cement and peloidal sediments under the microscope because of their small size; it is easier to recognize them under a scanning electron microscope (SEM). These peloids are sized between 20 to 60  $\mu\text{m}$ , composed of dense microcrystalline calcite centres, likely bacterial/microbial product (Chafetz, 1986, Sun and Wright, 1989; 1998), encased with euhedral and subhedral micron-sized calcite crystals (Figure 5.5). These marine cements are precipitated on substrates with a relatively slow-rate of accumulation with little or no disturbance of their sediment cover (Macintyre, 1984; Marshal and Davies, 1981). From petrographic and chemical studies of these peloids, Macintyre (1985) claimed that the texture of the peloids indicate that they possibly originate from chemical processes with repeated nucleation around centres of growth. This is often used as an indicator of shallow marine settings (Flügel, 2004).

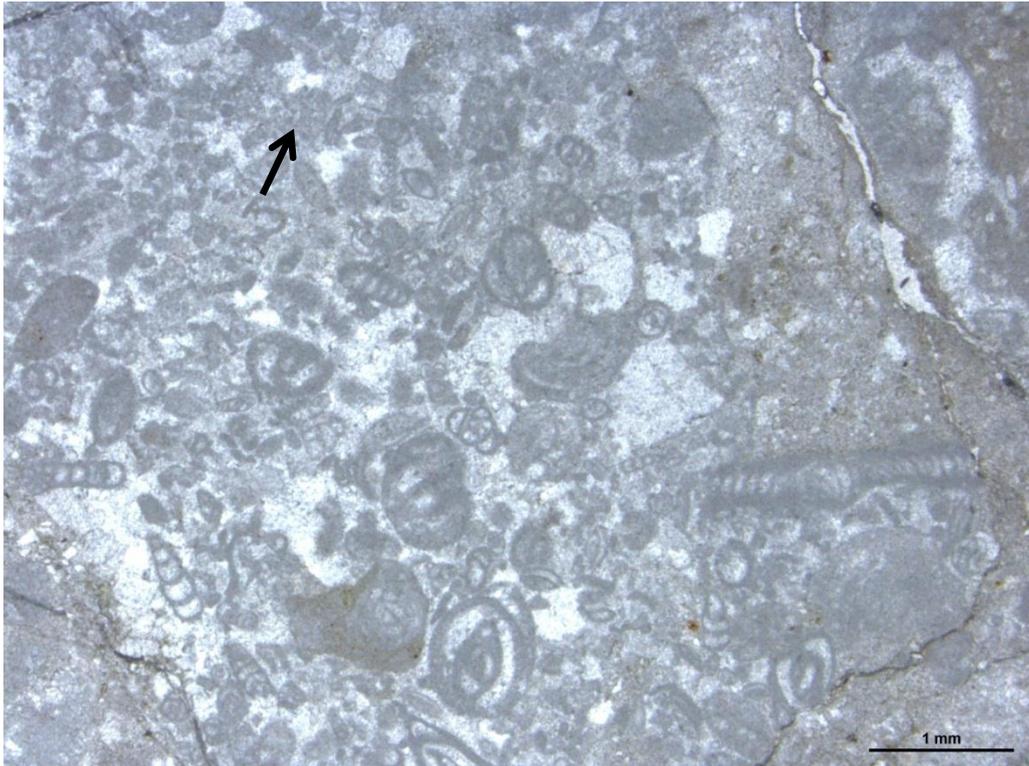


Figure 5.3: Photomicrograph of peloidal cement (marked with arrow) mixed with micrite matrix around bioclasts. Unstained thin-section from Awa Spi area (sample DS.12).

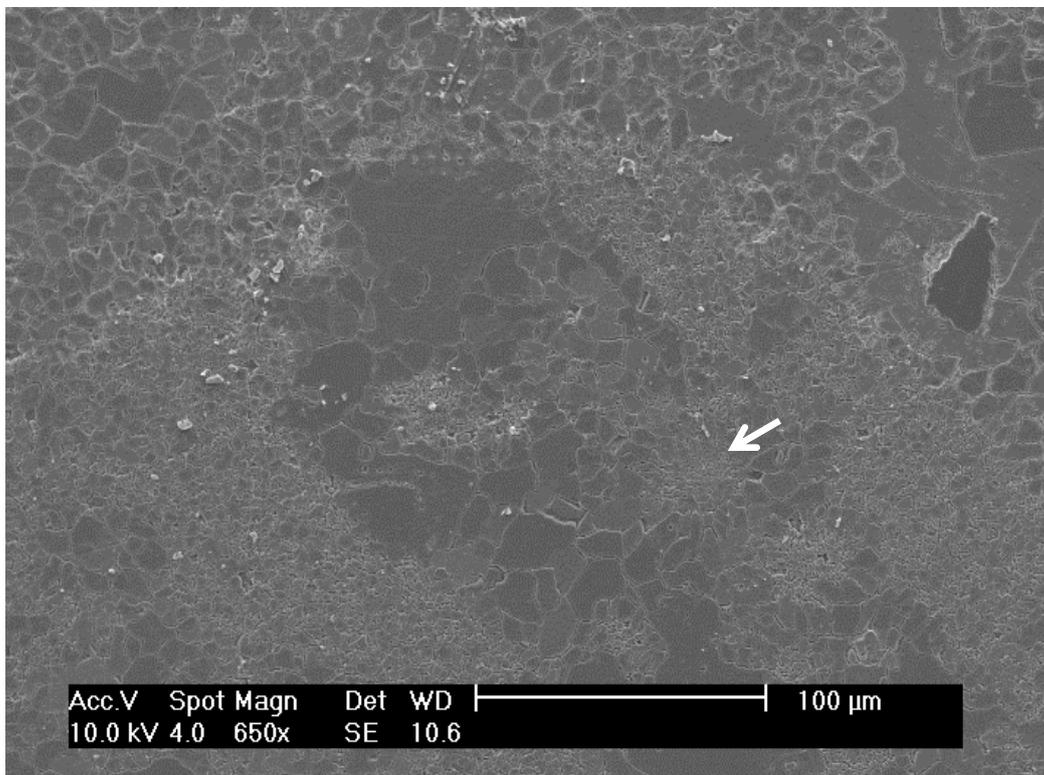


Figure 5.4: Scanning electron micrograph of peloidal cement (marked with arrow) growing on the surface of echinoderm fragment. Awa Spi locality, sample number DS.12.

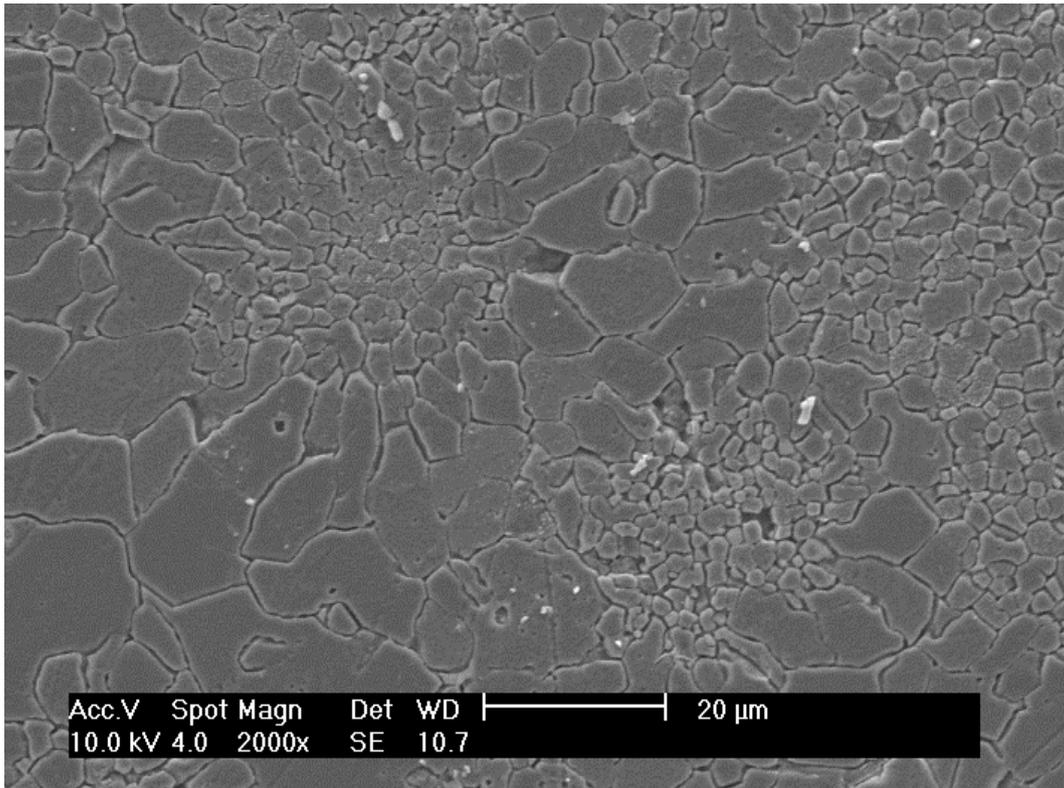


Figure 5.5: Maximized scanning electron micrograph of peloidal cement of figure 5.4 showing euhedral/subhedral rims surrounding centres of dense microcrystalline calcite. Awa Spi locality, sample number DS.12.

- **Aragonite replacement:**

Aragonite is a meta-stable carbonate mineral that dissolves easily and leaves mouldic porosity in bioclasts such as gastropods and bivalves. This process is a common feature and occurs in the early stages of diagenesis, which is widely recognized in the coral bioherm (CB), ooidal grainstone (OG) and also SP microfacies. This dissolution of aragonite was followed by filling the mouldic porosity with stable low-magnesium calcite (LMC) cement (see Figure 4.31). The process replacement depending on the time of dissolution of aragonite, the lithification of carbonate mud matrix as micritized envelope and the precipitation of low-Mg calcite. Replacement may occur before or after the lithification of carbonate mud. In cases where dissolution occurs before

lithification of carbonate mud and precipitation of low-Mg calcite, the void will not be present. In contrast, if dissolution of aragonite occurs after lithification of carbonate mud and before precipitation of low-Mg calcite, the internal moulds will be preserved. The aragonite replacement being related to terrestrial exposed surfaces or fresh water lenses (extending to the marine environment) are points to be investigated in the future, having gone beyond the scope of this thesis.

- **Dolomitization:**

The mineral dolomite  $\text{CaMg}(\text{CO}_3)_2$  is not a common diagenetic feature in the study area, it is recognized by its euhedral rhombic shape which can be easily distinguished from calcite from its stain colour and shape in thin sections with staining (for more detail of staining techniques see Appendix 2.1). Dolomite can be found in different textures: non-planar crystals in a xenotopic mosaic, planar-e crystals (euhedral) in an idiotopic mosaic, and planar-s crystals (subhedral) in a hypidiotopic mosaic (following the classification of Sibley and Gregg, 1987). All the dolomites in the study area are non-ferroan. Dolomite can replace particular components of the original sediment; this is described as fabric selection (partial dolomitization); or in some cases dolomite can replace all components of the sediment and is called total dolomitization. In this study area, dolomites are found in RR and NR-3 microfacies and occur as scattered very fine (hundreds of micron) crystals of idiotopic (euhedral) dolomite (see Figures 4.13 and 4.54). It is composed of a selective fabric; the matrix is more affected than other components. Murray (1960), Friedman (1964), Folk (1965), Schmidt (1965), Land (1967) and Ashquith (1967) believe

that, probably because most of the original carbonate mud matrix consists of aragonite and high magnesium calcite, they are metastable and susceptible to dolomitization. This process can take place in the early phase of diagenesis. Except the dolomites in NA microfacies are composed of almost totally dolomitized, non-ferroan, tightly packed, idiotopic (euhedral) and hypidiotopic (subhedral) crystals mostly matrix selective with few skeletal grains (see Figure 4.64).

This indicates that the dolomitization is more common in the relatively shallow marine inner ramp than the mid ramp microfacies, which confirms the Al-Qayim and Khaiwka (1980) result that they determined the dolomitization rate is less common basinward; this may be indicative of reflux dolomites.

Dolomite might form in many stages of diagenesis, from directly after deposition to deep burial settings (Adams and MacKenzie, 1998), so it cannot be diagnostic of a particular environment. Petrographic study is not enough in all cases to study dolomite and analyse the mechanism of dolomitization without having chemical analysis. However, simple petrographic criteria can be used for determination of timing dolomite formation; in this case the grains are in point contact, so dolomite can be described as pre-compaction, pre-pressure solution and post cementation; as the dolomite which is present in the Gully Oolite, mostly contains scattered pre-compaction dolomite rhombs (Hird and Tucker, 1988).

- **Bioclast neomorphism:**

The process of neomorphism is defined as the *in situ* replacement of one mineral by another by Adams and MacKenzie, (1998); this term in carbonate

sedimentology is used to describe aragonite's alteration to calcite. Neomorphism is not widely recognized in the study area. It is found in the coral bioherm (CB) microfacies. The replacement of aragonite by calcite is clearly seen in corals in which relicts of the original coral are retained in the new calcite crystals. The resulting replaced crystals have irregular shapes with curved boundaries (see Figure 5.6).



Figure 5.6: Photomicrograph of aragonitic coral altered by calcite spar in which the relict of original coral is retained. Un-stained thin-section from Core of Aj Dagh Anticline (sample number CA.19).

- **Aggrading neomorphism:**

Aggrading neomorphism is the process of increased crystal size by neomorphism and recrystallization which can happen during early diagenesis. Mud-grade carbonate is replaced by microspar and pseudospars in CB and SP microfacies by neomorphism (see Figure 5.7) in which neomorphic spars

can form from a previously lithified micritic matrix by recrystallization and aggrading neomorphism, during mineralogical stabilization, through high-Mg calcite replacement by low-Mg calcite (see also Section 5.4.3), which leads to the release of Mg ions into the pore water. After removing these ions from the pores with fresh water, the micrite crystals start to grow until they reach microspar size (Folk, 1959, 1965, 1974). Any crystal sizes more than 30 microns are pseudospars; crystals between 5 to 30 microns are known as microspars and the term micrite is used for the smallest particles with an average crystal size of less than 4 or 5 microns (Folk, 1965; Bathurst, 1975).

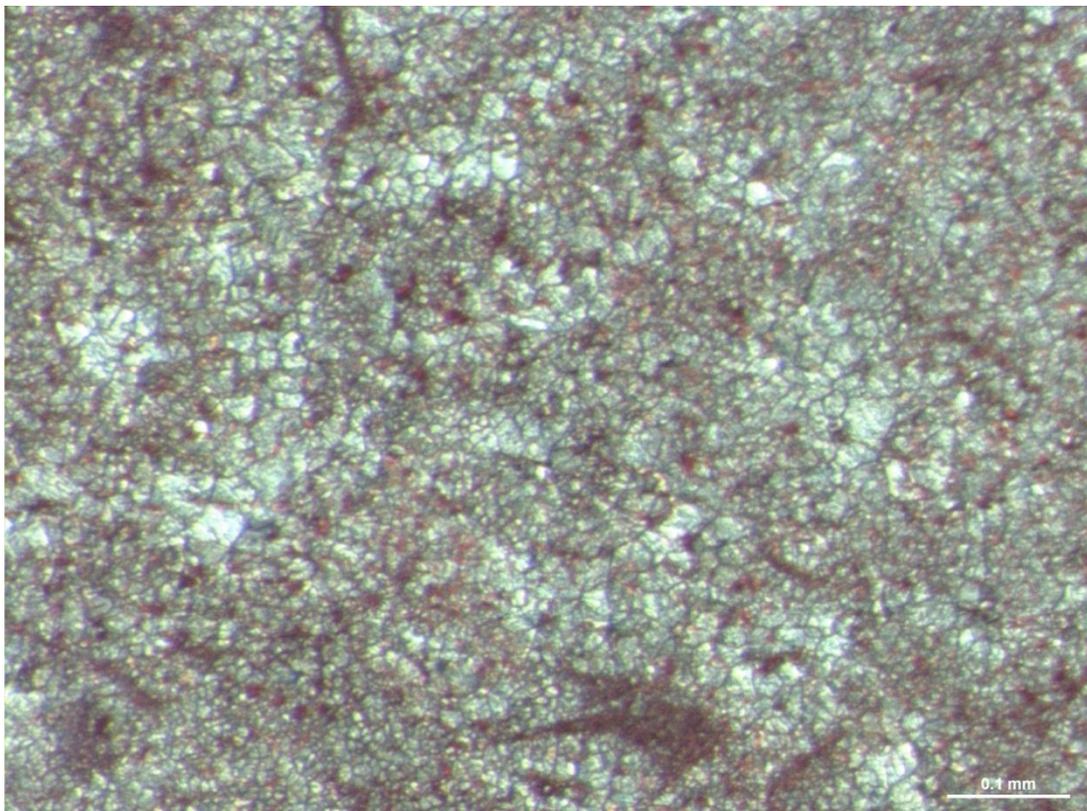


Figure 5.7: Photomicrograph of neomorphic spar originating from the recrystallization of former micrite. Stained thin-section from Hazar Kani locality (sample number AS.6).

- **Non-ferroan calcite cementation:**

The non-ferroan calcite cementation is mainly intergranular or fills the molluscan moulds. It reflects oxidizing conditions during cementation either filled open packed or relatively compacted textures. There are different types of non-ferroan calcite cement in the study area, as listed below:

1. **Blocky cement:**

Blocky cements are widely recognized in SP and MP-1 microfacies in the study area, and consist of medium to coarse grained polyhedral crystals. The sizes of the crystals range from tens of microns to millimetre scale, in addition to crystal boundaries are mostly straight with some irregular boundaries (see Figure 4.24). This type of cement is usually associated with meteoric phreatic and burial environments, but are rare in a marine environment (Scholle and Ulmer-Scholle, 2003; Flügel, 2004). This cement may be derived from pre-existing cement which can be originate from the dissolution of aragonite or might act as late cement filling the remaining pore spaces in meteoric environment.

2. **Dripstone or pendant cement:**

Dripstone or pendant cement is not widely recognized in the study area. It is recognized only in the SP-3 microfacies located 10 metres below the sub-aerial exposure surface. It is characterized by its unique shape in which cement is only precipitating on the lower part of the grains. This type of cement is present in the early stage of diagenesis as a result of the gravitational force of a water droplet holding onto the lower part of a grain (see Figure 5.8). It develops after many cycles of drainage and precipitation of a hanging droplet (Tucker and Wright, 1990).

This type of cement can develop in beachrocks, but beachrock cements are typically very thin, inclusion-rich, but because of this cement is inclusion free, it may be characteristic of meteoric vadose cement, where rainfall infiltrates through the vadose zone in meteoric lens as a result of subaerial exposure and dissolution following a fall in sea level.

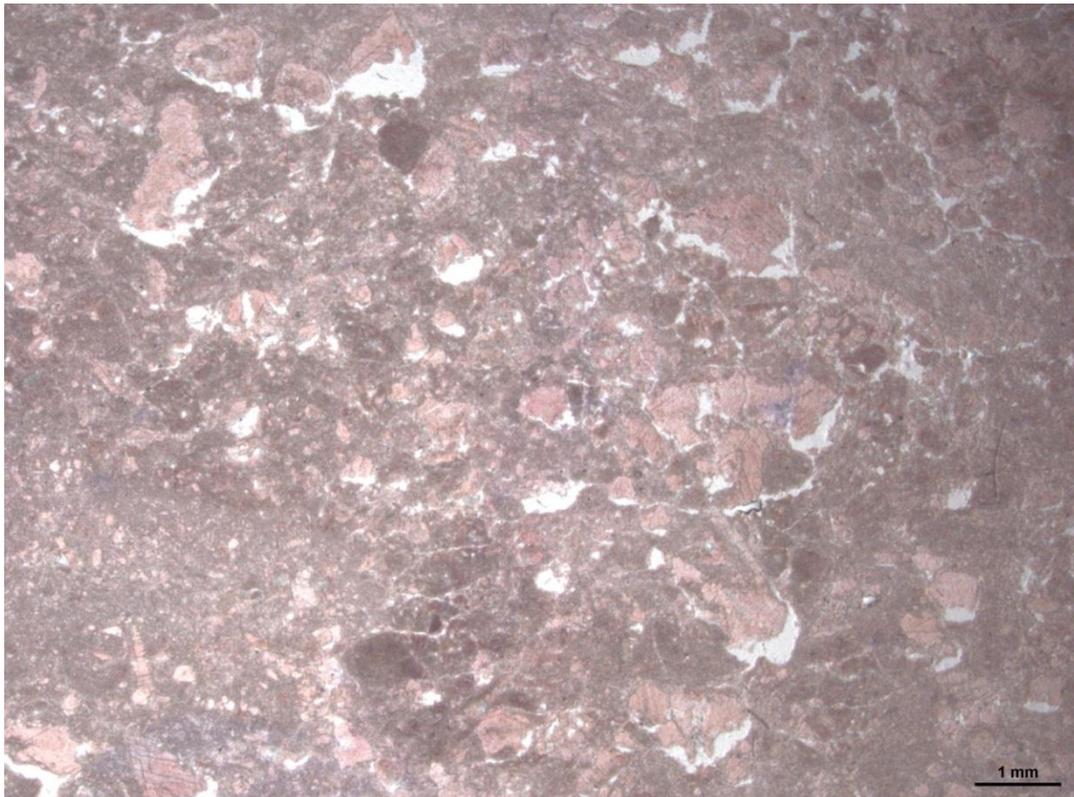


Figure 5.8: Photomicrograph of skeletal packstone/wackestone with growing pendant cement underneath the echinoid fragments. Thin-section from Core of Aj Dagh Anticline (sample number CA.23).

### 3. Syntaxial cement:

Syntaxial overgrowth or syntaxial rim cement is considered to be a major diagenetic process in the study area, and it can be found in most of the microfacies; it consists of coarse spar cements which develop in optical continuity on grains or earlier cement. This kind of cement is commonly seen in echinoderm-rich rocks (Bathurst, 1971), where the original grain has been

overgrown by cement (Figure 5.9). It can be seen that the cement crystals are in optical continuity with adjacent echinoderms. This type of cement is not diagnostic of a particular environment; it may form in all meteoric, marine and burial settings (Scholle and Ulmer-Scholle, 2003). These cements, from marine settings are inclusion-rich with cloudy appearance; in contrast to the overgrowth cement from meteoric and burial settings, it is clear and inclusions free (Flügel, 2004).

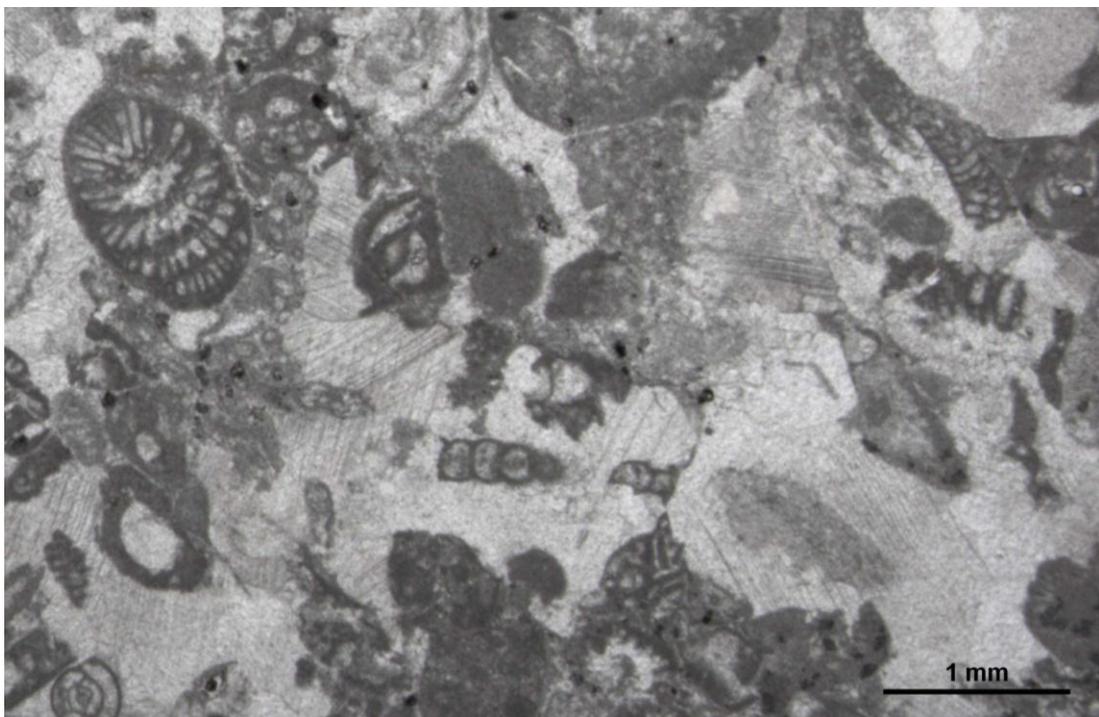


Figure 5.9: Photomicrograph of skeletal grainstone with syntaxial cement on echinoid fragments at lower-right of the photomicrograph. Un-stained thin-section from Zinana area (sample number Z.3).

#### 4. Drusy cement:

Drusy cements are characteristic of true-pore filling cements in intergranular and intraskeletal pores, moulds and fractures. This type of cement has been recognized in SP-1 and SP-3 microfacies as intergranular pore and intraskeletal mould filling cement (see Figure 5.10, 5.11) and their crystals are

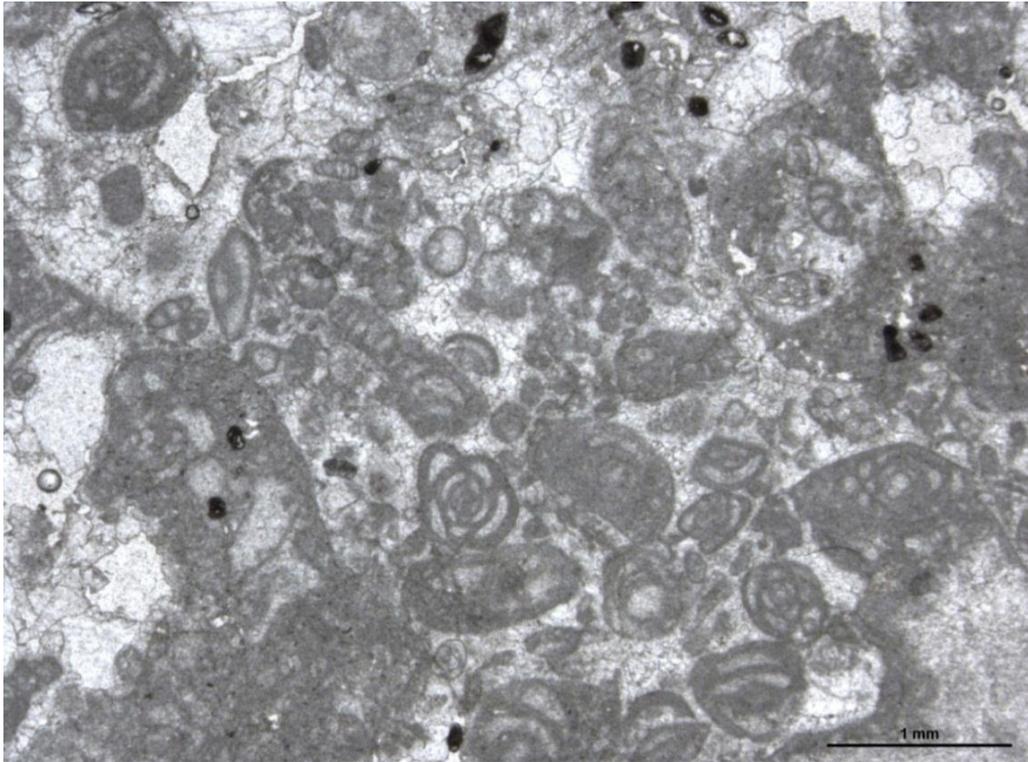


Figure 5.10: Photomicrograph of skeletal grainstone with developing of drusy cement as intergranular cement at upper-centre part of the photomicrograph. Un-stained thin-section from Zinana area (sample number Z.19).

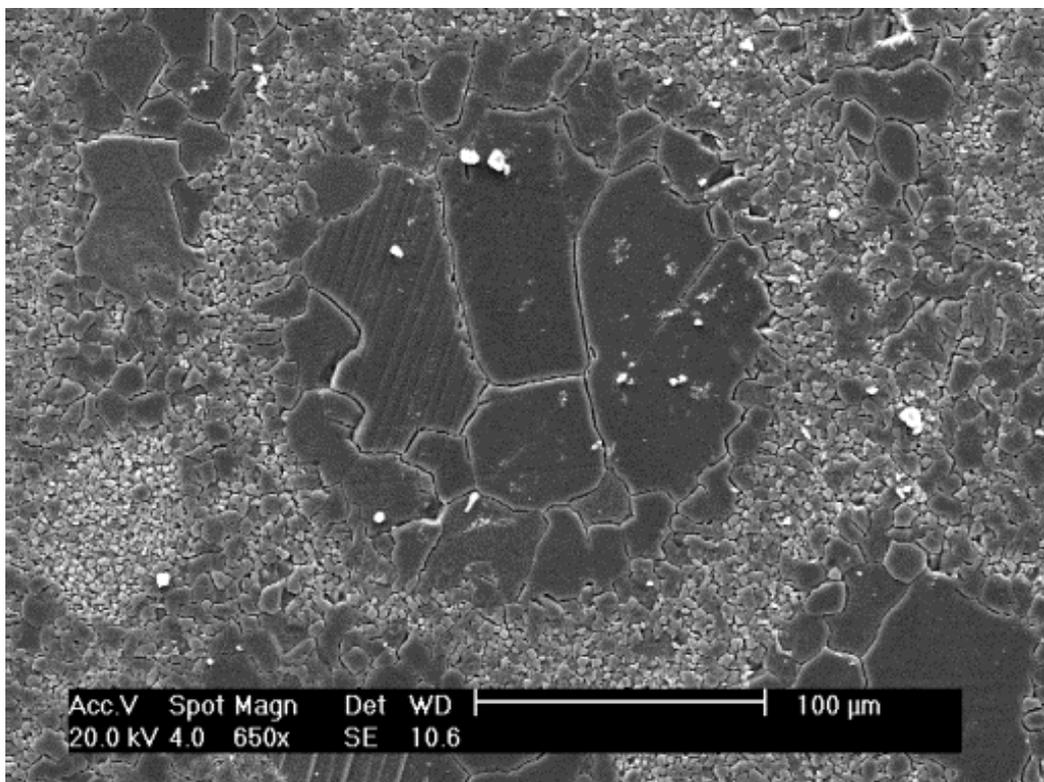


Figure 5.11: Scanning electron micrograph of intraskeletal moulds filled with drusy cement, from Hazar Kani area (sample number AS.9).

characterized by equant and anhedral to subhedral forms. As a result of competitive growth, crystals increase in size away from substrates towards the centre of pore spaces; usually their sizes are more than 10 microns. This feature characterises many limestones fully cemented in meteoric and burial settings (Adams and MacKenzie, 1998; Scholle and Ulmer-Scholle, 2003). This type of cement may precipitated in meteoric setting in the study area, because of there is no evidence of burial has been found in this horizon.

#### 5. Early cement:

Early cement associated with hardgrounds is another form of non-ferroan calcite cements present in Zinana and Sagrama localities. It is composed of fine granular cement which developed in shallow marine carbonate with cemented zones up to few millimetres thick associated with hardgrounds. This type of marine cement has features like grain truncations formed as a result of boring or erosion (see figure 5.12). Hardgrounds may act as permeability barriers but little is known about their continuities (Wright, 2006). Although, it may effect on the porosity preservation or losing it. The Middle Jurassic oolites in Paris basin is an example of early cementation which led to the preservation of the porosity (Purser, 1985).

#### **5.3.2: Mesogenetic stage:**

This stage of diagenesis includes all those diagenetic processes that take place during burial. The processes which occur in this realm are listed below:



Figure 5.12: Early cement associated with hardground with criteria of grain truncation (1), micro-boring (2) and planar surface(3). Un-stained thin-section from Zinana locality. Scale 1cm=1mm.

- **Compaction:**

Both types of compaction, mechanical and chemical, are common in the study area, especially chemical compaction in the form of grain-to-grain sutured contact (see Figure 4.52), clay seams (see Figure 4.41) and stylolites (see Figure 5.13), with no evidence of diagenetic bedding in the study area, in addition to mechanical compaction, which results in fractures in the grains (see Figure 4.53). Compaction is widely found in most of the microfacies such as: PG, CB, NR and PK microfacies. Mechanical compaction usually takes places with a lack of early cementation, while chemical compaction develops after deeper burial (Tucker and Wright, 1990; Scholle and Ulmer-Scholle, 2003).

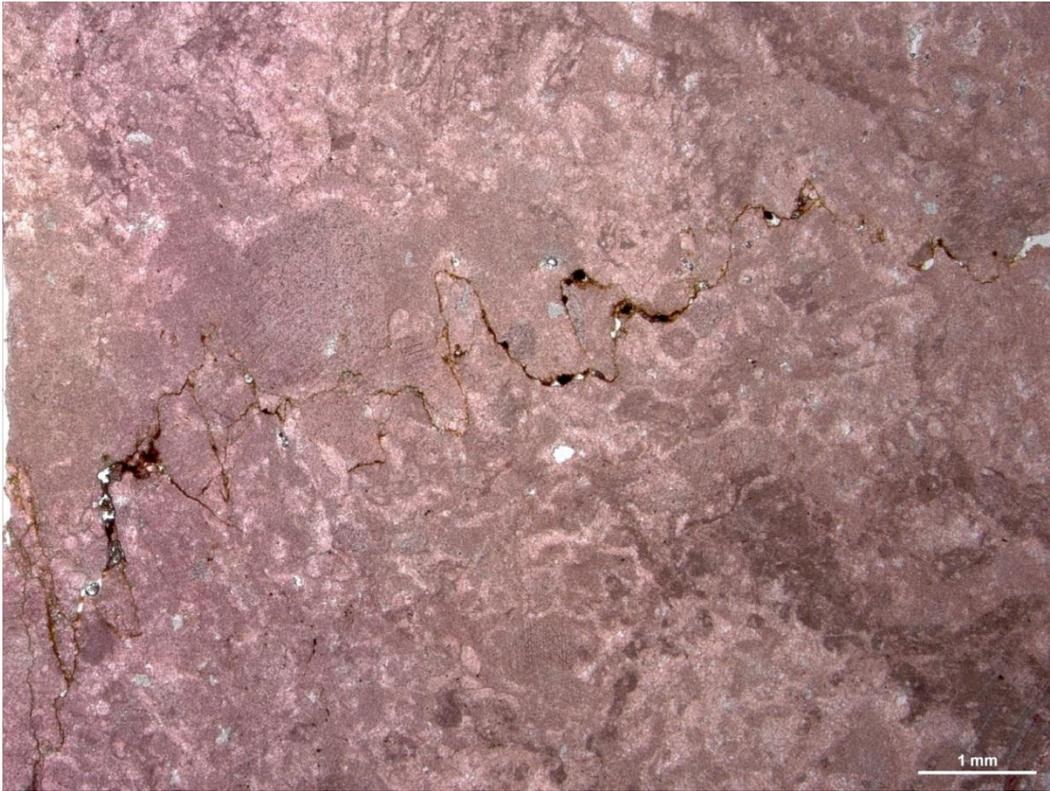


Figure 5.13: photomicrograph of pressure solution 'stylolites'. Stained thin-section from Bellula Gorge (sample number BL.64).

Initial mechanical compaction can occur with shallow burial, of one metre, (Flügel, 2004) as changes in packing, reorientation, dehydration and reduction of mud volume of up to 75% of the original porosity, moreover, compaction of up to half the original thickness and up to a 50-60% loss of porosity needs at least hundreds of metres of burial depth.

Although cementation one of the main processes that can reduce porosity during shallow burial, in order to reduce porosity to the level of a typical carbonate, either mechanical and chemical compactions and/or cementation must happen. Budd (2001; 2002) using Palaeogene carbonates from Florida, focused on effects of reduced permeability with depth, to evaluate how cementation, mechanical and chemical compaction (including pressure solution) affected loss of permeability (K) and how the pore networks and

permeability respond differently to them. The mechanical compaction was least effective in decreasing permeability than cementation, and pressure solution was more effective. In matrix-rich limestones the permeability change with depth is low, this may indicate that these sediments have undergone early cementation. Whereas in the grain-rich limestones there is a decrease in permeability with depth. Moreover, he documented that permeability loss with burial occurs faster than the burial related porosity loss for the same group of rocks. This explains that permeability is more sensitive to burial compaction than limestone porosity due to its effect on the pore throats and increasing tortuosity of the pores network. In the deep subsurface the grain-supported limestones have the best reservoir potential higher than the average matrix permeability in the near-surface realm. Furthermore, Melzer and Budd (2008) determined that the pore geometry and permeability respond to both compaction and cementation differently; in which cement-dominated samples have higher porosity in intermediate sized pores at higher permeability than the compaction-dominated samples. Compaction cannot make a significant change in porosity in pore throats smaller than 1  $\mu\text{m}$  at permeability more than 20 md; while, cement-dominated diagenesis in permeability below 100 md and small pore throats generates large amount of porosity. These differences indicate that cementation changes the original interparticle pores to polyhedral and sheet-like pores connected by smaller pore throats, whereas compaction only constricts the original interparticle porosity in smaller intergranular pore throats.

- **Ferroan calcite cement:**

Ferroan calcite is not as common as non-ferroan calcite in the study area. It is widely recognized in the ooidal grainstone (OG) microfacies in the form the replacement of calcite matrix, or the replacement of aragonite. In the case of the replacement of aragonite, the ferroan calcite cement filled the former aragonite moulds in the late stages of the replacement as it is present in bivalves (see Figure 4.6).

During early diagenesis the early non-ferroan calcite cement was precipitated in open packed texture in the ooidal grainstone (OG) microfacies, and then followed by burial diagenesis, in which the oxygen in pore-waters is used up, and in the reducing burial environments calcite cements may contain ferrous iron ( $\text{Fe}^{2+}$ ) which can substitute for some of the calcium up to several thousand ppm in order to form the ferroan calcite cement and fill the former aragonite moulds. This type of calcite can be distinguished from non-ferroan calcite cement by staining the cement with potassium ferricyanide (Dickson, 1965, 1966).

- **Fractures and veins:**

Fractures and veins are other features which develop in different diagenetic stages in several microfacies. Fractures and veins, in the study area, are present in different forms, from tiny cracks, up to 1 mm wide cement-filled veins. The history of these fractures exhibits three stages: early fractures, burial fractures, and uplift. In which the non-ferroan calcite-filled fractures and cracks suggest an early stage of occurrence, which might have resulted from dissolution and desiccation (Braithwaite, 1983). Also during burial limestones

suffered from fracturing and veining. After the precipitation of ferroan calcite spar during burial, limestones were cross-cut by non-ferroan calcite fractures as seen in the Zinana area (see Figure 5.14). The fracturing of carbonate rocks is important because it enhances permeability and porosity so as to increase the reservoir potential and also helps in the understanding of the post-sedimentary sequence of events in carbonate rocks (Flügel, 2004).



Figure 5.14: Photomicrograph of non-ferroan calcite spar filled fracture cuts both non-ferroan and ferroan calcite spar. Stained thin-section from Zinana area (sample number Z.30).

### **5.3.3: Telogenetic stage:**

This stage of diagenesis includes all the diagenetic processes that occur as a result of the uplift and affected by meteoric solutions (Morrow and McIlreath, 1990). The products of this stage are listed below:

- **Dissolution:**

Dissolution, and its associated karstification, is the most important diagenetic process to affect porosity enhancement in the upper part of the Kirkuk Group by developing karstic porosity in which the karstic pore size reaches several metres. Karstic porosity is solutional porosity where the pore diameter exceeds 5-10 mm, allowing flow to change from laminar to turbulent leading to increase in the rate of dissolution (Wright, 2006). Dissolution may happen in limestone at the end stage of diagenesis, after uplift and access by meteoric solutions. This feature is clearly seen in the Awa Spi locality of the southwestern limb of the Aj Dagh Anticline (see Figure 5.15). Several factors may cause karstic porosity, such as carbonic acid, acidity caused by the decay of organic matter, mixing corrosion, basinal fluids (H<sub>2</sub>S and CO<sub>2</sub>) and thermal effects (Wright, 2006). The karstic porosity in the study area might form due to carbonic acid; this interpretation is supported by the occurrence of an acidic spring several kilometres away from the study area.



Figure 5.15: Field photo of man size karst in the Awa Spi locality, southwestern limb of Aj-Dagh Anticline.

## **5.4 Scanning Electron Microscopic (SEM) study of Micrite:**

### **5.4.1 Preface:**

As a range of matrix-rich depositional facies were available, the opportunity was taken to assess if different sources of calcium carbonate could be identified between shallow water and deeper water materials. In addition, in order to identify particular types of micrite, a range of bioclasts of known original mineralogy were also studied. For this purpose thirty samples were carefully selected in order to include most of the common bioclasts, peloids and matrices in which the texture of these grains might provide a guide to find the source of the matrices in both shallow and deeper water (more detail regarding bioclasts, peloids and matrices textures and their interpretations are in 5.4.2.1 and 5.4.3).

This study follows the size-category terminology developed by Folk (1959,1965) and uses the term “micrite” for microcrystalline limestones, with means crystal sizes smaller than  $4\mu\text{m}$ , and the term “microspar” for those with mean sizes larger than that value.

The micrite matrix was investigated under a scanning electron microscope in order to identify the precursor mineralogy of micrite. Understanding of the primary mineralogy of micrite precursors is helpful for understanding porosity evolution, the preservation or destruction of microporosity in fine-grained limestone, as well as the physico-chemical nature of oceans at different times (Lasemi and Sandberg, 1993).

## **5.4.2 Results:**

### **5.4.2.1 Micrite matrix and bioclasts:**

For each bioclast several microfacies were examined and the average results were used to describe the texture. As well as for peloids and micritic matrices.

Matrix: Samples from both shallow and deeper marine facies were investigated in polished slightly etched limestone blocks using SEM. Firstly; shallow marine micrite matrices show polyhedral crystals with straight curvilinear boundaries. Many platy clays form partial or complete clay cages which surround the micrite crystals (see Figure 5.16a, b, c, d); where the micrite crystals meet clays they are straight or curvilinear sided. The crystal sizes of micrite matrices were established by measuring the maximum diameter of the crystals from several microfacies such as: MP-1, MP-2, SP-1, SP-2, RR, NR-1, NR-2 and NR-3; the crystal size usually ranges between 2 to 5  $\mu\text{m}$  in which the average size is 3 to 4  $\mu\text{m}$  (see Figure 5.17). During the investigation, very rare square or elongated pits were observed (see Figure 5.16c, d). Moreover, the microporosity in this type of matrix is relatively low averaging 8.7 % (for more detail on microporosity see 5.4.2.4).

Secondly; in deeper marine micrite matrices, in addition to polished-etched limestone blocks, a few broken limestone blocks were examined in order to locate the bioclasts, crystal shapes and sizes easier. These show straight curvilinear crystal boundaries with polyhedral shape. Very rare clay cages were found around the crystals with smaller size compared to the shallow marine micrite matrices. From the PK-1, PK-2 and PK-3 microfacies, crystal sizes for deeper micrite matrix ranged between 1 to 3  $\mu\text{m}$  with average 1 to 2  $\mu\text{m}$  (see Figures 5.18 and Figure 5.19a, b, c, d). No pitted crystals were found

during the investigation of deeper marine micrite. Furthermore, the microporosity in this type of micrite matrix is relatively higher than the previous one with average of 13.1% (for more detail on microporosity see 5.4.2.4).

**Bioclasts:** At relatively lower magnifications bioclasts were evident in the polished/etched limestone blocks under SEM; their distinct shape helps to identify them. Under SEM, primary aragonitic bioclasts, such as corals in CB microfacies, have a lighter grey colour from the replacement of the original aragonite, no or very rare inclusion were found on the surface of the crystals (see Figure 5.20a, b, c, d). Calcitic bioclasts, such as benthic foraminifera and red algae, along with peloids, have a granular or elongated texture under higher magnification. Miliolids, which would have had a high-Mg calcite composition, have a granular texture with straight/curvilinear boundaries and polyhedral crystal shapes. Average crystal sizes are 3 to 4  $\mu\text{m}$  and neither inclusion on the surface of crystals nor clay cages between crystals were found in PG, MP-1, MP-2, SP-1, SP-2 and SP-3 microfacies (see Figures 5.21a, b and 5.22). *Nummulites*, also had a former high-Mg calcite precursor, have an elongated crystal shape, with average crystal sizes ranging between 15 to 20  $\mu\text{m}$ ; during investigation of NR-1, NR-2 and NR-3 microfacies, pitted crystals were observed with a four-sided/rhombic type pits. No clay cages were found between crystals (see Figures 5.23a, b and 5.24). Red algae are another bioclast which was investigated under the SEM from NR-1, NR-2 and RR microfacies; they have a granular texture with a straight/curvilinear crystal boundary with average size 3 to 4  $\mu\text{m}$ . No inclusions were found on the surface of the crystals, clay cages were absent (see Figures 5.25a, b and 5.26). Finally, peloids which may originally form from micritized bioclasts

and/or faecal pellets (for more detail on peloids see Section 4.3.2a), would probably have had a former high-Mg calcite precursor have a granular texture and crystal shapes are straight/curvilinear with average size of 3  $\mu\text{m}$ . From PG, MP-1, SP-1, SP-2 and SP-3 microfacies, very rare pitted crystals were observed with a few clay cages around the crystals (see Figures 5.27a, b and 5.28) (see Table 5.2).

	Inclusions	Average crystal size ( $\mu\text{m}$ )	Clay cage
Miliolids	No	3-4	No
Nummulites	Yes	15-20	No
Red algae	No	3-4	No
Peloids	No or rare	3	Yes
Shallow water matrix	No or rare	3-4	Yes
Deep water matrix	No	1-2	Rare

Table 5.2: Different crystal sizes and presence or absence of inclusion and clay cages in micrite and some selected bioclasts in addition to peloids.

In deeper marine matrices, in PK-1, PK-2 and PK-3 microfacies, few bioclasts were recognized such as planktonic foraminifera and coccolith debris in both polished/etched and broken limestone blocks (see Figure 5.29a, b, c).

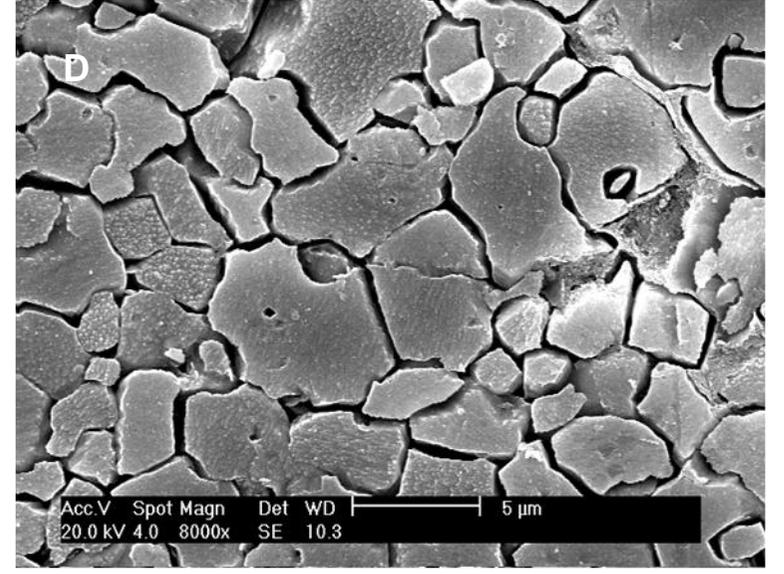
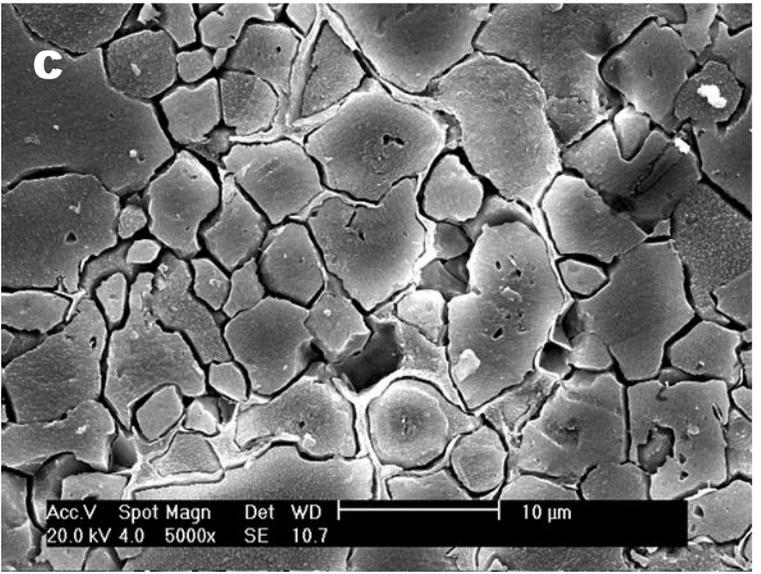
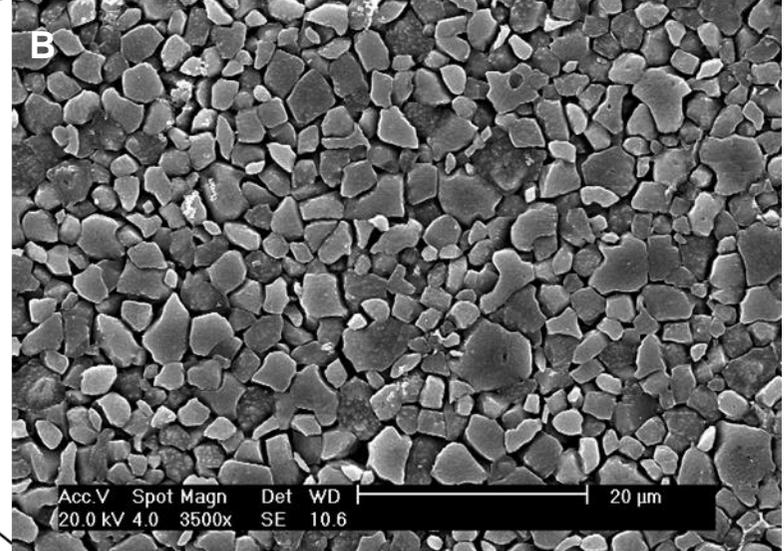
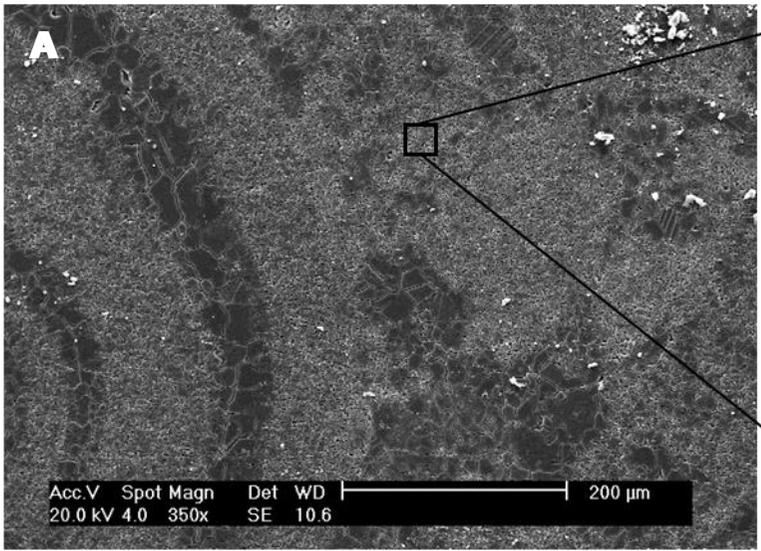


Figure 5.16: (A) Scanning electron micrograph of shallow marine micritic matrix on the central top of the photo, miliolids wall is on the left hand side of the photo (from PG microfacies, sample AS.1). (B) Higher magnification of scanning electron micrograph of the shallow marine carbonate matrix. (C and D) SEM micrograph of shallow marine carbonate micrite with different thickness clay cages around the micrite crystals with different pit shapes and sizes (from RR microfacies, sample SD.8).

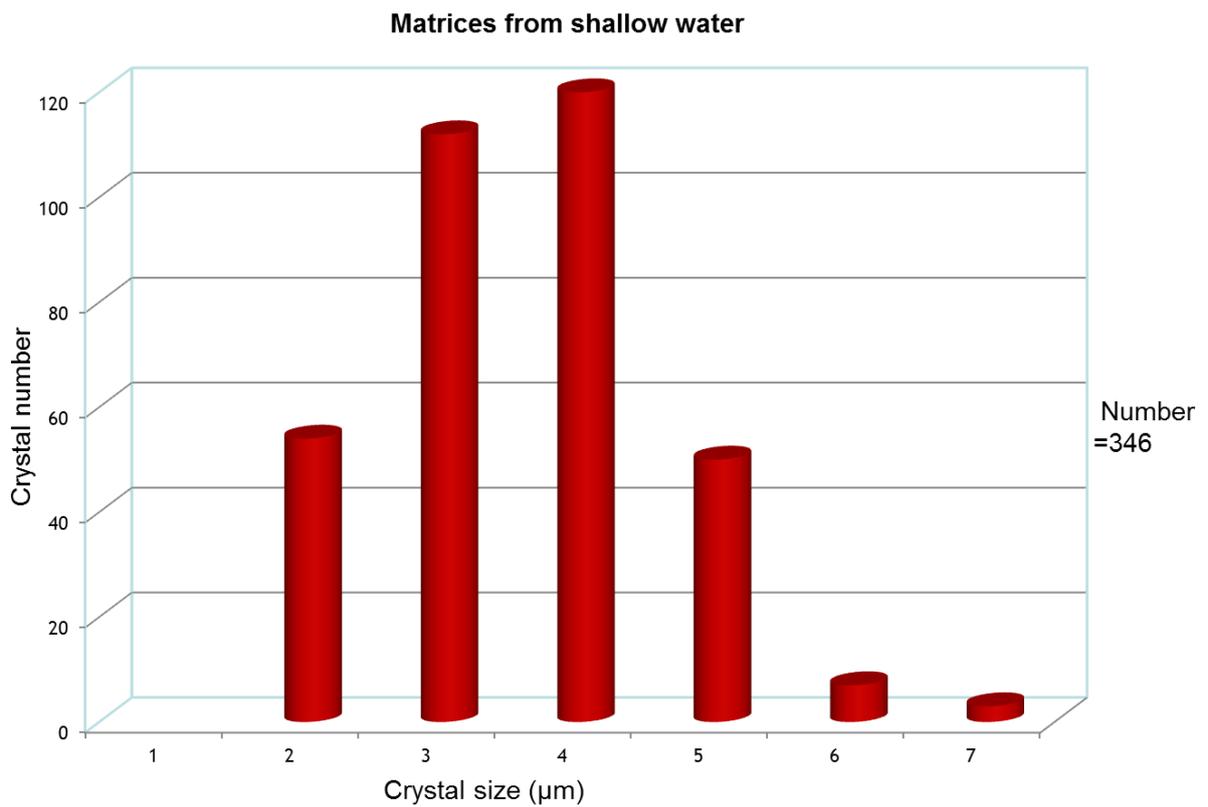


Figure 5.17: Histogram showing the crystal size of shallow marine matrices. 346 crystals were measured from ranges of microfacies.

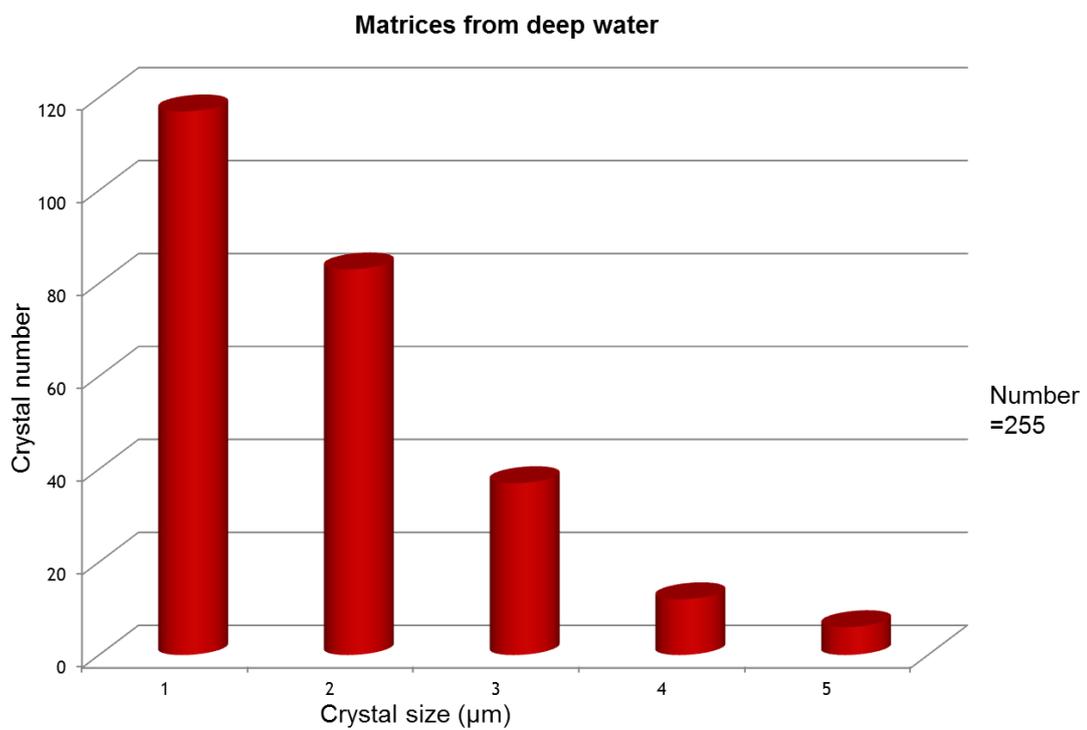


Figure 5.18: Histogram showing the crystal size of deeper marine matrices. 255 crystals were measured from ranges of microfacies.

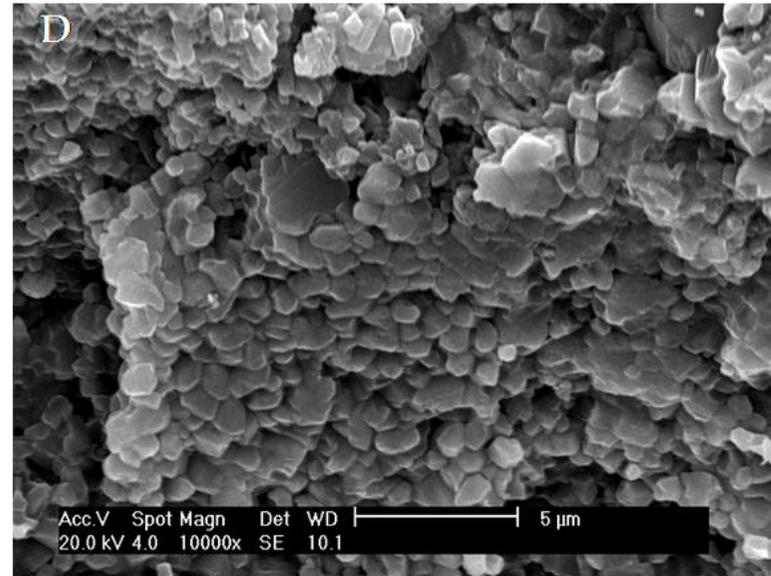
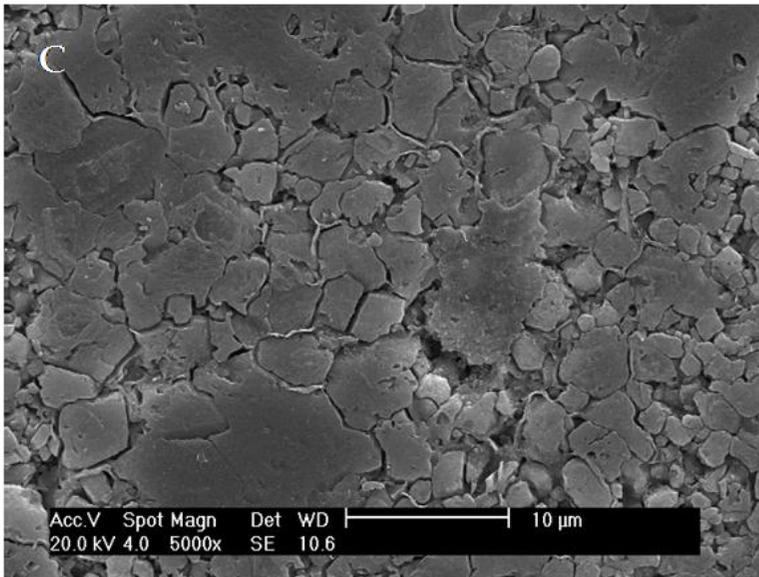
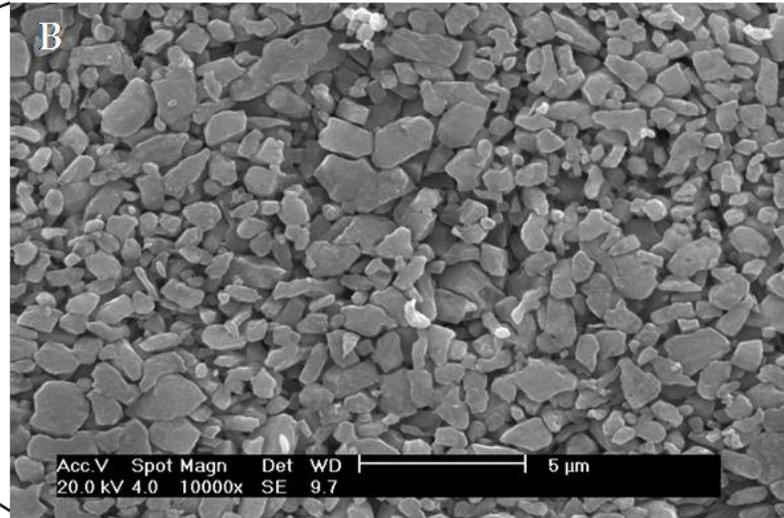
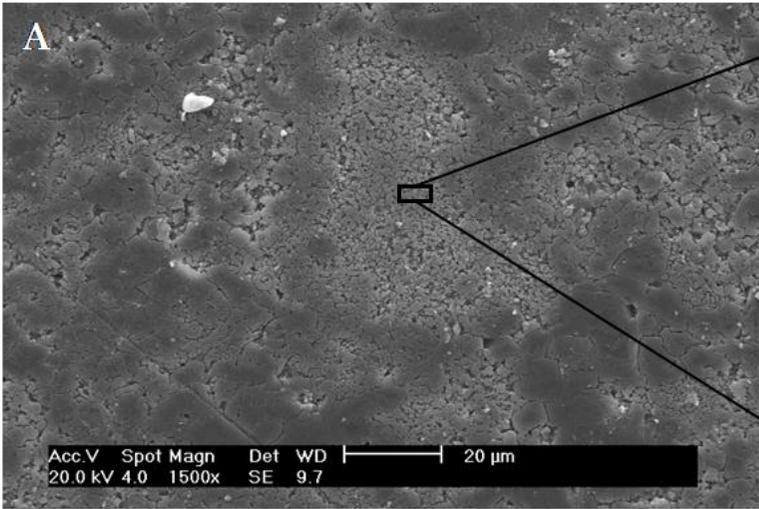


Figure 5.19: (A) Scanning electron micrograph showing deeper marine micritic matrix (from PK-3 microfacies, sample BL.38), (B) Higher magnification of scanning electron micrograph of the outer ramp carbonate matrix showing porous matrix, (C) SEM micrograph of deeper marine carbonate micritic matrix with very thin clay cages developed around the crystals (from PK-2 microfacies, sample BL.27), (D) Broken surface of deep marine carbonate micritic matrix showing small sized, subhedral crystals (from PK-2 microfacies , sample BL.48).

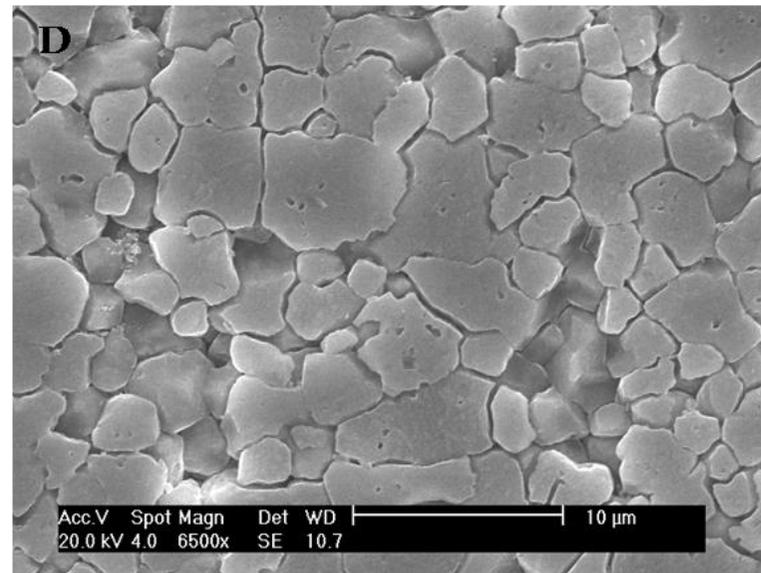
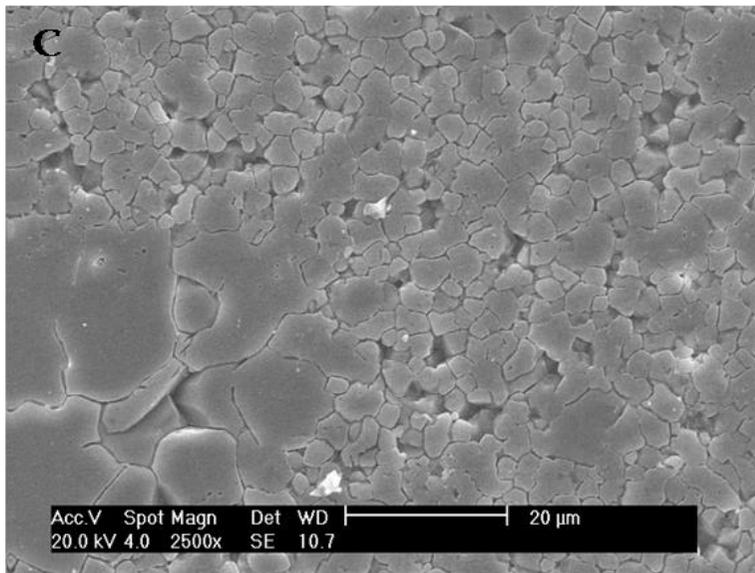
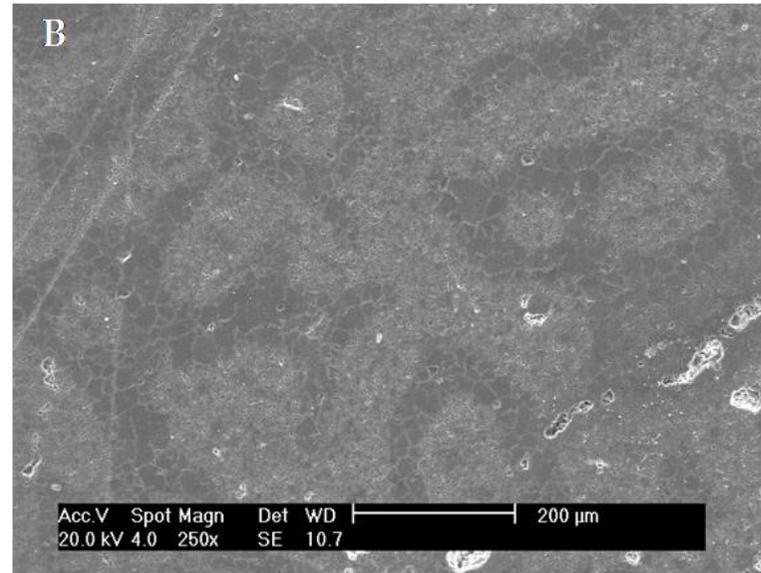
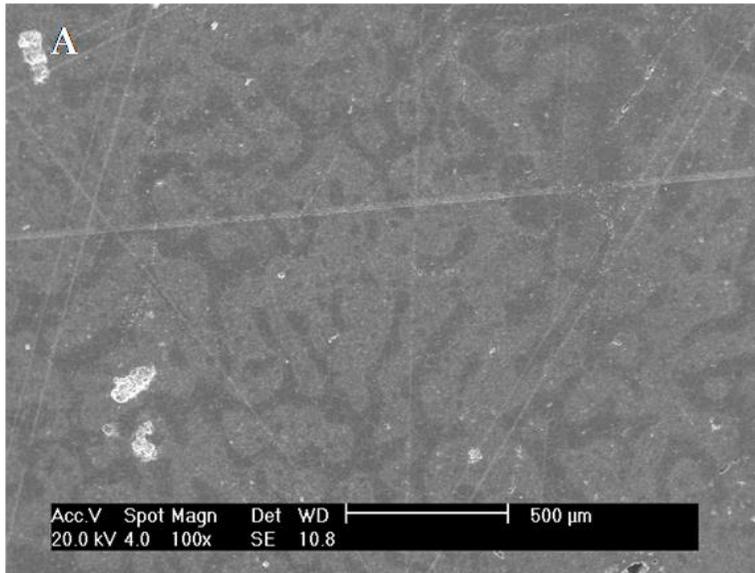


Figure 5.20: (A) Scanning electron micrograph of coral wall (from CB microfacies, sample BL.62). (B, C and D) Higher magnification of scanning electron micrograph of corals showing subhedral to anhedral crystal size with very few inclusions in their crystals.

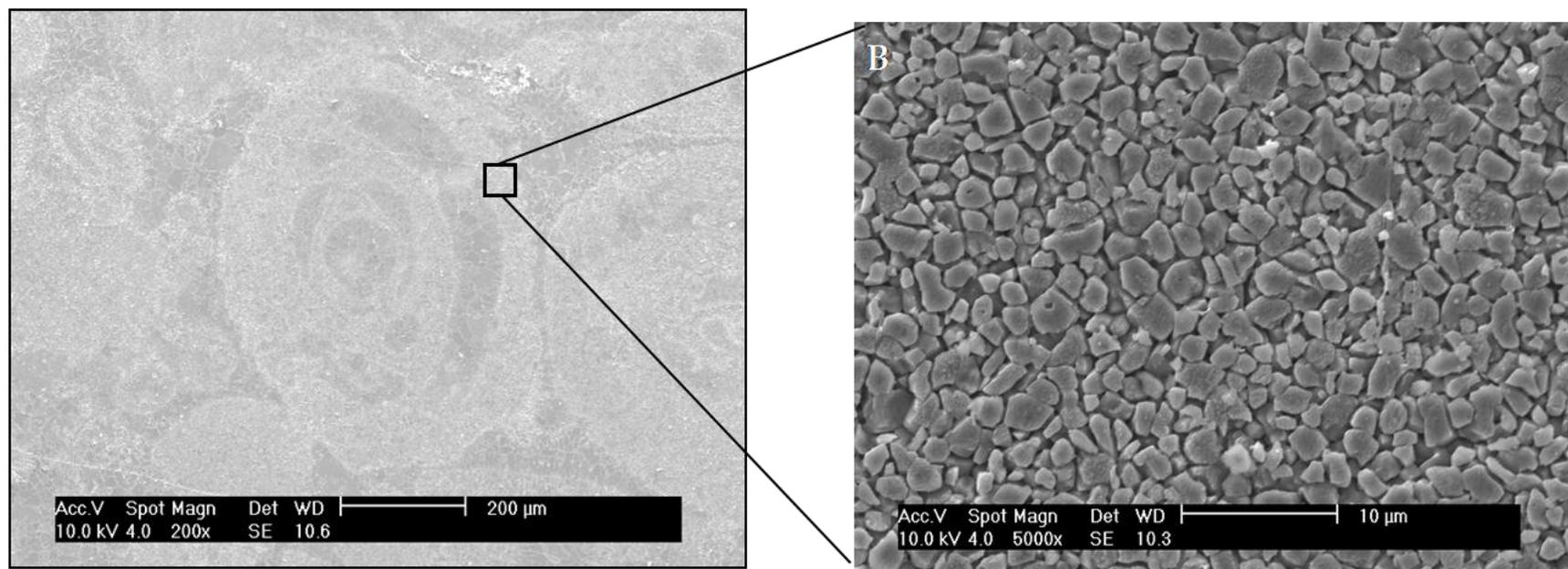


Figure 5.21: (A) Scanning electron micrograph of micritized miliolids (from SP-1 microfacies, sample DS.12). (B) Higher magnification of the micritic wall of miliolids showing very well sorted, subhedral crystals with no inclusions have noticed on the surface of the crystals.

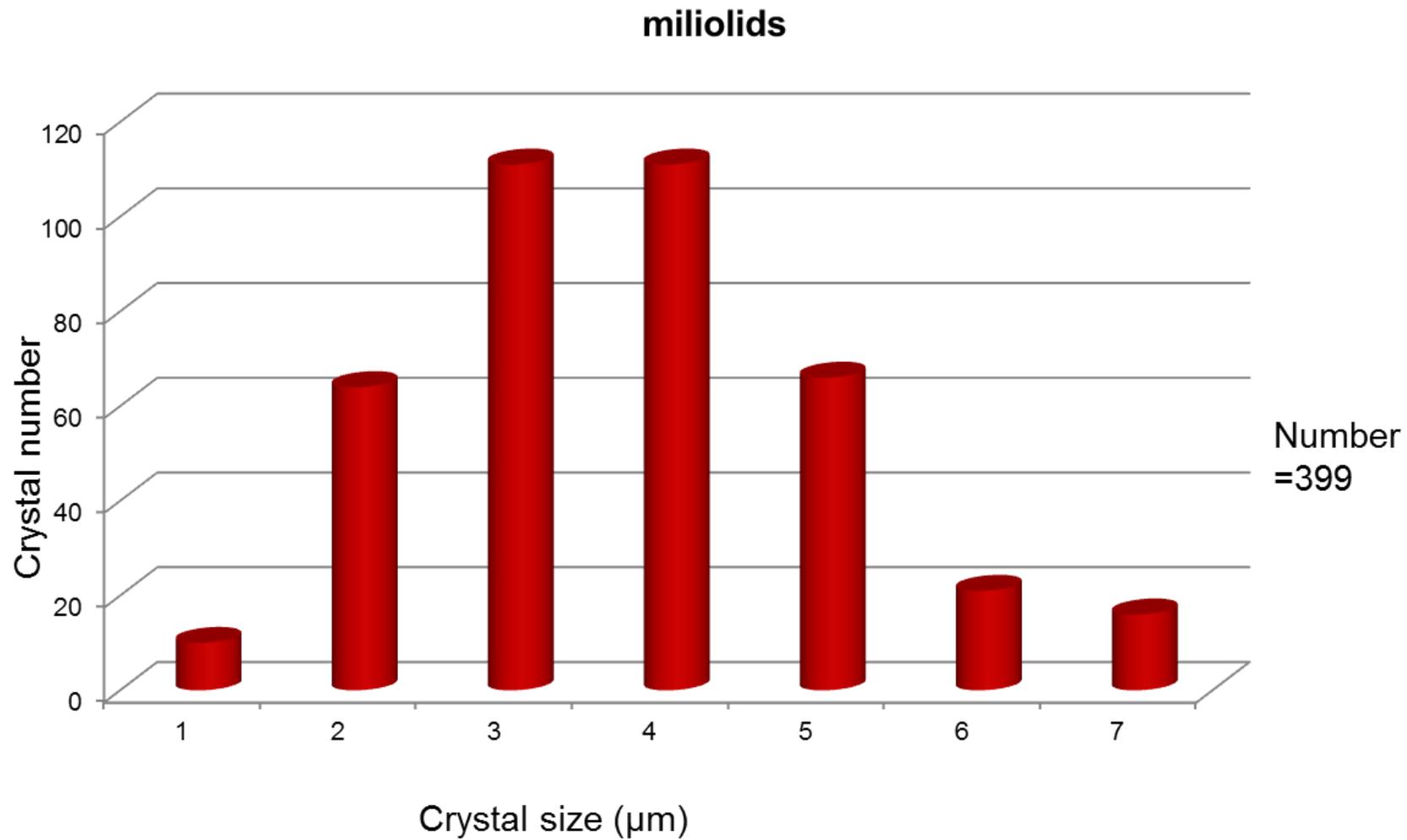


Figure 5.22: Histogram showing the crystal size of miliolids. 399 crystals were measured from ranges of microfacies.

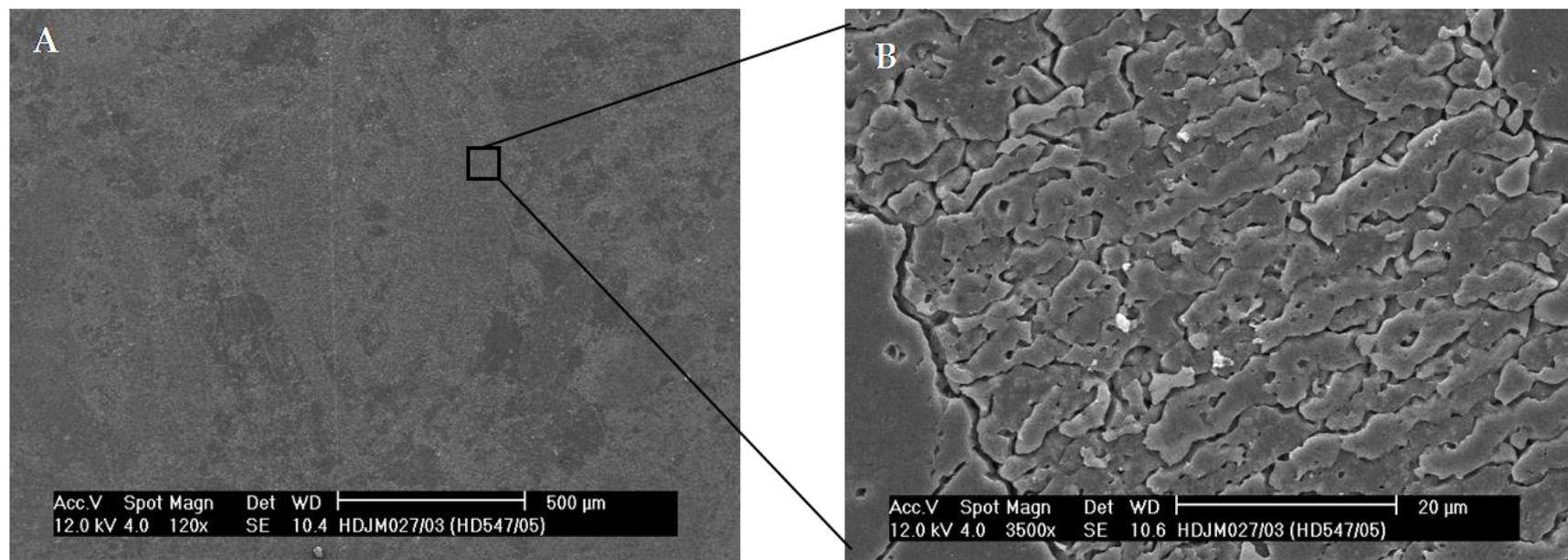


Figure 5.23: (A) Scanning electron micrograph of *Nummulites* (from NR-3 microfacies, sample BS.18). (B) Higher magnification of the wall of *Nummulites* showing elongate crystals with having inclusions on the surface of the crystals.

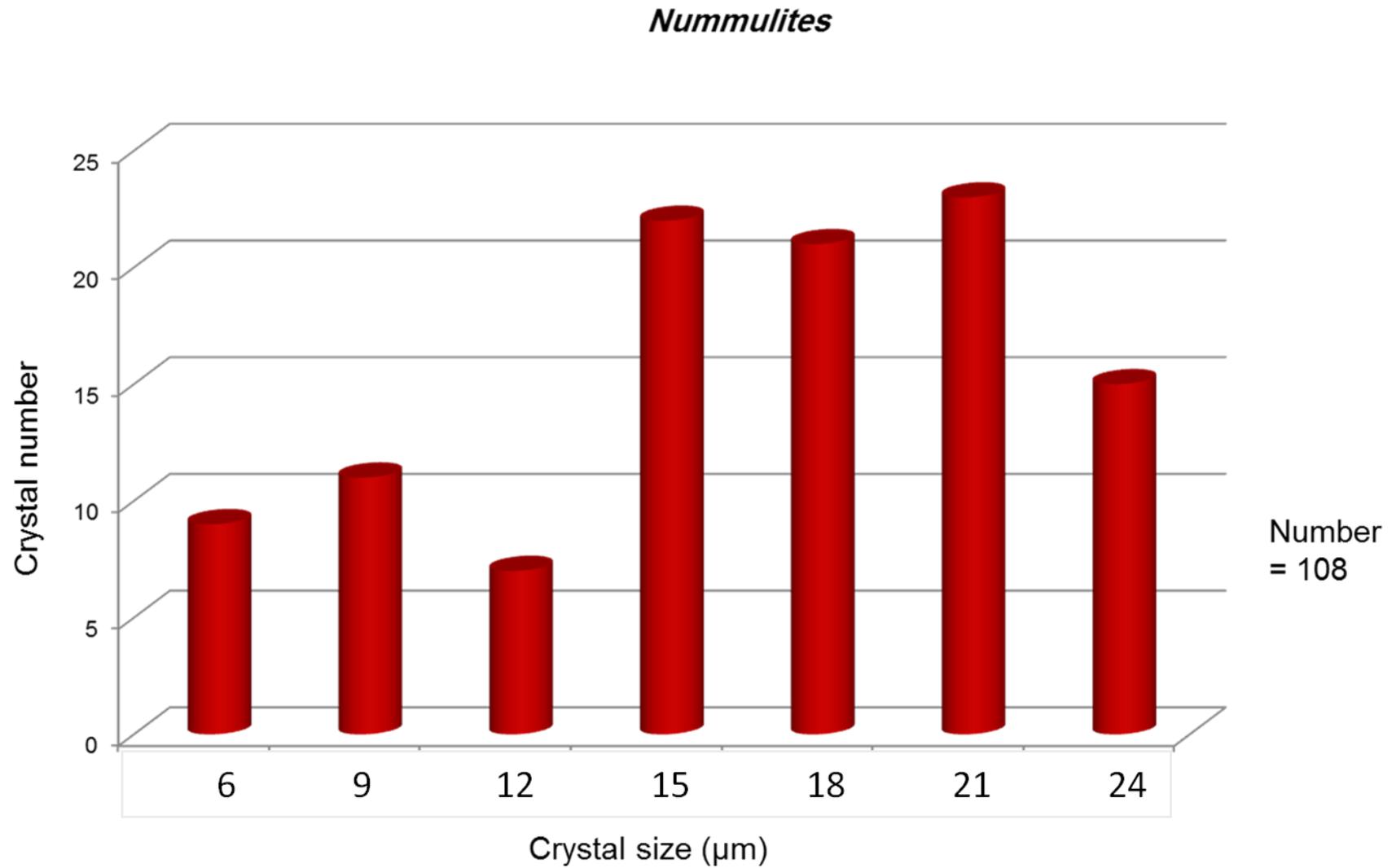


Figure 5.24: Histogram showing the crystal size of *Nummulites*. 108 crystals were measured from ranges of microfacies.

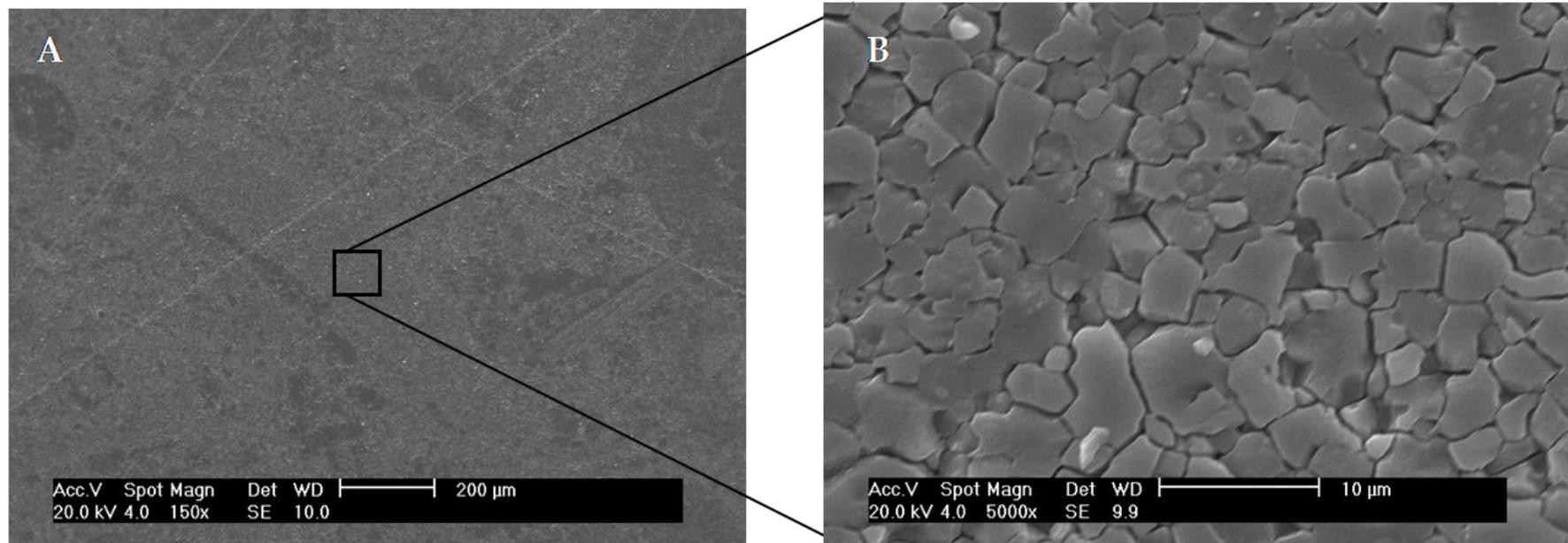


Figure 5.25: (A) Scanning electron micrograph of red algae (from NR-2 microfacies, sample AW.10), (B) Higher magnification of the micritized wall of red algae showing well sorted subhedral crystals with no inclusions were found on the surface of the crystals.

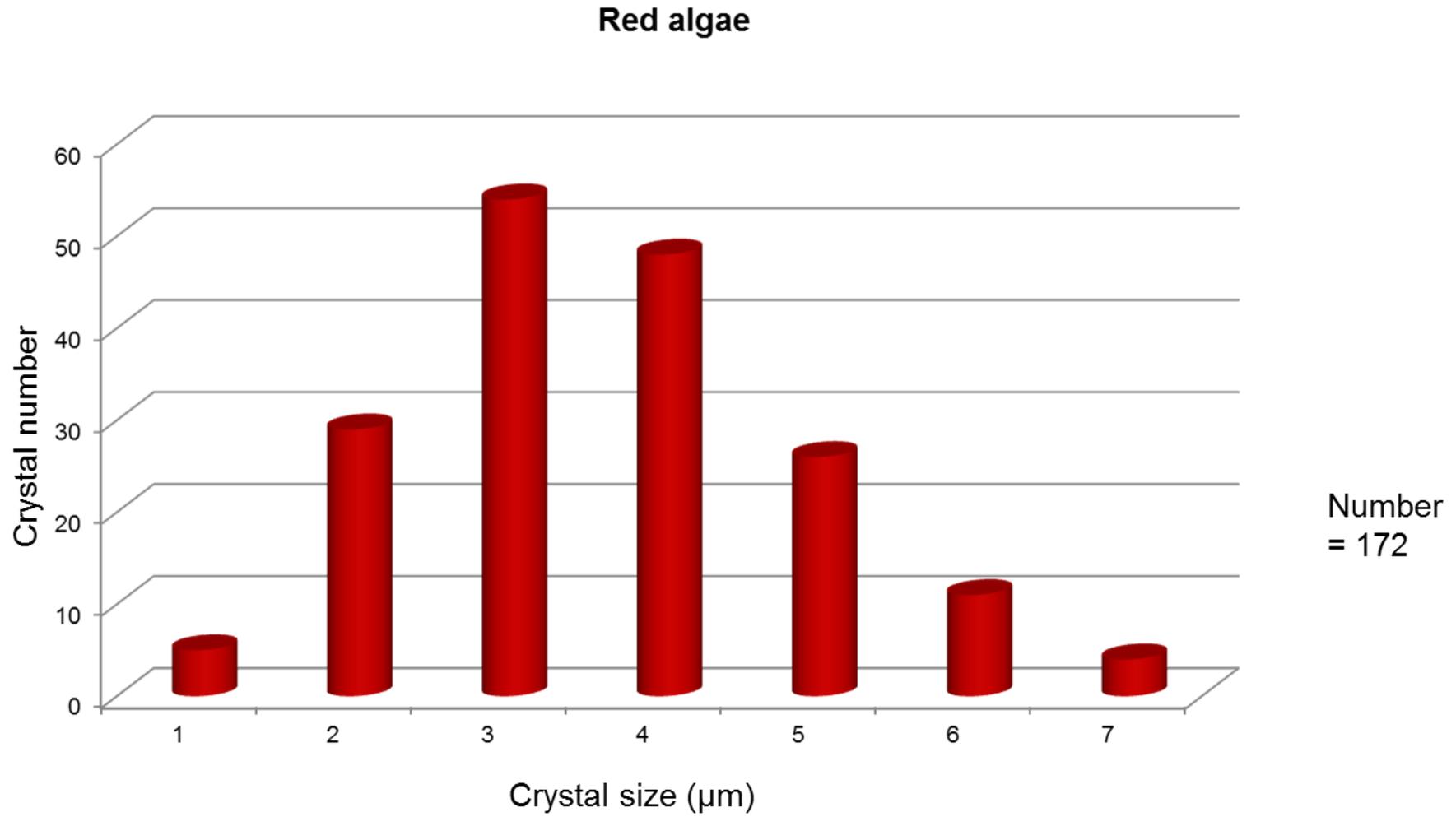


Figure 5.26: Histogram showing the crystal size of red algae. 172 crystals were measured from ranges of microfacies.

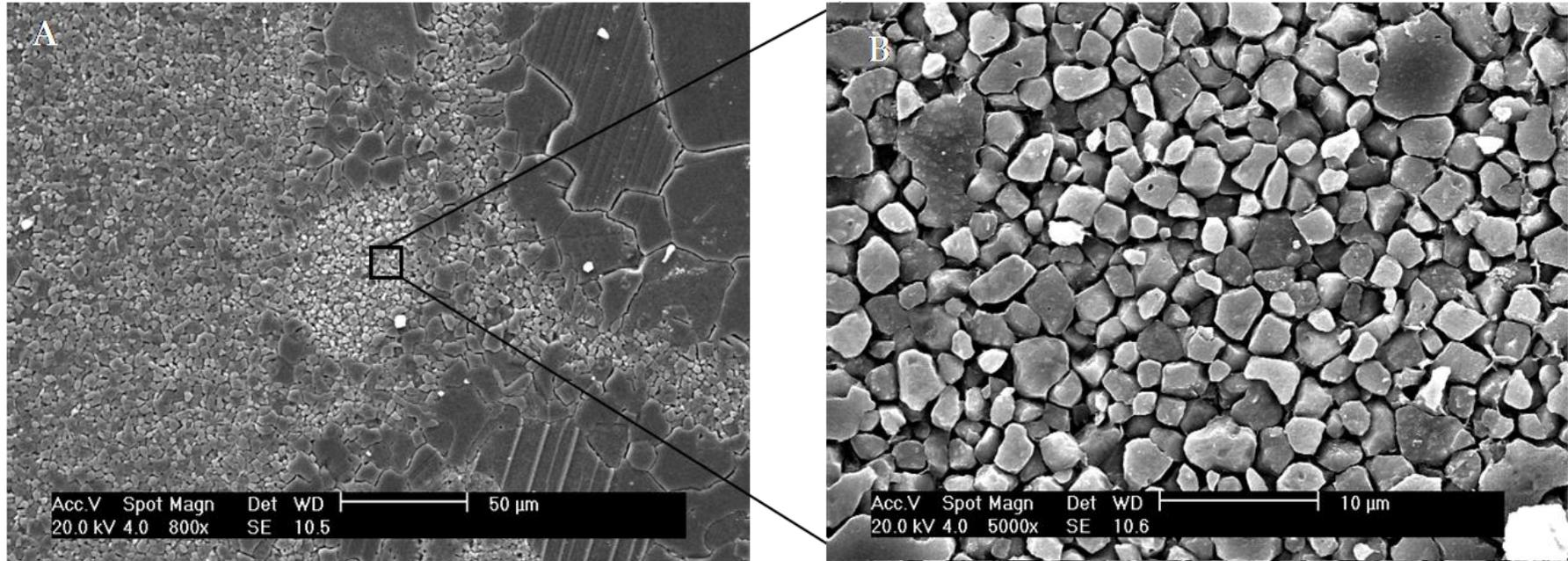


Figure 5.27: (A) Scanning electron micrograph of peloids (from SP-1 microfacies, sample AS.9), (B) Higher magnification of the peloids showing well sorted subhedral crystals with no inclusions were found on the surface of the crystals.

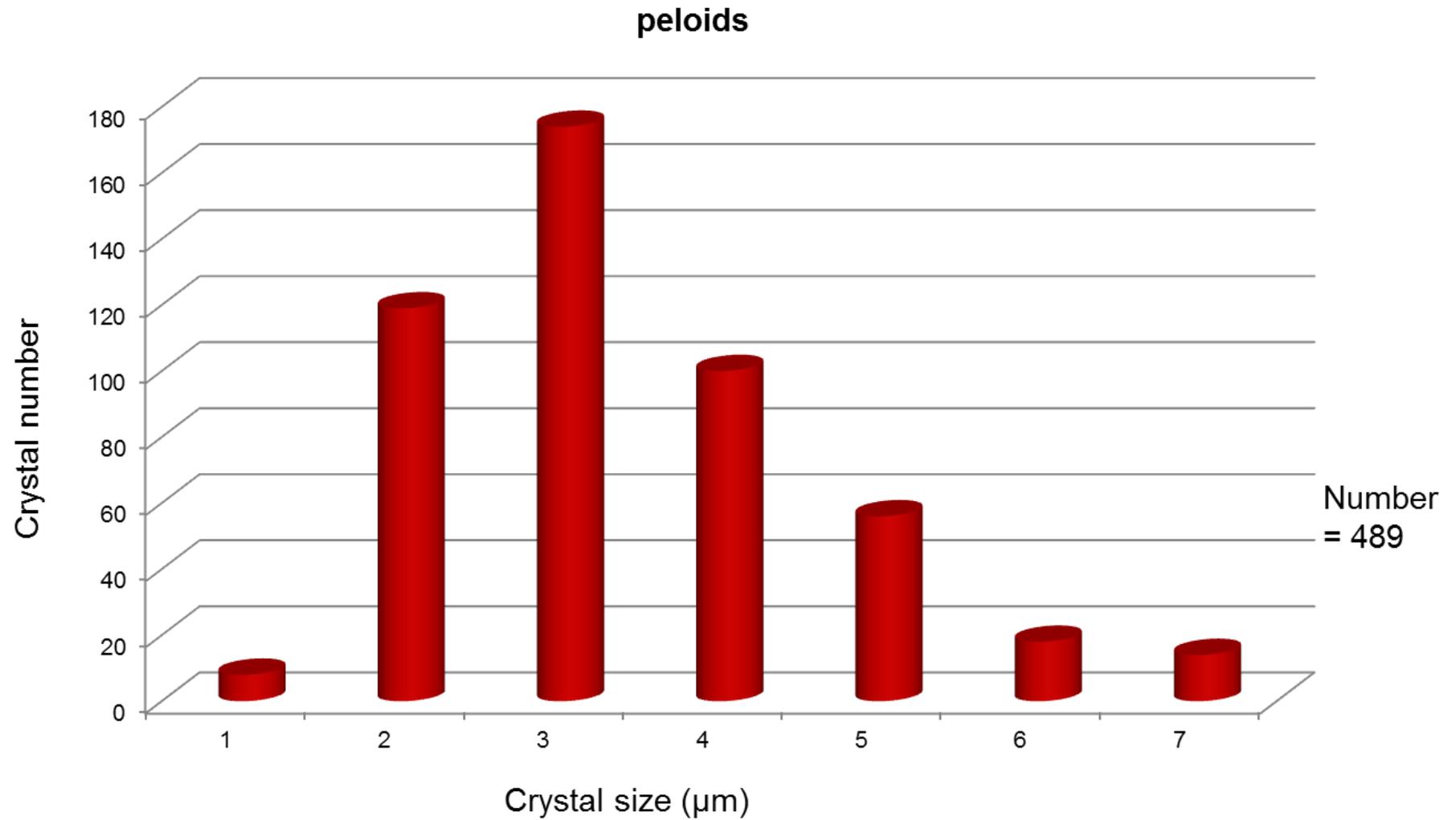


Figure 5.28: Histogram showing the crystal size of the peloids. 489 crystals were measured from ranges of microfacies.

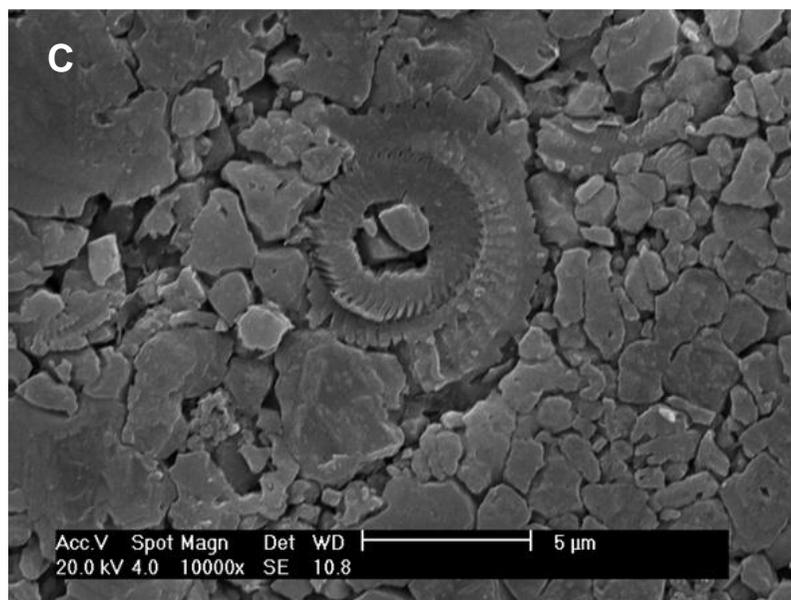
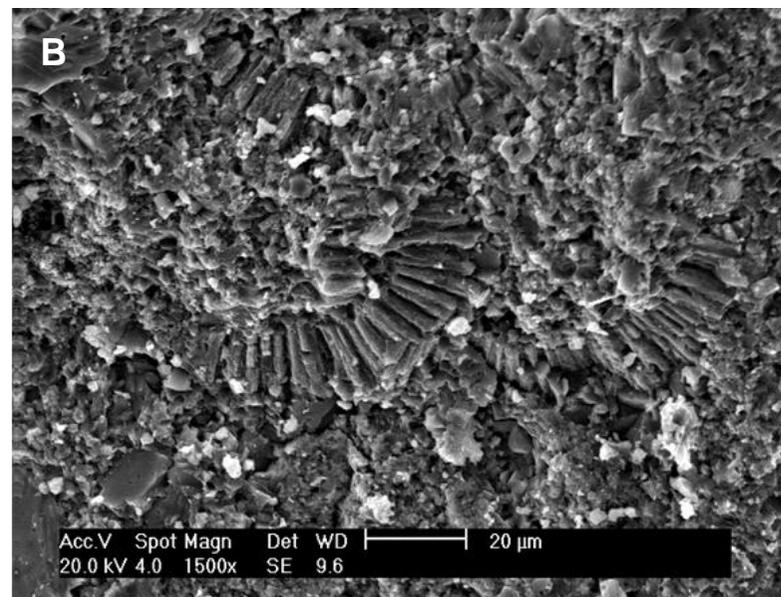
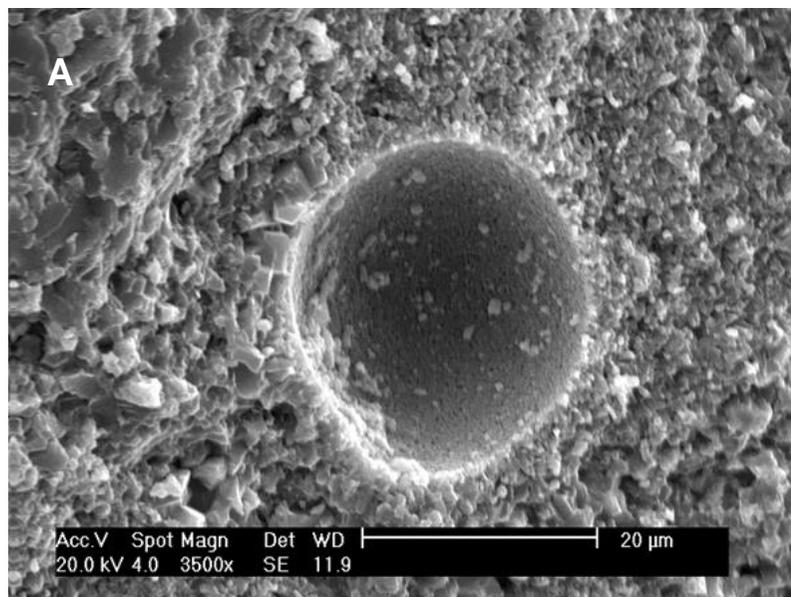


Figure 5.29: (A) Broken surface of deep marine limestone showing cast of planktonic foraminifera chamber (from PK-2 microfacies, sample BL.27), (B) Broken surface of deep marine limestone with a coccolith in the centre of the photo (from PK-2 microfacies, sample BL.27), (C) Scanning electron micrograph of polished-etched surface of deep marine limestone with present of coccolith (from PK-2 microfacies, sample BL.27).

#### **5.4.2.2 Pits:**

Pits, including different shapes and sizes, were observed in limited crystal types. Pitted crystals show distribution patterns that appear to be random. They are 2  $\mu\text{m}$  or more long and 1  $\mu\text{m}$  wide in elongated pits, and 1-2  $\mu\text{m}$  diameters in square/rhombic pits. Pits mostly occur inside crystals (i.e. intracrystalline) with very few pits occurring at crystal boundaries (see Figures 5.30a, b, c, d and 5.31a, b, c, d). In most cases, pits occur singularly, though they may also join to each other to form a cluster shape. Usually, pits are empty; rarely are filled with debris.

#### **5.4.2.3 Clay cages:**

Incomplete clay cages surround the micritic crystals in the matrix as well as microspheres and exhibit different thicknesses, ranging from 1-2  $\mu\text{m}$  up to 7  $\mu\text{m}$  (see Figure 5.32). They have straight slightly curvilinear boundaries. They are largely found in-between shallow marine micritic crystals such as MP-1, MP-2, PG, NR-2, SP-1, CB and RR microfacies and are rarely seen in deeper marine micrite only thin clay cages were found in PK-1 microfacies (for more details see Section 5.4.3). Some clay shards may be present in elongated pits within crystals which are slightly smaller than the pits (see Figure 5.30a, b, c, d).

From X-ray diffraction, the composition of clay cages can be determined. The presence of potassium (K), aluminium (Al), silica (Si), magnesium (Mg) and iron (Fe) suggests that the clay cages are illite (see Table 5.3).

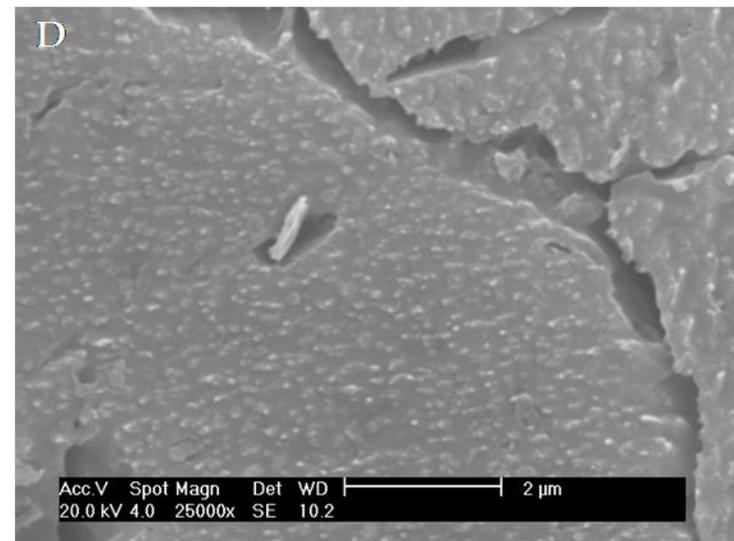
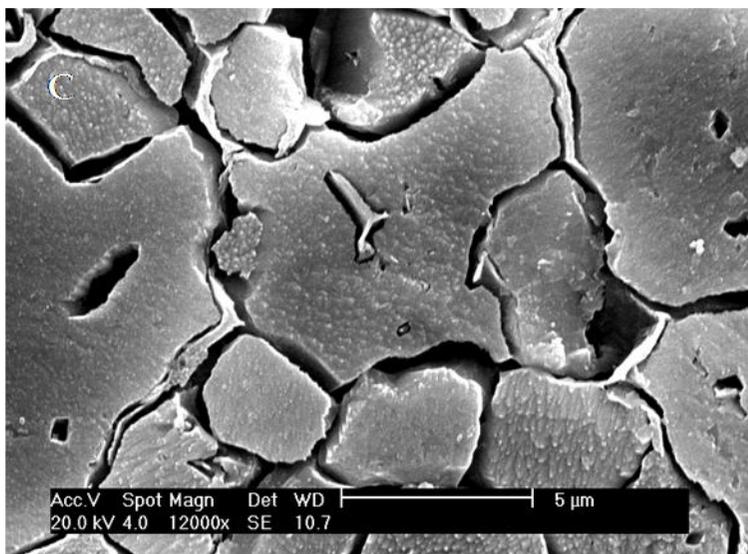
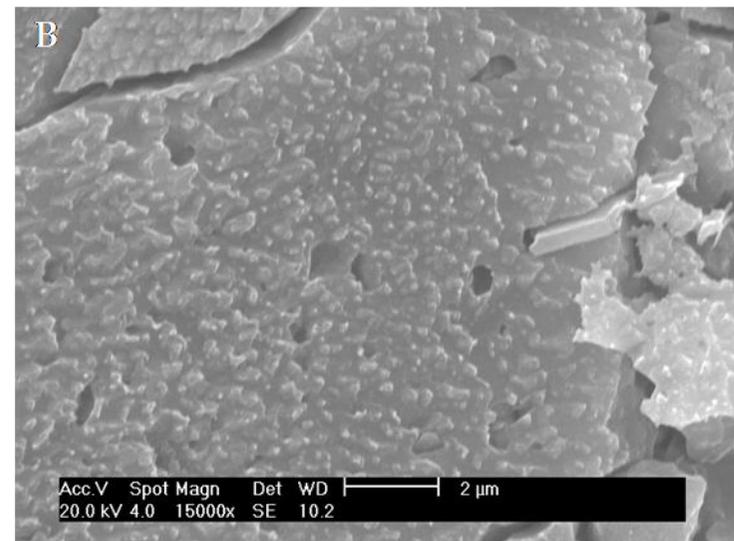
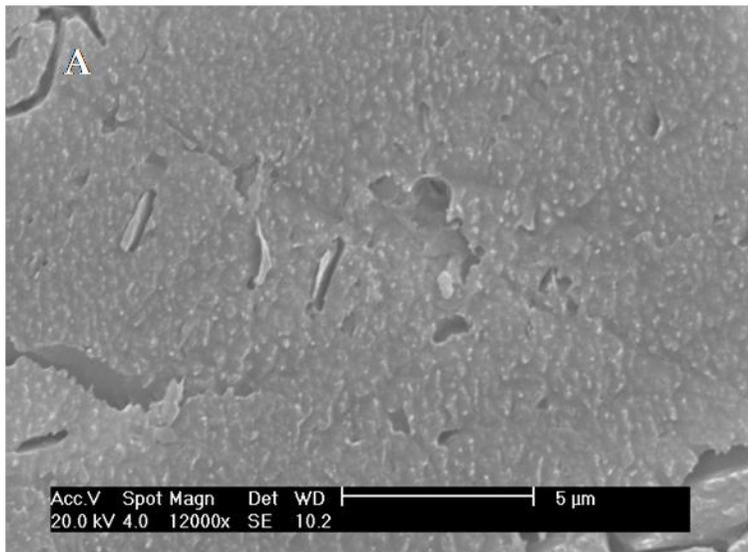


Figure 5.30: (A-D) Scanning electron micrograph of elongate pits inside crystals and at the boundary of the crystals mostly filled with clay shards. (A and B: from PG microfacies, sample AS.1; C: from MP-2 microfacies, sample DS.8; D: from MP-1 microfacies, sample CA.16).

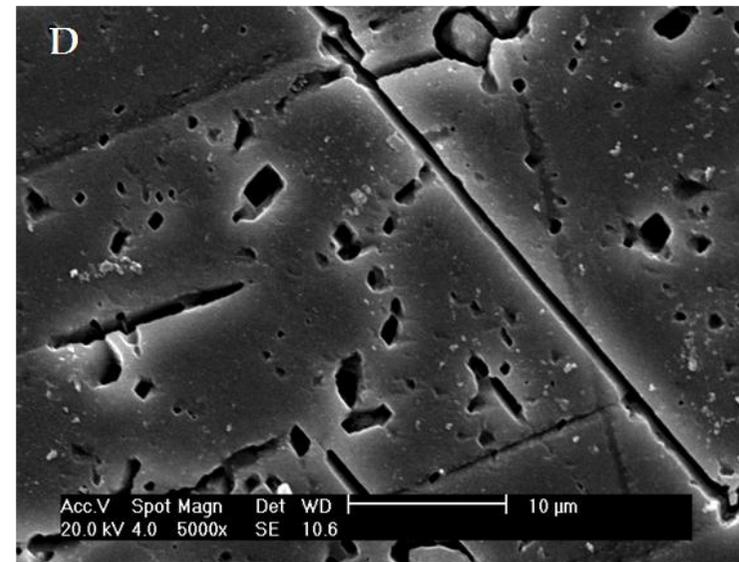
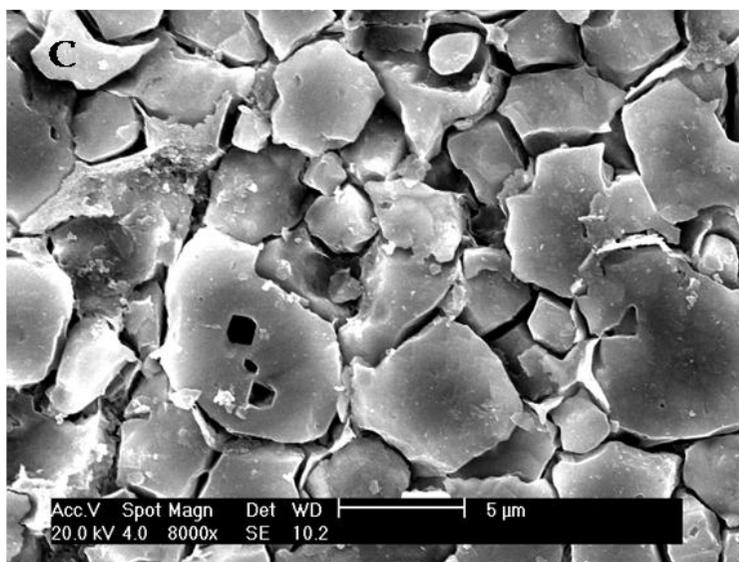
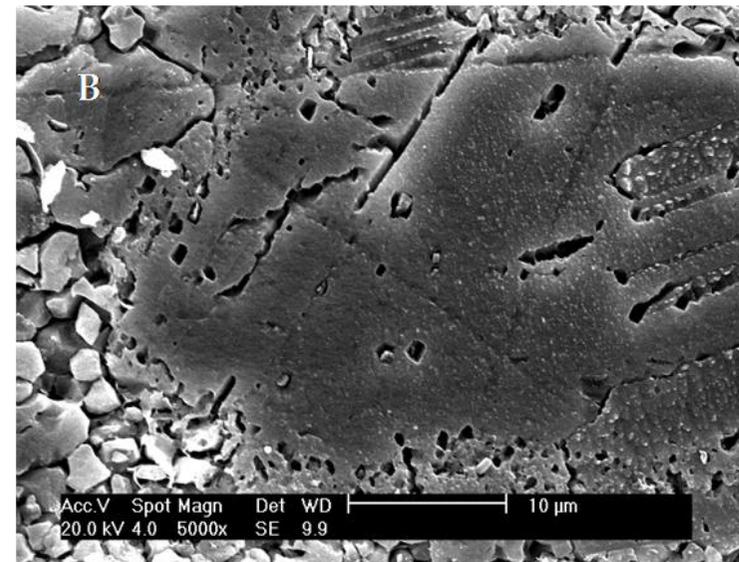
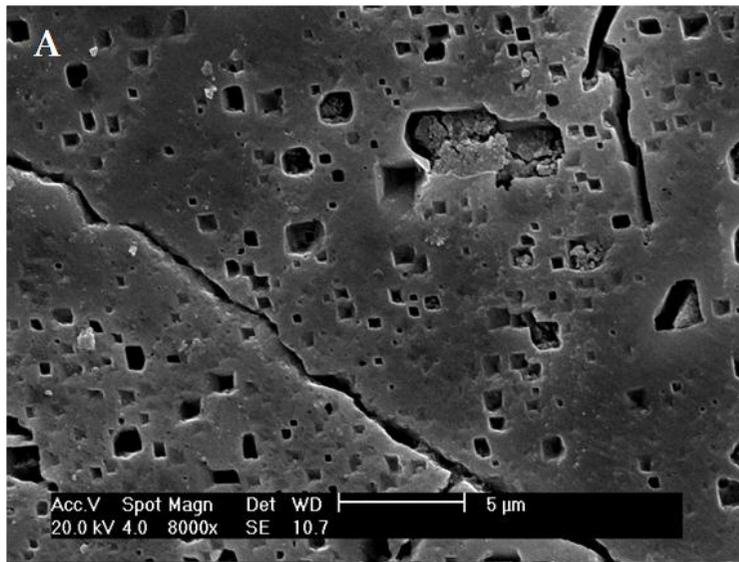


Figure 5.31: (A-D) Scanning electron micrograph of four sided pits on the surface of the crystals as singular and aggregates (A: from SP-2 microfacies, sample Z.27; B: from PG microfacies, sample AS.1; C: from MP-2 microfacies, sample AS.4; D: from SP-1 microfacies, sample AS.9).

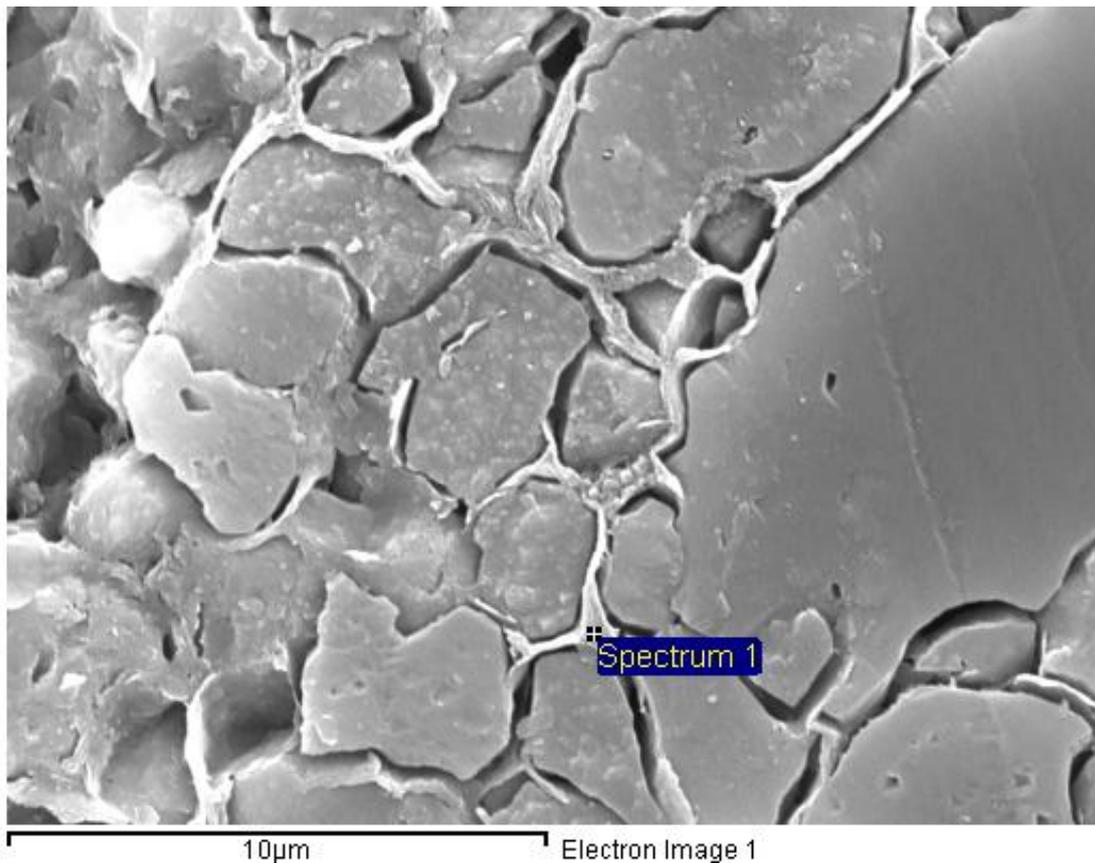


Figure 5.32: Scanning electron micrograph shows the micrites and microspars from shallow marine is surrounded by clay cages in different thickness (sample Z.17).

Element	Weight %	Atomic%	Comp%	Formula
Mg K	2.32	2.03	3.85	MgO
Al K	11.73	9.25	22.17	Al <sub>2</sub> O <sub>3</sub>
Si K	28.17	21.34	60.27	SiO <sub>2</sub>
K K	6.68	3.64	8.05	K <sub>2</sub> O
Fe K	4.40	1.68	5.66	FeO
O	46.69	62.07		
<b>Totals</b>	100.00			

Table 5.3: This table shows weight percentage of each element which present in the composition of clay.

#### **5.4.2.4 Microporosity:**

Microporosity is developed in many ancient micritic limestones, including significant petroleum reservoirs as in the Middle East and especially in Cretaceous reservoirs. Intercrystalline microporosity is usually composed of 5 to 10  $\mu\text{m}$  wide in diameter in which form more than 20% of porosity, and more than 1md of permeability, in addition to secondary microporosity have less than 64  $\mu\text{m}$  wide in diameter (Moshier, 1989). In carbonate rocks microporosity is sometimes referred to as 'chalky' porosity and samples exhibiting microporosity as chalky textured. Chalks are composed predominantly of pelagic nanno-fossils and microfossils deposited on deeper shelves and basins (Flügel, 2004).

The microporosity of micritic matrices from both shallow (MP-1, MP-2, SP-1, SP-2, CB, NR-1 and PG microfacies) and deeper (PK-1, PK-2 and PK-3 microfacies) settings has been examined using digital image analysis (Anselmetti et al., 1998) in order to determine the control of microporosity and its distribution and variation across ramp settings. In terms of matrix-dominated facies, two distinct rock fabrics and pore systems have been identified: (1) low microporosity inner-mid ramp (shallow marine) microfacies and (2) higher microporosity outer ramp/basinal (deep marine) microfacies. In the first pore system, the average pore sizes are 0.5  $\mu\text{m}$ , with a range from 0.2 up to 1  $\mu\text{m}$ . The average microporosity measured from digital image analysis is 8.7%. This range is clearly lesser than the one described by Moshier (1989); this may be because of these matrices were sourced from metastable precursors (more detail is in 5.4.3), and were recrystallized and replaced under meteoric waters, undergoing loss of primary porosity. While, in

the second pore system, the average pore sizes are 1.5  $\mu\text{m}$  ranges from 0.5 up to  $> 2 \mu\text{m}$ , with an average microporosity 13.1%. In the deeper water mud-rich facies have more porosity than shallower ones. The latter, being composed of more stable low-Mg calcite underwent less recrystallization and retained some primary porosity; in this respect they have behaved like chalks.

Microporosity has been widely studied in many ancient micrite-rich limestones, including a number of recent studies (Lambert et al. (2006); Richard et al. (2007); Munnecke et al. (2008); Fournier and Borgomano (2009); da Silva et al. (2009); Volery et al. (2009); Volery et al. (2010a, b); Brigaud et al. (2010); Volery et al. (2011); Deville de Periere et al. (2011)). It may occur as both primary intercrystalline and secondary microporosity during the early and late stages of diagenesis. Early cementation is a most important mechanism for porosity reduction in carbonate micrite (Lasemi et al., 1990), and during stabilization, metastable minerals can release cement and cause precipitation in adjacent micropores; the growth of cement in the micropore systems of fine-grained sediments leads to a decrease in microporosity. If cementation ceases shortly after stabilization, microporosity can be retained to form a porous micro-rhombic micrite texture. In contrast, in the case of complete cementation, and occluding microporosity, a mosaic texture of anhedral micrite will be produced.

### 5.4.3 Interpretation:

From the precursor mineralogical composition of the carbonate fraction (aragonite, high-Mg calcite and low-Mg calcite) information can be derived about palaeo-environmental conditions, e.g. extensive aragonite production usually takes place in shallow water carbonate factories, while pelagic carbonate production is dominated by calcite organisms (Munnecke and Westphal, 2005).

Two distinct types of precursor mineralogy of micrite were interpreted by Lasemi and Sandberg (1983, 1984, 1993), from the Pleistocene micrites of south Florida and the Bahamas, based on the presence and absence of aragonite relics and pits with strontium levels. An abundance of aragonite relics and pits in the polished lightly etched surfaces of microspar with a relatively high strontium level ( $\approx 800$  ppm) are referred to as aragonite dominated precursors (ADPs); whereas calcite dominated precursors (CDPs) are characterized by an absence of aragonite relics and pits in micrite-dominated limestones with a low average strontium content ( $\approx 400$  ppm).

In terms of evaluating the aragonite component of any precursor, it was noticed that most of the micrite textures examined were lacking in relics with very few pits (no pits were found in deep marine micrite); this raises the possibility that the micrite matrix may not have formed during aragonite sea intervals (Figure 5.33 illustrates the trends of biotic and abiotic marine precipitates during calcite and aragonite sea intervals). In contrast to aragonite constituents, the process of stabilization of high-Mg calcite alters with very small changes in the microfabric texture. The effects of magnesium loss and possible microdolomite generation on the resulting calcite microfabric

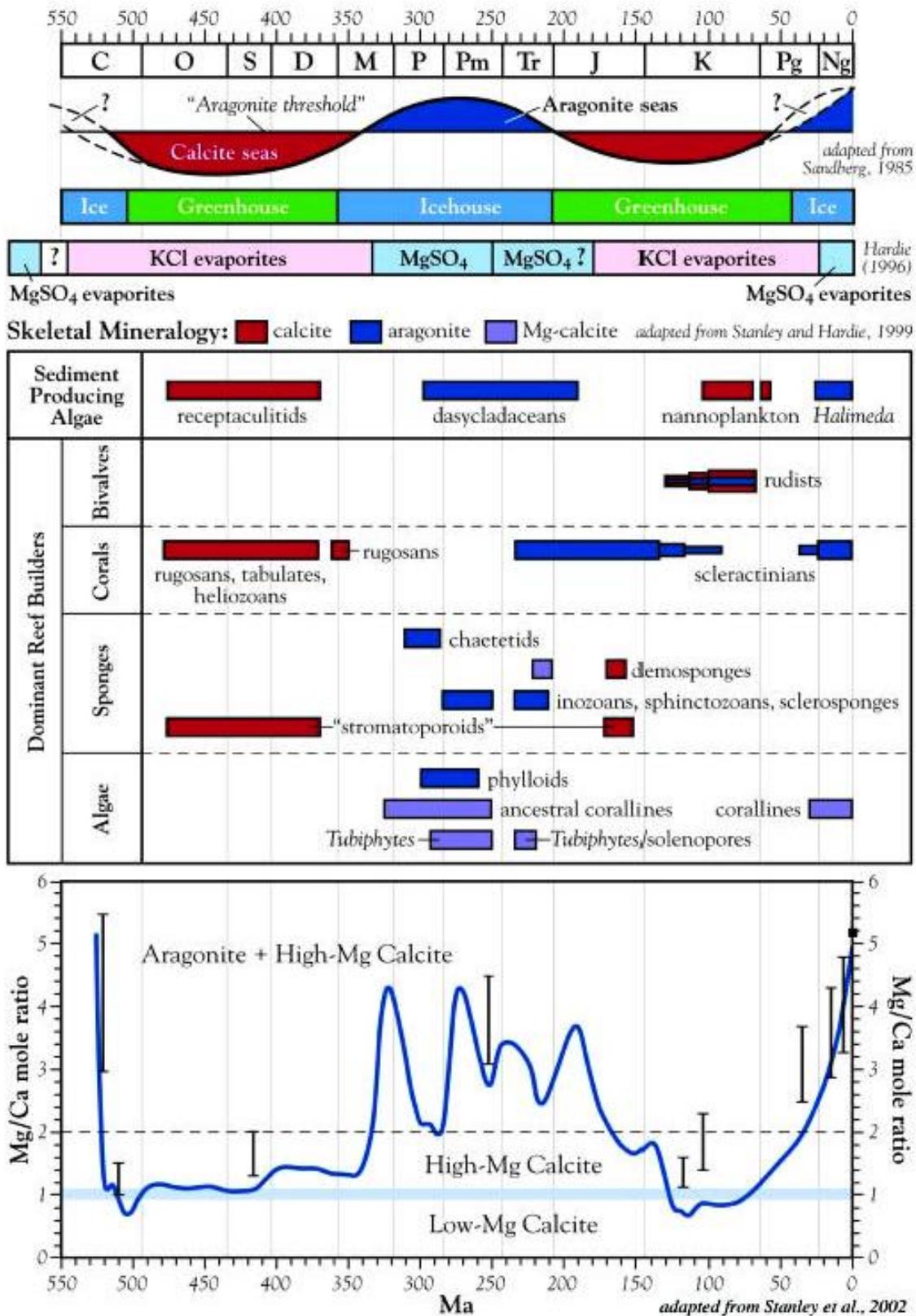


Figure 5.33: Phanerozoic trends of biotic and abiotic marine precipitates. (Sandberg, 1985, Hardie, 1996; Stanley and Hardie, 1999; Stanley et al. 2002; compilation by Montanez, 2002).

are not readily identifiable because there is no clear change in the texture of the matrix. The diagenetic effects of the alteration of high-Mg calcite into low-Mg calcite and microdolomite may occur during the earliest stages of diagenesis (Lowenstam, 1961; Winland, 1968; Towe and Hemleben, 1976; Munnecke et al., 1997; Westphal, 1998). A very good explanation of the process of stabilization of high-Mg calcite, from miliolids of the Eocene age to low-Mg calcite, is given by Towe and Hemleben (1976); miliolids had a magnesium content of about one-third of unaltered modern miliolids when tested, without any significant change in textural modification, even at the SEM level.

A pitted texture with both elongated and square shapes was found in several micrite and microspar crystals, especially in the shallow marine carbonates. The presence of clay shards within the crystals raises the possibility that elongated pits are not long sections of aragonite relics. Another possibility for presence of square/rhombic pits is that they might be casts of microdolomite which were formed during the alteration of high-Mg calcite to low-Mg calcite, but traces of microdolomite were not found inside the square pits, another possibility is the pits might reflect pyrite crystals that have been plucked out of the surface of the crystals during the preparation (polishing and etching) of the sample.

Based on petrographic observations, different crystal shapes, sizes and textures of microspars were recognized. Microspars may originate from different sources; on the one hand, microspars represent the primary cement formed in the early stages of diagenesis, as discussed in the case studies of Pliocene carbonates from the Bahamas and Silurian limestone from Gotland

(Munnecke et al., 1997). On the other hand, microspar may fill secondary porosity when sand-sized grains may have dissolved, leaving an open space into which microspar is precipitated. Microspars that occur in patches may be interpreted as cement which precipitated into secondary pore spaces as cavities formed by solution (Steinen, 1978). Alternatively, microspars can form from a previously lithified micritic matrix by recrystallization and aggrading neomorphism, during mineralogical stabilization, through high-Mg calcite replacement by low-Mg calcite (for more detail see 5.3.1 in aggrading neomorphism) (Folk, 1959, 1965, 1974). This study supports Folk's (1959, 1965, 1974) opinion because of these facts: first of all, the non-uniform distribution thickness of clay cages around microspars, the partial remnants of clay within the crystals and displaying clay are evidence for the displacive growth of calcite cement as microspar crystals during the stabilization of metastable minerals. The pushing away of clay matrix by micritic crystals is thought to be because of the active force of crystal growth (Folk, 1965; Bathurst, 1975). This feature can easily be found in shallow marine carbonate mud, because the origin of this matrix may source from high-Mg calcite bioclasts. However, clay cages are rarely found in deeper marine carbonate mud, as they may originally have been formed from a low-Mg calcite source such as planktonic forams and coccoliths. Secondly, microporosity is not uniformly distributed across matrix-rich ramp carbonates, reflecting different origins and precursor mineralogy; the shallow marine carbonates preserve less microporosity than outer ramp/basinal facies, this also supports neomorphism and recrystallization causing loss of primary microporosity,

while in deeper marine micrite the evidence for recrystallization is less common and this retains some primary microporosity.

This illustrates the different sources of “mud” across a ramp; inner-mid ramp muds had a hemi-pelagic source and could have been mostly sourced from high-Mg calcite benthic foraminifera and red algae, with little possibly of partial aragonite dominating; in contrast to the outer ramp muds “chalks”, were sourced from plankton, are largely composed of low-Mg calcite, as they are mineralogically stable. During burial, diagenesis chalks are formed by a combination of mechanical and chemical compaction and cementation (Borre and Fabricius, 1998). The mechanism of chalk cementation is due to pressure solution and the reprecipitation of cement. Chalk diagenesis is related to two main factors: maximum depth of burial and pore-water chemistry (Scholle, 1977). Diagenetic mud produced by early aragonite dissolution and reprecipitation (diagenetic bedding) was not an important component of the depositional setting of this case study.

However, mud grade carbonate can be produced from several sources, such as: (1) Disintegration of calcareous algae, such as halimedaceans and especially dasycladaceans which would have had an aragonite composition and red algae which have a high-Mg calcite composition. (2) Microbial precipitates (automicrite) including peloidal cements in which most likely have former high-Mg calcite precursor. (3) Abrasion of carbonate grains may source from both aragonitic and high-Mg calcite precursors. (4) Fish excreta; Perry et al. (2011) concluded that tropical marine fish can produce and excrete various forms of precipitated non-skeletal calcium carbonate from their guts (low-Mg calcite, high-Mg calcite and aragonite), but they are mostly

composed of very fine-grained (more than 2  $\mu\text{m}$ ) high-Mg calcite crystals which dominate their excretory product. (5) Direct precipitation of aragonite and possibly calcite during calcite sea intervals (Figure 5.33). (6) Disintegration of planktons which would have had a low-Mg calcite composition. (7) Diagenetic precipitates, during shallow burial low-Mg calcite can produce diagenetic bedding. But the exact origin would be difficult to ascertain after diagenesis.

### **5.5 Oxygen-Carbon stable isotopes:**

Stable isotope tests were carried out for twenty three samples for only shallow and deeper marine micritic matrices; it was hard to differentiate different types of forams from other component such as peloids during drilling in polished limestone blocks. The oxygen isotope composition for both shallow and deeper marine matrices have negative values; the analysed data show very light value ranges between -7.6 to -9.2 PDB for shallow marine matrices and less light values -2.1 to -3.6 PDB for deeper marine matrices. Meanwhile, carbon isotopes have a wider range from positive to negative values; the deeper marine micrites have positive value ranges between +0.78 to +3.5, and the shallow marine micrites have negative value ranges between -1.4 to -7.4 (see Table 5.4). The results of the carbon and oxygen isotopic analyses of different lithology are shown in Figure 5.34.

From the results that the Late Eocene to Oligocene shallow marine micrite matrices for both oxygen and carbon isotopic values are very light, indicating likely meteoric diagenetic water. The isotopic composition of these matrices is

controlled to a large extent by characteristic light isotopic composition of meteoric water.

In the rock record, the low oxygen isotopic values were indicators of fresh water origin (Hays and Grossman, 1991).

Sample identity	Microfacies	18/16-O (Vs.PDB)	13/12-C (Vs. PDB)	
Deep marine matrix	BL.27	PK-2	-3.0206085	0.786804
	BL.31	PK-3	-2.3811194	2.0439116
	BL.35	PK-3	-2.413751	1.8389546
	BL.37	PK-3	-2.1639318	1.8966689
	AW.16	PK-1	-2.8437046	1.7289138
	SD.24	PK-2	-3.667677	3.5669417
	BL.39	PK-3	-3.289094	1.3741073
	BL.41	PK-2	-3.0207733	1.8443066
	BL.46	PK-2	-3.396895	1.912214
	BL.48	PK-2	-2.9677478	1.4478293
Shallow marine matrix	AS.5	MP-2	-7.687991	-6.7451259
	AS.9	SP-1	-8.3793748	-7.3975968
	Z.17	MP-1	-7.8437907	-6.4317943
	BL.61	CB	-9.2899881	-2.2728702
	SG.26	SP-2	-9.2854805	-1.9666053
	BL.64	CB	-8.758654	-2.3461605
	BL.66	CB	-8.5406245	-2.5271981
	BS.20	SP-3	-8.4341211	-1.4115344
	BS.23	SP-2	-7.8364746	-6.3853651
	DS.8	MP-2	-7.671361	-6.1192155
	AW10	NR-2	-8.9679238	-4.9938934
	AW13	NR-2	-7.7495464	-5.3352904
	CA.5	PG	-7.6545176	-6.4673424



values: (1) light oxygen isotopic values (-2.0 to -3.5 PDB) in deeper marine carbonate micrite indicate limited alteration; and (2) very light oxygen isotopic values (-7.5 to -9.5 PDB) in shallower marine carbonate micrite indicate more diagenetic alteration. Therefore, this depletion in oxygen isotopes is caused by more mineralogical stabilization in the shallow marine facies.

### **5.6 Trace elements analysis:**

The Sr value in inner-mid ramp (shallow marine) facies ranges from 188 to 311 ppm, it falls below the value (400 ppm) of calcite dominated precursor (CDPs) which was described by Lasemi and Sandberg (1984; 1993), while the Mn value has a relatively high range of between 90 to 223 ppm. The Sr value decreases with the uptake of Mn as a result of mineralogical stabilization and neomorphism during alteration from high-Mg calcite to low-Mg calcite (Mazzullo and Bischoff, 1992; Webb et al., 2009) (see Figure 5.35). Several studies have attributed a low Sr concentration to the influence of meteoric water (Wu and Wu, 1996) and suggested that the micritic matrix was formed from high-Mg calcite mud (Wright et al., 1997). In contrast, outer ramp micrite (deeper marine) facies had an unexpectedly high Sr value range of between 497 to 806 ppm and very low Mn of between 11 to 32 ppm, indicating that these limestones did not undergo significant diagenesis. The upper value for Sr is closer to the values for what are regarded as aragonite dominated precursors (ADPs), which were described by Lasemi and Sandberg (1984; 1993); but this is in contrast to the textural evidence that supports an origin from a more stable probably low-Mg calcite precursor (see Figure 5.36). This relatively high Sr value may be interpreted as there being some other Sr-

bearing mineral present, such as celestite (strontium sulphate), that was leached during the dissolution procedure (Wheeley, 2006).

Moreover trace elements were carried out for few bioclasts such as, miliolids, *Nummulites* and red algae as well as for peloids. The Sr value for all of them is not more than (400 ppm) calcite dominated precursor (CDPs) range; they range between 156-257ppm, 179-347ppm, 113-237ppm and 148-347ppm respectively (see Table 5.5). These ranges are approximately similar to the shallow marine matrix range, this may illustrate that the source of mud in shallow marine environment could have been mostly sourced from benthic foraminifera and red algae.

In summary, trace elements and oxygen-carbon isotopic values of Kirkuk Group supports the SEM studies that the near shore facies underwent more alteration, possibly in meteoric fluids, in contrast to the basinal facies which either retained a considerable portion of the unaltered original low-Mg calcitic component or sourced somewhat from modified marine parentage.

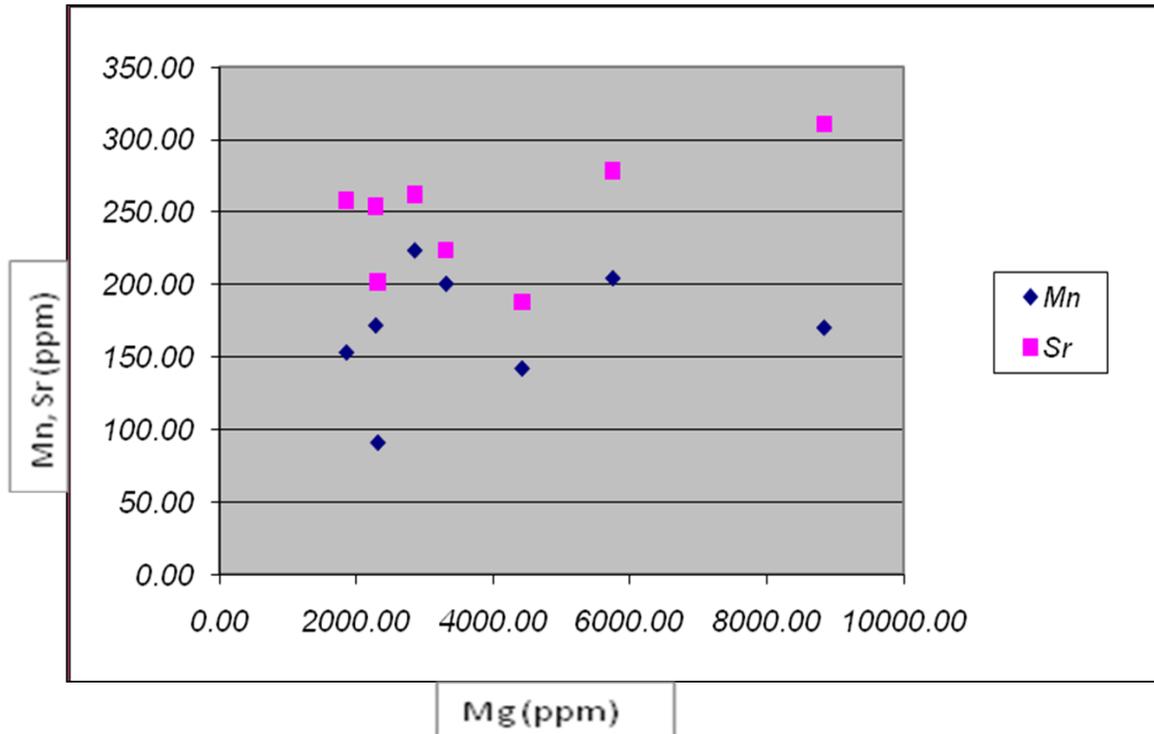


Figure 5.35: Inner-mid ramp facies trace elements (Mn and Sr versus Mg).

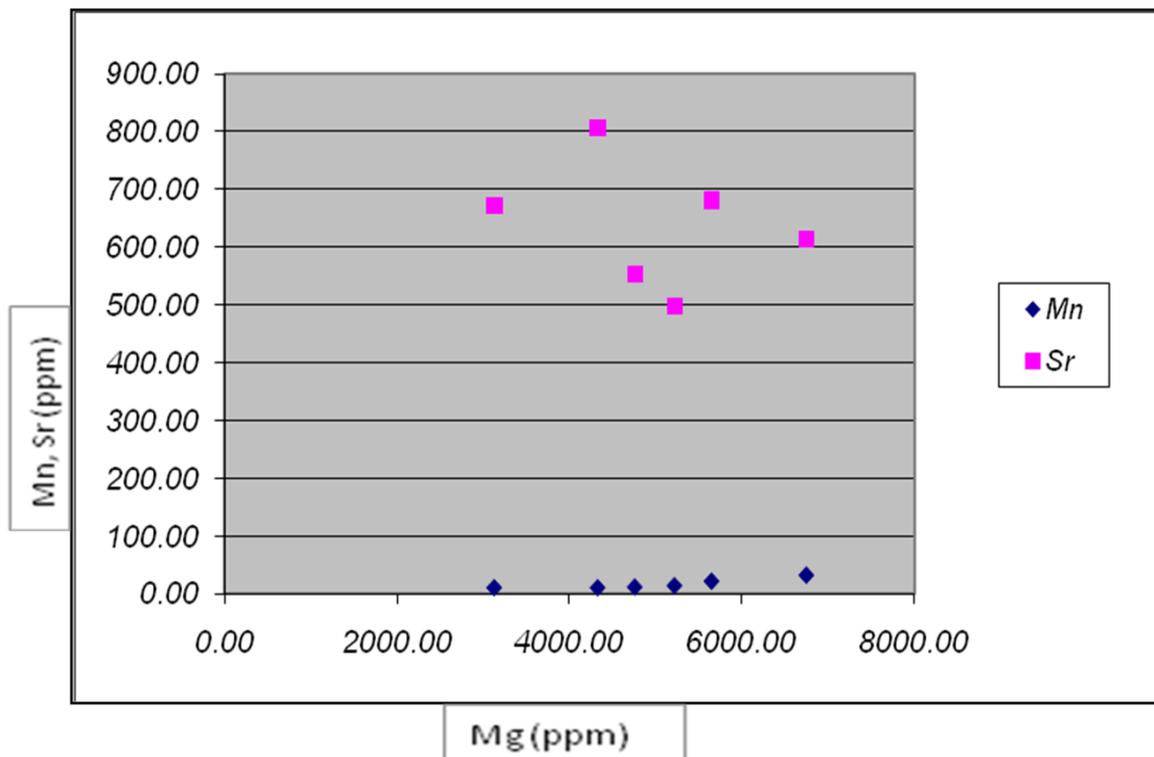


Figure 5.36: Outer ramp-basinal facies trace elements (Mn and Sr versus Mg).

	Region	<sup>88</sup> Sr (ppm)
<b>Miliolids</b>	Z17 Ar2 Ln1	257
	Z17 Ar1 Ln1	156.4
	Z17 Ar3 Ln1	234.8
	Z17 Ar2 Ln2	170.7
	Z27 Ar1 Ln1	232.8
	Z27 Ar5 Ln1	175.3
<b>Nummulites</b>	BL1 Ar1 Ln1	230.4
	BL3 Ar3 Ln1	216.7
	BL16 Ar2 Ln1	347.5
	BL15 Ar1 Ln1	319.6
	BL15 Ar2 Ln1	277.4
	AW10 Ar1 Ln1	189.8
	AW10 Ar1 Ln2	179.7
<b>Red algae</b>	AW10 Ar5 Ln1	190.6
	AW10 Ar5 Ln2	124.5
	AW10 Ar6 Ln2	113.8
	AW10 Ar2 Ln1	177.4
	AW10 Ar7 Ln1	161.6
	AW10 Ar3 Ln3	160.1
	AW10 Ar6 Ln2	113.8
	AW10 Ar2 Ln1	177.4
	AW10 Ar7 Ln1	161.6
	AW10 Ar3 Ln3	160.1
	AW13 Ar1 Ln1	237.7
	<b>Peloids</b>	Z17 Ar4 Ln1
Z27 Ar2 Ln1		347.3
Z27 Ar3 Ln1		191.4
Z27 Ar4 Ln1		284

Table 5.5: This table shows the strontium values in ppm for each of miliolids, *Nummulites*, red algae and peloids.

### **5.7 Paragenetic sequence:**

Previously, the diagenetic stages were subdivided into eogenetic, mesogenetic and telogenetic stages; a similar trend for describing the diagenetic history of the Kirkuk Group is used (see Table 5.1). In the eogenetic stage, the Kirkuk Group was affected to a considerable degree by early marine diagenesis. A negligible amount of early marine peloidal cement can be recognized in the upper part of this group; it fills the space around grains and the intraskeletal cavities of bioclasts, or occurs in small isolated microcavities. In addition there is micritization in different forms which affects most of the shallow marine carbonate facies.

A variety of calcite cements were widely precipitated before deep burial in the Kirkuk Group; meteoric vadose cement occurs in the form of pendant cement and is common 10 metres below the sub-aerial exposure surface which is present at the top of this group. Moreover early cements were associated with hardgrounds developed during phases of reduced sediment input in the top strata of Kirkuk Group. Meteoric (phreatic) cement is usually composed of non-ferroan calcite cements; it is represented by the blocky and drusy textures that develop mainly in the middle and lower parts of the Kirkuk Group. More diagenetic features can be recognized in the early phases of diagenesis near the surface; such as dissolution of aragonite. The dissolution of aragonitic skeletal grains took place near the surface, caused by the influx of updip derived meteoric waters; subsequent cementation, produced iron-poor calcite spars. Due to the dissolution, large volumes of secondary porosity were

produced (see Figure 4.24); this may occur in the meteoric vadose or upper part of the meteoric phreatic zone. In addition to neomorphism, it is present in the form of bioclast neomorphism and aggrading neomorphism. Subsequently, early dolomite, with a very limited presence, occurs as scattered rhombs in the matrix, may illustrate that the original carbonate matrix mud consists of metastable mineral such as, high-Mg calcite and/or aragonite. During mineralogical stabilization, through high-Mg calcite replacement by low-Mg calcite leads to the release of Mg ions into the pore water and formed dolomite rhombs. Although, on an SEM scale, the empty square/rhombic pits were found in which they might be casts of microdolomite which were formed during the stabilization of metastable mineral.

The second stage of diagenesis is the mesogenetic phase; it comprises mechanical compaction which can occur in shallow burial due to a lack of extensive early cementation. The mechanism of chemical and post-cement compaction is attributed to burial. Chemical compaction which developed widely during deeper burial resulted in the formation of stylolites and clay seams, leading to the reprecipitating of cement and occluding porosity around the stylolite on the one hand, and developing secondary porosity along the line of the stylolite on the other hand. Furthermore, cementation, mechanical and chemical compaction are three main processes which can reduce porosity during burial. Another form of diagenesis present in this stage is deep burial cement, including ferroan calcite cement which precipitated in an anoxic environment, is absent in the Kirkuk Group, but this type of cement is clearly seen in the Jeribe Formation facies located on the top of this group. Diagenetic mud produced by early aragonite dissolution and reprecipitation

(diagenetic bedding) was not an important component of the depositional setting in this case study.

One of the features in the telogenetic stage of diagenesis are fractures and veins which can be found in different stages of diagenesis from early to late, present in different forms and sizes. In this stage fractures have been filled with meteoric calcite cements which cross-cut late ferroan cement (see Figure 5.14). After uplift, the upper part of the Kirkuk Group was affected by dissolution and karstification which caused by the influx of meteoric water. As a result, large amount of secondary porosity were produced. In this stage of diagenesis there is no evidence of dedolomitization present in the Kirkuk Group.

### **5.8 Summary and conclusion:**

Several diagenetic processes are recognized and classified into three stages: eogenetic, mesogenetic and telogenetic. The eogenetic stage includes micritization, peloidal marine, aragonite replacement, dolomitization, neomorphism and non-ferroan calcite cementation; the mesogenetic stage includes ferroan calcite cementation, fracture and compaction; and finally the telogenetic stage includes dissolution. The diagenetic processes are summarized in Table 5.1.

For the inner-mid ramp matrices carbon and oxygen stable isotopic values are negative indicating probable meteoric diagenesis (see Figure 5.34). The relatively low Sr and Mg values and up-take of Mn implies recrystallization and the probable replacement of high Mg-calcite and aragonite under meteoric fluids (see Figure 5.35). In the outer ramp facies the presence of coccolith and

planktic foraminifer debris indicates less diagenetic modification; the carbon and oxygen stable isotopic values show a less altered range (see Figure 5.36), with very low Mn and relatively high Sr and Mg values also supporting less alteration. The textural and geochemical evidence supports an origin from a more stable, likely low Mg-calcite precursor (see Figure 5.37). In addition into two different pore systems in each of them.

Petrographical, sedimentological, stable isotopes and trace elements offer evidence indicating that sub-aerial exposure and meteoric diagenesis were the most important diagenetic processes affecting the shallow carbonate facies of the Kirkuk Group Formations; the meteoric dissolution resulting in the enhancement of secondary porosity, in addition to occluding primary porosity during stabilization of metastable minerals. However the deeper marine carbonate facies remain without significant changes to their primary porosity with no evidence of enhancing of secondary porosity.

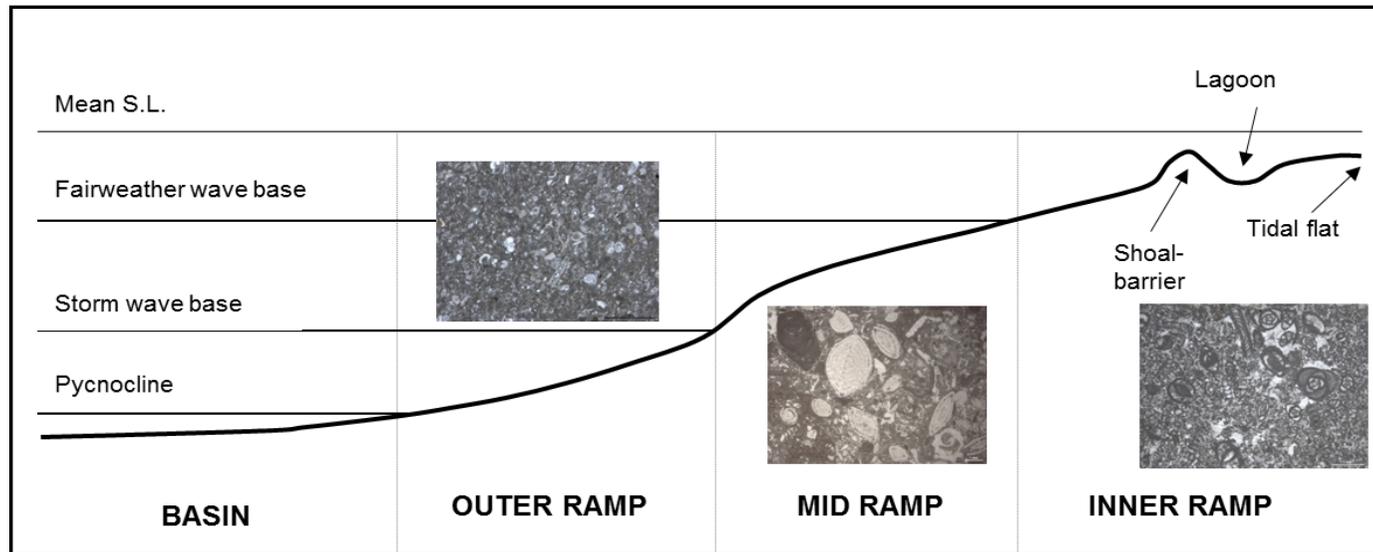


Figure 5.37: Ramp model showing two different rock fabrics. LMC: low-Mg calcite, HMC: high-mg calcite, S.L.: sea level.

Dominant lithologies	Wackestone-mudstone	Packstone-grainstone
Microfauna	Planktic forams	Benthic forams
Bedding	Thin bedded	Massive-thick bedded
Porosity	Primary porosity (13.1%)	Recrystallization, loss in primary porosity (8.7%)
Stable isotope	Marine isotopic value	Meteoric isotopic value
precursor mineralogy	LMC	Aragonite-HMC

## **Chapter Six:**

### **Sequence Stratigraphy**

#### **6.1 Preface:**

Sequence stratigraphy focuses on changes in depositional trends across sedimentary basin within a chronostratigraphic framework. According to Vail et al. (1977), depositional sequences represent the sum of sea level-related accommodation change and the change in sediment supply. Sequence stratigraphy deals with the study of rock relationships within a time-stratigraphy framework of genetically related strata bounded by surfaces of non-conformity, non-deposition and correlative conformity, which separate conformable successions and surfaces caused by flooding events of strata called sequence boundaries (Vial et al., 1977; Posamentier et al., 1988; van Wagner, 1995).

Relative sea level changes control accommodation space creation; parasequence sets can be associated with specific periods of a relative sea level curve. The depositional systems contemporary to each period of sea level curve from individual parasequences with defined stacking patterns which form system tracts (Ketzer, 2002).

Three main systems tracts are defined: low-stand system tract (L.S.T.), transgressive system tract (T.S.T.) and high-stand system tract (H.S.T.) which are bounded by sequence boundary types SBT I, SBT II and SBT III.

A new sequence usually starts with a low-stand system tract L.S.T. associated with a type I sequence boundary, in which relative sea level falls

off the shelf, and is associated with a type II sequence boundary, where relative sea level falls to somewhere between the old shoreline and the shelf break. A type III sequence boundary forms when the sea level rises faster than the system can aggrade and a transgressive systems tract in which a marine hiatus overlies the preceding high-stand tract, and with no significant fall of relative sea level (Schlager, 1998, 1999, 2002). A T.S.T. is characterized by a back stepping parasequence; and an H.S.T. is characterized by a prograding/off-lapping parasequence (Vail et al., 1991). The T.S.T. and H.S.T. are separated by a maximum flooding surface (mfs) characterized by a maximum landward shift in open marine facies belts. The detailed rate of sediment supply and accommodation creation with their relation to system tracts is summarized by Schlager (2005); as an example, when the rate of sediment supply exceeds the rate of accommodation creation this leads to the creation of a high-stand system tract, in contrast to a transgressive system tract where the rate of accommodation creation exceeds the rate of sediment supply.

The Oligocene-Early Miocene carbonate sequence of the Kirkuk Group is composed of nine formations. The Kirkuk Group is bounded by the Late Eocene Avanah and/or Jaddala Formations below and by either Early Miocene Jeribe and/or Fatha Formations above the upper boundary. This succession almost manifests the first sequence of Megasequence AP11 between Pg30 and Ng10 (Sharland et al., 2001; Sharland et al., 2004; Al-Banna, 2008; Al-Juboury and McCann, 2008; Aqrabi et al., 2010, Ameen et al., 2012) and has been defined by different hierarchical cycles (Tables 6.1), some of which are bounded by major sequence boundaries (for more details

see Chapter Two Section 2.3 and Figures 2.4 and 6.10). The lower parts of the Oligocene sequences developed after a long period of subaerial exposure and erosion in which the lower contact was unconformable, it is called the Supra-Dammam Unconformity (Al-Husseini, 2008) and developed a sequence boundary type one (SBT I) (Lawa, 2004; Al-Qayim, 2006). Because the Kirkuk Group succession was deposited on a shallow water ramp, sea level behaviour may have played a significant role in defining the sedimentology, thickness, lateral extent and sequence stratigraphy of this succession. The Kirkuk Group Formations in the first five localities in the study area are separated by the Khanaqin fault from the last three localities have relatively shallower microfacies (for more details on the Khanaqin fault see Section 6.3 and Figure 6.11).

<b>Tectono-Eustatic/ Eustatic Cycle Order</b>	<b>Sequence Stratigraphic Units</b>	<b>Duration (my)</b>	<b>Relative Sea Level Amplitude (m)</b>	<b>Relative Sea Level Rise/Fall Rate (cm/1,000 yr)</b>
First	-	> 100	-	<1
Second	Supersequence	10-100	50-100	1-3
Third	Depositional Sequence Composite Sequence	1-10	50-100	1-10
Fourth	High Energy Sequence Parasequence and Cycle Set	0.1-1	1-150	40-500
Fifth	Parasequence, High-Frequency Cycle	0.01-0.1	1-150	60-700

Table 6.1: Classification of hierarchical stratigraphic cycles (after Einsele et al., 1991).

## **6.2 Sequence stratigraphy of the Kirkuk Group:**

Each section is analysed separately in order to identify both local (possibly tectonic) and possible eustatic signals.

### **6.2.1 Sagrama section:**

The Kirkuk Group succession in the Sagrama area is separated from the underlying Late Eocene Avana Formation by a hard ground (see Chapter Four Section 4.2.11). The Late Eocene succession is composed of peloidal grainstone 'PG' and the bioclasts are indicators for shallow marine carbonates. It comprises the upper part of a 3rd order tectonostratigraphic megasequence AP 10 (Sharland et al., 2001). It is hard to find the system tract for PG microfacies in this locality because it needs to be seen in relation to underlying and overlying facies.

The Eocene sedimentation terminated due to a regional eustatic sea level fall which led to non-deposition and erosion across the Arabian Plate (Jones and Racey, 1994; Goff et al., 1995; Ellis et al., 1996). This eroded surface (Supra Dammam Unconformity) marks a sequence boundary type one (SBT 1) between megasequence AP10 and AP11. In the Zagros (Kurdistan) foreland basin (more detail is in section 6.3), the duration of this break shows a progressive decrease from the Zagros suture towards the Arabian platform, i.e. from the High Fold Zone "HFZ" towards the Low Fold Zone "LFZ". On the north-eastern limb of this structure, a sequence boundary of type one was recognized by Lawa (2004) with the presence of an incised valley; and in this section, which is located at the approximate boundary between HFZ and LFZ,

a sequence boundary type I is not well developed and the hard ground separates the previously mentioned mega-sequences.

The Kirkuk Group is composed of a 3rd order cycle (according to Einsele et al., 1991) located in the lower part of tectonostratigraphic megasequence AP11 which lasted for more than 10 my. As the Sagrma area was located near the edge of the basin (details are in Section 1.2), only 4.5 metres of Early Aquitanian Anah Formation sediments were deposited and represent the Early Miocene in this area. It comprises medium- to thick-bedded skeletal packstone and represents shallow water inner ramp deposits of microfacies SP-2 (Figure 6.1). There is no clear change in facies due to the very short duration of the deposition of this formation and it is located at the periphery of the Oligocene sag basin; it could represent either transgressive system tract (TST) or highstand system tract (HST). The approximate break between the Late Eocene Avanah Formation and the Early Aquitanian Anah Formation in this locality may reach 10 Ma (more detail is in the Stratigraphic logs in Appendix.3).

Moreover, in the upper part, the Early Miocene Fatha Formation moved from the top of the Kirkuk Group to approximately 500 metres away due to active tectonic movement in the area in which there was short break at lasted for 2 Ma separating between them.

### **6.2.2 Zinana village section:**

At the lower part of the Kirkuk Group, the Late Eocene Avanah Formation has similar facies to the previous locality (for more details see Section 6.2.1). The break between these two different 3rd order sequences at least 5 Ma, starting

Formations		microfacies	System tract	Sea level	
				deep	shallow
Kirkuk Group	Anah	SP-2	HST/ TST	SBT I  Could be HST or TST	
Avanah		PG		SBT I  Un-known system tract	

Figure 6.1: Sequence stratigraphy of exposed formations in Sagrma area. SBT1 is sequence boundary type 1, HST is high stand system tract and TST is transgressive system tract.

from the latest Late Eocene to the earliest Late Oligocene with the disappearance of all the Early Oligocene. Towards the centre of the basin, 'south-west', the thickness of the Kirkuk Group increases. The Kirkuk Group succession in this area consists mainly of medium- to thick-bedded peloidal, skeletal packstone/grainstone (MP-1) in the up-dip direction and skeletal grainstone (SP-3) and skeletal packstone (SP-2) in the down-dip direction. The lower part of the Kirkuk Group in this section, the Bajawan Formation, is dominated by skeletal grainstone which is commonly interbedded with peloidal skeletal packstone/grainstone (MP-1) (details of microfacies are in Chapter 4). In the upper part of the unit, the main lithology is skeletal packstone of the Anah Formation. It could represent highstand system tract (HST) with an

overall shallowing upward (coarsening upward) trend. Therefore, the shallowing upward trend was formed due to progradation in relative sea level which developed a high-stand system tract. It occurs when the rate of sediment supply is more than the rate of accommodation space creation, so then the sediment aggrades and/or progrades and fill up the space, leading to shifting the shoreline towards the sea (Figure 6.2).

The thickness of the Kirkuk Group in this section is more than the previous one, as there are two factors controlling the thickness of the cycles: the accommodation space (relative sea-level rise) and sediment supply.

The upper contact of the Kirkuk Group is unconformable and makes a type I sequence boundary; this is followed by an Early Miocene Jeribe formation. There was a short break between these two sequences (approximately less than 1 Ma).

### **6.2.3 Hazar Kani village section:**

The Late Eocene Avanah Formation is composed of PG microfacies, similar to the previous two sections (as mentioned in Section 6.2.1). Then, a fall in sea level resulted in the exposure of the ramp carbonate sediment and forms a sequence boundary type I due to the presence of incised valley. A sequence boundary type I is formed by an abrupt fall in relative sea level (van Wagoner et al., 1990), this is followed by a low-stand system tract. It comprises a low-stand wedge, which is made up of fluvial deposits within incised valleys that can be recognized by the presence of a thick conglomerate layer. This layer separates the Late Eocene Avanah Formation from the Bajawan Formation of the Kirkuk Group (Figure 6.3). The approxima-

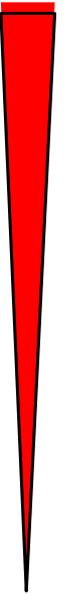
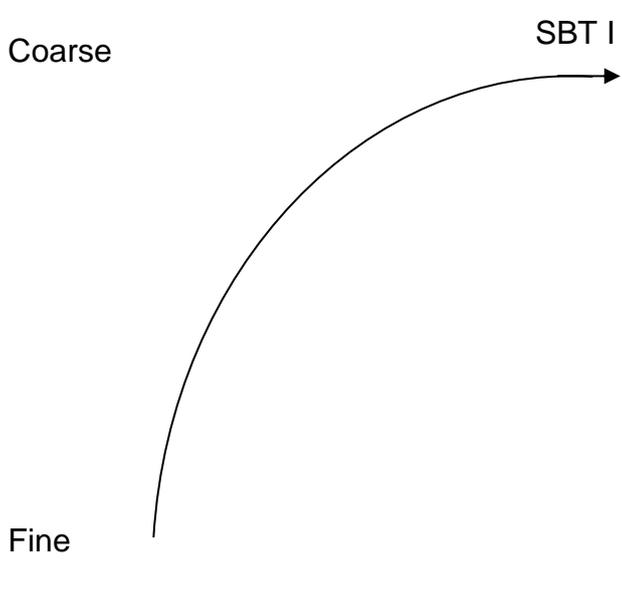
Formations		Microfacies	System tract	Depositional sequence	Sea level	
					Deep → shallow	
Kirkuk Group	Anah	SP-2	HST			
	Bajawan	SP-3				Coarse
		MP-1				Fine
		SP-3				
Avanah	PG			Un-known system tract	SBT I	

Figure 6.2: Sequence stratigraphy of exposed formations in Zinana area. SBT1 is sequence boundary type 1 and HST is high stand system tract

te break made by this exposure surface is at least 5 Ma.

The sequence is usually deposited between two episodes of relative sea level fall, as it is presence in this section. The Kirkuk Group deposits are composed initially with very shallow restricted inner ramp peloidal wackestone/calcimudstone (MP-2) microfacies which then changes to skeletal grainstone (SP-3) microfacies of the shallow marine inner ramp, after that deepening into coral bioherm (CB) from a mid-ramp setting, and finally the

inner ramp (SP-1) microfacies start to appear. As a result, the Kirkuk Group in this locality has deepening upward (fining upward) trend, representing transgressive system tracts (T.S.T.); these comprise a retrogradational parasequence set formed during transgression of sea level in which the carbonate microfacies shifts landward. A fall in sea level led to the forming of an unconformable boundary between the Kirkuk Group and the Jeribe formation, which produced a sequence boundary type I. The duration of the break between these two sequences is about 1 Ma.

#### **6.2.4 Core of the Aj Dagh Anticline section:**

As for moving towards depocentre 'SW' (from high-folded zone (HFZ) to low-folded zone (LFZ)) of the basin, the deeper facies start to appear. The Late Eocene succession (Avanah Formation) is composed of mid-ramp skeletal packstone (NR-2) and inner-ramp peloidal grainstone (PG), and the bioclasts are an indicator for changing the relative sea level from relatively deeper marine to shallow marine carbonates (Figure 6.4). This relative sea level change can be recognized twice. As a result, a shallowing upward (coarsening upward) sequence is generated. During regression and a high-stand system tract, the rate of sediment supply is more than the rate of accommodation space creation. A fall of the Eocene sea was recorded and there was a non-deposition for more than 5 Ma, this is because of this area was uplifted during the Early Oligocene, as in all previous localities. During the Late Oligocene-Early Miocene (Bajawan and Anah Formations) the occurrence of frequent changes in the microfacies reflects probably

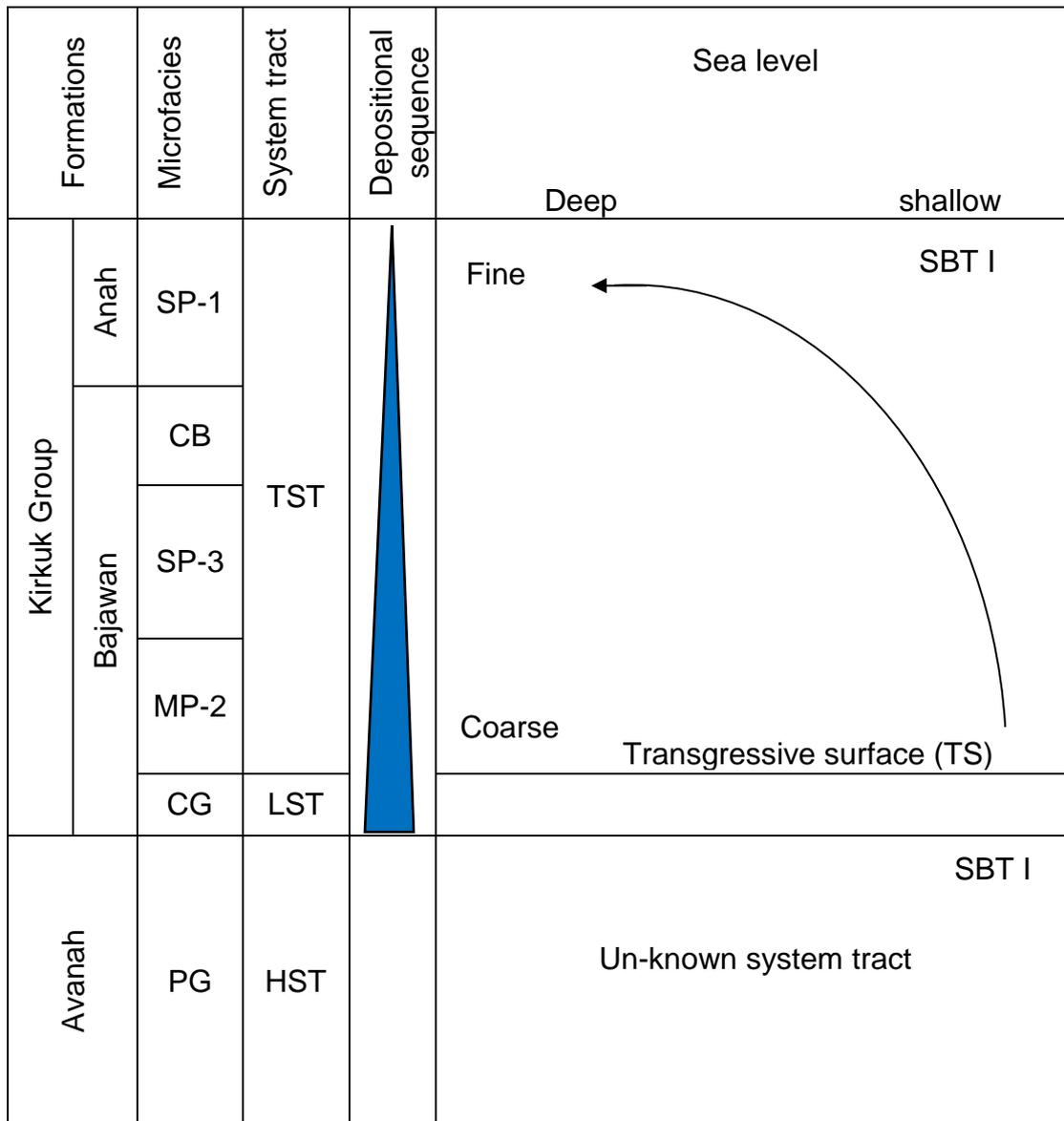


Figure 6.3: Sequence stratigraphy of exposed formations in Hazar Kani Village. SBT1 is sequence boundary type 1, LST is low stand system tract and TST is transgressive system tract.

tectonic instability in the basin. The basal Kirkuk Group starts with a new transgression in which a very shallow water MP-1 microfacies at the base passes upwards to shallow water skeletal grainstone (SP-3 microfacies), then it is followed by restricted very shallow peloidal wackestone/mudstone (MP-2 microfacies). The transgressive sea shows progressive deepening (fining

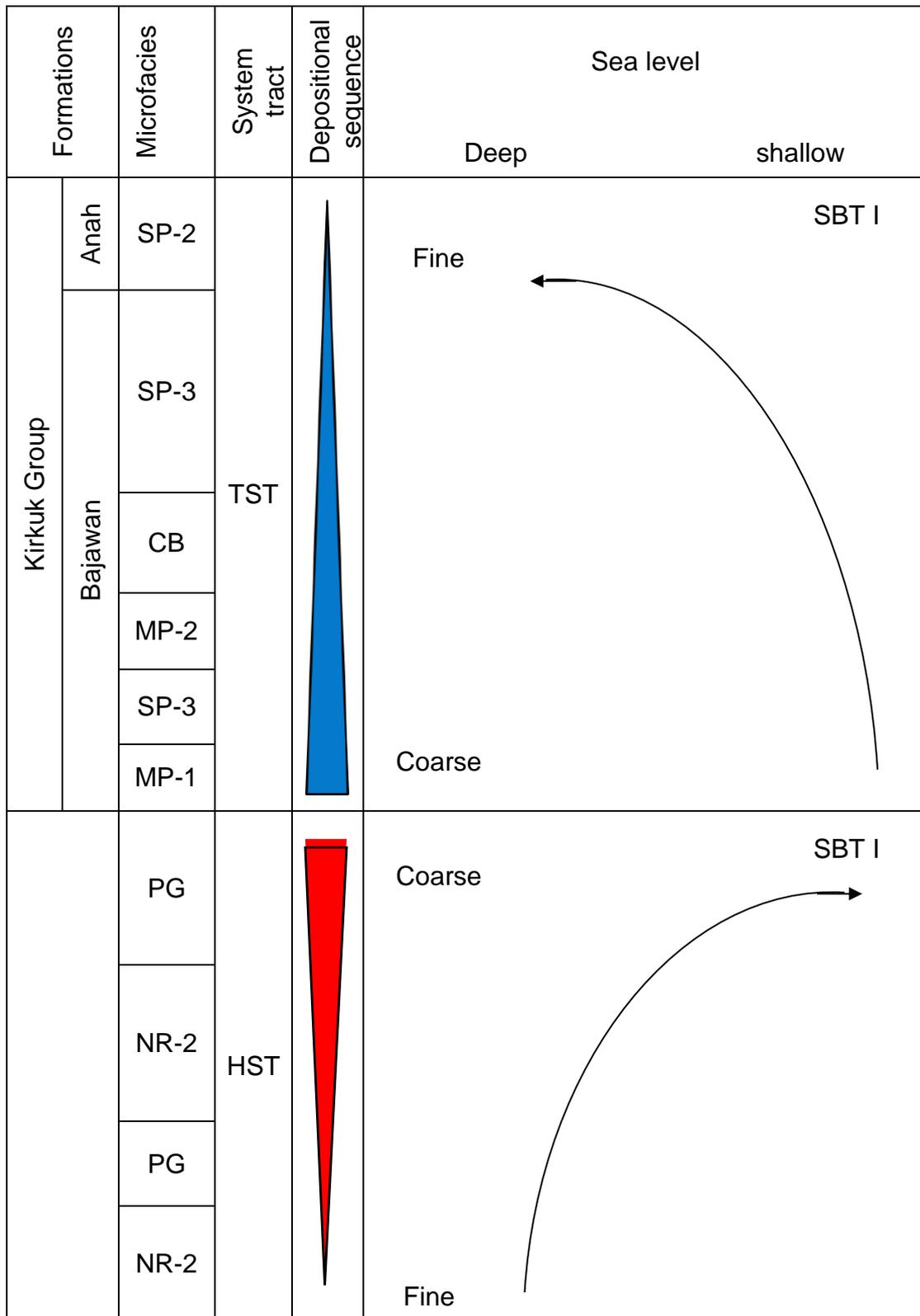


Figure 6.4: Sequence stratigraphy of exposed formations in Core of Aj Dagh Anticline. SBT1 is sequence boundary type 1, HST is high stand system tract and TST is transgressive system tract.

upward) and is associated with mid-ramp coral bioherm (CB) microfacies. This sequence is terminated with a deposition of SP-3 and SP-2 microfacies. The Kirkuk Group is overlain unconformably by the Jeribe Formation and makes sequence boundary type I. There is a short break between these two sequences approximately 1 Ma.

#### **6.2.5 Awa Spi section:**

In the Awa Spi locality of the Late Eocene succession, from up-dip to down-dip is composed of inner ramp peloidal grainstone (PG) and mid-ramp skeletal packstone (NR-2 and NR-3) of the Avanah Formation and possibly outer ramp/basinal (PK-1) of the Jaddala Formation (Figure 6.5). The bioclasts in these microfacies are a good indicator for change in relative sea level. Therefore, deepening upward trend (fining upward) was generated and could be interpreted as the product of retrogradational parasequence set (T.S.T.). Furthermore, a transgressive system tract, in which the sedimentation kept pace with rising sea level and the increasing rate of subsidence.

The transgressive cycle of the Late Eocene is terminated with a rapid fall in sea level followed by exposure and production of a soil in a terrestrial environment is represent a forced regression of sea level in a relatively short time. This followed by a thick layer of conglomerate which represents a low-stand system tract (L.S.T.) (as presented in Section 6.2.3); then, the Late Oligocene microfacies starts to appear, this may indicate that at least 5 Ma is missing between the Late Eocene and Late Oligocene microfacies. The Late Oligocene microfacies start with very shallow restricted water, inner ramp (MP-2) microfacies of Bajawan Formation and then changes to shallow water

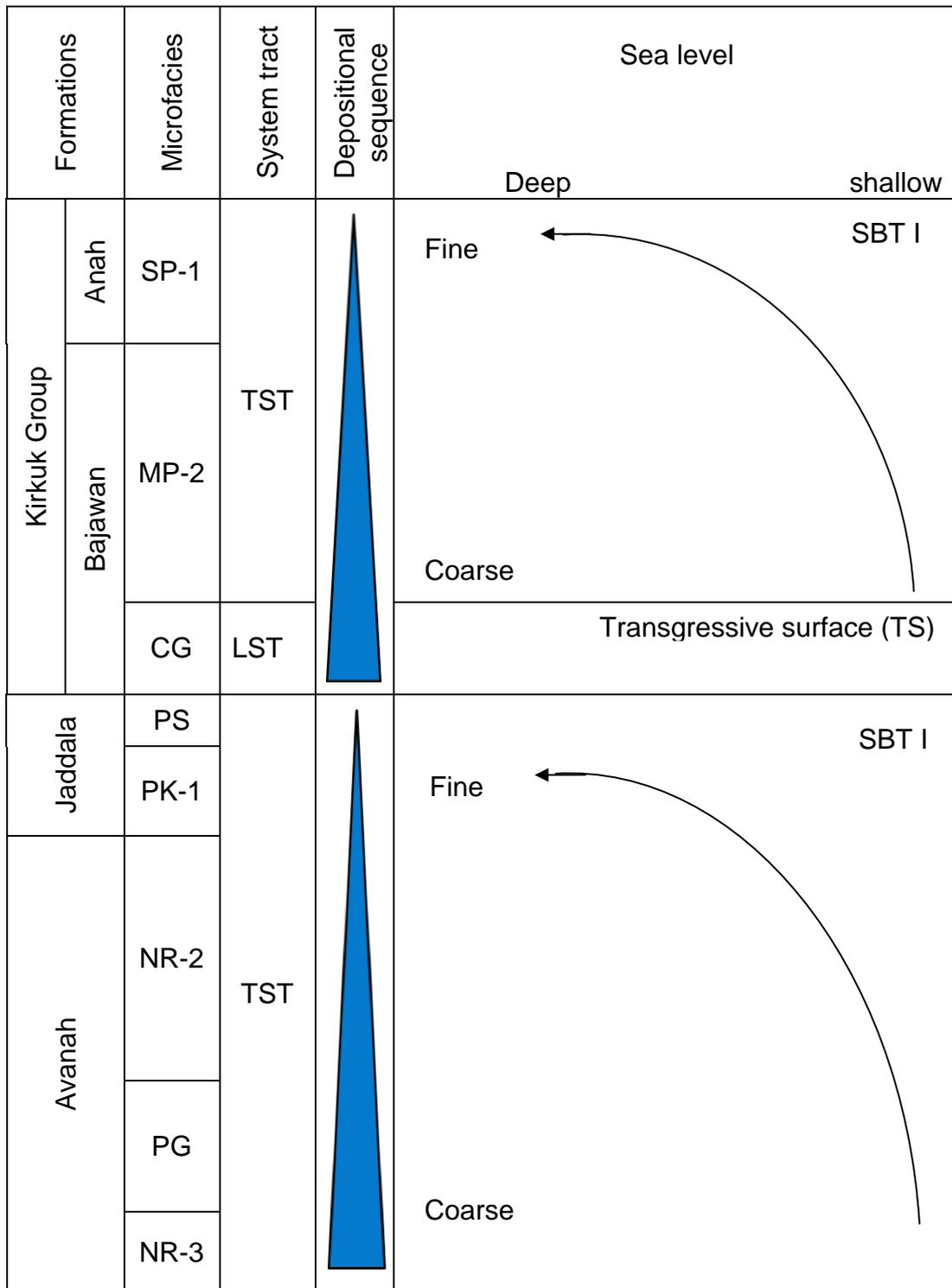


Figure 6.5: Sequence stratigraphy of exposed formations in Awa Spi area. SBT1 is sequence boundary type 1, LST is low stand system tract and TST is transgressive system tract.

inner ramp (SP-1) microfacies of the Anah Formation with more diverse fauna which is relatively deeper than the first microfacies. Therefore, in the Late Oligocene sequence of this section, there is relative deepening upwards (fining upward) due to a transgression in relative sea level representing a transgressive system tract (T.S.T.). As a result, if the rate of sediment supply is less than the accommodation creation then sediments can retrograde landward and the parasequence stack called retrogradational (van Wagoner et al., 1990).

As much as relative sea level continues to fall, the carbonate factory shuts down and subaerial diagenesis operates on the exposed sediments (James and Kendall, 1992). The upper boundary of the Kirkuk Group suggests subaerial exposure (see also Chapter Five, section 5.3.1 in Non-ferroan calcite cementation part 2. Dripstone or pendant cement) which separates this group from the Early Miocene Jeribe Formation with very short break between them and represents a sequence boundary type I. This is in addition to the presence of karstification and dissolution in the upper part of the Kirkuk Group (more detail is in Chapter Five, section 5.3.3).

#### **6.2.6 Bamu Gorge section:**

The Middle to Late Eocene succession of the Avana Formation is composed of intercalated shallow marine skeletal packstone NA and peloidal grainstone PG microfacies and then changes to mid-ramp NR microfacies which represent relatively deeper water. The bioclasts are an indicator for change in relative sea level from relatively shallower to deeper marine carbonate and vice versa. Therefore, from overall change in sea level deepening upward

(fining upward) trend was generated. In the Bamu Gorge locality, the break between the Late Eocene Avanah Formation (*Discocyclina* biozone) and the Late Oligocene Bajawan Formation (*Praerhapydionina delicata* biozone) is at least 5 Ma with the disappearance of all the Early Oligocene based on the foraminifera zonations (for more detail on biozones go to Chapter Three, Figure 3.4). The Late Oligocene-Early Miocene sequence of the Bajawan and Anah Formations is composed of shallow marine skeletal grainstone and packstone (SP) microfacies. The microfacies of these formations could be HST or even TST as the stacking pattern of inner ramp shallow depositional environments does not justify the subdivision into system tracts (Figure 6.6). It is not necessary for the sequence to contain all three system tracts of the standard model, especially in carbonates; the sequence commonly lacks a low-stand system tract (L.S.T.) (Schlager, 2002).

The duration of missing time between the Kirkuk Group and the Fatha Formation is approximately 2 Ma and a sequence boundary type I separates them with the presence of a hard ground in the uppermost part of the strata at the boundary (see also Chapter Four, section 4.2.4b). The surface of hard ground is irregular and abrupt due to boring and erosion (Molenaar and Zijlstra, 1997).

### **6.2.7 Bellula Gorge section:**

The Late Eocene microfacies in the Bellula Gorge locality suggest deeper conditions than in the rest of the localities. It is composed of proximal deeper marine (NR-3) microfacies of the Avanah Formation and then changes to outer ramp/basinal (PK) microfacies of the Jaddala Formation. The deepening

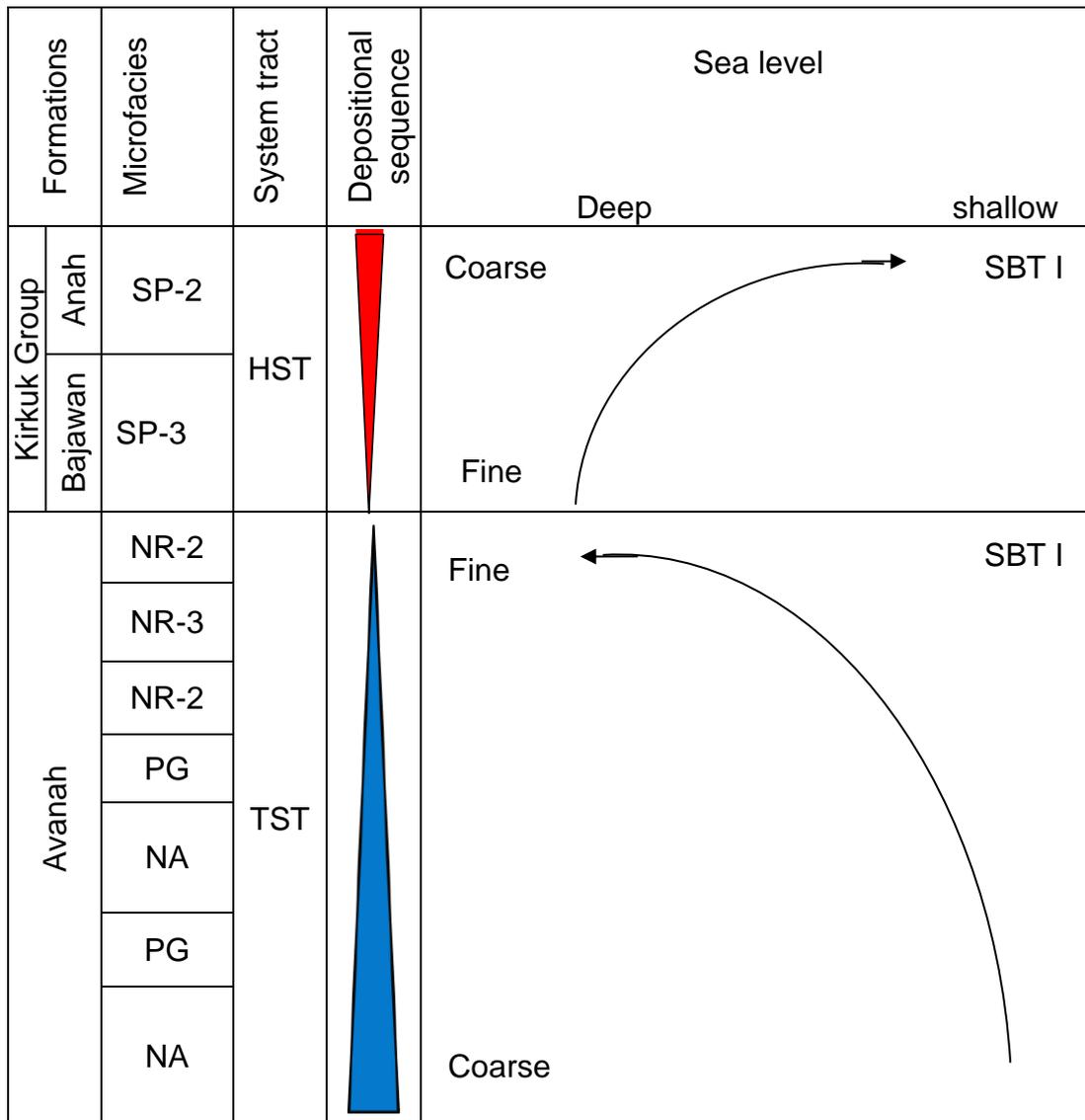


Figure 6.6: Sequence stratigraphy of exposed formations in Bamu Gorge area. SBT1 is sequence boundary type 1, HST is high stand system tract and TST is transgressive system tract.

upward (fining upward) microfacies represent rising sea level due to increasing accommodation space creation in which the maximum space of accommodation has a maximum rate of planktonic foraminifera. The stacking pattern of these microfacies could be interpreted as the product of a retrogradational parasequence set. This is followed by a new cycle of Early Oligocene, and so contact between the Late Eocene Jaddala Formation and

the Early Oligocene Sheikh Alas Formation is unconformable with presence of a short break between them and may form a sequence boundary type I.

The Kirkuk Group has only an Early Oligocene Sheikh Alas Formation composed of a thick bedded mid-ramp (NR-1 and CB) of microfacies which the stacking pattern of microfacies could be attributed to the product of deposition within either High stand system tract (HST) or transgressive system tract (TST) (Figure 6.7). The Kirkuk Group succession is followed by the Early Miocene Fatha Formation occurring unconformably which makes a sequence boundary type I. The approximate break time between them is about 7 Ma.

#### **6.2.8 Sharwal Dra section:**

In the Sharwal Dra section the Kirkuk Group attains maximum thickness; it is more than 122 metres and only the uppermost part of the Kirkuk Group was deposited which is the Early Miocene Azkand Formation and Ibrahim member. It starts with a thick to massive bed of shallow open marine mid-ramp setting (RR and CB) of microfacies of the Azkand Formation in which the stacking pattern of the microfacies below Ibrahim member may has characteristics in common with Shelf Margin System Tract (SMST) with slightly progradational to aggradational parasequence set. And then a thin layer of outer ramp/basinal (PK-2) microfacies of the Ibrahim member were deposited may represents a condense section deposits. After that the stacking pattern of microfacies in the Early Miocene Azkand Formation could be attributed to the product of retrogradational parasequence set (TST) with fining upward trend (Figure 6.8). The upper contact of the Azkand Formation (Kirkuk Group) could

not be determined due to it being located on Iranian soil, in addition to the risk of unexploded bombs from the Iraq-Iran war.

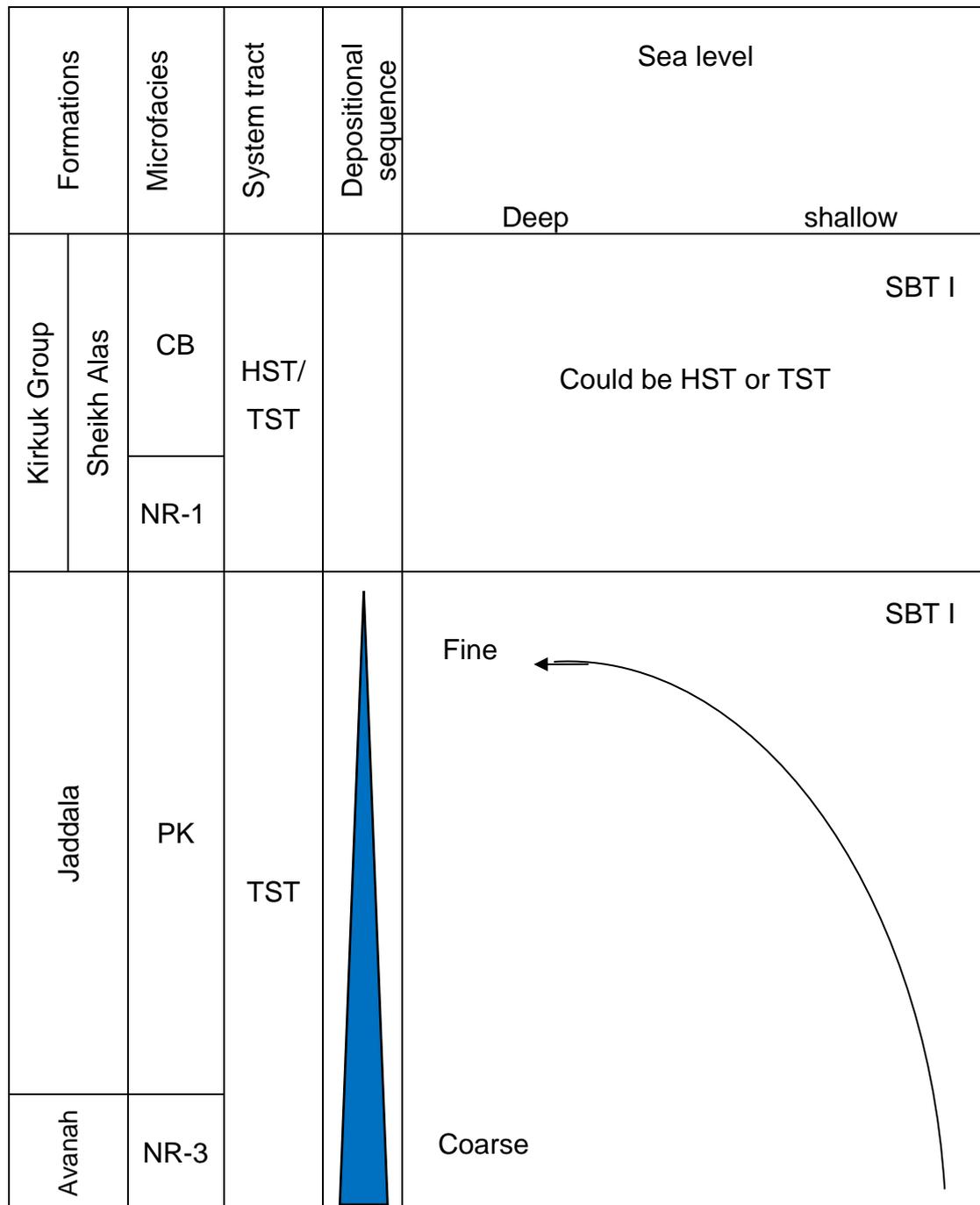


Figure 6.7: Sequence stratigraphy of exposed formations in Bellula Gorge area. SBT1 is sequence boundary type 1, HST is high stand system tract and TST is transgressive system tract.

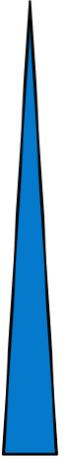
Formations		Microfacies	System tract	Depositional sequence	Sea level	
Kirkuk Group	Azkand	RR & CB	TST		Deep	shallow
	Ibrahim	PK-2			Condence section	SBT II
	Azkand	RR & CB	SMST		Shelf Margin System Tract (SMST) with Progradational/Aggradational Parasequenc sets	

Figure 6.8: Sequence stratigraphy of exposed formations in Sharwal Dra area. SBT II is sequence boundary type 2, SMST is shelf margin system tract and TST is transgressive system tract.

### **6.3 Summary and conclusions:**

During Middle to Late Eocene the Avana and Jaddala Formations were deposited in almost all sections in the study area. Due to tectonics the shallow-marine carbonates prograded and moved bidirectionally between south-east and north-west which led to a rapid narrowing and final closure of the Zagros foreland basin (Liu, 2006). The formation of the Zagros foreland basin (Kurdistan foreland basin) was initiated in the Paleocene with continental collision between the Arabian Plate and Eurasia along the Zagros suture and formed the Zagros foreland basin which oriented north-east to south-west. The collision and uplift caused a south-westward shift in the facies belts, marking the onset of the final closure of Neo-Tethys (Beydoun, 1991; Goff et al., 1995). The deposition of these formations followed the accumulation of the Paleocene-Eocene Kolosh, Sinjar, Sagrama and Gercus Formations which were deposited in the foreland basin (see Figure 6.9) during the tectonostratigraphic megasequence 'TMS' AP10, which lasted some 29 Ma, from 63-34 Ma (Sharland, 2001; Lawa, 2004).

An eustatic sea level fall was recorded in the study area producing the unconformable boundary between TSM AP10 and AP11 which matches the major sea level regression and the Supra-Dammam Unconformity described by Al-Husseini (2008) (more details are provided in Section 6.2.1).

After that accommodation space was rapidly created and sedimentation was initially dominated by carbonates of the Kirkuk Group in which the Kirkuk Group sequence developed in a relatively narrow, sag basin on a ramp setting. This group is located in the first sequence of the tectonostratigraphic megasequence 'TMS' AP11, between Pg30 and Ng10 (see Figure 6.10)

(Sharland et al., 2001; Sharland et al., 2004; Simmons et al., 2007; Ehrenberg et al., 2007; Al-Banna, 2008; Al-Juboury and McCann, 2008; Aqrabi et al., 2010, Ameen et al., 2012), (details of the palaeogeography is in Chapter Two, Section 2.3).

According to Einsele et al.'s (1991) classification (see Table 6.1), the Kirkuk Group comprises one 3rd order sequence within two 4th orders located between two unconformable surfaces at its lower and upper boundaries which can be correlated to the global and regional regression of sea level; in which the first 4th order sequence is located at Rupelian and composed of only the Sheikh Alas Formation. The second 4th order sequence is composed of the Bajawan, Anah, Azkand and Ibrahim Formations (see Figures 6.9, 6.10). These two cycles are incomplete as a result of non-deposition within the sequence; this was due to the palaeoconfiguration of the basin, in addition to localized tectonic activity. The Kirkuk Group sequence has different subdivisions according to different authors; Grabowski and Liu (2008) divided the Oligocene Kirkuk Group into two sets of progradational shelfal to shelf-margin limestones that pass laterally into basinal limestone where the tops of each shelfal sequence were subaerially exposed and eroded. While, Ameen and Qadir (2012) divided the Kirkuk Group into three fourth orders Oligocene sequences, within one third order cycle. And Al-Qayim (2006) considered that the cyclical nature of the sediments of the Kirkuk Group was composed of one 2nd order which can represent a three-fold third order cycle of fairly consistent facies architecture.

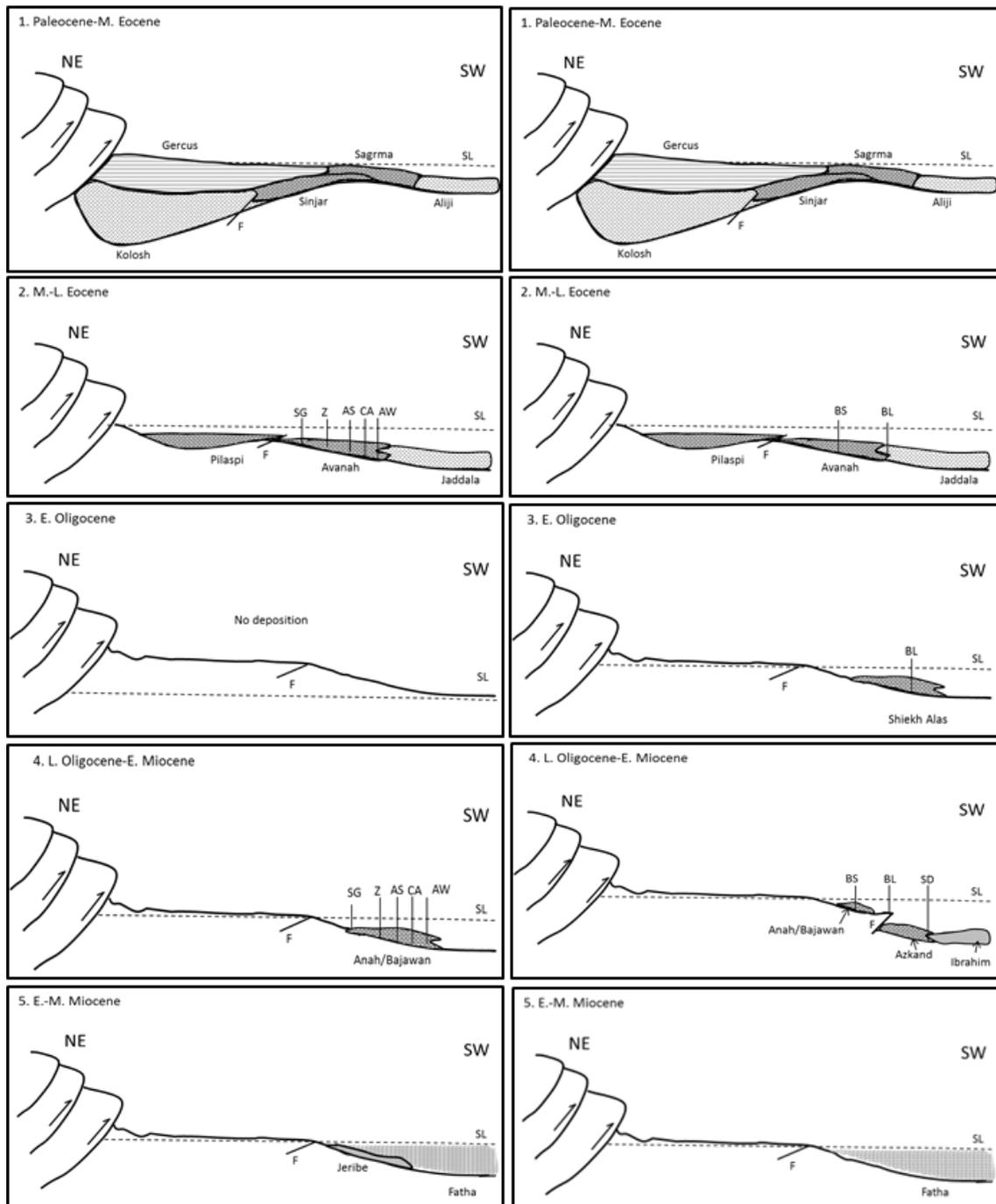


Figure 6.9A: Left column: Depositional model for the western side of Khanaqin Fault including Sagrma (SG), Zinana village (Z), Hazar Hani village (AS), Core of Aj Dagh Anticline (CA) and Awa Spi sections (AW). Right column: Depositional model for the eastern side of Khanaqin Fault including Bamu Gorge (BS), Bellula Gorge (BL) and Sharwal Dra (SD) sections. (for more detail on Khanaqin Fault and sections position see next paragraph and Figure 6.11).

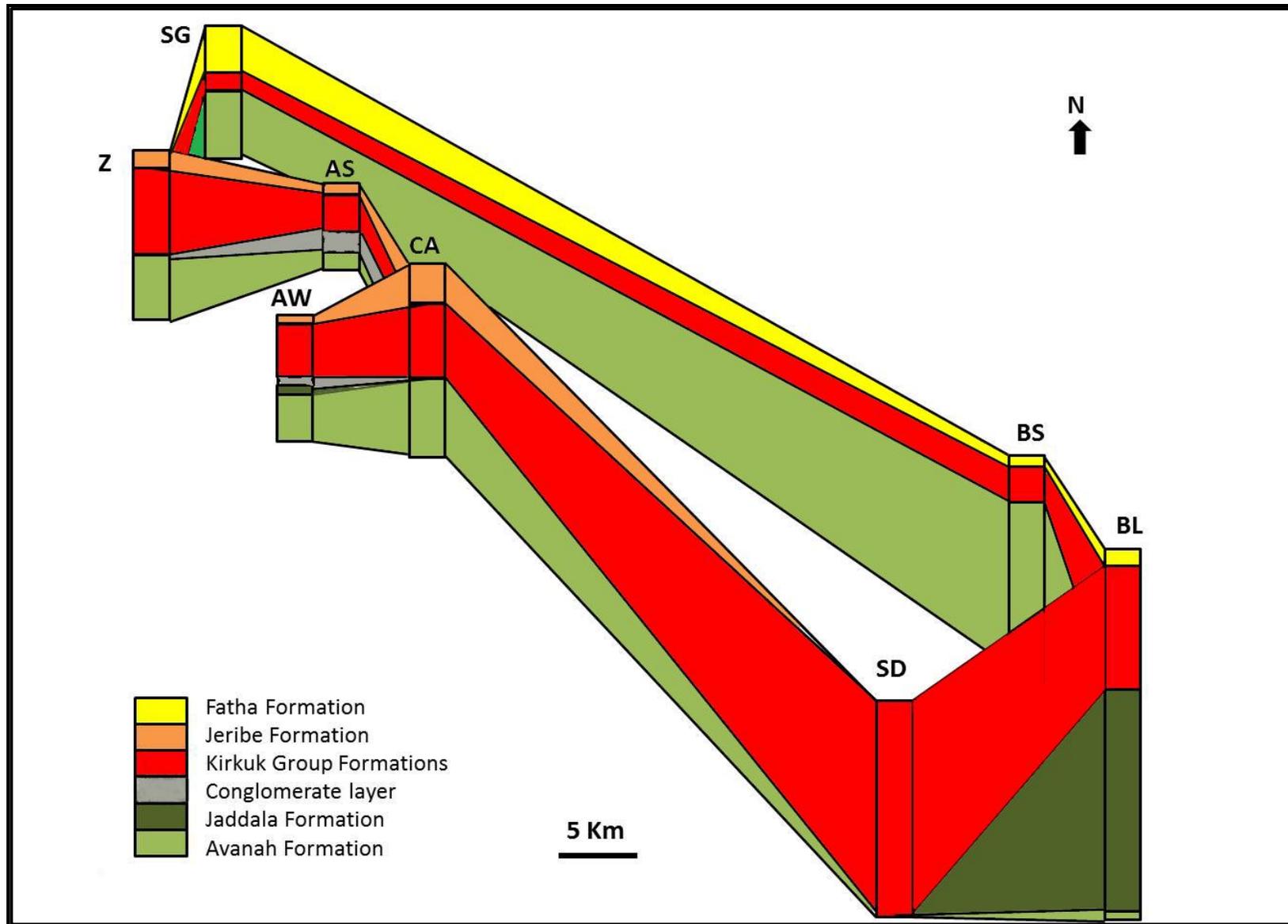


Figure 6.9B: Fence diagram of the study area. The accurate thickness of each column is in sedimentary logs in appendix 3.



After deposition of the Kirkuk Group, in most of the sections in the study area, shallow marine conditions were briefly re-established at the base of the Jeribe Formation. Following this major but short-lived flooding event, the structural or stratigraphic result is interpreted to have occurred at the foredeep basin and to have resulted in rapidly rising salinity, leading to the deposition of the Fatha (previously named Lower Fars) Formation (see Figure 6.9). As the Zagros fold belt emerged, flysch-type clastics of the Late Miocene Injana (Upper Fars) Formation and Pliocene Bakhtiari Formation molass were deposited (Jones and Racey, 1994) that can be recognized in the stratigraphic south-west continuation of this structure.

Within the deep and narrow Zagros foreland basin, on the north-eastern side; up to 6,000 m of sediments were deposited in this foredeep between the Oligocene and the present day (during TMS AP11) (Golf et al., 1995; Mukhopadhyay et al., 1996).

The tectonostratigraphical and structural evidence indicates the influence of the Khanaqin Fault in the study area (see Figure 6.11). The Khanaqin Fault is a basement fault with a significant strike-slip displacement on the surface (Kent, 1958, 1979; Baker et al., 1993; Barzegar, 1994; Berberian, 1995; Sepehr, 2001; Hessami et al., 2001). It is one of the main active basement faults (Allen et al., 2004) and played a significant role in the tectonic evolution of the Zagros Fold-Thrust. This fault divided the basement into two major blocks, namely the Eastern Arabian Block and the Western Arabian Block (Weijermars, 1998; Bahroudi and Talbot, 2003; Ibrahim, 2009) which marks the eastern limit of the Kirkuk Embayment.

The Khanaqin Fault separates the Sagrma, Zinana, Hazar Kani, Core of Aj Dagh and Awa Spi localities that are located on the western side of the fault, with the Bamu Gorge, Bellula Gorge and Sharwal Dra localities on the eastern side (see Figure 6.11). The activity of the fault resulted in thinner shallower Kirkuk Group Formations on the western side than on the eastern side of the fault. Furthermore, the thickness increases towards the normal depocentre of the Kirkuk basin which has a south-west orientation on the western side of the fault, whereas the depocentre of the eastern side has shifted towards south-east towards the Asmari basin due to presence of the Khanaqin fault. As a result, the Kirkuk Group Formations in the Bamu Gorge, Bellula Gorge and Sharwal Dra localities can be correlated with the Asmari Formation. Moreover they are relatively thicker than the first group localities; this proves the fact that the Asmari Formation is thicker than the Kirkuk Group Formations. The Sharwal Dra has the maximum thickness of Kirkuk Group due to its locality on the Iraq-Iran border which has the nearest position from the depocentre of the Asmari basin.

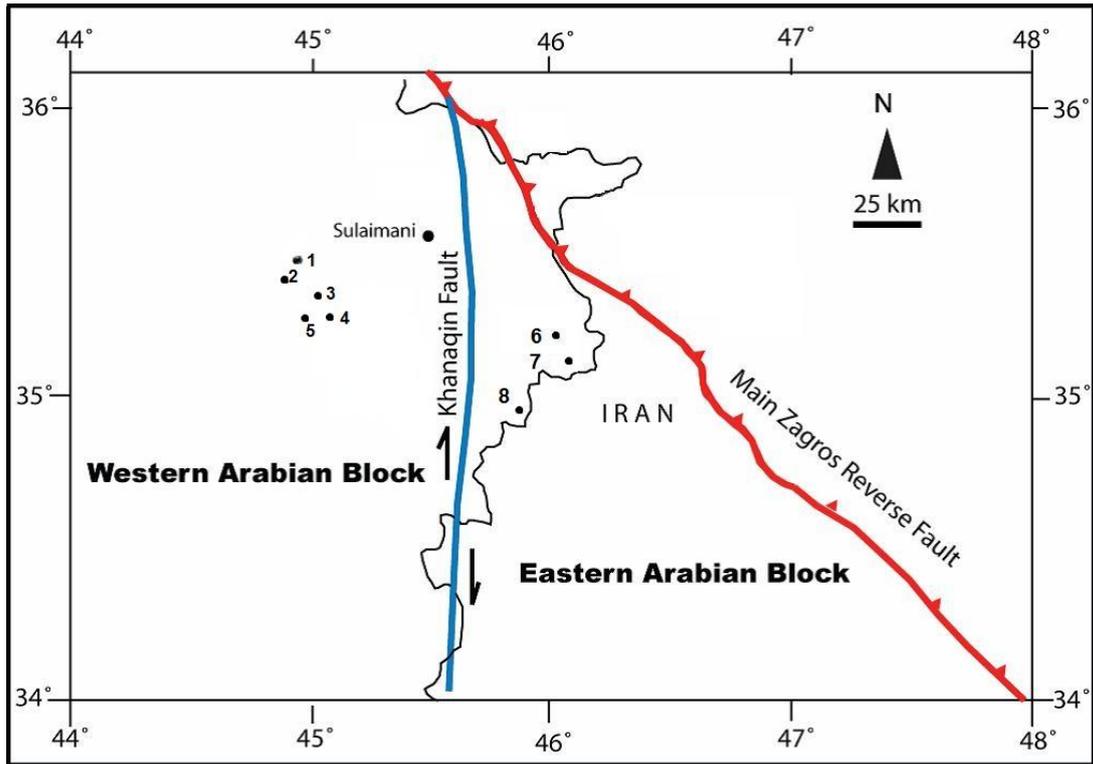


Figure 6.11: The north-south trending Khanaqin Fault crosses the study area (modified from Ibrahim, 2009). 1. Sagrma section, 2. Zinana village section, 3. Hazar Hani village section, 4. Core of the Aj Dagh Anticline section, 5. Awa Spi section, 6. Bamu Gorge section, 7. Bellula Gorge section and 8. Sharwal Dra section.

## Chapter Seven:

### Conclusions and Recommendations

#### 7.1 Conclusions:

The physical, petrographical, isotopic and trace elements investigations of the eight sections in the study area reveal several important conclusions; the main conclusions are listed as follows:

1. Presence of only some members of the Kirkuk Group with different thickness in all eight localities. The whole Kirkuk Group could not have been deposited in the study area because of their locations near to the periphery of the basin in addition to the configuration of the Kirkuk Basin due to local tectonic activity.
2. The study of benthic foraminifera and their correlation to the global shallow benthic zones (SBZ) of Cahuzac and Pognant (1997) and Serra-Kiel et al. (1998); reveals that the age of the Kirkuk Group in the study area corresponds to the Oligocene (Rupelian-Chattian) and Early Miocene (Aquitanian).
3. The biozones identified are composed of two Eocene biozones with three biozones from the Oligocene-Early Miocene of Kirkuk Group; from older to younger:
  - i. *Alveolina* biozone (AL);
  - ii. *Discocyclina* biozone (DI);
  - iii. *Nummulites fichteli* biozone (NF);
  - iv. *Praerhapydionina delicata* biozone (PD);

v. *Austrotrillina howchini* biozone (AH).

4. *Nummulites* rich Avana Formation from Late Eocene was incorrectly described as Sheikh Alas Formation of Early Oligocene by several authors. These *Nummulites* rich layers contain *Pellatispira* sp. which is the index fossil for the latest Late Eocene age and locates few metres before Eocene-Oligocene boundary.
5. Although the previous studies established the depositional environment of the Kirkuk Group as reefal, this study considers that deposition took place on a homoclinal carbonate ramp, because of lateral variations in microfacies; gradual deepening with no evidence of steep slope suggest that there was no effective barrier or slope break, and only patch reefs have been detected except in Sharwal Dra locality.
6. From the petrographical study, the microfacies indicates palaeoenvironments ranging from terrestrial to open marine settings (down-ramp) in nine microfacies zones. In addition to the distribution of foraminiferal assemblages allows the ramp to be divided into three parts: inner ramp; middle ramp and outer ramp.
7. The paragenetic sequence in the study area are classified into: (1) an eogenetic stage including micritization, peloidal marine cement, aragonite replacement, neomorphism, dolomitization and non-ferroan calcite cementation; (2) a mesogenetic stage including ferroan calcite cementation, fracture and compactions; and finally (3) a telogenetic stage including dissolution.
8. Ranges of bioclasts of known original mineralogy with micrite matrix from both shallow and deeper marine were selected from matrix-rich

microfacies in order to determine the source of the matrices in both shallow and deeper water. The result shows the different sources of “mud” across a ramp; inner-mid ramp muds have a hemi-pelagic source and could have been mostly sourced from high-Mg calcite benthic foraminifera and red algae, with little possibly of partial aragonite dominating; in contrast to the outer ramp muds “chalks”, were sourced from plankton, are largely composed of low-Mg calcite, as they are mineralogically stable. Although the exact origin would be difficult to ascertain after diagenesis.

9. Trace elements and oxygen-carbon isotopic values supports the SEM study that the inner-mid ramp microfacies underwent more alteration, possibly in meteoric fluids, in contrast to the outer ramp/basinal microfacies supports an origin from a more stable, likely low Mg-calcite precursor.
10. Two distinct rock fabrics and pore systems have been identified: (1) low microporosity inner-mid ramp microfacies. This may because of it was sourced from metastable precursors and were recrystallized and replaced under meteoric waters, undergoing loss of primary porosity; (2) higher microporosity outer ramp/basinal microfacies. It composed of more stable low-Mg calcite underwent less recrystallization and retained some primary porosity.
11. Shallow marine carbonates affected by sub-aerial exposure and meteoric diagenesis, in which meteoric dissolution resulting in the enhancement of secondary porosity, in addition to occluding primary porosity during stabilization of metastable minerals. Whereas, the

deeper marine carbonate remain without significant changes to primary porosity with little evidence of enhancing of secondary porosity.

12. The Kirkuk Group comprises of two 4th order sequences within one 3rd order sequence, in which the first 4th order sequence is located at Rupelian and composed of only the Sheikh Alas Formation. The second 4th order is located in Chattian-Early Aquitanian and composed of the Bajawan, Anah, Azkand and Ibrahim Formations.
13. Khanaqin Basement Fault cross-cut the study area into two parts and leads to developing two different depositional sequences with different thickness in each side of the fault.

## **7.2 Recommendations for future work:**

1. In addition to benthic foraminifera, planktonic foraminifera is another important component to determine the age of the Kirkuk Group successions.
2. Sr dating is also vital and important to emphasize the biostratigraphic aspects.
3. Well data and seismic profile across the study area is necessary for subsurface structural settings.
4. It is necessary to determine the porosity and permeability of the Kirkuk Group in order to evaluate the reservoir characteristic.
5. The Kirkuk Group strata needs more detailed study to investigate its hydrocarbon potential; as the study area can be an extension of the giant Kirkuk Oil Field.

## **References:**

- Abid, A. A., Sayyab, A. S., 1989. Restudy of the sortidae (foraminifera) of the Anah Formation (Late Oligocene-Early Miocene). *Bulletin of Iraqi Natural History Museum*, **2**, 15-57.
- Adams, C.G. 1967. Tertiary Foraminifera in the Tethyan, American and Indo Pacific Provinces. In Adams, C.G., and Ager, D.V. (eds.), *Aspects of Tethyan biogeography, Systematics Association, Special Publication*, London, **7**, 195-217.
- Adams, C.G. 1968. A revision of the foraminiferal genus *Austrorillina* parr. *Bulletin of the British Museum, Natural History, Geology Series*, **16**, 73-97.
- Adams, C.G. 1970. A reconsideration of the East Indian letter classification of the Tertiary. *Bulletin of the British Museum, Natural History, Geology Series*, **19**, 87-137.
- Adams, A. E., MacKenzie W. S., 1998. A colour atlas of carbonate sediments and rocks under the microscope. *Oxford University Press, USA*.
- Aigner, T., 1983. Facies and origin of nummulitic buildups: an example from the Giza Pyramids Plateau (Middle Eocene, Egypt). *Neues Jahrbuch für Geologie und Paläontologie. Abhandlungen*, **166**, 347–368.
- Al-Banna, N. Y. 1997. Sedimentological and stratigraphical study of the Upper Oligocene-Middle Miocene, west Mosul, Iraq. PhD. Thesis, *University of Mosul, Iraq*, 177 p.

- Al-Banna, N. Y., 2008. Stratigraphic Note: Oligocene/Miocene boundary in northern Iraq. *GeoArabia-Manama*, **13**, 187.
- Al-Banna, N. Y., Amin, M. A., Al-Hashimi, W. S. 2002. Oligocene-Miocene boundary in Sheikh Ibrahim and Sasan areas, northwest Iraq. *Iraqi Journal of Earth Science*, **2**, 37-47.
- Al-Eisa, M. E. 1992. The two subdepositional cycle of the Early Miocene in Kirkuk oil field area, north Iraq. *Journal of Geological Society of Iraq*, **25**, 41-58.
- Al-Hashimi, H. A. J., Amer, R. M. 1985. Tertiary microfacies of Iraq. *Directorate General for Geological Survey and Mineral Investigation*.
- Al-Husseini, M. I., 2008. Middle East geological time scale 2008. Cenozoic Era, Cretaceous and Jurassic periods of Mesozoic Era. *GeoArabia*, **13**, 1.
- Al-Juboury, A. I., McCann, T., 2008. The Middle Miocene Fat'ha (Lower Fars) Formation, Iraq. *GeoArabia* **13**, 141-174.
- Al-Naqib, K. M., 1960. Geology of the southern area of Kirkuk Liwa, Iraq. *2<sup>nd</sup> Arab Petroleum Congress, Beirut*, **2**, 45-81.
- Al-Qayim, B. A. J., Khaiwka, M. H., 1980. Depositional environment and diagenesis of the Oligocene reef cycles, Kirkuk Oil Field, northern Iraq. *Modern Geology*, **7**, 177-190.
- Al-Qayim, B., 2006. Sag-Interior Oligocene Basin of North-central Iraq: Sequence Stratigraphy and Basin Overview (abstract), *Middle East Conference and Exhibition; Manama, Bahrain*.
- Allen, M. B., Jackson, J., Walker, R., 2004. Late Cenozoic reorganization of the Arabia-Eurasia collision and the comparison of

the short term and long term deformation rates. *Tectonics*, **23**, TC2008, 1-16.

- Ameen, F. A., Koyi, H., Ibrahim, A. O., 2012. Tectonostratigraphy of the north-western segment of Zagros fold thrust belt. In press JPG.
- Ameen, F. A., Qadir, P. O., 2012. New Paleo-shorelines of the prolific Oligocene / Aquitanian sequences across Zagros Fold Thrust Belt. Kurdistan Region (N-Iraq). Abstract. EAGE. First workshop about hydrocarbon exploration and field development in Iraq. Istanbul.
- Amirshahkarami, M., Vaziri-Moghaddam, H., Taheri, A. 2007. Sedimentary facies and sequence stratigraphy of the Asmari Formation at Chaman-Bolbol, Zagros Basin, Iran. *Journal of Asian Earth Sciences*, **29**, 947-959.
- Andrews, J. E., 1991. Geochemical indicators of depositional and early diagenetic facies in Holocene carbonate muds, and their preservation potential during stabilisation. *Chemical Geology*, **93**, 267-289.
- Anketell, J. M., Mriheel, I. Y., 2000. Depositional environment and diagenesis of the Eocene Jdeir Formation, Gabes–Tripoli Basin, western offshore Libya. *Journal of Petroleum Geology*, **23**, 425–447.
- Anselmetti, F. S., Luthi, S., Eberli, G. P., 1998. Quantitative characterization of carbonate pore systems by digital image analysis. *American Association of Petroleum Geologist Bulletin*, **82**, 1815-1836.
- Aqrabi, A. A. M., Horbury, A. D., Goff, J.C., Sadoon, F.N., (2010). The Petroleum Geology of Iraq. *Scientific press*. 424pp.

- Ashquith, G. B., 1967. The marine dolomitization of the Mifflin Member Platteville Limestone in southwest Wisconsin. *Journal of sedimentary Petrology*, **37**, 311-326.
- Babashekh, S. M. R., 2000. Hydrogeochemistry of caves and springs in Sangaw- Chamchamal area in NE- Iraq. (Unpublished M.Sc Thesis), *College of Science, Baghdad University*.
- Baccelle, L., Bosellini, A. 1965. Diagrammi per la stima visiva: della composizione percentuale nelle rocce sedimentarie, *Università degli studi di Ferrara. Sezione IX, Scienze Geologiche e Paleontologiche*, **1**, 59-62.
- Bahroudi, A., Talbot, C. J., 2003. The configuration of the basement beneath the Zagros Basin. *Journal of Petroleum Geology*, **26**, 257-282.
- Baker, C., Jackson, J., Priestly, K., 1993. Earthquakes on the Kazerun line in the Zagros Mountains of Iran, strike-slip faulting within a fold and thrust belt. *Geophysics*, **115**, 41-61.
- Bandy, O. L., 1964. General correlation of foraminiferal structure with environment. In: Imbrie, J., Newell, N. (Eds.), *Approaches to Paleoecology*. Wiley, New York, pp. 75–90.
- Barzegar, F., 1994. Basement fault mapping of E Zagros folded belt (SW Iran) based on space-born remotely sensed data, 10th thematic conference on geologic remote sensing. *Exploration Environment and Engineering*, **10**, 455-466.
- Bassi, D., 1998. Coralline algal facies and their palaeoenvironments in the late Eocene of northern Italy (Calcare di Nago Trento). *Facies*, **39**, 179–202.

- Bassi, D., Hottinger, L., Nebelsick, J. H., 2007. Larger foraminifera from the upper Oligocene of the Venetian area, north-east Italy. *Palaeontology*, **50**, 845-868.
- Bassi, D., Nebelsick, J. H., 2010. Components, facies and ramps: Redefining Upper Oligocene shallow water carbonates using coralline red algae and larger foraminifera (Venetian area, northeast Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **295**, 258-280.
- Bathurst, R. G. C., 1971. Carbonate sediments and their diagenesis: Developments in Sedimentology. No. 12. *Elsevier, Amsterdam*, 620pp.
- Bathurst, R. G. C., 1975. Carbonate sediments and their diagenesis: Development in Sedimentology. Second enlarged edition. *Elsevier Science Ltd, Amsterdam*. 658pp.
- Beavington-Penny, S. J., Racey, A. 2004. Ecology of extant nummulitids and other larger benthic foraminifera: applications in palaeoenvironmental analysis. *Earth-Science Reviews*, **67**, 219-265.
- Beavington-Penny S. J., Wright, V. P., Woelkerling, W. J., 2004. Recognising macrophyte-vegetated environments in the rock record: a new criterion using 'hooked' forms of crustose coralline red algae. *Sedimentary Geology*, **166**, 1 –9.
- Behnam, H. A., 1975. Biostratigraphical study of the Lower and Upper Fars Formations at Hatra-Qaiyarah area, Jazira sesert, *Iraq*.
- Behnam, H. A., 1977. Stratigraphy and Palaeontology of Duhok-Ain Zalah area. *Baghdad*.

- Behnam, H. A. 1979. Stratigraphy and Paleontology of Khanaqin area NE Iraq. *D. G. of Geological Survey and Mineral Investigation. Iraq.*
- Bellen, R. C. V. 1956. The stratigraphy of the Main Limestone of the Kirkuk, Bai Hassan and Qara Chauq Dagh structures in Northern Iraq. *Journal of the Institute of Petroleum*, **42**, 233-263.
- Bellen, R. C. V., Dunnington, H., Wetzel, R., Morton, D. 1959. Lexique Stratigraphique, International. *Asie, Iraq*. 333p.
- Berberian, M., 1995. Master blind thrust faults hidden under the Zagros Folds: Active basement tectonics and surface morphotectonics, *Tectonophysics*, **241**, 193-224.
- Beydoun, Z. R., 1991. Arabian Plate hydrocarbon geology and potential a plate tectonic approach. *American Association of Petroleum Geology*, **33**, 77p.
- Borre, M., Fabricius, I. L., 1998. Chemical and mechanical processes during burial diagenesis of chalk: an interpretation based on specific surface data of deep-sea sediments. *Sedimentology*, **45**, 755-769.
- BouDagher-Fadel, M. K., 2008. Evolution and geological significance of larger benthic foraminifera, *Elsevier Science*. 540 pp.
- Boukhary, M., Abdelghany, O., Bahr, S., Hussein-Kamel, Y., 2005. Upper Eocene large foraminifera from the Dammam Formation in the United Arab Emirates along the Oman border. *Micropaleontology*, **51**, 487-504.
- Braithwaite, C. J. R., 1983. Calcrete and other soils in Quaternary limestones: structures, processes and applications. *Journal of the Geological Society*, **140**, 351-63.

- Brandano, M., Frezza, V., Tomassetti, L., Pedley, M., Matteucci, R., 2009. Facies analysis and palaeoenvironmental interpretation of the Late Oligocene Attard Member (Lower Coralline Limestone Formation), Malta. *Sedimentology*, **56**, 1138-1158.
  
- Brasier, M. D., 1975a. Ecology of Recent sediment-dwelling and phytal foraminifera from lagoons of Barbuda, West Indies. *Journal of Foraminiferal Research*, **5**, 42–62.
  
- Brasier, M. D., 1975d. An outline history of seagrass communities. *Palaeontology*, **18**, 681-702.
  
- Brewer, R., 1964. Fabric and Mineral Analysis of Soils. *Wiley, New York, N.Y.*, 470 pp.
  
- Brigaud, B., Vincent, B., Durlet, C., Deconinck, J. F., Blanc, P., Trouiller, A., 2010. Acoustic Properties of Ancient Shallow-Marine Carbonates: Effects of Depositional Environments and Diagenetic Processes (Middle Jurassic, Paris Basin, France). *Journal of Sedimentary Research*, **80**, 791-807.
  
- Buday, T., 1980. Regional Geology of Iraq: Vol. 1, Stratigraphy and paleogeography: IIM Kassab and SZ Jassim (Eds). *DG of Geological Survey and Mineral Investigation*. 445p.
  
- Budd, D. A., 2001. Permeability loss with depth in the Cenozoic carbonate platform of west-central Florida, *American Association of Petroleum Geologists Bulletin*, **85**, 1253-1272.
  
- Budd, D. A., 2002. The relative roles of compaction and early cementation in the destruction of permeability in carbonate grainstones:

a case study from the Paleogene of west-central Florida, USA. *Society for Sedimentary Geology*, **72**, 116-128.

- Burchette, T., Wright, V. P., 1992. Carbonate ramp depositional systems. *Sedimentary Geology*, **79**, 3-57.
- Buxton, M. W. N., Pedley, H. M., 1989. A standardized model for Tethyan Tertiary carbonate ramps. *Journal of the Geological Society*, **146**, 746-748.
- Cahuzac, B., Poignant, A., 1997. Essai de biozonation de l'Oligo-Miocène dans les bassins européens à l'aide des grands foraminifères néritiques. *Bulletin de la Société géologique de France*.
- Chafetz, H. S., 1986. Marine peloids; a product of bacterially induced precipitation of calcite. *Journal of Sedimentary Research*, **56**, 812-817.
- Chassefiere, B., Lundhardt, O. Levy, A., 1969. Données nouvelles sur les cadoules (édifices coquilliers) de la lagune de Thau (Hérault). *Compte Rendu Sommaire Des Seances De La Societe Geologique De France*, **5**, 140-142.
- Chesters, K. I. M., Gnauck, F. R., Huggies, N. F., 1967. Angiospermae. In Harland, W. B. et al. (eds.). *The Fossil Record*. *Geological Society, London*, **2**, 269-289.
- Choquette, P. W., Pray, L. C., 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. *American Association of Petroleum Geologists Bulletin*, **54**, 207-250.
- Colby, N., Boardman M. 1989. Depositional evolution of a windward, high-energy lagoon. Graham's Harbor, San Salvador, Bahamas. *Journal of Sedimentary Petrology*. **59**, 819-834.

- Ctyroky, P., Karim, S. A., 1971a. Stratigraphy and paleontology of the Oligocene and Miocene strata near Anah, Euphrates valley. *Manuscript report, Geosurv, Baghdad*.
- De Man, E., Van Simaey, S., 2004. Late Oligocene warming event in the southern North Sea basin: benthic foraminifera as paleotemperature proxies. *Netherlands Journal of Geosciences/ Geologie en Mijnbouw*, **83**, 227-239.
- DenHartog, C., 1970. Origin, evolution and geographical distribution of the sea-grasses. *Verhandelingen-Koninklijke Nederlandse Akademie van Wetenschappen Afdeling Natuurkunde*, **59**, 12–38.
- Deville de Periere, M., Durllet, C., Vennin, E., Lambert, L., Bourillot, R., Caline, B., Poli, E., 2011. Morphometry of micrite particles in cretaceous microporous limestones of the Middle East: Influence on reservoir properties. *Marine and Petroleum Geology*, **28**, 1727-1750.
- Dickson, J. A. D., 1965. A modified staining technique for carbonates in thin section. *Nature*, **205**, 587.
- Dickson, J. A. D., 1966. Carbonate identification and genesis as revealed by staining. *Journal of Sedimentary Petrology*, **36**, 491-505.
- Ditmar, V., Iraqi-Soviet team, 1971. Geological Conditions and Hydrocarbon Prospects of the Republic of Iraq-Northern and Central Parts. *Iraq National Oil Company Library, Baghdad (unpublished)*.
- Drobne, K., 1977. Alvéolines paléogènes de la Slovénie et de l'Istrie. *Schweiz Paläontol Abh*, **99**, 1–132.
- Drooger, C., Laagland, H., 1986. Larger foraminiferal zonation of the European-Mediterranean Oligocene. *Proceedings of the Koninklijke*

*nederlandse akademie van wetenschappen. Series B. Palaeontology, geology, physics, chemistry, anthropology.* **89**, 135-148.

- Dunham, R. J., 1962. Classification of carbonate rocks according to depositional texture. Classification of carbonate rocks: *American Association of Petroleum Geologists Memoir*, **1**, 108-121.
- Ehrenberg, S. N., McArthur, J. M., Pickard, N. A. H., Laursen, G. V., Monibi, S., Mossadegh, Z. K., Svana, T. A., Aqrawi, A. A. M., Thirlwall, M. F., 2007. Strontium isotope stratigraphy of the Asmari Formation (Oligocene- Lower Miocene), Southwestern Iran. *Journal of Petroleum Geology*, **30**, 107-128.
- Einsele, G., Ricken, W., Seilacher, A., 1991. Cycles and Events in Stratigraphy. *Springer-Verlag. New York.* 955pp.
- Ellis, A. C., Kerr, H. M., Cornwell, C. P., Williams, D. O., 1996. A Tectono-stratigraphic Framework for Yemen and its Implications for Hydrocarbon Potential. *Petroleum Geoscience*, **2**, 29-42.
- Embry, A. F., Klovan, J. E., 1971. A Late Devonian reef tract on northeastern Banks Island, NWT. *Bulletin of Canadian Petroleum Geology* **19**, 730.
- Enos, P., 1977. Holocene sediment accumulations of the south Florida Shelf margin. In: Enos, P., Perkins, R.D. (Eds.), Quaternary Sedimentation in South Florida. *Geological Society of America Memoir*, **147**, 1–130.
- Eva, A., 1980. Pre-Miocene seagrass communities in the Caribbean. *Palaeontology*, **23**, 231-236.
- Flügel, E., 1982. Microfacies analysis of limestone. Berlin-Heidelberg, New York. *Springer.* 633p.

- Flügel, E. 2004. *Microfacies of carbonate rocks: analysis, interpretation and application*, Springer Verlag. 984p.
- Folk, R. L., 1959. Practical petrographic classification of limestones. *American Association of Petroleum Geologist Bulletin*, **43**, 1-38.
- Folk, R. L., 1965. Some aspects of recrystallization in ancient limestones. In Pray, L. C., Murray, R. S. (eds). *Dolomitization and limestone diagenesis: Tulsa, OK. Petrology of Sedimentary Rocks*, **13**, 14-48.
- Folk, R. L., 1974. The natural history of crystalline calcium carbonate: effect of magnesium content and salinity. *Journal of Sedimentary Petrology*, **44**, 40-53.
- Fournier, F., Borgomano, J., 2009. Critical porosity and elastic properties of microporous mixed carbonate-siliciclastic rocks. *Society of Exploration Geophysicists*, **74**, E93-E109.
- Friedman, G.M., 1964. Early diagenesis and lithification in carbonate sediments. *Journal of Sedimentary Research*, **34**, 777-813.
- Gedik, F., 2008. Foraminiferal description and biostratigraphy of the Oligocene shallow marine sediments in Denizli region, SW Turkey. *Revue de Paléobiologie*, **27**, 25–41.
- Geel, T., 2000. Recognition of stratigraphic sequences in carbonate platform and slope deposits: empirical models based on microfacies analysis of Palaeogene deposits in southeastern Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **155**, 211-238.

- Ghafor I. M., 2004. Biometric Analysis of *Lepidocyclina* (Nephrolepidina) and *Miogypsinoides* from Baba and Azqand Formations (Oligocene-Miocene) in Kirkuk area, Iraq. (Ph.D Thesis), *College of science, Sulaimani University, Kurdistan*, 159p.
  
- Ghose, B.K., 1977. Paleoecology of the Cenozoic reefal foraminifers and algae—a brief review. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **22**, 231–256.
  
- Gilham, R.F., Bristow, C.S., 1998. Facies architecture and geometry of a prograding carbonate ramp during the early stages of foreland basin evolution: lower Eocene sequences, Sierra del Cadí, SE Pyrenees, Spain. In: Wright, V.P., Burchette, T.P. (Eds.), *Carbonate Ramps. Geological Society of London Special Publication*, **149**, 181–203.
  
- Goff, J. C., Jones, R. W., Horbury, A. D., 1995. Cenozoic basin evolution of the northern part of the Arabian plate and its Control on hydrocarbon habitats. In: Al-Hussein, M. I., (eds.). *Middle East Petroleum Geosciences. Gulf. Petro Link, Bahrain*, **94**, 402-412.
  
- Grabowski, G., Liu, C., 2008. Sequence stratigraphy and depositional history of the Eocene-Miocene carbonates and evaporites in the subsurface of the northern Mesopotamian Basin, northeast Iraq. In: *8th Middle East Geosciences Conference and Exhibition*, Bahrain, Manama (Abs.).
  
- Grabowski, G., Liu, C., 2009. Ages and Correlation of Cenozoic Strata of Iraq. *International Petroleum Technology Conference. Doha-Qatar*.
  
- Grabowski, G., Liu, C., 2010. Strontium-Isotope Age Dating and Correlation of Phanerozoic Anhydrites and Unfossiliferous Limestones of Arabia. *American Association of Petroleum Geologist, Middle East Geoscience Conference and Exhibition. Manama-Bahrain*.

- Grimsdale, T. F., 1977. Cretaceous and Tertiary foraminifera from the Middle East. *Bulletin of the British Museum (Natural History)*.
- Grover, G., Read, J., 1978. Fenestral and associated vadose diagenetic fabrics of tidal flat carbonates, Middle Ordovician New Market Limestone, southwestern Virginia. *Journal of Sedimentary Research*, **48**, 453.
- Hakimzaheh, S., Seyrafian, A., 2008. Late Oligocene-Early Miocene benthic foraminifera and biostratigraphy of the Asmari Formation south Yasuj, north-central Zagros basin, Iran. *Carbonates and Evaporites*, **23**, 1-10.
- Hallock, P., 1979. Trends in test shape with depth in large, symbiontbearing foraminifera. *Journal of Foraminiferal Research*, **9**, 61–69.
- Hallock, P., 1983. Larger foraminifera as depth indicators in carbonate depositional environments. *American Association of Petroleum Geologists Bulletin*, **67**, 477–478.
- Hallock, P., Glenn, E. C., 1986. Larger foraminifera: a tool for palaeoenvironmental analysis of Cenozoic depositional facies. *Palaios*, **1**, 55–64.
- Haq, B. U., Hardenbol, J., Vail, P. R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, **235**, 1156-1167.
- Hardie, L. A., 1977. Sedimentation on the modern carbonate tidal flats of northwest Andros Island, Bahamas. The Johns Hopkins University. *Studies in Geology*. **22**.

- Hardie, L. A., 1996. Secular variations in seawater chemistry: an explanation for the coupled secular variation in the mineralogies of marine limestones and potash evaporates over the past 600 m.y. *Geology*, **24**, 279-283.
- Hays, P. D., Grossman, E. L., 1991. Oxygen isotopes in meteoric calcite cements as indicators of continental paleoclimate, *Geology*, **19**, 441-444.
- Hedberg, H. D., 1976. International stratigraphic guide: A guide to stratigraphic classification, terminology, and procedure. *Wiley New York*. 199 pp.
- Henson, F. R. S., 1950a. Cretaceous and Tertiary reef formations and associated sediments in Middle East. *American Association of Petroleum Geology Bulletin*, **34**, 215–238.
- Henson, F. R. S., 1950b. Middle Eastern Tertiary Peneroplida (Foraminifera) with remarks on the phylogeny and taxonomy of the family. Thesis. *Leiden University, Netherlands*.
- Hessami, K., Koyi, H. A., Talbot, C.J., 2001a. The significance of strike-slip faulting in the basement of the Zagros Fold-Thrust Belt. *Journal of Petroleum Geology*, **24**, 5-28.
- Hird K, Tucker M. E., 1988. Contrasting diagenesis of two Carboniferous oolites from South Wales: a tale of climatic influence. *Sedimentology*, **35**, 587-602.
- Hottinger, L., 1960. Recherches sur les Alvéolines du Paléocène et de l'Éocène. *Schweiz Paläontol Abh.* **75**, 1–243.

- Hottinger, L., 1973. Selected Palaeogene larger foraminifera. In: Hallam, A. (Ed.), *Atlas of Palaeobiogeography*. Elsevier, Amsterdam, pp. 443–452.
- Hughes, G. W., Beydoun, Z. R., 1992. The Red Sea-Gulf of Adan: Biostratigraphy, lithostratigraphy and palaeoenvironments. *Journal of Petroleum Geology*, **15**, 135-156.
- Ibrahim, A. O., 2009. Tectonic style and evolution of the NE segment of the Zagros fold-thrust belt, Sulaimani Governorate. Kurdistan region, NE Iraq. PhD. Thesis. *University of Sulaimani, Sulaimani, Iraq*. 187pp.
- Imam, M. M., Galmed, M. A., 2000. Stratigraphy and microfacies of the oligocene sequence at Gabal Bu Husah, Marada Oasis, South Sirte Basin, Libya. *Facies*, **42**, 93-106.
- James, G. A., Wynd, J. G., 1965. Stratigraphic nomenclature of Iranian oil consortium agreement area. *Bulletin of American Association of Petroleum Geology*, **49**, 2182-2245.
- James, N. P., Kendall, A. C., 1992. Introduction to carbonate and evaporite facies models. In Walker, R. G., James, N. P. (Eds.). *Facies models: response to Sea-level changes*. *Geological Association of Canada*, pp. 265–275.
- Jassim, S. Z., Karim, S. A., Basi, M., Al-Mubarak, M. A., Munir, J., 1984. Final report on the regional geological survey of Iraq, Volume 3, Stratigraphy. Manuscript report, *Geological Survey of Iraq*.
- Jassim, S. Z., Goff, J. C., 2006. *Geology of Iraq*. Dolin. 341pp.
- Jones, R. W., Racey, A., 1994. Cenozoic stratigraphy of the Arabian Peninsula and Gulf. In: Simmons, M. D. (Ed.). *Micropalaeontology and*

*hydrocarbon exploration in the Middle East. Chapman and Hall, London, 273-303.*

- Kendall, C. G. S. C., Skipwith, P. A. E., 1969. Holocene shallow-water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, southwest Persian Gulf. *Assoc. Petroleum Geologists Bulletin*, **53**, 841-869.
- Kent, P. E., 1958. Recent studies of south Persian salt plugs. *American Association of Petroleum Geology*, **42**, 2951-2972.
- Kent, P. E., 1979. The emergent Hormuz salt plugs of Southern Iran. *Journal of Petroleum Geology*, **2**, 117-144.
- Ketzer, J. M. M., 2002. Diagenesis and Sequence Stratigraphy: An Integrated Approach to Constrain Evolution of Reservoir Quality in Sandstones. PhD. Thesis, *Acta Universitatis Upsaliensis, Uppsala*.
- Khanqa , P. A., Karim, S. A., Sissakian, V. K., Karim, K. H., 2009. Lithostratigraphic study of a Late Oligocene-Early Miocene succession, south of Sulaimaniyah, NE Iraq. *Iraqi Bulletin of Geology and Mining*, **5**, 41-57.
- Kharajiany, S. O. A., 2008. Sedimentary facies of Oligocene rock units in Ashdagh mountain-Sangaw District-Kurdistan Region. MSc. Thesis (un-published). *University of Sulaimani. Sulaimani*. 106p.
- Kuile, B. T., Erez J., 1984. In situ growth rate experiments on the symbiont-bearing foraminifera *Amphistegina lobifera* and *Amphisorus hemprichii*. *The Journal of Foraminiferal Research*, **14**, 262-276.
- Lackpour, M., Chilingar, G., Kalantari,, A. 2008. Asmari Limestone of Iran: A giant of oil and gas Production. *Energy Sources-Part A Recovery Utilization and Environmental Effects*, **30**, 1523-1533.

- Lambert, L., Durlet, C., Loreau, J. P., Marnier, G., 2006. Burial dissolution of micrite in Middle East carbonate reservoirs (Jurassic-Cretaceous): keys for recognition and timing. *Marine and Petroleum Geology*, **23**, 79-92.
- Land, L. S., 1967. Diagenesis of skeletal carbonates. *Journal of Sedimentary Petrology*, **37**, 914-930.
- Larsen, A. R., 1976. Studies of recent Amphistegina: taxonomy and some ecological aspects. *Israel Journal of Earth-Sciences*, **25**, 1–26.
- Lasemi, Z., Sandberg P. A., 1983. Recognition of original mineralogy in ancient micrites [abs.]. *American Association of Petroleum Geologists Bulletin*, **67**, 499-500.
- Lasemi, Z., Sandberg P. A., 1984. Transformation of aragonite-dominated lime muds to microcrystalline limestones. *Geology*, **12**, 420-423.
- Lasemi, Z., Sandberg P. A., 1993. Microfabric and compositional clues to dominant mud mineralogy of micrite precursors. *Springer Verlag*, 173-185.
- Lasemi, Z., Sandberg, P. A., Boardman, M. R., 1990. New microtextural criterion for differentiation of compaction and early cementation in fine-grained limestones. *Geology*, **18**, 370-373.
- Lawa, F. A. A., Ali, S. S., Kareem. K. H., 2000. Geological and hydro geological survey of Sulaimanyiah and Kirkuk area. Part one. Cross-sections. *FAO. UN agency Baghdad-Iraq*. 220pp, 20 maps.

- Lawa F. A. A., Ali. S. S., Kareem. K. H., 2001. Geological and hydro geological survey of Sulaimanyiah and Kirkuk area. Part two. Cross sections. *FAO. UN agency Baghdad-Iraq*. 311pp, 20 maps.
  
- Lawa F. A. A., 2004. Sequence stratigraphic analysis of the Middle Paleocene-Middle Eocene in the Sulaimani District (Kurdistan Region). PhD. Thesis. University of Sulaimani. Sulaimani. 239p.
  
- Laursen, G. V., Mobini, S., Allan, T.vL., Pickard, N. A. H., Hosseiney, A., Vincent, B., Hamon, Y., Van-Buchem, F. S. P., Moallemi, A., Druillion, G., 2009, The Asmari Formation revisited: changed stratigraphic allocation and new biozonation: Shiraz, First International Petroleum Conference and Exhibition, European Association of Geoscientists and Engineers.
  
- Liu, C., Steinhaff, M., Mitchell, J., 2006. Evolution of the Mesopotamian Basin (Iraq): Campanian to Neogene. *GEO Middle East Conference and Exhibition; Manama, Bahrain (Abs.)*.
  
- Liu, Z., Pagani, M., Zinniker, D., DeConto, R., Huber, M., Brinkhuis, H., Shah, S. R., Leckie, R. M., Pearson, A., 2009. Global cooling during the Eocene-Oligocene climate transition. *Science*, **323**, 1187-1190.
  
- Loucks, R. G., Moody, R. T. J., Bellis, J. K., Brown, A. A., 1998. Regional depositional setting and pore network systems of the El Garia Formation (Metlaoui Group, lower Eocene), offshore Tunisia. In: MacGregor, D.S., Moody, R.T.J., Clark-Lowes, D.D. (Eds.), *Petroleum Geology of North Africa. Geological Society of London, Special Publication*, **132**, 355–374.
  
- Lowenstam, H. A., 1961, Mineralogy,  $^{18}\text{O}/^{16}\text{O}$  ratios, and strontium and magnesium contents of recent and fossil brachiopods and their bearing on the history of the oceans. *Journal of Geology*, **69**, 241–260.

- Luterbacher, H., 1998. Sequence stratigraphy and the limitations of biostratigraphy in the marine Paleogene strata of the Tremp Basin (central part of the southern Pyrenean foreland basin, Spain). In: De Graciansky, P.C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. Society for Sedimentary Geology Special Publication*, **60**, 303–309.
  
- Macintyre, I. G., 1984. Extensive submarine lithification in a cave in the Belize barrier reef platform. *Journal of Sedimentary Petrology*, **54**, 221-235.
  
- Macintyre, I. G., 1985. Submarine cements-The peloidal question. In Schneidermann, N., Harris P. M., Eds. *Carbonate cements. The Society of Economic palaeontologists and mineralogists, Special publication*, **36**, 109-116.
  
- Majid, A. H., Veizer, J. A. N., 1986. Deposition and Chemical Diagenesis of Tertiary Carbonates, Kirkuk Oil Field, Iraq. *AAPG Bulletin*, **70**, 898-913.
  
- Makris, J., Henke, C. H., 1992. Pull-apart evolution of the Red Sea. *Journal of Petroleum Geology*, **15**, 127-134.
  
- Man, E. De, Simaey S. Van, 2004. Late Oligocene Warming Event in the southern North Sea Basin: benthic foraminifera as paleotemperature proxies. *Netherlands Journal of Geosciences*.**83**, 227-239.
  
- Mapstone, N. B., 1975. Diagenetic history of a North Sea chalk. *Sedimentology*, **22**, 601-614.

- Marshall, J. F., Davies, P. J., 1981. Submarine lithification on windward reef slopes; Capricorn-Bunker Group, southern Great Barrier Reef. *Journal of Sedimentary Petrology*, **51**, 953-960.
- Martin, G. D., Wilkinson, B. H., Lohmann, K. C., 1986. The role of skeletal porosity in aragonite neomorphism-Strombus and Montastrea from the Pleistocene Key Largo limestone, Florida, *Journal of Sedimentary Research*, **56**, 194-203.
- Mazzullo, S. J., Bischoff, W. D., 1992. Meteoric calcitization and incipient lithification of recent high-magnesium calcite muds, Belize. *Journal of Sedimentary Petrology*, **62**, 196-207.
- Melzer, S. E., Budd, D. A., 2008. Retention of high permeability during shallow burial (300 to 500 m) of carbonate grainstones. *Journal of Sedimentary Research*, **78**, 548-561.
- Miller, K. G., Browning, J. V., Aubry, M. P., Wade, B. S., Katz, M. E., Kulpecz, A. A., Wright, J. D., 2008. Eocene Oligocene global climate and sea-level changes: St. Stephens Quarry, Alabama. *Bulletin of the Geological Society of America*, **120**, 34.
- Molenaar, N., Zijlstra, J. J. P., 1997. Differential early diagenetic low-Mg calcite cementation and rhythmic hardground development in Campanian–Maastrichtian chalk. *Sedimentary Geology*, **109**, 261–281.
- Montanez, I. P., 2002. Biological skeletal carbonate records changes in major-ion chemistry of paleo-oceans. *Proceedings of the National Academy of Sciences*, **99**, 15852-15854.
- Moody, R. T. J., 1987. The Ypresian carbonates of Tunisia—a model of foraminiferal facies distribution. In: Hart, M.B. (Ed.), *Micropalaeontology*

of Carbonate Environments. *British Micropalaeontology Society Series, Ellis Horwood, U.K.*, pp. 82–92.

- Morrow, D. W., Mcllreath, I. A., 1990. Diagenesis, general introduction. *In Diagenesis* (ed. Mcllreath I. A., Morrow D. W.), *Geoscience Canada, Reprint Series, 4*, 165-76.
- Moshier, S. O., 1989. Microporosity in micritic limestones: a review. *Sedimentary Geology, 63*, 191-213.
- Muhammed, Q. A., 1983. Biostratigraphy of Kirkuk Group in Kirkuk and Bai-Hassan areas. MSc. Thesis. *University of Baghdad. Baghdad-Iraq*.
- Mukhopadhyay, S., 2003. A rare foraminiferal assemblage with new species of *Nummulites* and *Globigerina* from the Eocene-Oligocene transition strata of Cambay Basin, India. *Micropaleontology, 49*, 65.
- Mukhopadhyay, A., Al-Sulaimi, J., Al-Awadi, E., Al-Ruwaih, F., 1996. An Overview of the Tertiary Geology and Hydrogeology of the Northern Part of the Arabian Gulf Region with Special Reference to Kuwait. *Earth-Science Reviews, 40*, 259-295.
- Munnecke, A., Westphal, H., Reijmer, J. J. G., Samtleben, C., 1997. Microspar development during early marine burial diagenesis: a comparison of Pliocene carbonates from the Bahamas with Silurian limestones from Gotland. *International Association of Sedimentologists, 44*, 977-990.
- Munnecke, A., Westphal, H., 2005. Variations in primary aragonite, calcite, and clay in fine-grained calcareous rhythmites of Cambrian to Jurassic age-an environmental archive?. *Facies, 51*, 592-607.

- Munnecke, A., Westphal, H., Kölbl-Ebert, M., 2008. Diagenesis of plattenkalk: examples from the Solnhofen area (Upper Jurassic, southern Germany). *Sedimentology*, **55**, 1931-1946.
- Murray, R. C., 1960. Origin of porosity in carbonate rocks. *Journal of Sedimentary Petrology*, **30**, 59-84.
- Murray, J. W., 1965. The Foraminiferida of the Persian Gulf. 2. The Abu Dhabi Region. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **1**, 307-332.
- Murray, J. W., 1966. The Foraminiferida of the Persian Gulf. 3. The Halat al Bahrani region. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **2**, 59-68.
- Nebelsick, J.H., Bassi, D., Drobne, K., 2000. Microfacies analysis and palaeoenvironmental interpretation of lower Oligocene, shallow-water carbonates (Gornji Grad Beds, Slovenia). *Facies*, **43**, 157–176.
- Nebelsick, J. H., Rasser, M. W., Bassi, D., 2005. Facies dynamics in Eocene to Oligocene circumalpine carbonates. *Facies*, **51**, 197-217.
- Numan, N. M. S., 2000. Major Cretaceous tectonic events in Iraq. : *Rafidain Journal Society*, **11**, 32-54.
- Okhravi R., Amini A., 1998. An example of mixed carbonate-pyroclastic sedimentation (Miocene, Central Basin, Iran). *Sedimentary Geology*, **118**, 37-57.
- Palike, H., Norris, R. D., Herrle, J. O., Wilsom, P. A., Coxall, H. K., Lear, C. H., Shackleton, N. J., Tripathi, A. K., Wade, B. S., 2006. The heartbeat of the Oligocene climate system. *Science*, **314**, 1894.

- Pedley H. M., 1996. Concepts in sedimentology and palaeontology, models for carbonate stratigraphy from the Miocene reefs of the Mediterranean region. In: Franseen E. R., Esteban M., Ward W. C., Rouchy J. M. (Eds). Miocene reef distributions and their associations in the Central Mediterranean region: An overview. *Society of Economic Paleontologists and Mineralogists, Special Publications*, **5**, 73–87.
- Perry, C. T., 1998. Grain susceptibility to the effects of micro-boring: Implications for the preservation of skeletal carbonates. *Sedimentology*, **45**, 39-51.
- Perry, C. T., Salter, M. A., Harborne, A., R., Crowley, S. F., Jelks, H. L. Wilson, R. W., 2011. Fish as major carbonate mud producers and missing components of the tropical carbonate factory. *Proceedings of the National Academy of Sciences*, **108**, 3865-3869.
- Pomar, L., 2001. Types of carbonate platforms: a genetic approach. *Basin Research*, **13**, 313-334.
- Ponikarov, V. P., Kazmin, V. C., Mikhailov, I. A., Razvaliyev, A. V., Krashennnikov, V. A., Kozlov, V. V., Souliidi-kondra-tiyev, B. D., Mikhailov, K. Y., Kulskov, V. V., Faradzhev, V. A., Mirzayev, K. M., 1967. The geology of Syria. Part 1, 94p.
- Posamentier, H. W., Jervey, M. T. and Vail, P. R., 1988: Eustatic controls on clastic desposition I. Concetual framwork. In: Wilgus, C. K., Hastings, B. S, Kendall, C. G. st. C., Posamentier, H. W., Ross, C. A., Van Woonger, J. C., (eds.). *Sea Level Changes - an integrated approach. SEPM Special publication*, **42**, 109-124.
- Prothero, D. R., Schwab, F. L., 2004. Sedimentary geology: an introduction to sedimentary rocks and stratigraphy. *WH Freeman*.

- Purser, B. H., 1985. Dedolomite porosity and reservoir properties of Middle Jurassic carbonates in the Paris Basin, France. *Carbonate Petroleum Reservoirs: Berlin, Springer*. 341-356.
- Pusey, W. C., 1975. Holocene carbonate sedimentation on northern Belize Shelf. In: Wantland, K.F., Pusey, W.C. (Eds.), *Belize Shelf-Carbonate Sediments, Clastic Sediments, and Ecology. American Association of Petroleum Geology*, **2**, 131–233.
- Racey, A., 1994. Biostratigraphy and palaeobiogeographic significance of Tertiary nummulitids (foraminifera) from northern Oman. In: Simmons, M.D. (Ed.), *Micropalaeontology and Hydrocarbon Exploration in the Middle East. Chapman and Hall, London*, 343-370.
- Racey, A., 2001. A review of Eocene *Nummulite* accumulations: structure, formation and reservoir potential. *Journal of Petroleum Geology*, **24**, 79-100.
- Ra'cz, L., 1979. Paleocene carbonate development of Ras al Hamra, Oman. *Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine*, **3**, 767–779.
- Reichel, M., 1964. Alveolinidae. In: Moore, R.C. (Ed.), *Treatise on Invertebrate Paleontology, Part C. Protista, vol. 2. University of Kansas Press, Lawrence, KA*, pp. 503–510.
- Richard, J., Sizun, J. P., Machhour, L., 2007. Development and compartmentalization of chalky carbonate reservoirs: The Urgonian Jura-Bas Dauphine platform model (Genissiat, southeastern France). *Sedimentary Geology*, **198**, 195-207.
- Romero J., Caus E., Rossel J., 2002. A model for the paleoenvironmental distribution of larger foraminifera based on late

- Middle Eocene deposits of the margin of the south Pyrenean basin (NE Spain). *Palaeogeography, Palaeoclimate and palaeoecology*, **179**, 43-56.
- Sampo, M., 1969. Microfacies and microfossils of the Zagros area, southwestern Iran (from Permian to Miocene). *Leiden*.
  - Sandberg, P. A., 1985. Nonskeletal aragonite and pCO<sub>2</sub> in the Phanerozoic and Proterozoic. *American Geophysical Union Monograph*, **1**, 585-594.
  - Sartorio, D., Venturini, S., 1988. Southern Tethys biofacies. *Agip, Milan*, 235 pp.
  - Schlager, W., 1998. Exposure drowning and sequence boundary on carbonates platform. In Camoin, G. F., and Davies, P. J., (eds.) Reefs and carbonate platforms in the Pacific and Indian Oceans. *Oxford, Alden Press*, **25**, 3–21.
  - Schlager, W., 1999: Type 3 sequence boundaries. *Society for sedimentary geology, special a publication*, **63**, 5-45.
  - Schlager, W., 2002. Sedimentology and sequence stratigraphy of carbonate rocks. *Amsterdam, Vrije Universiteit/ Earth and Life Sciences*. 146 pp.
  - Schlager, W., 2005. Carbonate sedimentology and sequence stratigraphy. *Amsterdam, Netherlands, Vrije Universiteit/ Faculty of Earth and Life Sciences*. 200pp.
  - Schmidt, V., 1965. Facies, diagenesis, and related reservoir properties in the Gigas Beds (Upper Jurassic), Northwestern Germany. In: Pray, K. C., Murray, R.C. (eds.) Dolomitization and limestone diagenesis.

*Society of Economic Paleontologists and Mineralogists, Special publication*, **13**, 124-168.

- Scholle, P. A., 1977. Chalk diagenesis and its relation to petroleum exploration: oil from chalks, a modern miracle. *American Association of Petroleum Geologists Bulletin*, **61**, 982-1009.
- Scholle, P. A., Ulmer-Scholle, D. S., 2003. A Color Guide to the Petrography of Carbonate Rocks: Grains, textures, porosity, diagenesis. *The American Association of Petroleum Geologists Memoir* Tulsa, Oklahoma, U.S.A. 459pp.
- Sengupta, S., 2000. Problems of classifying early Oligocene reticulate Nummulites (Foraminiferida) from southwestern Kutch, Gujarat. *Journal-Geological Society of India*. **56**, 673-678.
- Sengupta, S., 2002. A Note on Test Shape of *Nummulites cf. fichteli* Michelloti Form A (Foraminiferida) from the Early Oligocene deposit of southwestern Kutch, India. *Journal-Geological Society of India*, **60**, 223-224.
- Sepher, M., 2001. The tectonic significance of the Kazerun fault zone, Zagros Fold-Thrust Belt, Iran. Ph.D. Thesis, *Imperial College, London*. 237p.
- Serra-Kiel J., Regunanat., S., 1984. Paleoecological conditions and morphological variation in monospecific banks of Nummulites: an example. Bulletin des Centres de Recherches Exploration Production Elf-Aquitaine. *Memoire*, **6**, 557-563.
- Serra-Kiel, J., Hottinger, L., Caus, E., Drobne, K., Ferrandez, C., Jauhri, A. K., Less, G., Paclovec, R., Pignatti, J., Samsó, J. M., Schaub,

- H., Sirel, E., Strougo, A., Tambareau, Y., Tosquella, J., Zakrevskaya, E., 1998. Larger foraminiferal biostratigraphy of the Tethyan Paleocene and Eocene. *Bulletin of Society of Geology De la France*, **169**, 281-299.
- Seyrafian, A., Vaziri-Moghaddam, H., Arzani, N., Taheri, A., 2011. Facies analysis of the Asmari Formation in central and north-central Zagros basin, southwest Iran: Biostratigraphy, paleoecology and diagenesis. *Revista Mexicana de Ciencias Geológicas*, **28**, 439-458.
  - Shakeri, A., Douraghinejad, J., Moradpour, M., 2007. Microfacies and sedimentary environments of the late Oligocene-early Miocene Qom Formation of the Gooreh Berenji region (Jandaq area, central Iran). *GeoArabia-Manama*, **12**, 41.
  - Sharbazheri, K. M. E., 1983. Study of foraminifera and microfacies of the Avanah limestone [Middle Eocene], Dohuk area, North Iraq. MSc. Thesis. *University of Mosul, Iraq*.
  - Sharland, P. R., Archer, R., Casey, D. M., Davies, R.B., Hall, S.H., Heward, A.P., Horbury, A.D., Simmons, M. D., 2001. Arabian Plate Sequence Stratigraphy. *GeoArabia, special publication, Gulf Petrol. Ink*, Bahrain, 321p.
  - Sharland, P. R., Archer, R., Casey, D. M., Davies, R. B., Simmons, M. D., Sutcliffe, O. E., 2004. Arabian plate sequence stratigraphy-revisions to SP2. *GeoArabia*, **9**, 199-214.
  - Sibley, D. F., Gregg, J. M., 1987. Classification of dolomite rock textures. *Journal of Sedimentary Research*, **57**, 967-975.

- daSilva, A. C., Loisy, C., Cerepi, A., Toullec, R., Kiefer, E., Humbert, L., Razin, P., 2009. Variations in stratigraphic and reservoir properties adjacent to the Mid-Paleocene sequence boundary, Campo section, Pyrenees, Spain. *Sedimentary Geology*, **219**, 237-251.
  
- Simmons, M. D., Sharland, P. R., Casey, D. M., Davies, R. B., Sutcliffe, O. E., 2007. Arabian Plate sequence stratigraphy: potential implications for global chronostratigraphy, *GeoArabia*, **12**, 101-130.
  
- Sinclair, H. D., Sayer, Z. R., Tucker, M. E., 1998. Carbonate sedimentation during early foreland basin subsidence: the Eocene succession of the French Alps. In: Wright, V.P., Burchette, T.P. (Eds.), Carbonate Ramps. *Geological Society of London Special Publication*, **149**, 205–227.
  
- Sirel, E., 2003. Foraminiferal description and biostratigraphy of the Bartonian, Priabonian and Oligocene shallow-water sediments of the southern and eastern Turkey. *Revue de Paléobiologie*, Genève, **22**, 269-339.
  
- Sissakian, V. K., Al-Kadhmi, J. A. M., Deikran, D. B., Fattah, A. S., 1996. Tectonic Map of Iraq, *State establishment of Geological survey and Mining, Ministry of Industry and Minerals, Baghdad, Republic of Iraq*.
  
- Smout, A., Eames, F. E., 1958. The genus *Archaias* (Foraminifera) and its stratigraphical distribution. *Paleontology*, **1**, 207-223.
  
- Stanley, S. M., Hardie, L. A., 1999. Hypercalcification: paleontology links plate tectonics and geochemistry to sedimentology. *GSA Today*, **9**, 1–19.

- Stanley, S. M., Ries, J. R., Hardie, L. A., 2002. Low-magnesium calcite produced by corraline algae in seawater of Late Cretaceous composition. *Proceedings of the National Academy of Sciences*, **99**, 15323-15326.
- Steinen, R. P., 1978. On the diagenesis of lime mud: Scanning electron microscopic observations of subsurface material from Barbados, W. I. *Journal of Sedimentary Petrology*, **48**, 1139-1148.
- Sun S. Q., Wright, V. P., 1989. Peloidal fabrics in Upper Jurassic reefal limestone, Weald basin, southern England. *Sedimentary Geology*, **65**, 165-181.
- Sun S. Q., Wright, V. P., 1998. Controls on reservoir quality of an Upper Jurassic reef mound in the Palmers Wood Field area, Weald Basin, southern England. *American Association of Petroleum Geologists Bulletin*, **82**, 497-515.
- Towe, K. M., Hemleben, C., 1976. Diagenesis of magnesian calcite: evidence from miliolacean foraminifera. *Geology*, **4**, 337-339.
- Tucker, M. E., 1985. Shallow-marine carbonate facies and facies models. *Geological Society of London, Special Publications*, **18**, 147-169.
- Tucker, M. E., Wright, V. P., Dickson, J., 1990. Carbonate sedimentology. Wiley-Blackwell.
- Vail, P. R., Mitchum, R. M., Todd, R. G., Widmier, J. M., Thompson, S., Sangree, J. B., Bubb, J. N., Hatlelid, W. G., 1977. Seismic stratigraphy and global changes of sea level, Part 3. In C. E. Payton, ed., *Seismic Stratigraphy - Applications to Hydrocarbon Exploration*. *American Association of Petroleum Geologists Memoirs*, **26**, 63-81.

- Vail, P. R., Audemard, F., Bowman, S. A., Eisner, P. N., Perez-Cruz, G., 1991. The stratigraphic signature of tectonics, eustasy, and sedimentation. In G. Einsele, W. Ricken, and A. Seilacher, (eds.). Cycles and events in Stratigraphy: Part II: Larger Cycles and Sequences. *Springer-Verlag, Berlin*, p. 617-659.
  
- Van Wagoner, J. C., Mitchum, R. M., Campion, K. M., and Rahmanian, V. D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops for high-resolution correlation of time and facies. *AAPG Methods in Exploration Series*, **7**, 55pp.
  
- Van Wagoner, J. C., 1995. Sequence stratigraphy and marine to non-marine facies architecture of foreland basin strata, Book Cliffs, Utah, USA. In: Van Wagoner, J. C., Bertram, G. T., (edi.). Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and subsurface examples from the Cretaceous of North America. *American Association of Petroleum Geology*, **64**, 137-224.
  
- Vaziri-Moghaddam, H., Kimiagari, M., Taheri, A., 2006. Depositional environment and sequence stratigraphy of the Oligo-Miocene Asmari Formation in SW Iran. *Facies*, **52**, 41-51.
  
- Volery, C., Davaud, E., Foubert, A., Caline, B., 2009. Shallow-marine microporous carbonate reservoir rocks in the Middle East: relationship with seawater Mg/Ca ratio and eustatic sea level. *Journal of Petroleum Geology*, **32**, 313–325.
  
- Volery, C., Davaud, E., Foubert, A., Caline, B., 2010a. Lacustrine microporous micrites of the Madrid Basin (Late Miocene, Spain) as analogues for shallow-marine carbonates of the Mishrif reservoir Formation (Cenomanian to Early Turonian, Middle East). *Facies*, **56**, 385–397.

- Volery, C., Davaud, E., Durllet, C., Clavel, B., Charollais, J., Caline, B., 2010b. Microporous and tight limestones in the Urgonian Formation (Late Hauterivian to Early Aptian) of the French Jura Mountains: focus on the factors controlling the formation of microporous facies. *Sedimentary Geology*, **230**, 21–34.
- Volery, C., Suvorova, E., Buffat, P., Davaud, E., Caline, B., 2011. TEM study of Mg distribution in micrite crystals from the Mishrif reservoir Formation (Middle East, Cenomanian to Early Turonian). *Facies*, **57**, 605-612.
- Wade, B. S., Palike, H., 2004. Oligocene climate dynamics. *Paleoceanography*, **19**, 4019.
- Ward, W., 1975. Petrology and diagenesis of carbonate eolianites of northeastern Yucatan Peninsula, Mexico. *Carbonate Sediments, Clastic Sediments, and Ecology*, **2**, 500–571.
- Webb, G. E., Nothdurft, L. D., Kamber, B. S., Kloprogge, J. T., Zhao, J. X., 2009. Rare earth element geochemistry of scleractinian coral skeleton during meteoric diagenesis: a sequence through neomorphism of aragonite to calcite. *Sedimentology*, **56**, 1433-1463.
- Weijermars, R., 1998. Plio-Quaternary movement of the East Arabian block. *GeoArabia*, **3**, 509-540.
- Westphal, H., 1998. Carbonate platform slopes: a record of changing conditions. Lecture Notes in Earth Sciences, 75. Berlin, Heidelberg, New York, *Springer Verlag*, 179 pp.
- Wheeley, J. R., 2006. Taphonomy, sedimentology and palaeoenvironmental interpretation of Middle Ordovician Limestones,

Jamtland, Sweden. Unpublished PhD thesis, *Cardiff University, Earth-Sciences Department*. 198pp.

- Wieder, M., Yaalon D., 1974. Effect of matrix composition on carbonate nodule crystallization. *Geoderma*, **11**, 95-121.
- Wilson, J. L., 1975. Carbonate Facies in Geologic History. *Springer Verlag*. 471p.
- Winland, H. D., 1968. The role of high Mg calcite in the preservation of micrite envelopes and textural features of aragonite sediments. *Journal of Sedimentary Research*, **38**, 1320-1325.
- Wolf, K. H., Conolly J. R., 1965. Petrogenesis and paleoenvironment of limestone lenses in Upper Devonian red beds of New South Wales. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **1**, 69-111.
- Wright, V. P., 1982b. Calcrete palaeosols from the Lower Carboniferous Llanelly Formation, South Wales. *Sedimentary geology*, **33**, 1-33.
- Wright, V. P. 1992. A revised classification of limestones. *Sedimentary geology*, **76**, 177-185.
- Wright, V. P., 2006. Carbonate Depositional Systems: Reservoir Sedimentation and Diagenesis. Course Notes, Geoscience Training Alliance (unpublished) *Nautilus, Hermitage, UK*.
- Wright, V. P., Tucker M. E. 1991. Calcretes: an introduction. *International Association of Sedimentologists*, **2**, 1-22.

- Wright, V. P., Alonso Zarza A. M., Sanz, M. E., Calvo, J. P., 1997. Diagenesis of Late Miocene micritic lacustrine carbonates, Madrid Basin, Spain, *Sedimentary Geology*, **114**, 81-95.
- Wu, Y., Wu, Z., 1996. Two-phase diagenetic alteration of carbonate matrix: Middle Ordovician limestones, Taiyuan City area, China. *Sedimentary Geology*, **106**, 177-191.
- Youkhanna, R. Y., Hradecky, P., 1977. Report on Regional Geological Mapping of Khanaqin - Maidan Area (Part I), *Geological Survey Department, State Organization of Geological Survey and Mineral Investigation*.
- Youhanna, A. K., 1983. Biostratigraphy of some Tertiary and Cretaceous formations. Khleissia well no.1, northwest Iraq. (Unpublished report), *INOC Geological labs, Baghdad*. 30p.
- Zachos, J. C., Quinn, T. M., Salamy, K. A., 1996. High-resolution (10<sup>4</sup> years) deep-sea foraminiferal stable isotope records of the Eocene-Oligocene climate transition. *Paleoceanography*, **11**, 251-266.
- Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present. *Science*, **292**, 686-693.
- Ziegler, M. A., 2001. Late Permian to Holocene Paleofacies Evolution of the Arabian Plate and its Hydrocarbon Occurrences. *GeoArabia*, **6**, 60p.

## **APPENDICES:**

### **Appendix 1: Methodology:**

Two field seasons took place in northern Iraq in the spring and summer of 2008 and 2009. Eight localities were chosen for study in four different structures; Aj Dagh, Sagrama, Bamu and Sharwal Dra Anticlines. In Aj Dagh anticline four localities were selected in order to 1) assure the doubt of lots of researchers about whether the Kirkuk Group succession is present or not and 2) to correct the wrong designation of Late Eocene Avanah Formation as the Early Oligocene Sheikh Alas Formation in previous studies. In the other four localities in those three structures it was expected to have multiple examples of the Kirkuk Group succession. In this study area there were few old reports mentioned that the Kirkuk Group may present in some of these structures without having a detailed work on the area. These sections are expected to be as a part of extension of a giant structure of Kirkuk Oil Field in Kirkuk area.

Samples were collected according to change in physical property of the limestone where obvious lithofacies changes occurred and or every almost one to two metres with no obvious change. The section was also logged during the sample collection. All the hand specimen samples were brought back to Sulaimani University in order to saw the small hand specimen to be ready for making thin-sections and making core samples with 5 cm diameter and 5-10 cm long from big hand specimen for further use. In total 133 kg of hand specimen samples were shipped, to United Kingdom, to Cardiff University-rock preparation laboratory to finalize the preparation for making more than 200 thin-sections and sending 110 samples to Open University of London to

finish the rest of samples to be ready for staining (detailed of staining technique is in Appendix 2.1) and examination under transmitted microscope. Several thin-sections have been re-done for better quality of description.

## **Appendix 2: Techniques:**

### **2.1 Thin-section staining technique:**

The technique used to produce half stained thin-section is based on Dickson's (1965, 1966) procedure. In 1965, Dickson modified staining technique for carbonates in thin-section, and also in 1966 he modified this technique slightly and used the method to demonstrate the process of carbonate diagenesis in limestones.

In order to make the staining three solutions were used each in different tray; The first tray was filled with 1.5% of hydrochloric acid (HCL), the second tray was filled with 0.2 gm of Alizarin Red S (ARS) per 100 ml of 1.5% HCL mixed with 2.0 mg of Potassium Ferricyanide (PF) in a ratio ARS:PF=3:2 and the third tray was filled with 0.2 mg of Alizarin Red S (ARS) per 100 ml of 1.5% HCL. Half of un-covered thin-sections have been submerged into the first solution for 10-15 seconds in order to have slightly etched surface, and then rinsed with distilled water gently. Then they were submerged for 45 seconds in the second solution, and then rinsed with distilled water. Finally the thin-sections were submerged in the third solution for 15 seconds, and then rinsed again with distilled water. At last thin-sections left in room temperature for about one hour in order to dry. This procedure was processed for about 319 thin-sections.

## **2.2 Scanning electron microscopy (SEM):**

Numerous mudstone, wackestone and packstone textured limestone blocks from all over eight localities were selected and polished using 600 and 1000 grit silicon carbide powder, cleaned with distilled water and then etched in 1% acetic acid for up to 20 seconds. The etched solutions were filtered through 0.02  $\mu\text{m}$  Millipore filter on order to collect any material falling from the limestone block during etching process. All polished limestone blocks and Millipore filter were coated with gold for about 10-15 minute and then examined with a scanning electron microscope (Veeco FEI XL30 ESEM) and back scatter BSEM in the School of Earth, Ocean and Planetary Sciences Laboratory at Cardiff University. Moreover electron back scattered diffraction (EBSD) has been used for clay cages and few micrite and microspar crystals.

## **2.3 Laser ablation inductively coupled plasma-mass spectrometry:**

Analyses were carried out in the School of Earth, Ocean and Planetary Sciences at Cardiff University, using a Thermo X Series2 ICP-MS coupled to a New Wave Research UP213 UV laser to determine the geochemistry of carbonate samples. The laser beam used for analysis diameter was 100 $\mu\text{m}$ . Laser energy was  $\sim 7\text{mJ}$  and the laser repetition rate set at 4Hz. Helium gas was used for ablation initial transport from the laser cell and this was combined with argon outside the cell as the sample was transported to the ICP-MS. Thermo Plasmalab time-resolved analysis (TRA) data acquisition software was used with a total acquisition time of 90s per analysis, allowing 20s for background followed by 60s for laser ablation and 10s signal washout. The Plasmalab software was used for initial data reduction with

post-processing in Excel. The calibration employed NIST614, NIST612 and NIST610 reference glasses to produce a 4 point (including the origin) calibration curve. Data were normalised to Ca (assuming pure  $\text{CaCO}_3$ ) and adjusted accordingly to match the measured or assumed Ca concentration. Instrumental drift was monitored and corrected for by repeat analysis of NIST612 after every 10 unknowns.

#### **2.4 Oxygen/Carbon isotope:**

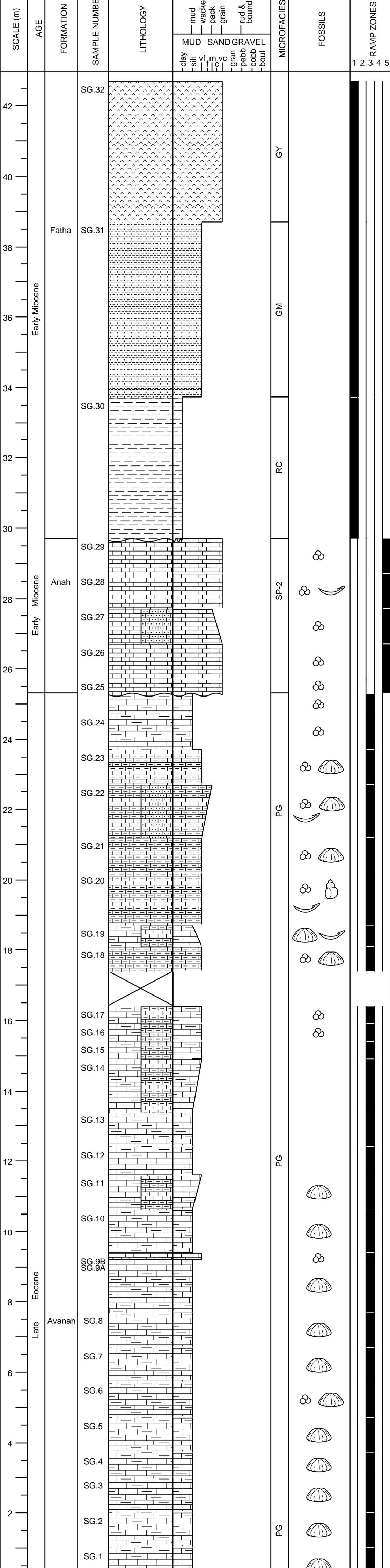
Both hand drilling and micro-drilling were used for over twenty selected samples in order to have a micrite matrix powder. Drilling was done on limestone blocks with at least one polished surface, in order to differentiate the micrite matrix from grains. Hand drilling was used for those coarse grained limestones which can easily see both matrix and grains, while for micro-drilling the Wave Research Micromill was used to drill in finer grained limestone to avoid mistake during drilling. The powder samples were weighed on a Sartorius microbalance and then sent to isotope laboratory in the School of Earth, Ocean and Planetary Sciences at Cardiff University, in order to prepare oxygen and carbon isotopes for both shallow marine and deep marine micritic matrix on a gas bench III and analysed on a Thermo Electron Delta V advantage. Standards used were inhouse Carrara and international NBS19. Precision is 0.1 for both  $^{13}\text{C}$  and  $^{18}\text{O}$ . All values are reported to PDB scale.

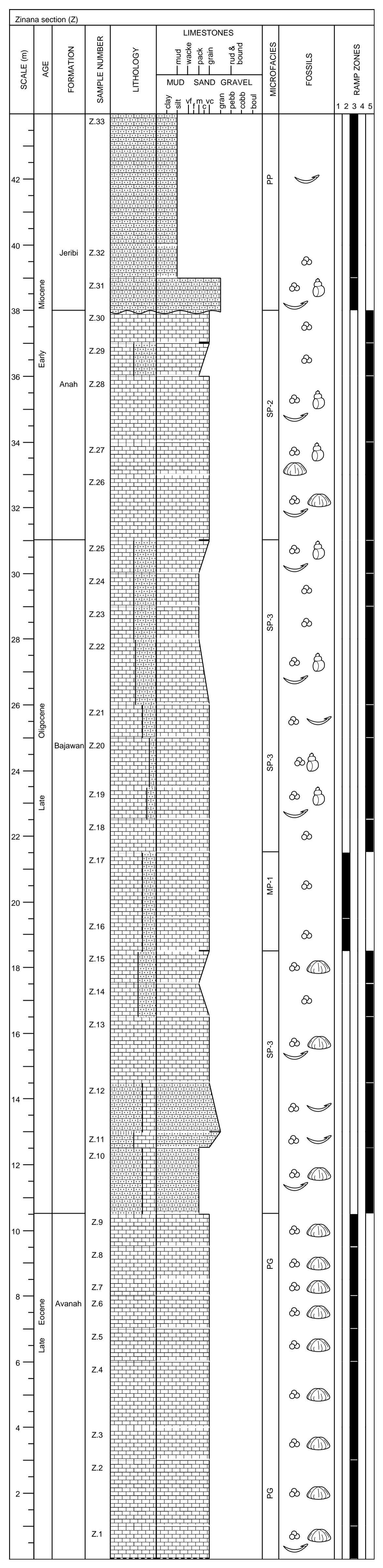
#### **Appendix 3: Sedimentary logs:**

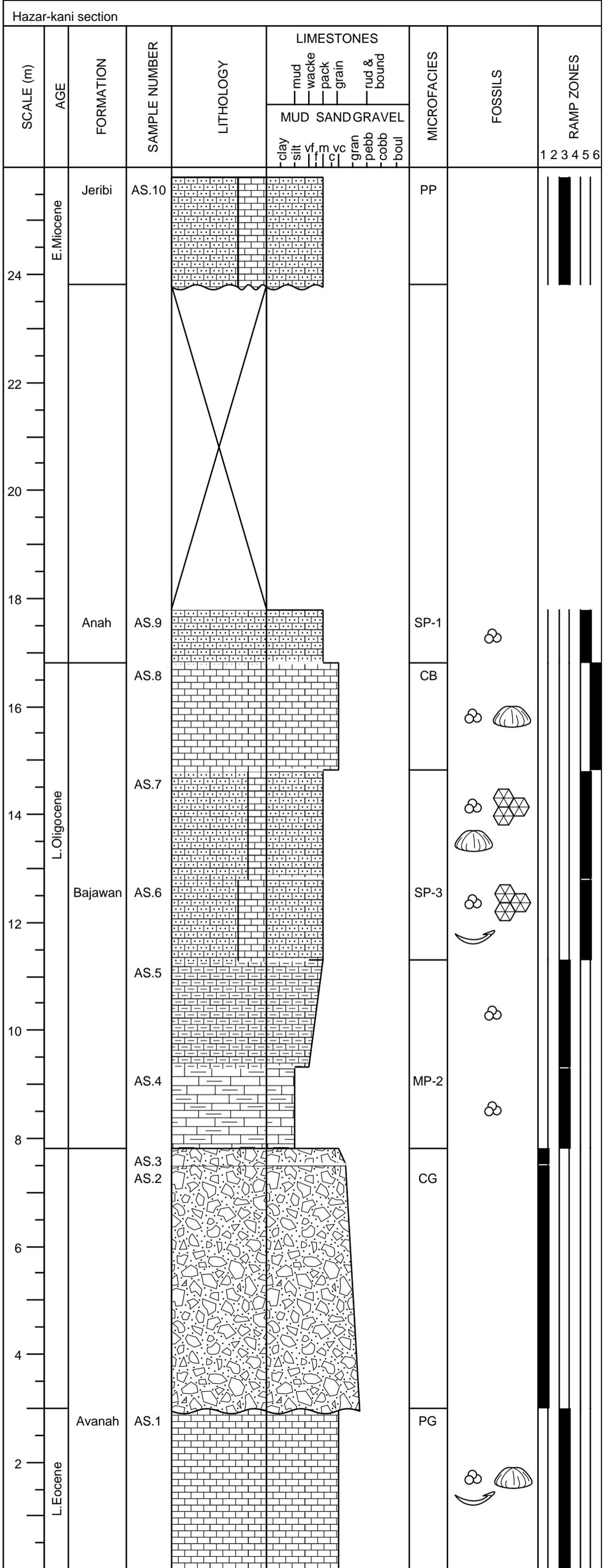
Full sedimentary logs of all eight sections of the Kirkuk group were produced by using Sedlog software, this software developed by Royal Holloway

University of London geologists. For each locality there is a detailed texture, bioclasts, thickness, formation name, age and ramp zone facies were pointed for each sample. The detailed logs for each locality are listed below:

Sagma section



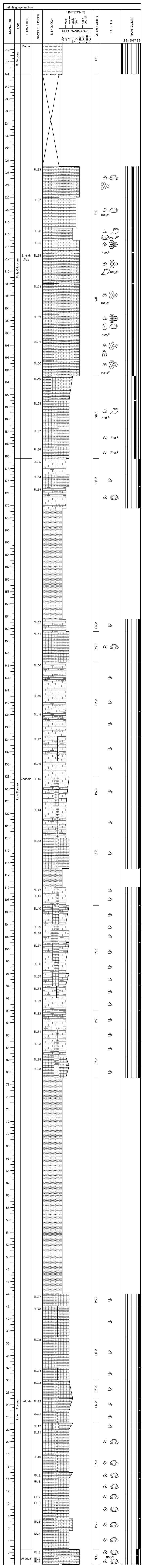












Sharwal Dra section

