Chapter IV
Microfacies and Depostional Environments

IV. Microfacies and Depositional Environments

This chapter deals with the microfacies associations and environmental interpretations of the Upper Cretaceous-Lower Eocene succession exposed in the Farafra Oasis. This interpretation is based on detailed litho- and microfacies descriptions as well as macro- and microfaunal types, abundance and diversity.

To achieve this target, more than 70 thin sections are prepared for representative rock samples of the fourteen measured stratigraphic sections. The thin sections are investigated for their litho- and biofacies characters to determine the different microfacies types relying on their skeletal and non-skeletal particles, texture, grain size and cementing material.

The planktic/benthic ratio, abundance, and diversity of the planktic and benthic foraminiferal assemblages are used to assort and interpret the palaeoenvironments of the studied microfacies associations. Careful consideration is given to the benthic foraminifers and macrofossils. The benthic foraminifers are most sensitive to the ecological factors whereas any marked change in the environmental conditions causes an abrupt change in the whole assemblages. The studies on living benthic foraminifers have shown that they flourish over a wide range of salinity from almost fresh water to hypersaline water (Boltovskoy and Wright, 1976). Since the solubility of the $CaCo_3$ increases with depth, the ratio of calcareous to agglutinated forms will be used as approximate index of water depth.

Most mollusks give reliable information about their mode of life, habits and habitat. Several morphoecological categories have been distinguished by Stanley (1972) including, infaunal shallow and deep burrowers, borers; eqifaunal byssally attached and cemented forms, free-lying and even swimming bivalves. The interior of the shells, shell shape and general morphologic features are usually directly related to the behavioral characteristics of the animal.

In fact, the macro- and microfaunal ecology helps much in understanding some biotic environmental parameters (e.g. temperature, salinity, paleodepth and dissolved oxygen availability) which assist, in-turn, to determine the environmental changes thought the Late Cretaceous-Early Tertiary time span.

In the present study, the paleodepth determination has been constructed based on well-established faunal relationships which include planktic species diversity, planktic/benthic ratio, keeled/non-keeled ratio and ratio of the present heterohelicids. The quantitative foraminiferal analyses have been calculated for about 500 rock samples, selected as representatives for the different exposed rock units occurring in the Farafra Oasis.

The identified planktic foraminiferal taxa include three groups, according to their morphological and taxonomic similarities. They are the heterohelicids, keeled and non-keeled planktic foraminiferas (Boersma and Premoli-Silva, 1983). Generally, many authors noticed that the abundance of heterohelicids group indicates shallow marine environments, while the keeled planktic foraminifers float in deeper water environments than the non-keeled forams. Their presence (i.e. keeled forams) may indicate deeper and/or warmer waters during deposition of the sediments containing them (Douglas and Sliter, 1966; Hart and Bailey, 1979; Hart, 1980; Boersma and Premoli-Silva, 1983; Caron, 1985).

The heterohelicids forms include *Guembelitria cretacea* Cushman, *Globoconusa daubjergensis* (Brönnimann), *Chilogumbelina morsei* (Kline), *Ch. Midwayensis* (Cushman), *Heterohelix globulosa* (Ehrenberg), *H. navaroensis* Loeblich, *H. striata* (Ehrenberg), *Planoglobulina carseyae* (Plummer), *P. glabrata* (Cushman), *Pseudotextularia elegans* (Rzehak), *Racemiguembelina fructicosa* (Egger), *Pseudoguembelina costulata* (Cushman), *P. excolata* (Cushman), *P. hariaensis* and *P. palpebra* (Brönneimnn and Brown).

The keeled forams include *Globanomalina pseudomenardii* (Bolli) *Contusotruncana* sp., *Globotruncana* sp., *Globotruncanita* sp., *Rugotruncana* sp., *Globotruncanella* sp., *Igorina albeari* (Cushman and Bermūdez) and *Morozovella* sp. While, the non-keeled forms include *Globanomalina compressa* (Plummer), *Pseudohastigerina* sp., *Rugoglobigerina* sp., *Praemurica* sp., *Igorina pusilla* (Bolli), *Acarinina* sp., *Parasubbotina* sp. and *Subbotina* sp.

The species richness (diversity) is represented by the total number of foraminiferal species in any sample. Generally, the diversity increases away from the shore up to middle and outer shelf depths and then decreases in deeper marine (Bandy and Arnal, 1960; Thiede, 1972; Olsson and Nyong, 1987). Thiede (1972) pointed out that species diversity and species dominance (the highest percentage occurrence of a species in a sample) of the planktic foraminifers change across the continental margins and in semi-land-locked seas, partly due to shoaling, which progressively eliminates deeper dwelling species. He noticed that diversity is higher in deep than in shallow waters, whereas dominance is higher in shallow waters.

The ratio of planktic to benthic species is lowest in the shallow marine waters and generally increases with depth until the Carbonate Compensation Depth (CCD). The planktic:benthic ratio is used in the present study to determine the depositional environments, which adopted after Murray (1976) and Olsson and

Nyong (1984) calculate the absolute depth values (D) by using the equation of Van der Zwann *et al.* (1990) as follows: $D = e^{(3.58718 + (0.03534 \times P \%)}$, Where (P) is the planktic percentage disregarding in faunal benthic taxa. He also mentioned that the productivity of planktics is higher in open pelagic waters and that of benthic ones is higher in shallower neritic environment.

Murray (1976) mentioned that the productivity of planktics is useful tool in understanding the circulation pattern and current intensities of marginal seas to open ocean. He classified the depositional environments according to planktic:benthic ratio as follows:

Inner Shelf

Shallow inner shelf: planktic:benthic ratio <5:95 (rare planktic tests).

Deep inner shelf: planktic:benthic ratio 5-<20:95-80.

Middle Shelf

Shallow middle shelf: planktic: benthic ratio 20-<30:80-70.

Deep middle shelf: planktic: benthic ratio 30-<40:70-60.

Outer continental slope (upper bathyal zone): planktic: benthic ratio <70:30.

While, Olsson and Nyong (1984) pointed out that the inner shelf (10-50 m depth) is characterized by low planktic percentages with low species diversity and high benthic percentages, whereas the middle shelf depth (50-100m) is characterized by 8-25% planktic foraminifera and higher diversity. They added that the outer shelf depth (100–200m) is marked by 30-70% planktic foraminiferal assemblage; whereas the continental slopes (200-800m) is characterized by 90% planktic foraminifera and a slight increase in benthic diversity.

Concerning the microfacies nomenclature, the limestone rocks are classified according to the nomenclature scheme of Dunham (1962) which is based on the original depositional texture of the carbonate rocks. Based on the abundance of the grains, two terms "mud-supported" and "grain supported" are introduced. Dunham (op. cit.) subdivided the carbonate rocks into the following six types:

1. Mudstone: Muddy carbonate rocks containing less than 10% grains. This term is synonymous with the micrite of Folk (1959 & 1962).
2. Wackestone: Mud-supported carbonate rocks containing more than 10% grains.
3. Packstone: Grain-supported muddy carbonate rocks.
4. Grainstone: Mud-free carbonate rocks.
5. Boundstone: Carbonate rocks showing signs of being organically bound during deposition.
6. Crystalline carbonate: Rocks which retaining too little of their depositional texture (crystalline dolomite, crystalline limestone).

The petrographic terminology and description of the dolostone rocks followed in the present study are those used by Friedman (1968) and Folk and Land (1975). On the other hand, the classification given by Okada (1971) for the sandstone is adopted here.

The Upper Cretaceous-Lower Eocene facies associations of the Farafra Oasis encompass a wide range of depositional environments, including the tidal flat to outer shelf slope (Table 4.1).

Table 4.1 The facies characteristics of the studied Upper Cretaceous-Lower Eocene sediments and their depositional environments in the Farafra Oasis.

Rock units	Lithology	Sedimentary structures	Microfacies types	Fossil types and abundance	Fossil diversity	Major taxa	Depositional environments
El-Hefhuf Fm. (11-34m thick)	Shale, mudstone, sandstone, dolostone	Fissile shale, cross-bedded and massive sandstone	Fissile shale, quartz arenite, oyster rudstone, dolostone	Fossiliferous with macrofauna in top part, low	Low	*Pycnodonte vesicularis* and shark teeth	Upper intertidal-upper deep subtidal
Khoman Fm. (5-55m thick)	Chalk, partly dolostone and mudstone	Maasive to stratified	Foram. wackestone, algal bindstone, lime-mudstone, dolostone, mudstone	Planktics and benthics, very high	High	*Globotruncana* and *Heterohelix*	Shallow inner to deep middle/outer shelf
Dakhla Fm. (1-10m thick)	Argillaceous chalk and calcareous shale	Maasive and fissile	Calcareous shale, foram. wackestone, foram. lime-mudstone	Planktics and benthics, medium to high	Moderate to high	*Parasubbotina, praemurica* and *Morozovella*	Shallow inner to middle/outer shelf
Tarawan Fm. (1-23m thick)	Chalky limestone	Thick-bedded and massive	Pelagic foram. packstone, foram. bioclastic packstone, foram. lime-mudstone	Planktics, low to very high	High with dwarf fauna	*Morozovella* and *Acarinina*	Shallow inner to outer shelf
Esna Fm. (20-100m thick)	Shale with argillaceous limestone	Fissile and massive	Pelagic shale, calcareous shale, foram. packstone, sandstone, algal stromatolites, anhydrite	Planktics, benthics, larger forams and macrofossils, low to high	High	*Morozovella, Alveolina, Nummulites* and pelecypods	Shallow inner to middle/outer shelf, rarely supratidal
Ain Dalla Fm. (70-80 thick)	Chalky limestone	Well-bedded, nodular, massive	Foraminiferal wackestone, alveolinid wackestone, sandy silicified dolostone, lime-mudstone	Planktics and larger forams, low to high	Moderate	*Acarinina* and *Alveolina*	lower intertidal to deep middle/outer shelf
Farafra Limestone (13-50 thick)	Limestone, chalk and dolostone	Thick bedded and massive, partly nodular	Foraminiferal packstone, Numm. Wacke-packstone, lime-mudstone, dolomitic lime-mudstone, calcareous shale	Larger benthics and macrofossils, low to high	Low	*Assilina, Alveolina, Nummulites* and miliolids	Lower intertidal to deep inner shelf

The following is a detailed description and interpretation of the detected microfacies associations in each the studied formations, arranged from older to younger:

IV.1 El-Hefhuf Formation

Five dominant facies associations are recognized in El-Hefhuf Formation. These are:

1. Upper deep subtidal shale/mudstone.
2. Shallow subtidal massive/cross-bedded sandstone (ferruginous quartz arenite).
3. Lower intertidal phosphatic sandy lime-mudstone.
4. Shallow/deep subtidal oyster rudstone with *Pycnodonte vesicularis*.
5. Upper intertidal sandy dolostone.

The following is a detailed description of the recognized facies.

1. Upper deep subtidal shale/mudstone

This lithofacies is predominant throughout the measured part of El-Hefhuf Formation in the Farafra Oasis, intercalating with the sandstone (Fig. 4.1). It has a cumulative exposed thickness of about 17m at Wadi Hennis, while it reaches about 2m thick at Bir El-Obeiyid. The shale is fissile, slope-forming, calcareous, sticky, soppy, gypsiferous, sandy, unfossiliferous and varicolored; grayish gray, yellowish gray and reddish brown. They are also highly ferruginated and partly glauconitic. The shale/mudstone sediments represent shallow water lagoonal facies deposited from suspension in a low energy environment, most probably in upper subtidal setting. The scarcity of faunal assemblages suggests abnormal conditions. Abdel Mohsen (2002) mentioned that the association of rare marine palynofossils with freshwater algae and abundance of the land-derived microflora suggests deposition in a

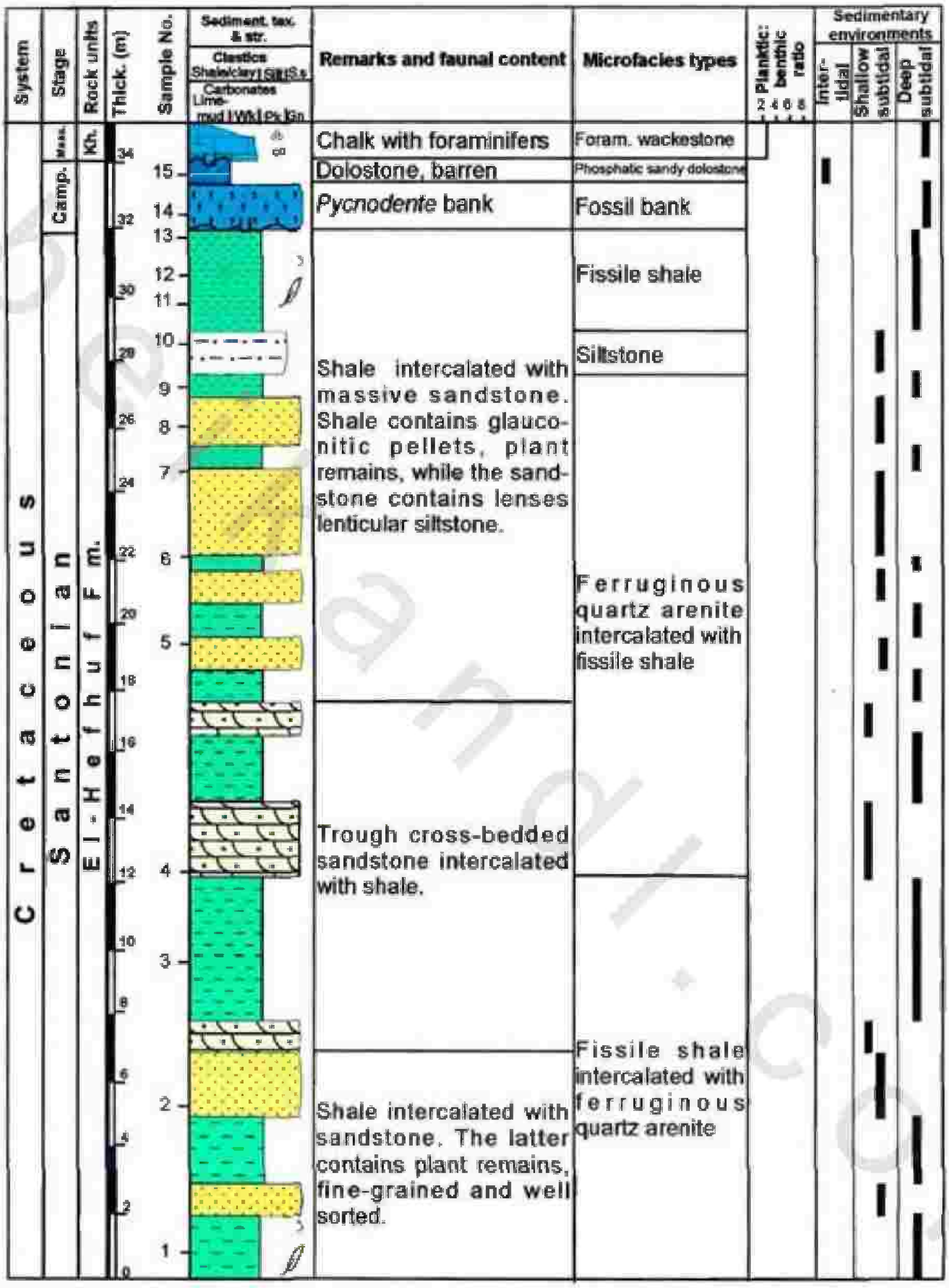


Fig. 4.1 Representative stratigraphic section of the exposed Santonian-Campanian El-Hefhuf Formation in Wadi Hennis, northeast Farafra Oasis, showing their microfacies types and sedimentary environments.

coastal to shallow marine conditions with strong influx of fresh water and and-derived material. A shallow-water, swampy environment is interpreted by Ibrahim and Abdel-Kireem (1997) to be prevailed during the deposition of El-Hefhuf Formation.

2. Shallow subtidal ferruginous quartzarenite

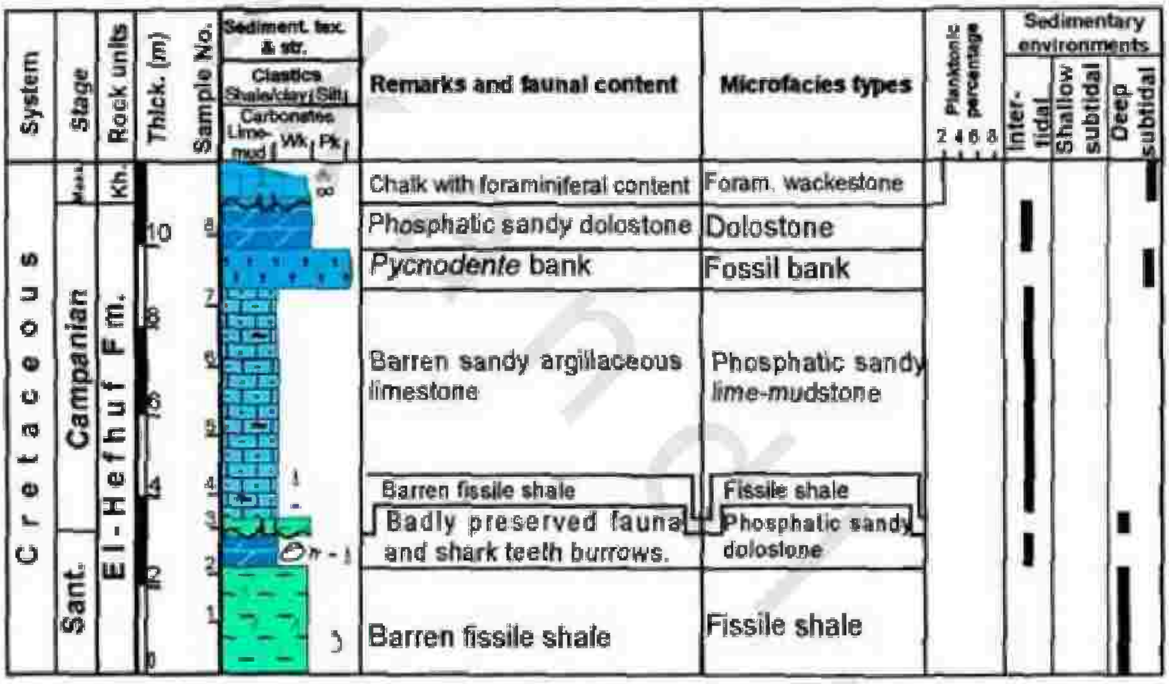
This microfacies type is widely distributed throughout El-Hefhuf Formation cropping out in Wadi Hennis area (Fig. 4.1). The sandstone is yellowish brown, moderately hard, massive, cross-bedded in part and barren in fauna.

Petrographically, the sandstone is composed of more than 95% quartz grains (quartz arenite). The quartz grains range in size from fine to very fine sand. They are well sorted, angular to subangular and monocrystalline showing a straight extinction (Fig 4.3). The quartz grains exhibit straight, curved and concava-convex contacts and have low sphericity. Very few badly preserved shell fragments of pelecyopod are present. Iron-oxides are sporadically occurred in the quartz arenite as fine disseminated spots and patches filling the intergranular pore spaces and coating on some quartz grains. Glauconitic pellets, pyrite and heavy minerals (e.g. biotite) are present in a few percentages as accessory minerals. Cementing materials are mostly iron-oxides.

The sandstone of El-Hefhuh Formation has been deposited in a prograding siliciclastic coast. The cross-bedded sandstone represents marine upper shallow subtidal sediments formed on a wide coast in areas of high wave energy and a steady supply of sands to the shoreline brought by rivers. While, the massive-bedded sandstone is interpreted to have been deposited in a lower shallow subtidal setting.

3. Lower intertidal phosphatic sandy lime-mudstone

This microfacies is recorded in east Shakhs El-Obeiyid. The lime-mudstone is yellowish brown, massive, moderately hard, argillaceous, partly dolomitic and highly fractured. It consists of a dense lime mud matrix which is partly recrystallized into microspar. Abundant fine sands are widely scattered throughout the matrix. The lime-mudstone is almost barren of any fauna. It has been deposited in a protected quiet-water lower intertidal setting.



Base unexposed

Fig. 4.2 Representative stratigraphic section of the exposed Santonian-Campanian El-Hefhuf Formation in east Shakhs El-Obeiyid, west Farafra Oasis, showing their microfacies types and sedimentary environments.

4. Shallow/deep subtidal oyster rudstone

This facies is characterized by the abundance of large pelecypod packed in psudospar, and dolomite rhombs that resulted from aggrading neomorphism and dolomitization of a former lime-mud matrix. Quartz grains of fine to medium size are also scattered within the rock.

The oyster rudstone that occurs near the top of El-Hefhuf Formation is marked by the presence of a low diversity assemblage of *Pycnodonte vesicularis* (Lamarck) forming a fossil bank with some scatter reworked fossils of Cenomanian age such as *Ilymatogyra* (*Afrogyra*) *africana* (Lamarck) and *Ceratostreon flabellatum* (Goldfuss) (Figs. 2.6 & 2.7). This indicates that Wadi Hennis was an ancient topographic low and received the reworked fauna from the surrounding Cenomanian sediments in Bahariya Oasis by rivers during deposition of the *Pycnodonte vesicularis* (Lamarck). The good preservation of the two valves in the *Pycnodonte vesicularis* (Lamarck) indicates that these species were not transported from their environment after death.

The *Pycnodonte vesicularis* (Lamarck), with their vesicular shells, are predominantly deep water oysters and are common in the shelf environment greater than 20m. The gryph shape of the *Pycnodonte vesicularis* (Lamarck) and small fixation area are adaptation to a free adult life on a muddy substrate and in calm water away from any fresh water influence and strong currents.

5. Upper intertidal phosphatic sandy dolostone

The dolostone facies is recorded in the top part of El-Hefhuf Formation at Wadi Hennis and East Shakhs El-Obeiyid areas (Figs. 4.1 & 4.2). Microscopically, the rock is made up of well-defined fine dolomite rhombs (60-80%), detrital quartz grains (8-10%), phosphatic grains (8-15%) and some skeletal particles less than 5% of the rock. The fine dolomite rhombs range in size from 20-40 micron. They are mainly idotopic to hypidotopic, equigranular and with dark clayey cores, occasionally zoned (Fig. 4.4). Sometimes, the pore spaces between the dolomite rhombs are completely filled with fine to medium-grained quartz sands. The size and fabric of the dolomite rhombs suggest early diagenetic

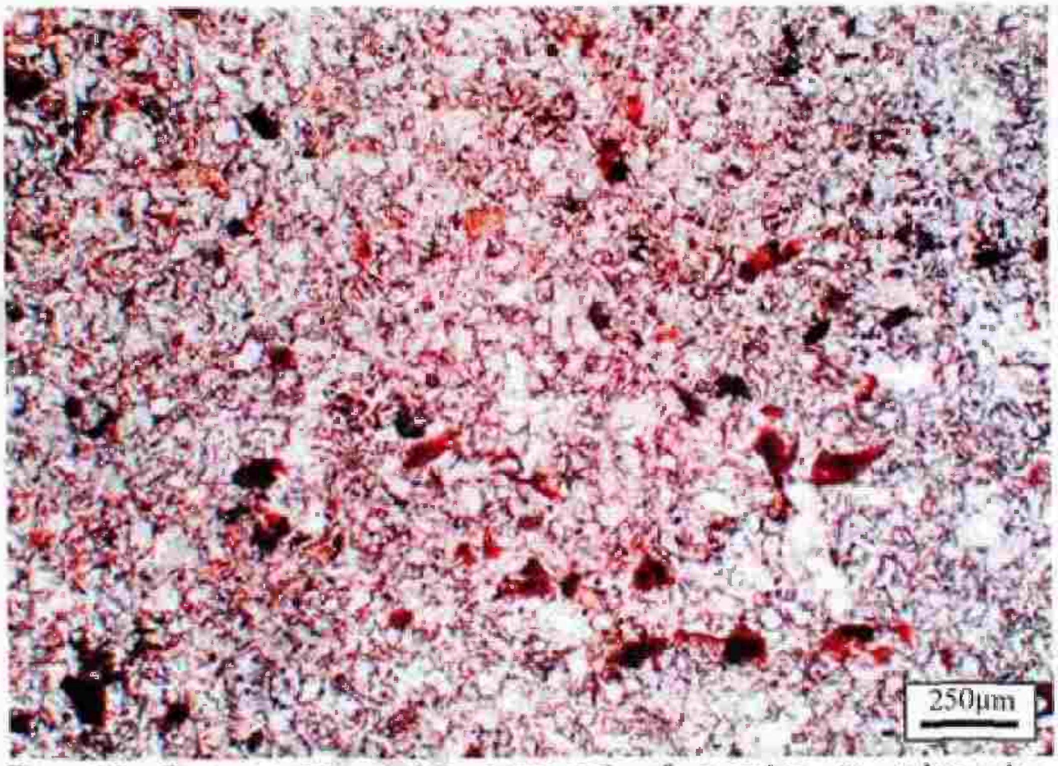


Fig. 4.3 Fine quartz grains composed of angular to subangular monocrystalline quartz grains cemented in iron-oxides. Lower shallow subtidal massive quartz arenite, Santonian, Wadi Hennis, bed No. 8.

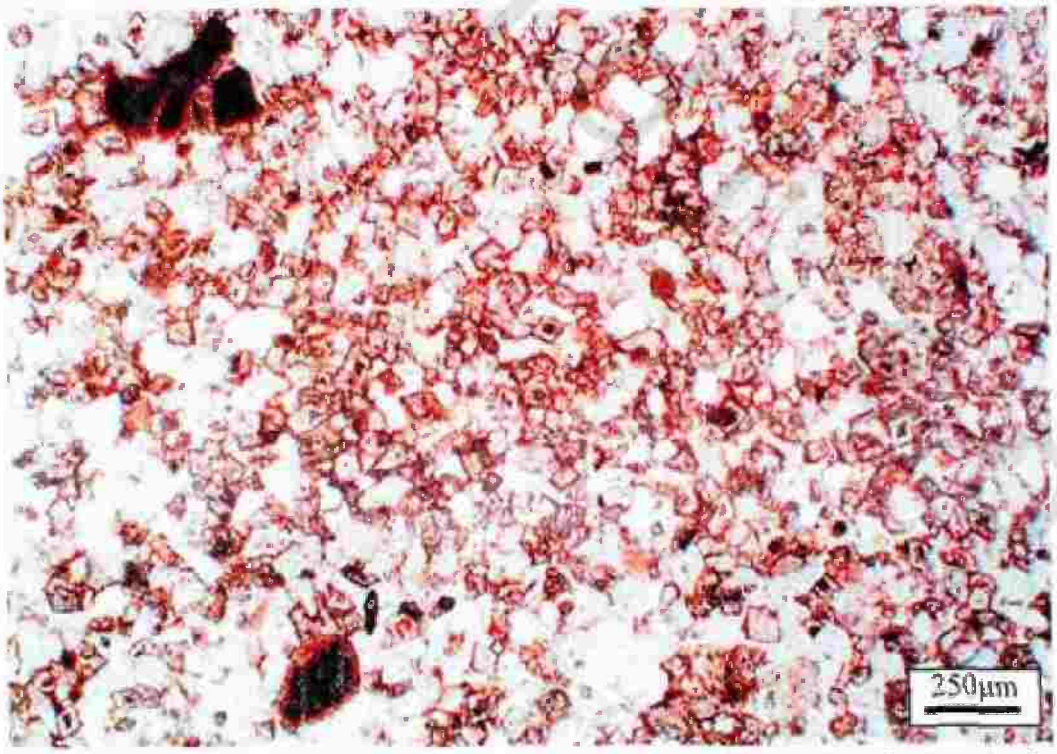


Fig. 4.4 Fine dolomite rhombs and quartz grains with scattered phosphatic grains embedded in a few microcrystalline calcite matrix. Upper intertidal phosphatic sandy dolostone, Campanian, east Shakhs El-Obeiyid, bed No. 5.

dolomitization of a clastic-rich carbonate sediment (sandy lime-mudstone) in an upper intertidal setting. High sand content most probably formed from wind action (wind blown sand).

This indicates that the dolostone was formed soon after deposition due to the almost complete dolomitization of the lime mud. The position of the dolostone at the end of a depositional cycle maintains this early diagenitic dolomitization. The sporadically occurred quartz grains are usually monocrystalline, sub-angular to sub rounded and shows a straight extinction. Some quartz grains exhibit calcite-quartz replacement. Relics of microcrystalline calcite (lime mud) and microsparite are sometimes present between the dolomite rhombs. Phosphatic grains are represented by rounded to angular, yellowish brown to pale brown vertebrate remains of bones and shark teeth ranging in size from 0.2 to 0.4 mm. The phosphate-bearing carbonate facies at the top gives evidence for depositional in a shallow marine regime, formed under a slightly reducing and restricted environment.

To summarize, the facies characteristics of El-Hefhuf Formation indicate deposition in a shallow marine environment with oscillations from intertidal to upper deep subtidal during the Santonian-Campanian time. Deeper conditions seem to have prevailed at the beginning of Campanian time, resulting in deposition of the oyster rudstone with *Pycnodonte vesicularis* (Lamarck).

IV.2 Khoman Formation

In the studied sections of the Farafra Oasis, the Khoman Formation is composed of monotonous massive to stratified white chalk (Fig 4.5). In Qur Hadida, the chalk is topped by interbeded mudstone and dolostone with algal stromatolites at the top most part. The Khoman Formation compresses the following four facies associations:

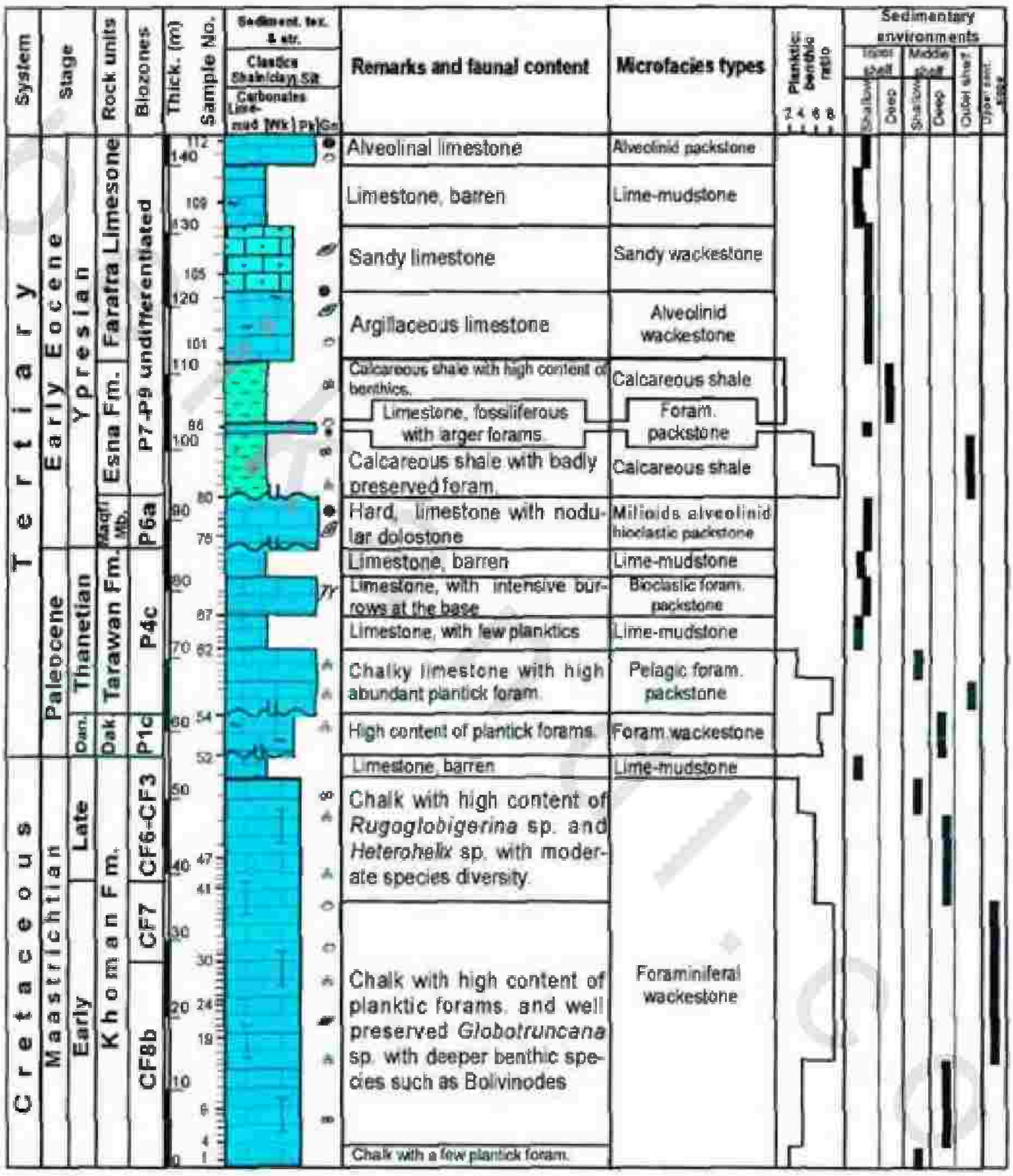
1. Deep middle shelf to upper continental slope foraminiferal wackestone
2. Shallow inner shelf mudstone
3. Lower intertidal lime-mudstone
4. Upper intertidal dolostone

The following is a detailed description of the recognized facies in the Khoman Formation.

1. Deep middle shelf to upper continental slope foraminiferal wackestone

The foraminiferal wackestone occupies the main part of the Khoman Formation (Fig. 4.5). Wackestone are mud-supported rocks with varying amount of skeletal particles, usually less than 40% of the rock content.

Petrographically, the foraminiferal wackestone is mainly made up of foraminiferal tests mainly of planktics with some smaller benthics which form together about 40% of the rock constituents. Additionally, very few phosphatic fragments are recorded. The foraminiferal tests are embedded in a dense grey lime mud matrix (Fig. 4.6). These tests are present in a complete form and in a fragmented manner. They are variable in size ranging from very fine to medium sand size with thin welled shells. Foraminiferal wells are often suffered from recrystallization, while their chamber lets are filled with granular spary calcite, partially filled with recrystallized lime mud. The most common planktic species are *Heterohelix* sp., *Rugoglobigerina* sp. and *Globotruncana* sp. The foraminiferal wackestone has been deposited in a quiet-water, open deep middle/outer shelf environment.



Base unexposed

Fig. 4.5 Representative stratigraphic section of the exposed Maastrichtian-Lower Eocene succession in northwest Ain Maqfi, east Farafra Oasis, showing their microfacies types and sedimentary environments.

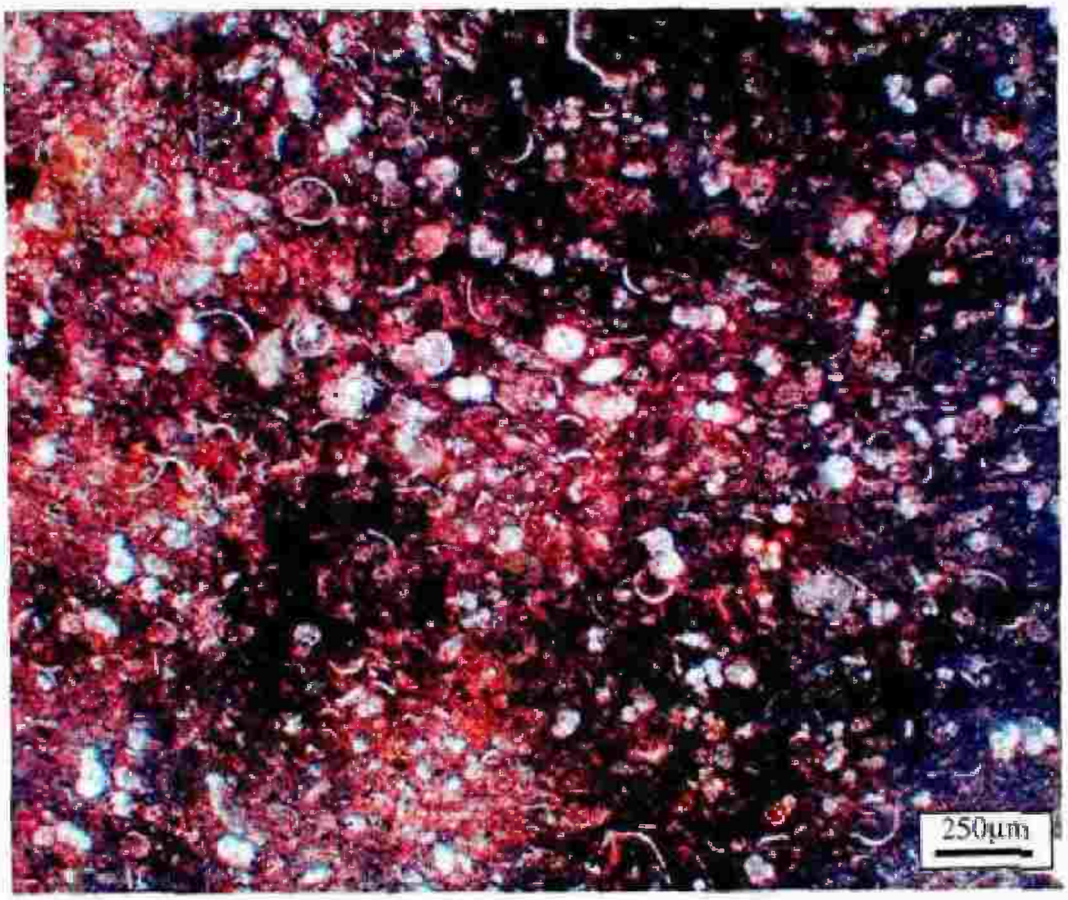


Fig. 4.6 Abundant planktic foraminiferal tests of *Globotruncana* sp. and *Heterohelix* sp. randomly disseminated in a dense lime mud matrix. Deep *middle/outer* shelf foraminiferal wackestone, Late Maastrichtian, Qur Hadida, bed No. 1.

A great number of foraminiferal species is recorded in the wackestone representing the richest part of the Khoman Formation. The foraminiferal content in the lower part of the Khoman Formation exposed in northwest Ain Maqfi starts with a relatively low P/b ratio (Fig. 4.5). The values of planktic % (P%) are about 41 which according to Van der Zwann *et al.* (1990) represent an absolute depth of 153m. Upwards, the sediments are characterized by somewhat raised values of the P/b ratios. They are characterized by high abundance and diversification of the high latitude group of the globotruncanids. Such globotruncanids suggests deep water under overall cooling climate. The obtained values of planktic% are about 67 which according to Van der Zwann *et al.* (op. cit.) denote an absolute depth of 386m.

Further additional evidence for the upper continental slope setting is exhibited from the recorded benthic foraminiferal assemblage which contains relatively abundant genera of deep water forms such as *Spiroplectammina*, *Gaudryina*, *Dorothia*, *Clavulinoides*, *Neoflabellina* and *Coryphostoma*.

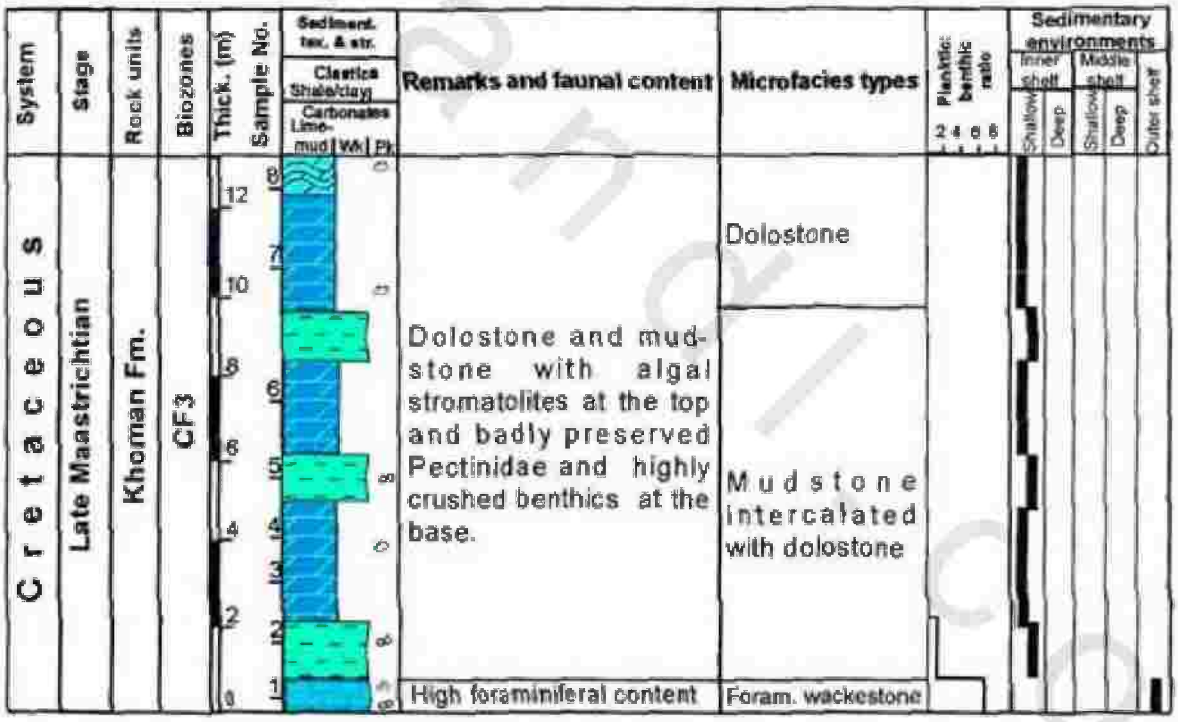
In fact, the upper continental slope depositional environment is indicated to parts of the foraminiferal wackestone due to the presence of the following criteria: 1) The presence of abundant planktic foraminifers with high species diversity, 2) The low species diversity of the benthic foraminifers, 3) The relatively small size of the planktics and benthics, 4) Very high planktic: benthic ratio and 5) The relative dominance of some index benthic foraminifers, which are restricted to the outer shelf-upper continental slope domain such as *Bolivinoides*. The latter is found in the Khoman Formation of the *Rugoglobigerina hexacamerata* and *Contusotruncana contuse* zones. Hewaidy, (1996) recorded the *Bolivinodes* from the northern Egypt in the middle to outer neritic or deeper environments. While, Ismail (2002) mentioned that the *Bolivinodes* (*draco draco* and *draco miliaris*) tend to occupy the outer neritic environment and may extend to a few meters toward the bathyal one.

The depositional environment starts to shallow again in the upper level of the Khoman foraminiferal wackestone (Fig. 4.5) because of the increase in the percentage of the rugoglobigerinids and the heterohelicids which can be regarded as a climatic warming pulse. Douglas and Savin (1978) and Boersma and Shackleton (1981) found that during the Cretaceous the lowest δ^{18O} values (warmest temperature) is registered in the tests of rugoglobigernids and globigerinelloides, whereas highest values (cold temperature) signify the globotruncanids. Eicher and Worstell (1970) documented that during transgression heterohelicids are the first to appear, whereas they are the last to disappear in regression. The abrupt increase in the heterohelicids in the upper part of the Khoman foraminiferal wackestone reflects falling in the sea-level which may be due to a local tectonic event. The shallowing conditions are also indicated by the sharp increase in the non-keeled planktic percentages.

The greater part of the Khoman Formation is dominated by one pectinid species of *Lyropecten* (*Aequipecten*) *mayereymari* (Nilsson). This is found in great abundance almost everywhere, from the northern descent of the Farafra Oasis to Bir Murr eastward and westward along Ain Dalla road. It also occurs in profusion at Qaret El Sheikh Abdalla. Pectinid bivalves are recorded from the outer shelf environment by Bottjer (1981). The mode of life of pectinids is an active swimmer. However, the presence of a cenolium indicates that the species, like most pectinids, was byssally attached in the young. In addition, the Khoman Formation includes *Pycnodonte vesicularis* (Lamarck), *Agerostrea ungulate* (Schlotheim), and the small-sized brachiopod *Terebratullina gracilis* Schlotheim. The bivalve fauna is of low diversity and composed totally of epifaunal elements. Kassab (1990) referred that the *Pycnodonte* assemblage is an outer shelf fauna. The generic diversity of the macrofauna is much more pronounced in the Maastrichtian part of the Dakhla Formation than in the Maastrichtian Khoman Formation. The Maastrichtian part of the Dakhla Formation contains population of *Exogyra*, *Arc* and *Nuculana*. This population lives in a shallow water regime.

2. Shallow inner shelf mudstone

This lithofacies occurs in the upper part of the Khoman Formation in Qur Hadida, intercalating with dolostone (Fig. 4.7).



Base unexposed

Fig. 4.7 Representative stratigraphic section of the exposed Maastrichtian rocks in Qur Hadida, east Farafra Oasis, showing their microfacies types and sedimentary environments.

The mudstone is calcareous, gypsiferous, yellowish gray and slope-forming. The fauna is badly-preserved and includes some benthics and planktics (Heterohelix and Rugoglobigerina). This fauna is crushed due to the action of the derived waves and currents. The very poor planktics and benthics and the crushed fauna indicate that the depositional environment was a shallow inner shelf (upper deep subtidal setting).

3. Lower intertidal Lime-mudstone

The foraminiferal lime-mudstone rocks are occasionally recorded in the Late Maastrichtian. They occupy the topmost part of the Khoman Formation in northwest Ain Maqfi (Fig. 4.5). Pterographically, the lime-mudstone is formed of a dense lime mud matrix, which appears as cloudy microcrystalline and cryptocrystalline calcite. The rock is almost barren of any fauna. It has been deposited in a protected, quiet-water lower intertidal setting.

4. Upper intertidal Dolostone

The dolostone rock is not a common facies in the studied Maastrichtian Khoman Formation, only recorded in the upper part of the formation at Qur Hadida (Fig. 4.7). Petrographically, the dolostone consists of interlocked coarse crystalline diagenetic dolomite rhombs (65-70%) and neomorphic spar. The dolomite rhombs are characterized by their idotopic to hypidotopic fabric, equigranular texture and the almost absence of any zoning, most of them with dark clayey cores and clear outer rims. Some dolomite rhombs are stained with iron-oxides which are also filling the inter-granular pore spaces. Ferruginous material post-dates dolomite formation. Porosity may reach up to 10% of the total rock. In some cases, the dolomite rhombs show clear intense dedolomitization (calcitization) with perfect rhombohedral cleavage (Fig. 4.8). The calcite crystals still retain the size and shape of the dolomite rhombs. Traces of the dolomite rhombs may be present. The complete almost distortion of the original

depositional fabric suggests late diagenetic dolomitization, which later affected by calcilization with the formation of calcite.

To summarize, the basal part of the Khoman Formation indicates deposition in a deep middle shelf environment (Fig. 4.5), whereas the overlying sediments of the upper part of the *Rugoglobigerina hexacamerata* CF8b Zone, have been deposited in a relatively deeper sea oscillating between outer shelf and upper continental slope depth. Shallower conditions of deep middle shelf water depth start with the upper part of the *Gansserina gansseri* CF7 Zone and the base of the overlying *Contusotruncana contuse* CF6 Zone. Very shallow conditions of shallow inner shelf dominated in the top part of the Khoman Formation due to the presence of the following criteria: 1) The abrupt decrease in abundance of planktic foraminifers, 2) abrupt increase in the heterohelicids and 3) The presence of the dolostone at Qur Hadida and lime-mudstone at the contact between the Maastrichtian Khoman/Paleocene Dakhla formations in northwest Ain Maqfi section (Fig. 4.5).

IV.3 Dakhla Formation

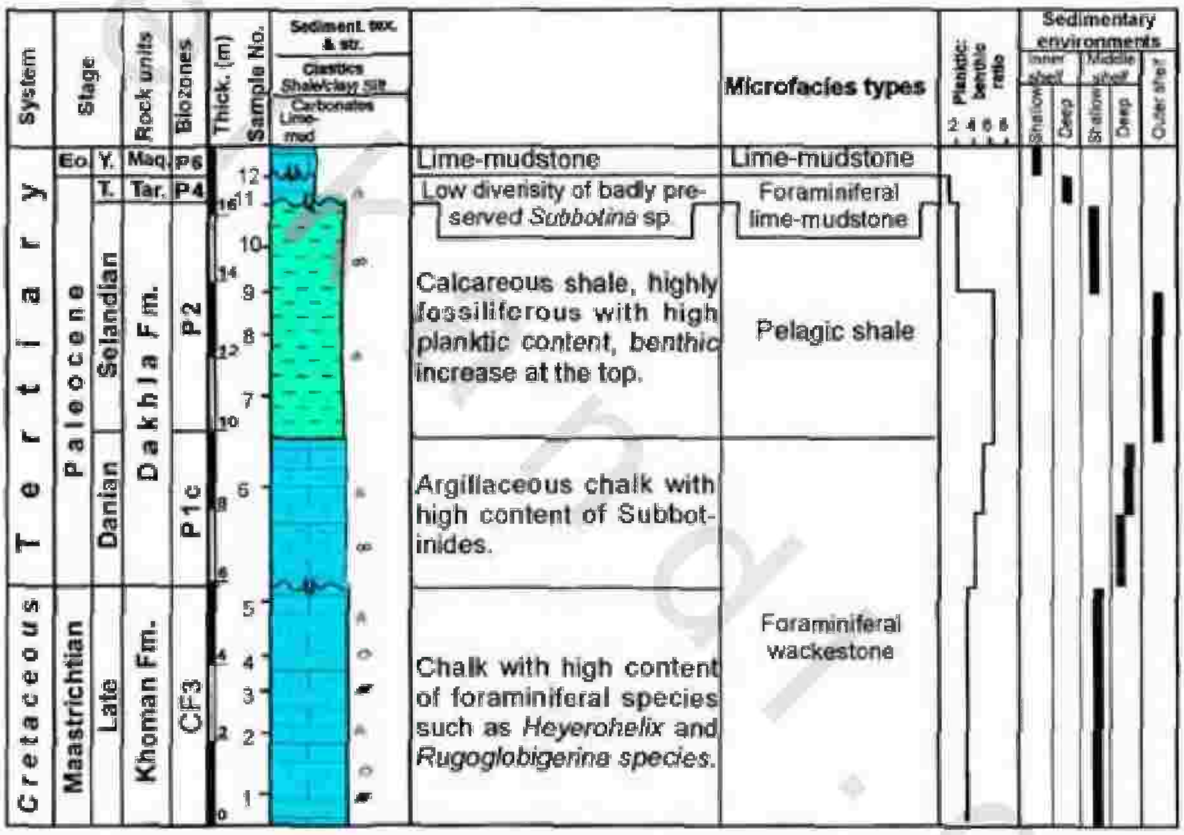
The Dakhla Formation is composed of two informal units; an argillaceous chalk at the base and a foraminiferal calcareous shale at the top. The formation includes the following three facies associations (Figs. 4.9 & 4.10).

1. Deep middle shelf foraminiferal wackestone
2. Deep middle/outer shelf pelagic shale
3. Shallow inner shelf foraminiferal lime-mudstone

The following is a detailed description of the recognized facies.

1. Deep middle shelf foraminiferal wackestone

The foraminiferal wackestone occurs in the lower part of the Dakhla Formation (Fig. 4.9). Petrographically, this facies is essentially made up of skeletal particles loosely packed in a dark and dense lime mud matrix. Skeletal particles are represented by complete and fragmented fine foraminiferal tests as well as rare molluscan shell, phosphatic teeth and echinoid spines (Fig. 4.11).



Base unexposed

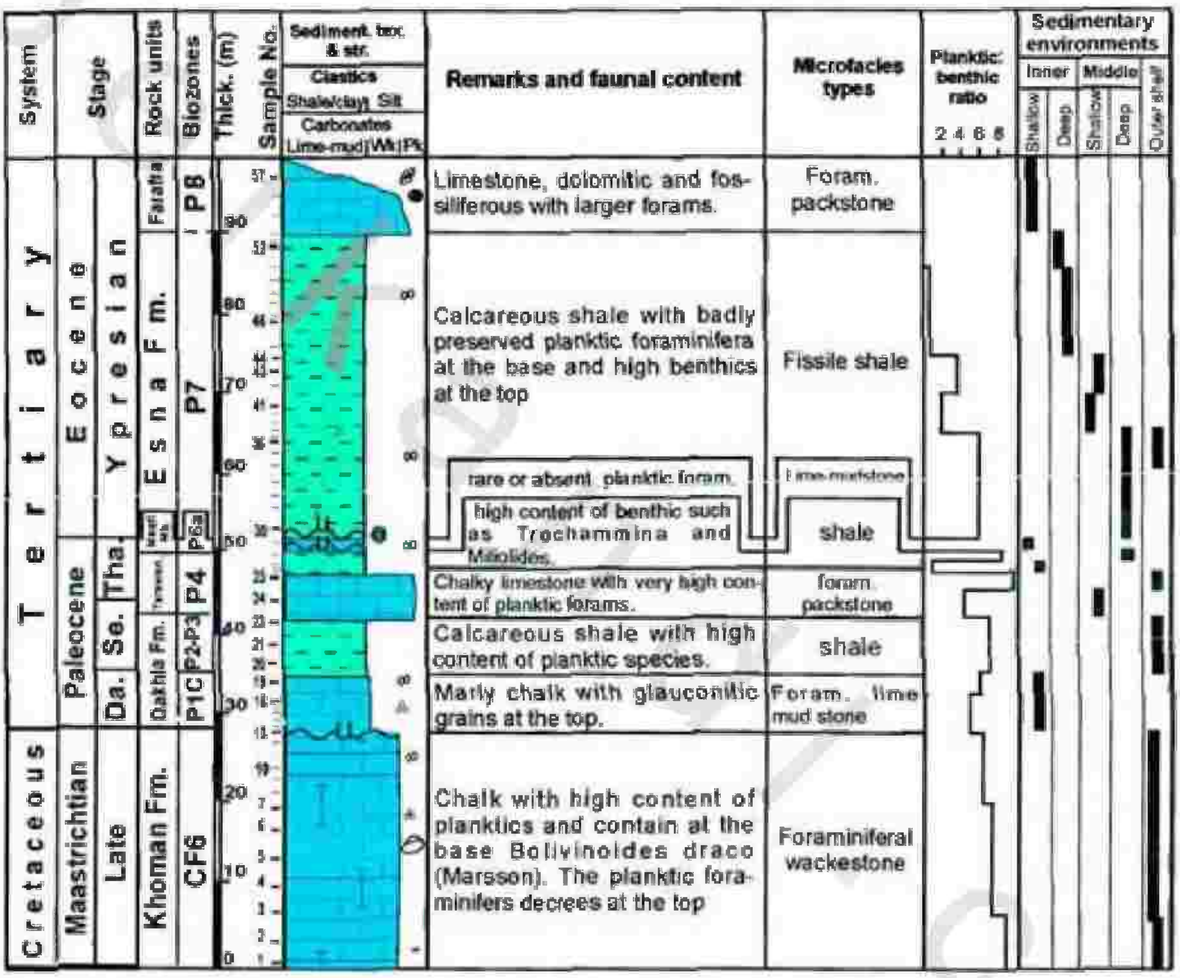
Fig. 4.9 Representative stratigraphic section of the exposed Upper Maastrichtian-Lower Eocene rocks in Bir Murr, east Farafra Oasis, showing their microfacies types and sedimentary environments.

Sometimes iron-oxides and green glauconitic grains occur filling the foraminiferal tests. Foraminiferal tests, representing mainly by planktics with rare benthics, are moderately sorted forming about 30% of the rock. The binding material is a lime mud matrix which is partially recrystallized into microspar. The unconformable relationships at the Cretaceous/Paleocene boundary (i.e. base of the Dakhla Formation) indicate the presence of shallowing and regression in sea-level during this interval. The lowermost bed in the Dakhla the foraminiferal wackestone gave a typical Danian fauna with many derived Maastrichtian fauna. This maintains the unconformity surface at the base of foraminiferal wackestone which is recorded in Shakhs El-Obeiyid, Bir Murr and Ain Maqfi sections (Fig 4.16, 4.9& 4.19). The re-establishment of a new planktic foraminiferal association apparently took place under changing environmental conditions that continued above the K/P boundary event. After the sea-level fall during the interval of the K/P boundary, the studied area was invaded by a major marine flooding in the Early Danian. The planktic foraminiferal percentage increased gradually and attained more than 80% of the faunal content.

In fact, the rapid replacement of one bio-assemblage by another is indicative of major changes in the depositional environment due to the changing of physical/chemical factors in the marine environment or due to some complex interaction between elements of the biological system. The foraminiferal wackestone has been deposited in a deep middle shelf setting due to its high P/b ratio.

2. Deep middle/outer shelf pelagic shale

This lithofacies marks the upper part of the Dakhla Formation. It is yellowish gray, slope forming, fissile, calcareous and highly fossiliferous with abundant planktics and some benthics. The lithologic characteristics and faunal content of this pelagic shale indicate deposition in a deep middle/outer shelf environment under quite water conditions. The lamination which is an essential structure in this shale supports deposition in quite water conditions. In some sections such as in northwest Bir Bidni, the planktic percentage reaches up to 60% of the rock (Fig. 4.10). The associated benthic assemblage includes some species of the genera *Textularia*, *Cibicidoides*, and *Cyroidinodes*. In the northern slope of El Quss Abu said, the planktic percentage in the top part of the upper calcareous shale of the Dakhla Formation is low to nil. The benthic species are the dominant foraminiferal type.



Base unexposed

Fig. 4.10 Representative stratigraphic section of the exposed Upper Maastrichtian-Lower Eocene rocks in northwest Bir Bidni (about 30km in Farafra-Ain Dalla road), west Farafra Oasis, showing their microfacies types and sedimentary environments.

Toward the end of the P2 Zone, a marked drop in the planktic percentage (from 65% to 38%) took place near the top part of the calcareous shale in Bir Murr (Fig. 4.9), which indicat clear shallowing conditions in the eastern part of the Farafra Oasis. These changes in planktic percentage indicate a drop in relative sea level from outer shelf to shallow middle shelf.

3. Shallow inner shelf foraminiferal lime-mudstone

The foraminiferal lime-mudstone is not a common microfacies type in the Dakhla Formation. It marks the lower unit of the Dakhla Formation in northwest Bir Bidni (Fig. 4.10).

Petrographically, the foraminiferal lime-mudstone is composed of small amounts of skeletal particles floting in a dense lime mud matrix (Fig. 4.12). Foraminiferal tests, representing the main component of these skeletal particles, are fragmented and badly preserved. Fine glauconitic grains are also recorded randomly disseminating in the lime mud matrix. The matrix is partially recrystallized into pseudospar. The foraminiferal lime-mudstone deposits in a shallow inner shelf regime. Haq *et al.* (1977) mentioned that a relatively warm climate had prevailed between 63 and 60 Ma (a time span corresponding to the *Globanomalina compressa-Praemurica uncinata* P1c Subzone, *Praemurica uncinata–Morozovella angulata* P2 Zone and part of the *Morozovella angulata-Globanomalina pseudomenardii* P3 Zone). During this time interval, the warming trend beginning from P1c to P3, except for the interval which contains common assemblage of the planktic foraminiferal assemblage such as *Subbotina* and *Globanomalina* that consistently recording the coolest water masses among Paleogene species.

To summarize, the facies characteristics and the vertical distribution of the studied fauna in the Dakhla Formation indicate a transgressive event of the sea level which increases at the top with the increasing of the planktic foraminifers.

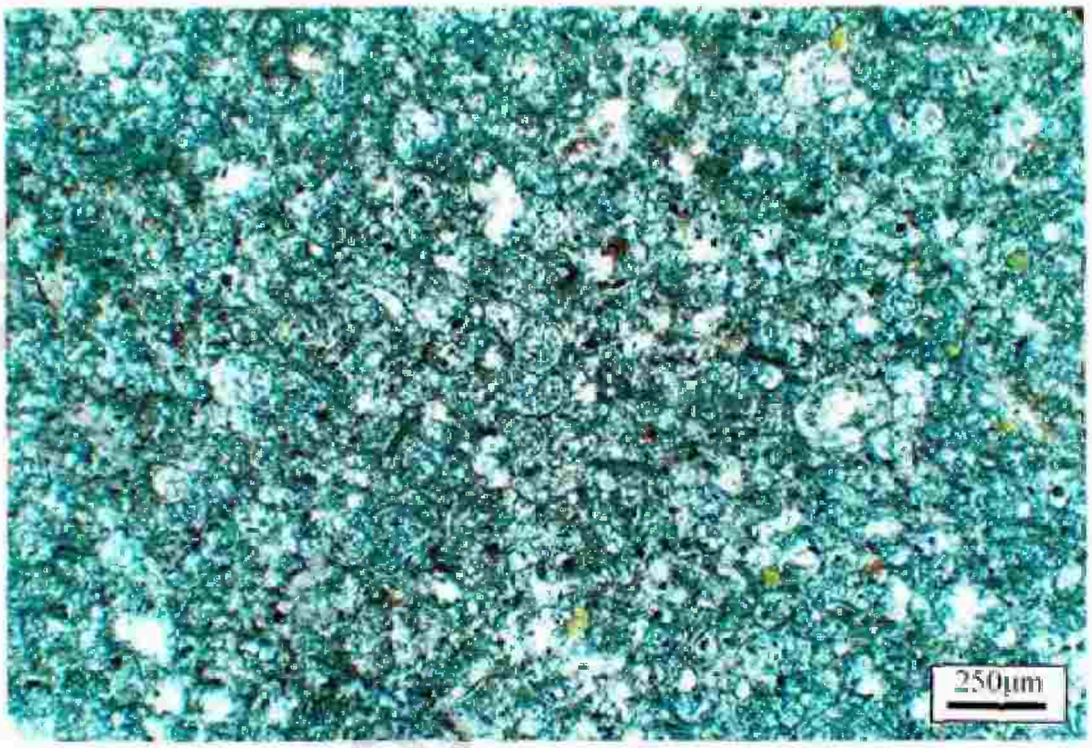


Fig. 4.11 Foraminiferal tests randomly disseminated in a dense partially recrystallized lime mud matrix with glauconitic grains filling the foraminiferal tests. Deep middle shelf foraminiferal wackestone, Early Paleocene, Bir Murr, bed No. 6.

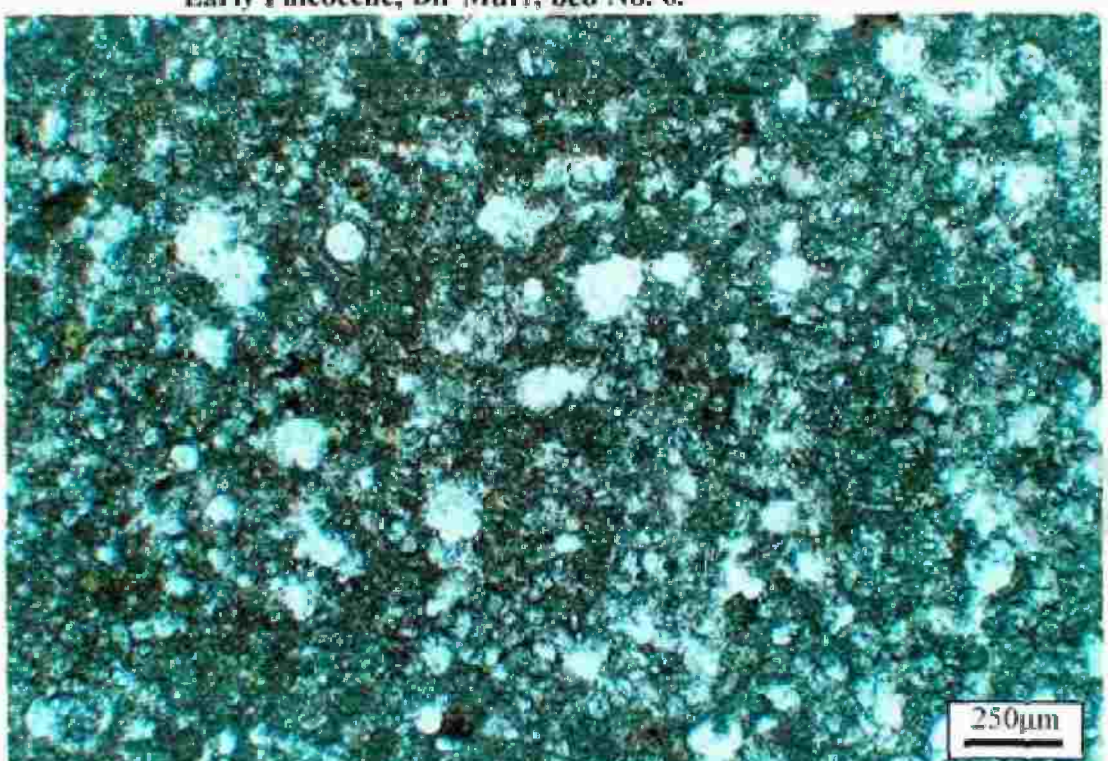


Fig. 4.12 Badly preserved foraminiferal tests embedded in a dense lime mud matrix. Lower intertidal foraminiferal lime-mudstone, Early Paleocene, northwest Bir Bidni, bed No. 19.

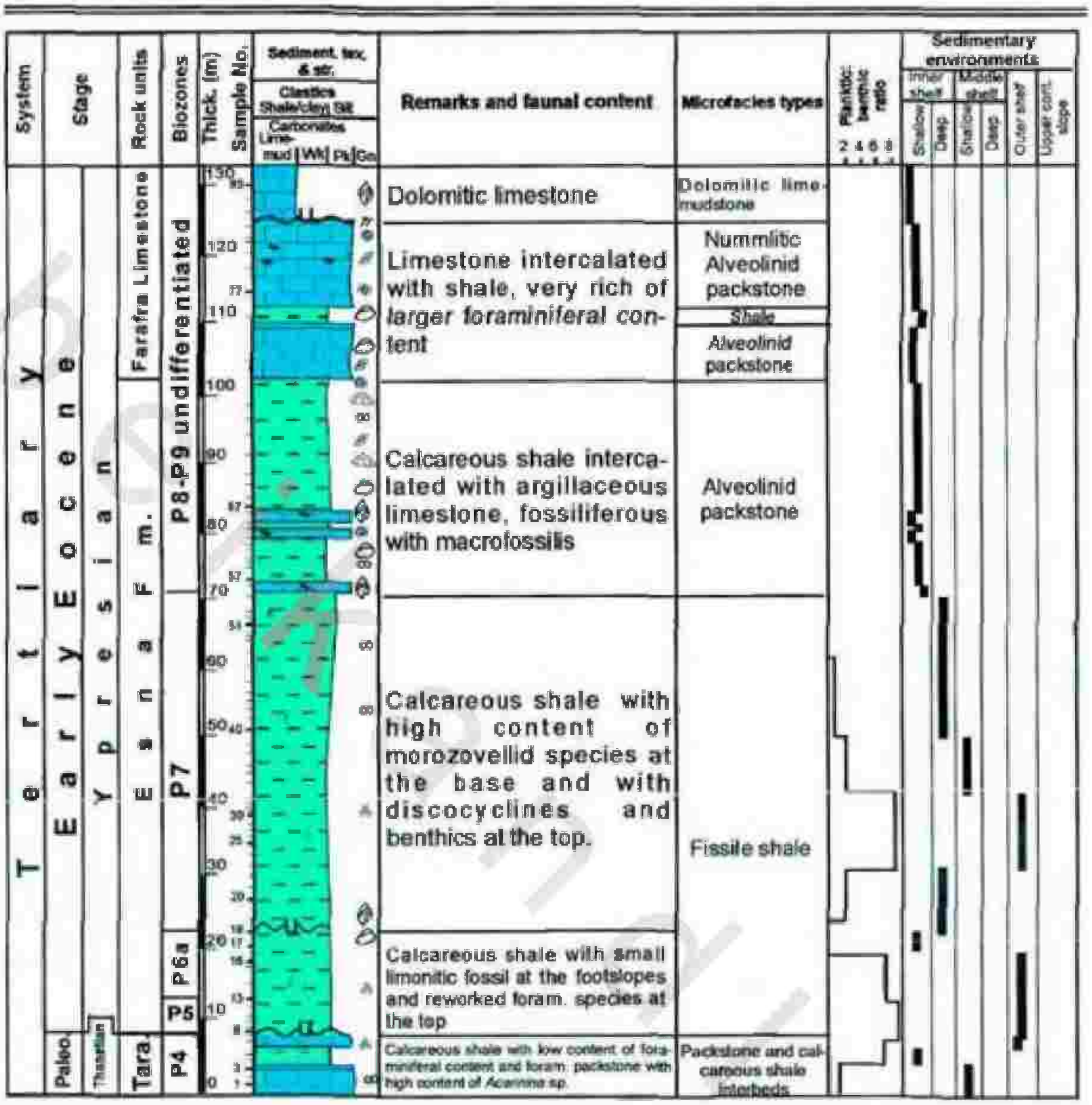
IV. 4 Tarawan Formation

The Tarawan Formation is composed of white to yellowish white, moderately hard chalky limestone with shale interbeds. It includes the following facies associations:

1. Outer shelf pelagic foraminiferal packstone
2. Outer shallow middle shelf pelagic shale
3. Lower shallow subtidal bioclastic foraminiferal packstone
4. Lower intertidal foraminiferal lime-mudstone

1. Outer shelf pelagic foraminferal packstone

The foraminiferal packstone is recorded at the top part of the Tarawan Formation in the northern slope of El Quss Abu Said Plateau and in the main part of the formation in Qaret Sheikh Abd Alla (Fig. 4.13 & 4.14). Packstone is a grain-supported rock with small amounts of lime mud matrix, usually not exceeds 15% of the rock content. The skeletal particles are the most distinctive constituents of the packstone rock. Petrographically, the packstone is made up of tightly-packed foraminiferal tests embedded in a dense lime mud matrix (Fig. 4.15). The foraminiferal tests are represented by planktics, rarely benthics. The tests are mostly recrystallized into microspar, while their chamber lets are filled with clear spary calcite cement. Few thin-walled oyster shells and dwarf gastropods are recorded. The planktics are characterized by their high frequency (more than 90%), high diversity and the abundance of *Morozovella* and *Acarinina* species. The keeled planktic species exceed largely both the non-keeled and heterohelicids species. They attain more than 60% of the planktic foraminiferal assemblages, while the non-keeled species attains less than 30% of this assemblage. The low benthic content (less than 10%) in the foraminiferal packstone rock is mostly calcareous type.



Base unexposed

Fig. 4.13 Representative stratigraphic section of the exposed Upper Maastrichtian-Lower Eocene rocks in the northern slope of El Quss Abu Said, Farafra Oasis, showing their microfacies types and sedimentary environments.

The abrupt increase in the planktic foraminiferal species in the Tarawan Formation is essentially attributed to a sudden flooding of the Tethyan water masses during the upper part of the *Globanomalina pseudomenardii* P4. The pelagic foraminiferal packstone has been deposited under deep water conditions in an outer shelf setting at water depth between 150 and 200m.

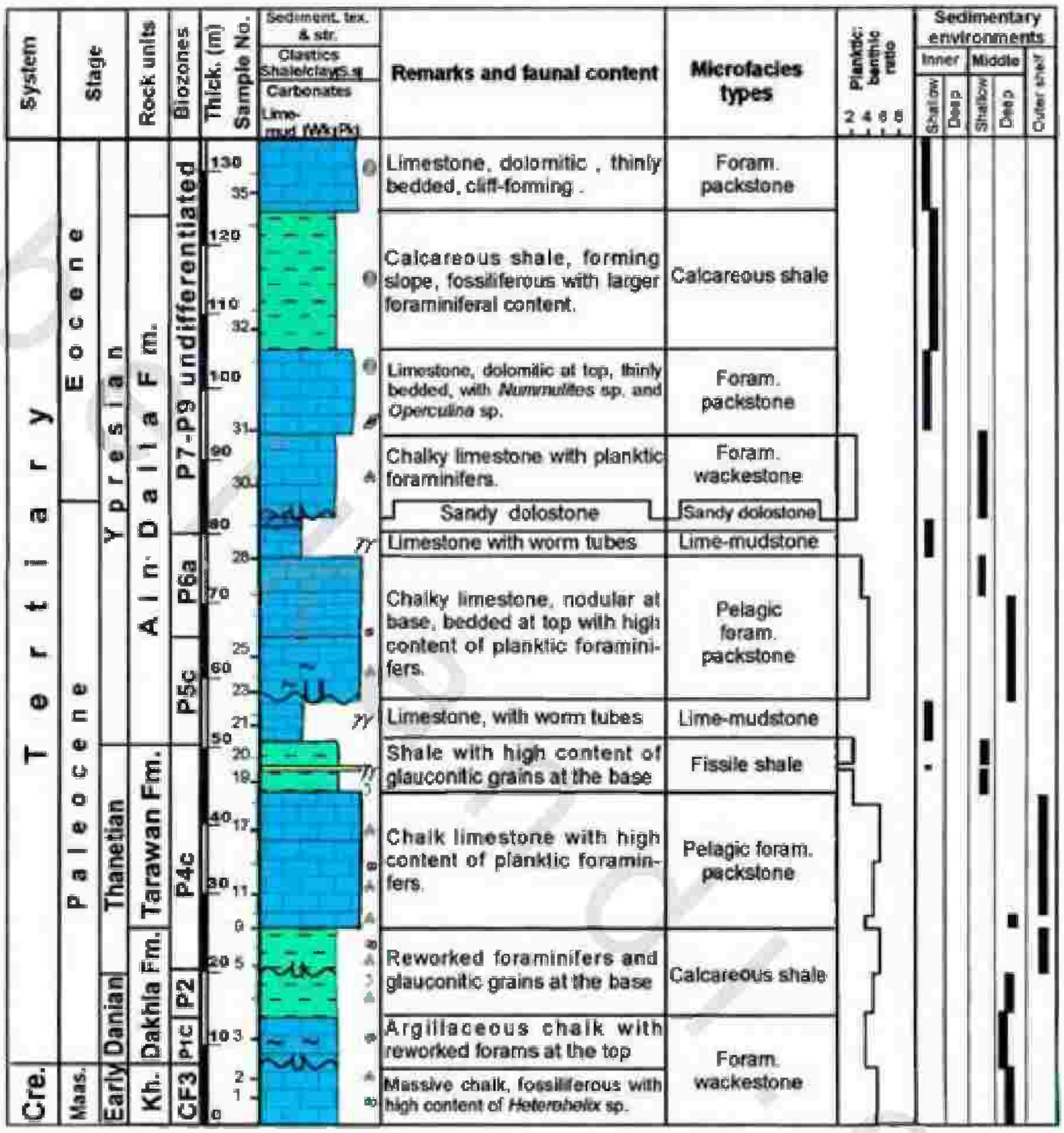


Fig. 4.16 Representative stratigraphic section of the exposed Upper Maastrichtian-Lower Eocene rocks in Shakhs El-Obeiyid, west Farafra Oasis, showing their microfacies types and sedimentary environments.

3. Lower shallow subtidal bioclastic foraminiferal packstone

The bioclastic foraminiferal packstone is only observed in the upper part of the Tarawan Formation measured in northwest Ain Maqfi (Fig. 4.5) Petrographically, the bioclastic foraminiferal packstone is composed of fossil debris, originally derived from larger foraminiferal tests as well as from ostracods, dwarf gastropods, echinoid spines and plates, together with a few algal fragments (Fig. 4.17). Some complete large benthics are also observed. Larger benthics are often recrystalized into pseudospar, rarely dense micritized. The skeleton debris is agglutinated in spary calcite with a small amount of lime mud. The presence of shallow marine larger benthic foraminiferal assemblage, indicate deposition in a lower shallow subtidal (shallow inner shelf) setting. In such shallow depth, the wave impact on the sea floor causes fragmentation of the faunal content.

4. Lower intertidal foraminiferal lime-mudstone

The foraminiferal lime-mudstone is recorded in Bir Murr with a thickness of 1m thick (Fig. 4.9). It contains a few amounts of badly preserved planktics such as *subbotina* sp., it also occurs in northwest Ain Maqfi (Fig. 4.5) and in Shakhs El-Obeiyid (Fig. 4.16). The lime-mudstone consists of a dense and dark grey lime mud matrix (more than 95%) with rare badly preserved planktic foraminiferal tests (Fig. 4.18). The lime mud is partly affected by aggrading neomorphism into microspar. Iron-oxides may partially fill some of the foraminiferal chambers. The iron-oxides are also present as spots and patches disseminating in the lime mud matrix. The voids and microfractures within the matrix are almost completely filled with sparry calcite and/or iron-oxide cements.

The lime-mudstone represents protected lower intertidal flat sediment commonly deposited shoreward of a low-energy, shallow-marine lagoon. The low faunal content suggests high salinity conditions restricted circulation with the open sea.

To summarize, the Late Paleocene *Globanomalina pseudomenardii* Zone of the Tarawan Formation is marked by a gradual upward shallowing conditions as evidenced from the rapid vertical variation in the facies associations and upward decrease

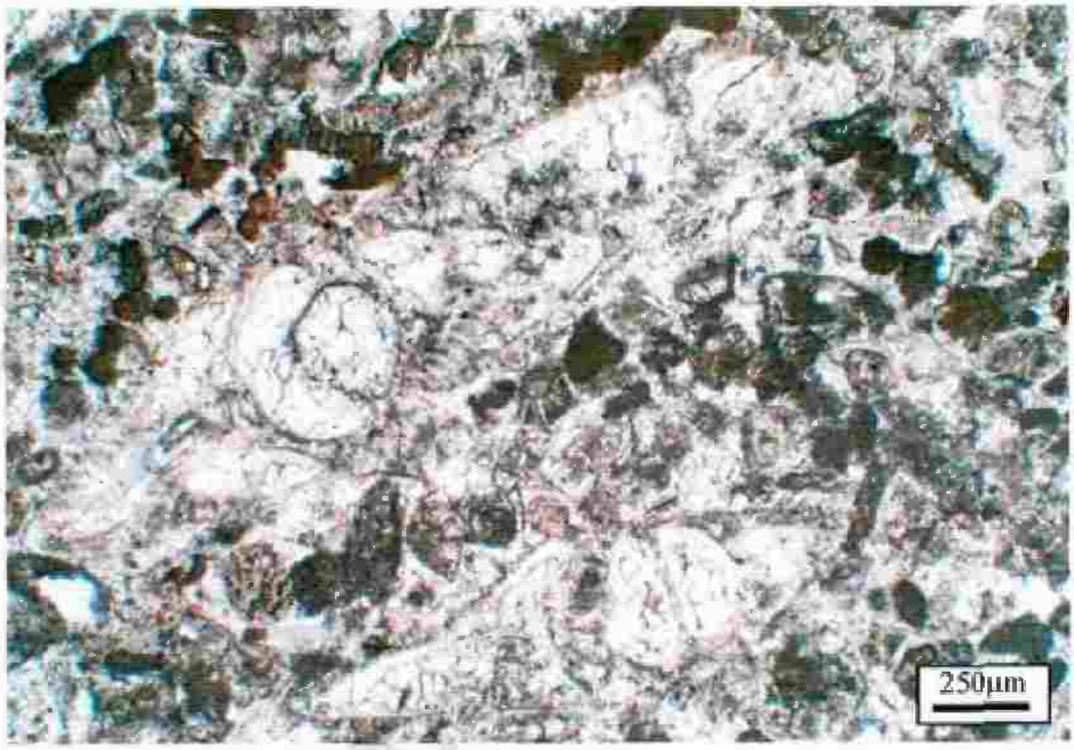


Fig. 4.17 Larger benthic foraminifers, pelloids and shell debris agglutinating in sparry calcite with a small amount of lime mud. Lower shallow subtidal bioclastic foraminiferal packstone, Late Paleocene, northwest Ain Maqfi, bed No. 71.

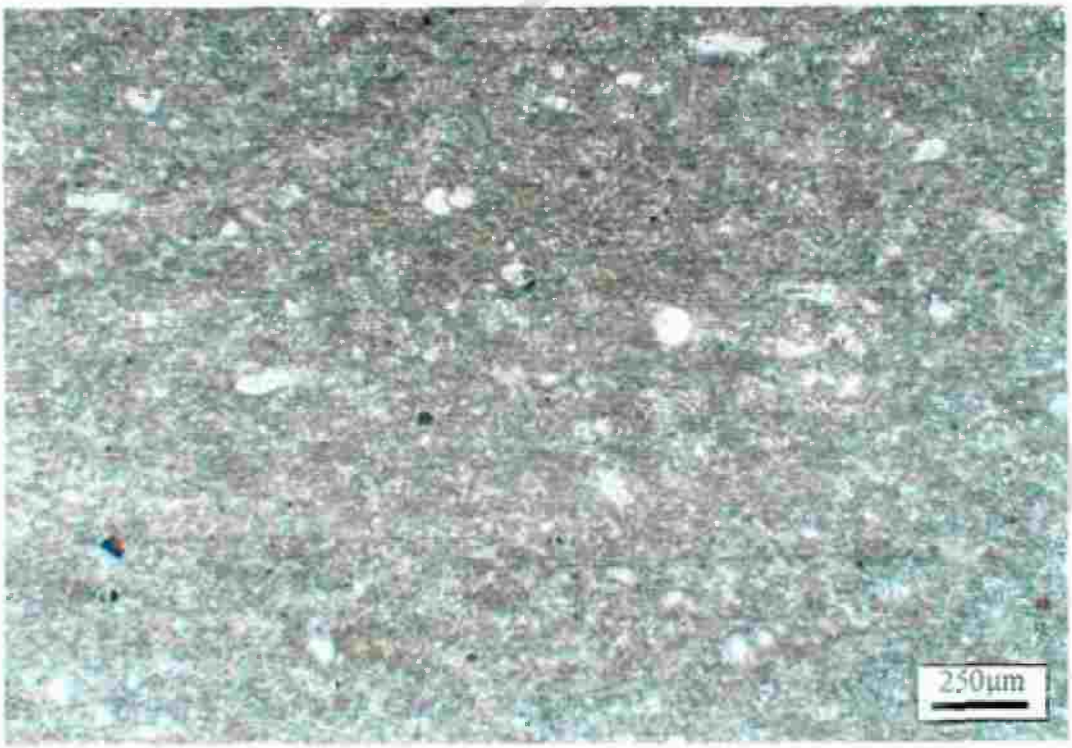


Fig. 4.18 Few amounts of planktic tests disseminated in a recrystallized lime mud matrix with some iron-oxides. Lower intertidal foraminiferal lime-mudstone, Late Paleocene, Bir Murr, bed No. 11.

in planktic/benthic ratio (Figs. 4.5 & 4.16). These shallowing most probably are connected with an episode of tectonic activity in the Egyptian Paleocene called the *Velascoensis* Event by Strougo (1986).

Haq *et al*. (1977) pointed out that by the beginning of the Late Paleocene, there was a cooling trend because the low spired subbotinid assemblage invaded the low latitudes and the high latitudes nannofloral *Prinsius martinii* assemblage spread to the low latitudes. Samir (1995) mentioned that through the Latest Paleocene (*Globanomalina pseudomenardii* and *Morozovella velascoensis* zones), a faunal turnover took place indicating an oceanic cooling. This is indicated by: 1) The decrease in abundance of the warm water indices (i.e. morozovelliods), from 48% to range between 31% to 26%, and 2) The increase in abundance of the cool water indices (i.e. the subbotinids) from 24% to range between 34% and 50%.

IV. 5 Esna Formation

The base of the Esna Formation in the eastern and northeastern parts of the Farafra Oasis is composed of alveolinid limestone of the Maqfi Member followed by shale intercalated with argillaceous limestone especially in the upper part of the formation (Fig. 4.19). While in the western escarpment of the oasis, the Esna Formation consists of calcareous shale which is intercalated with argillaceous limestone in the upper part.

The Esna Formation includes the following six facies associations:

1. Deep middle/outer shelf pelagic shale
2. Shallow inner shelf calcareous shale
3. Lower shallow subtidal miliolids alveolinid bioclastic packstone

4. Lower shallow subtidal foraminferal packstone
5. Supratidal sabkha
6. Lower shoreface calcareous quartz arenite

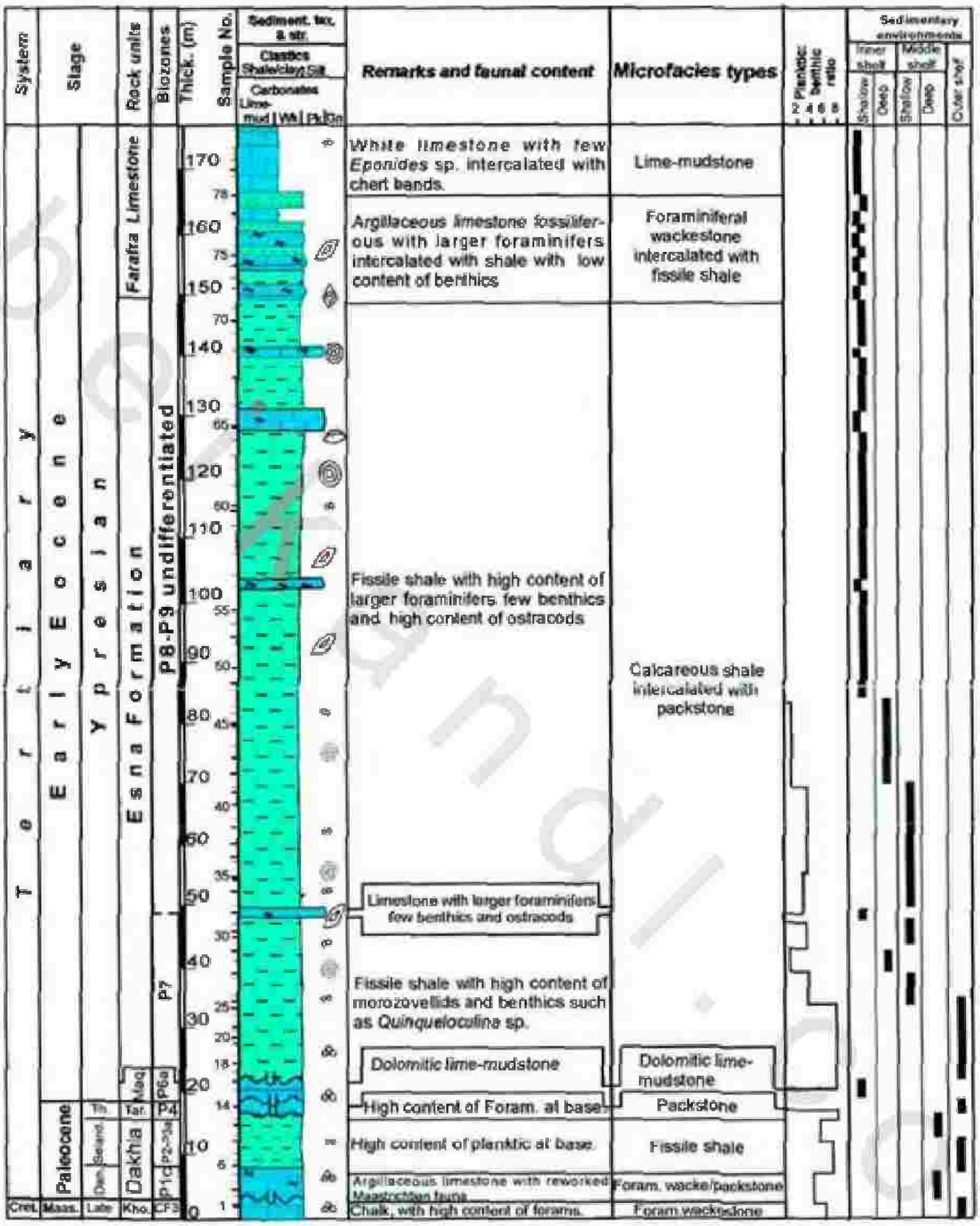
The following is a detail description and interpretation of the detected microfacies associations.

1. Deep middle/outer shelf pelagic shale

The pelagic shale is a common facies in the lower part of the Esna Formation. It is yellowish gray, dark gray, light olive gray in color, calcareous, fissile and fossiliferous with abundant and diverse foraminifers. The basal part of the Esna Formation is marked by a dominance of non-keeled planktic forms such as *Acarinina* and *Subbotina* (attains about 80%) and the warm-water species of *Morozovella* (single keeled forms) which increase rapidly upward. The occurrence of high diversity planktics munitions their deposition in a deep middle/outer shelf setting.

This calcareous shale contains many dwarf fauna especially at the base of the Esna Formation measured in southeast Qur Hadida and the northern slope of El Quss Abu Said (Fig 4.13). Whether the dwarf fauna represents a real phenomenon of stunting or not was one of the main themes discussed by Abdellatif (1990). Analyzing all the factors conducive to stunting (food supply, salinity, temperature, oxygen content, turbidity, exposure to waves, population, density and other factors) declared that many of the fossils of the dwarf fauna were small because they belong to naturally small species.

At about 15m, the base of the Esna Formation in the northern slope of El Quss Abu Said, the dwarf fauna are recorded in calcareous shale containing about 70% planktic and reworking fauna such as *Globanomalina* sp. as well as abundant benthic such



Base unexposed

Fig. 4.19 Representative stratigraphic section of the exposed Upper Maastrichtian-Lower Eocene rocks in southern Ain Maqfi, showing their microfacies types and sedimentary environments.

as *Bathysiphon arenaceus* Cushman which indicate shallower environment condition toward the top part of *Morozovella formosa formosa* and/or *Morozovella lensiformis* (P6a) Subzone (Fig. 4. 13). The foraminiferal tests are well preserved and not affected by any oxidation, except the reworked fauna. In this interval, the Subbotinids and Acarininids increase with low morozovelliods, in addition to, abundance of benthic forams such as *Lenticulina pondi* (Cushman), *Marginulina wetherelli* Jones, *Bulimina quadrata* Plummer, *B. pupoides* d' Orbigny, *Gaudryina soldadoensis* Cushman & Renz, *Nonionella africana* LeRoy and *Anomalinoides granosus* (Hantken). Towards the middle part of the Esna Formation (P7 Zone), the morozovellids markedly decrease again while the subbotinids increase. This clearly indicates the beginning of a cooling episode towards the middle and upper parts of the Esna Formation.

Most of the Cenozoic oxygen isotope palaeotemperature curves show a marked warming during the Early Eocene, which may have been the most uniformly warm episode of the Paleogene (Haq *et al.*, 1977; Savin, 1977, Wolfe, 1979).

Haq (1981) reviewed the global oceanic temperature conditions during the Paleogene based on the palaeobiogeographic migrations of the planktic organisms and on the oxygen-isotop data. He concluded that a number of warm and cool pulses occurred during the Early and Middle Paleocene, followed by a sustained warm and cool pulses occurred during the Latest Paleocene and extended into the Middle Eocene. However, there is considerable evidence indicating that the Early Eocene was the warmest interval of the Cenozoic (Frakes, 1979; Haq, 1981 and Kennett, 1982).

2. Shallow inner shelf calcareous shale

This calcareous shale is a dominant facies in the middle-upper part of the Esna Formation. It is intercalated with thin limestone interbeds. The shale facies is yellowish gray, compact, slope-forming, fissile and highly fossiliferous with larger foraminifers such as *Nummulites*, *Operculina* as well as molluscan shells and echinoids. The progressive shallowing of the sea in the middle-upper part of the Esna Formation is indicated by the constant occurrence of the bivalves, corals, echinoids and gastropods at different levels. These macro-invertebrates are characterized by high diversity especially in El Quss Abu Said Plateau (Fig. 4.20). The presence of such types of fossils proves that the calcareous shale have been deposited under upper deep subtidal shelf conditions.

3. Lower shallow subtidal miliolids alveolinid biocalstic packstone

The miliolids alveolinid biocalstic packstone is a common microfacies type in the alveolinid limestone of the Maqfi Member (Fig. 4.5). Petrographically, the rock is essentially made up of closely packed skeletal particles, which form about 70-80% of the rock content. The skeletal components are mainly of alveolines, rare nummulitids, echinoids spines, coralline algea and many dense micritized bioclasts. They agglutinated in sparry calcite cement with some subangular quartz grains (Fig. 4.21 & 4.22). The alveolinid are present in complete circular and well-rounded forms. Early isopachous calcite cement is often developed vertically on the bioclasts. The *Nummulites* are often recrystalized with relics of their fibrous well structures. The bioclasts are coarse-grained, moderately sorted and usually varied in shape from spherical to elongated forms. They undergo intense micritization to the point that they appear as dark ghosts or pseudo-pellets.

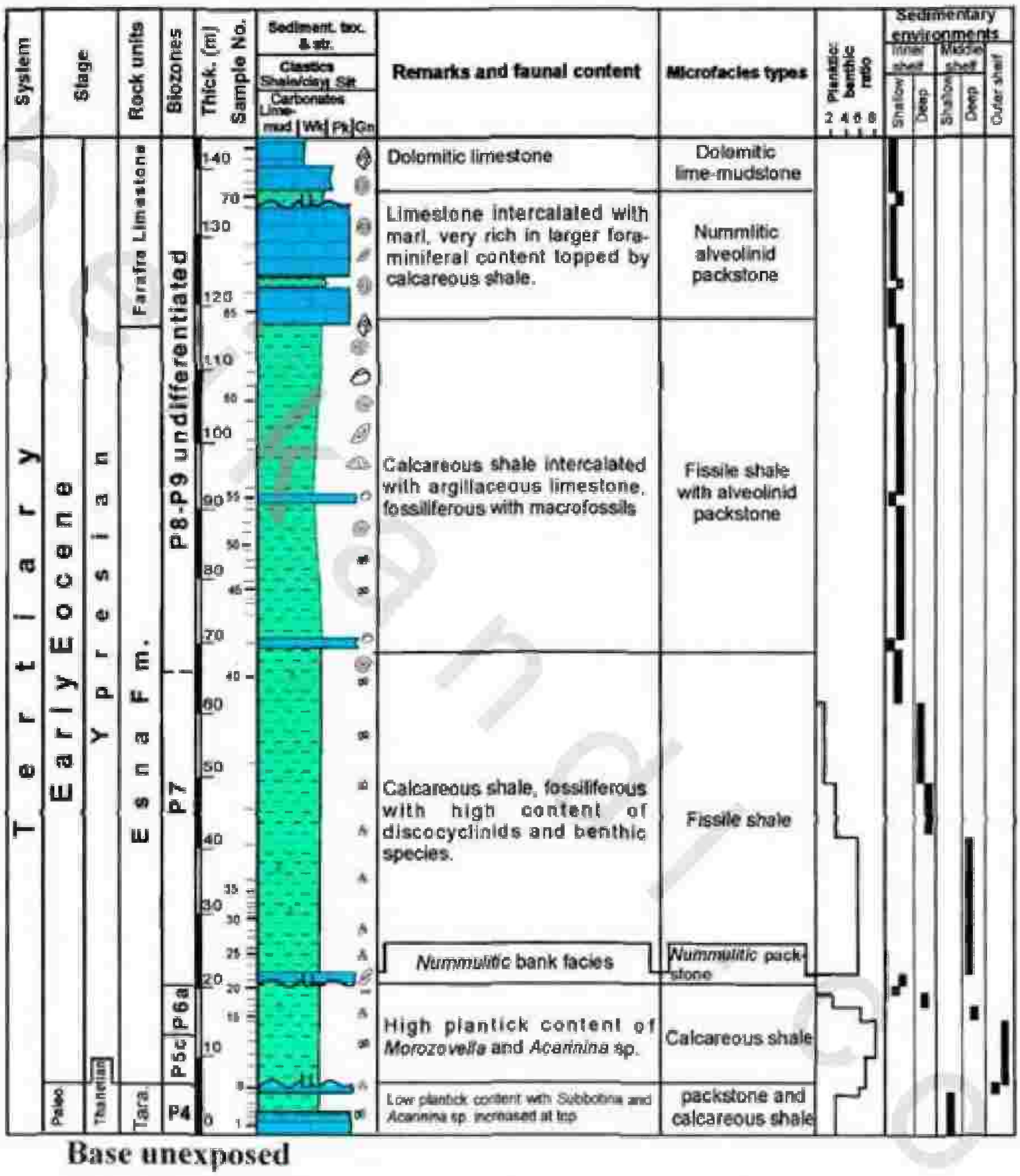
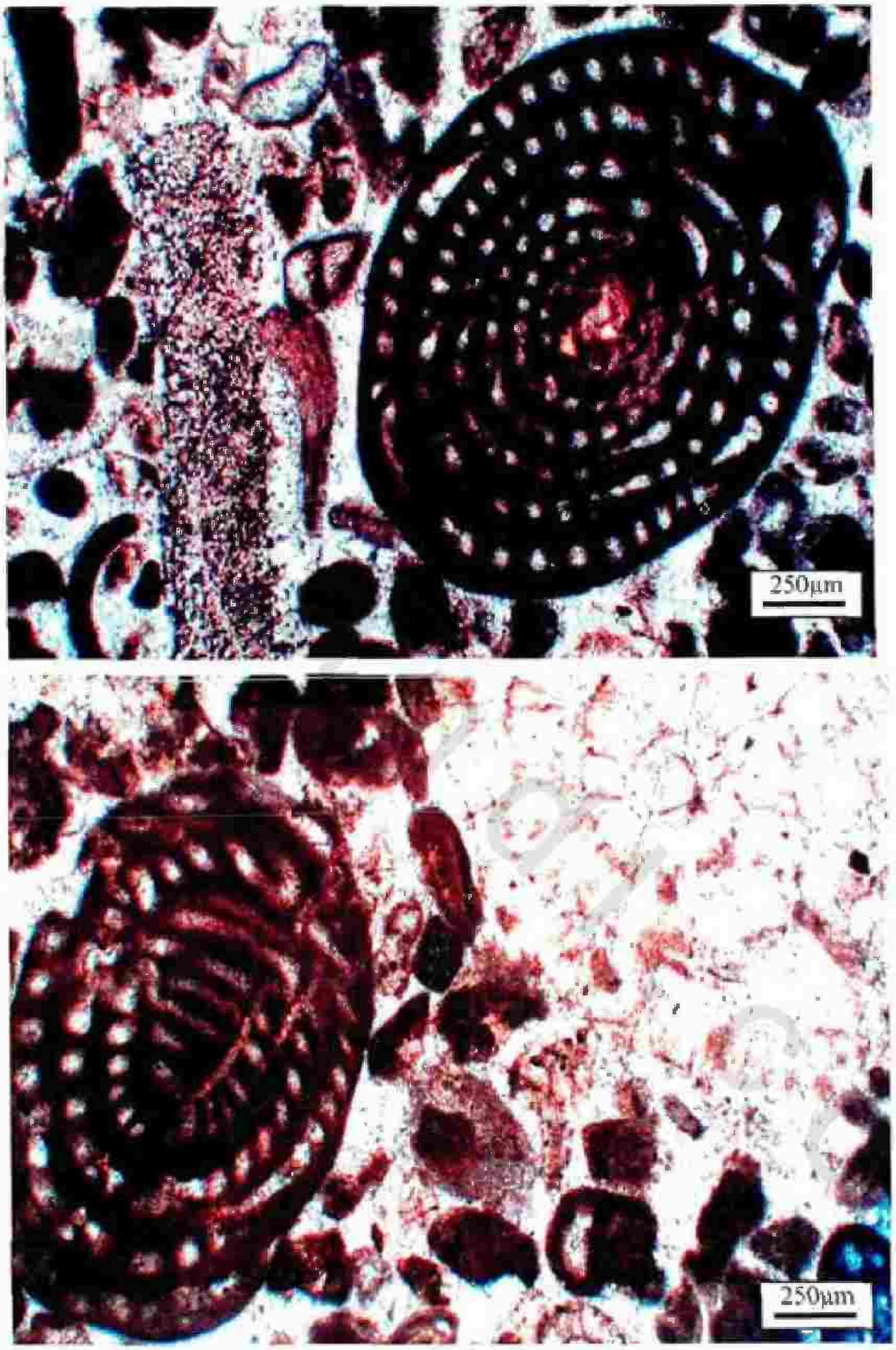


Fig. 4.20 Representative stratigraphic section of the exposed Upper Paleocene-Lower Eocene rocks in the southern slope of El Quss Abu Said, showing their microfacies types and sedimentary environments.



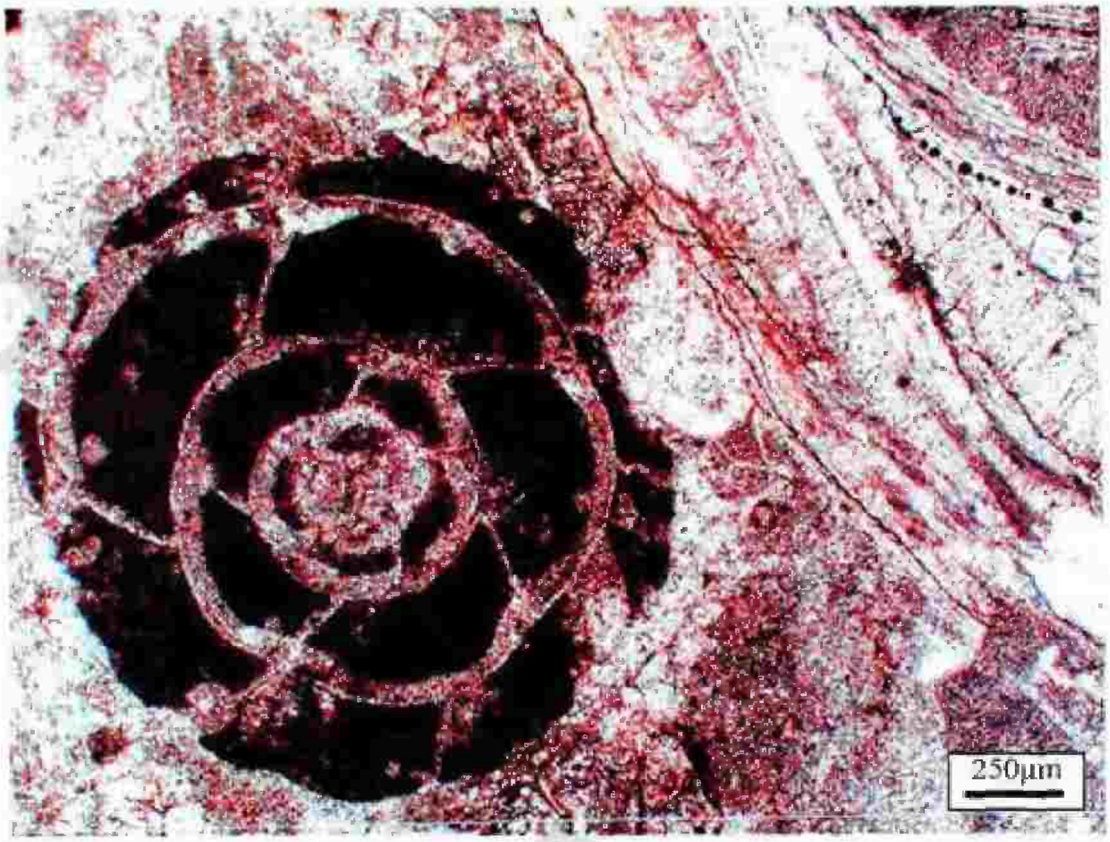
Figs. 4. 21- 22 Alveolines, echinoid spines and nummulites with dense micritized bioclastic grains cemented by clear sparry calcite. Lower shallow subtidal miliolids alveolinid packstone, northwest Ain Maqfi, bed No. 76.

The packstone represents agitated-water, lower shallow subtidal shoal sediments that commonly develop in the marine inner shelf under high current and wave activity. This interpretation is documented from: 1) The predominance of larger benthic foraminifers such as *Alveolina* sp. and *Nummulites* sp. 2) the practical absence of the planktic foraminiferal species and 3) The relative dominance of shallow marine fauna such as coralline algae and echinoids. The extensive broken and abraded shells as well as the rarity of lime mud matrix indicate the strong winnowing currents.

Murray (1973) pointed out that the larger foraminifers, which live in a subtropical-tropical environment, are occurring in the upper part of the continental shelf, within a relatively limited sector. The abundance of larger foraminifers indicates a drastic fall in relative sea level and the prevalence of normal salinity, which existed for a long time, providing favorable conditions for the rapid evolution of *Nummulites* and *Alveolina* (Tecskeméti, 1989).

4. Lower shallow subtidal of foraminiferal packstone

The foraminiferal packstone has a wide occurrence in the upper part of the Esna Formation in the Farafra Oasis. The rock is grain-supported with some lime mud matrix. Petrographically, the packstone is made up of skeletal particles (70%) embedded in a dark gray microcrystalline calcite. The skeletal particles are mainly represented by larger benthics (operculinids, alveolinid and nummulitids), echinoid spines, molluscan shell fragments and algal debris (Figs. 4.23 & 4.24). Calcitic bivalve shell fragments with foliated structure and aragonitic shell debris with dissolved moulds are the common molluscans. Most of the foraminiferal tests are badly preserved due to intense micritization. Some of the



Figs. 4.23, 24 Benthic foraminifers, calcareous bivalve shells and echinoid spine disseminated in a few dense lime-mud matrixe. Lower shallow subtidal foraminferal packstone, northwest Ain Maqfi, bed No. 96.

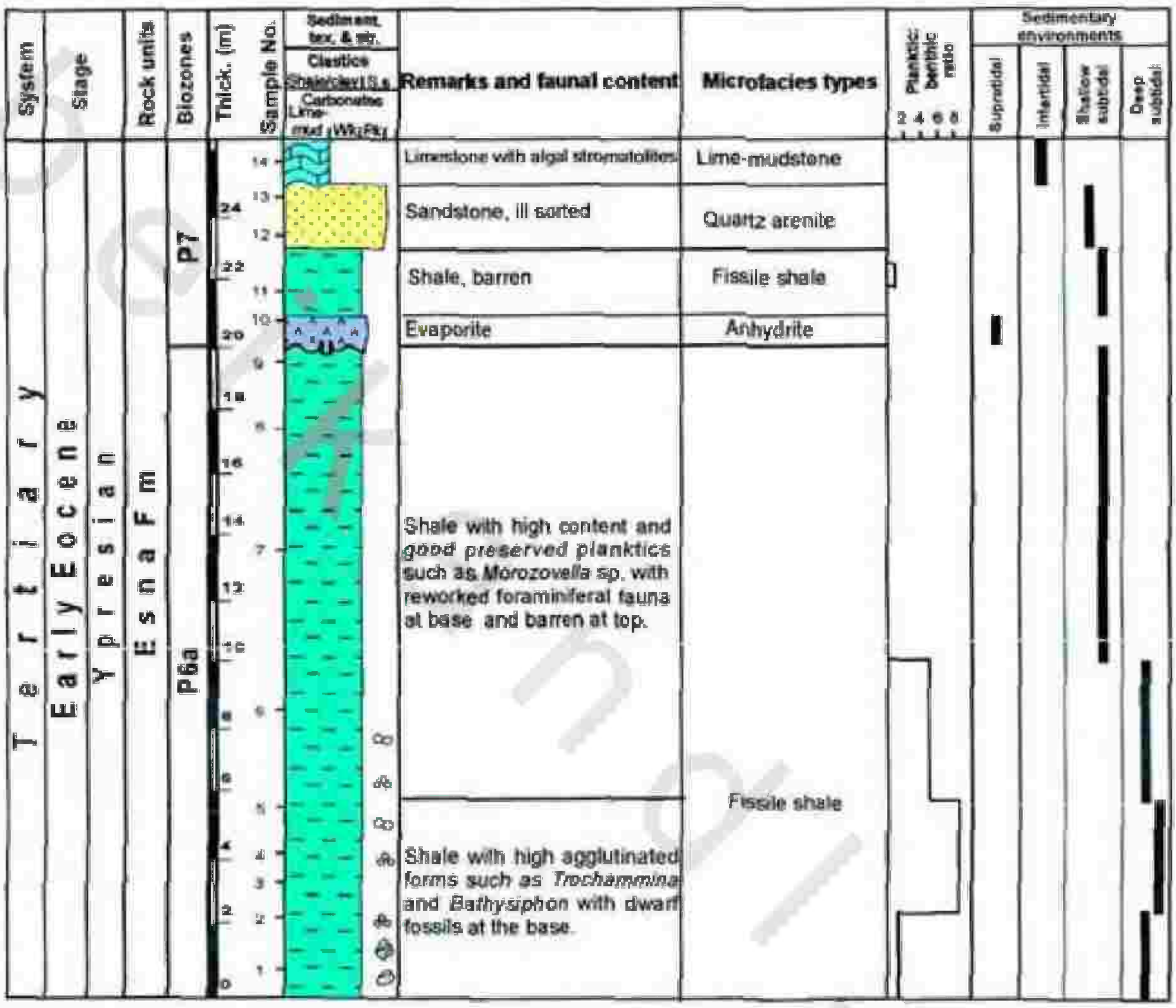
Nummulites tests are recrystallized into pseudospar with relics of their internal microstructure.

The larger foraminifers appear in repetitive banks, and their appearances are associated with a marked decrease in the abundance of the planktic and the diversity of the benthic species. Miliolids and rotaliids become important components in the limestone interbeds of the upper part of the Esna Formation, especially *Quinqueloculina gussensis* Schwager, *Spiroloculina esnaensis* LeRoy, *Eponides lotus* (Schwager), *cancris auricular* (Fichtel & Moll), *Rotalia calcariformis* (Schwager) and *Nonionella insecta* (Schwager), in addition to cibicidids and anomalinids.

In fact, the planktic foraminifers are absent in the upper part of the Esna Formation. The benthic fauna is very few, dominating by *Paralabamina aegyptiaca* (LeRoy) and *Rotalia calcariformis* (Schwager), suggesting a marginal shallow inner shelf environment. The bivalves, on the other hand, are abundant and the most common species are *Pycnodonte aviculina* (Oppenheim), *Spondylus aegyptiacus* Newton, *Euphenax zitteli* (Mayer-Eymar), *Gryphaeostrea eversa* (Melleville), *Ostrea multicostata* Desh and *Ostrea* (*Ostrea*) *aviola* Newton especially in El Quss Abu Said Plateau. Recent oyster seems to restrict to the near shore habitats. According to Kauffman (1967), those oysters that range out onto the shelf are predominantly small, delicate species. In most situations, oyster prefers brackish waters and only the brackish-water species from persistent buildups. Therefore, the upper part of the Esna Formation with its successive packages of oyster banks has been deposited in a shallow inner shelf setting, most probably intermittently subjected to lowering salinities.

5. Supratidal sabkha

The evaporite is only recorded in the Esna Formation of southeast Qur Hadid, measuring about 1m thick (Fig. 4.25).



Base unexposed

Fig. 4. 25 Representative stratigraphic section of the exposed Lower Eocene rocks in southeast Qur Hadida, east Farafra Oasis, showing their microfacies types and sedimentary environments.

Petrographically, the evaporite is formed of interlocked coarse granular and prismatic anhydrite crystals (Fig. 4.26). The individual anhydrite crystals vary in length from 0.3-1mm. Clayey material and a few quartz grains are disseminated between the anhydrite crystals. Fibrous anhydrite aggregates are also found in the form of radiating rosettes (Fig. 4.27). They are embedded in a fine anhydrite with randomly disseminated clayey and micritic materials. The evaporite facies represents very shallow salina deposits developed on a supratidal flat setting during arid climatic and hypersaline conditions. This salina resulted in the deposition of the subaqueous thin-laminated and upward prismatic gypsum which later pseudomorphously replaced by anhydrite due to diagenetic dewatering.

6. Lower shoreface calcareous quartz arenite

The calcareous quartz arenite is recorded in the upper part of the Esna Formation exposed at southeast Qur Hadida. It measure about 1m thick (Fig. 4.25). The rock consists of quartz grains (95%) cemented by microcrystalline calcite with some silty clayey matrix which filling completely the intergranular pore spaces. The quartz grains are very fine to coarse-grained, ranging in size from 100 to 900μm, poorly sorted and subangular to rounded. Most of the quartz grains are of monocrystalline type and exhibit straight to slightly undulose extinction. Calcite-quartz replacement is comman along the grain boundaries. Iron-oxides may be recorded as secondary cementing material. The sandstone facies represents a shallow subtidal deposit (lower shorefacie) of a silicaclastic beach.

To summarize, the faunal and lithologic characteristics of the Maqfi Member suggest deposition in a lower shallow subtidal environment. While, in the paleo-low areas, the basal part of the Esna Formation indicates deposition in a deep middle/outer shelf environment. Whereas, the overlying sediments of the middle and upper part of the Esna Formation is have been deposited under shallower conditions between shallow subtidal to upper deep subtidal setting (shallow inner shelf).

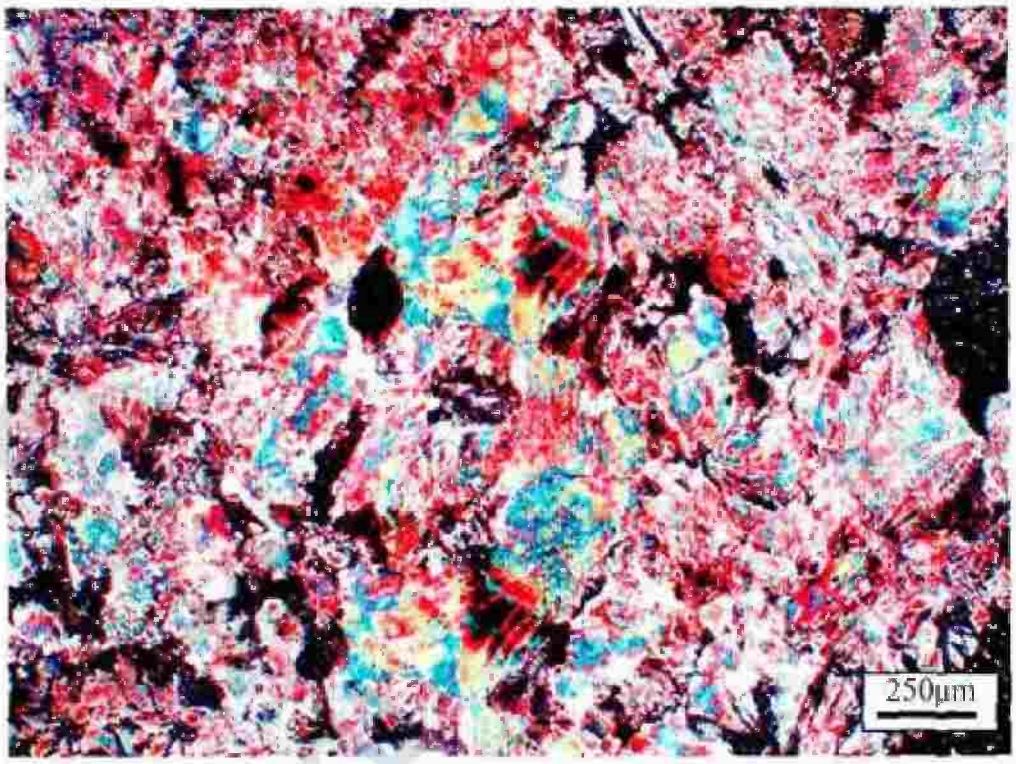


Fig. 4.26 Coarse granular and *prismatic anhydrite crystals* pseudomorphosed after gypsum. Supratidal sabkha facies, southwest Qur Hadida, bed No. 10

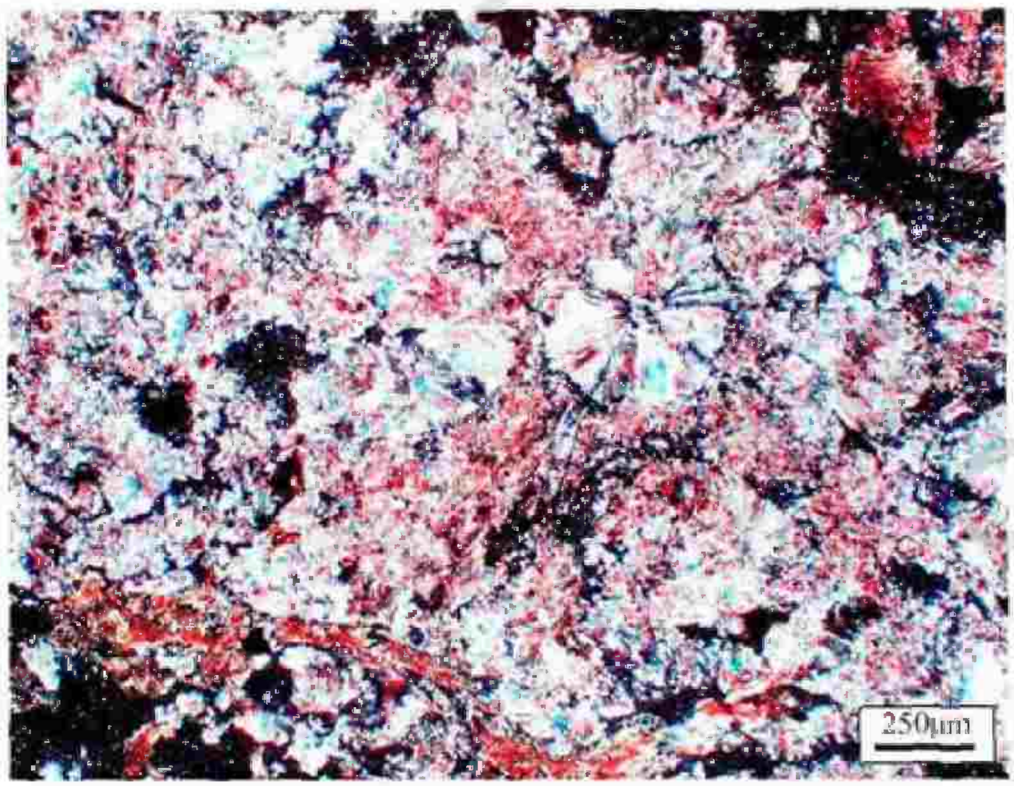


Fig. 4.27 Fibrous anhydrite aggregates in the form of radiating rosettes embedded in a fine equant anhydrite. Supratidal sabkha facies, *southwest Qur Hadida, bed No. 10.*

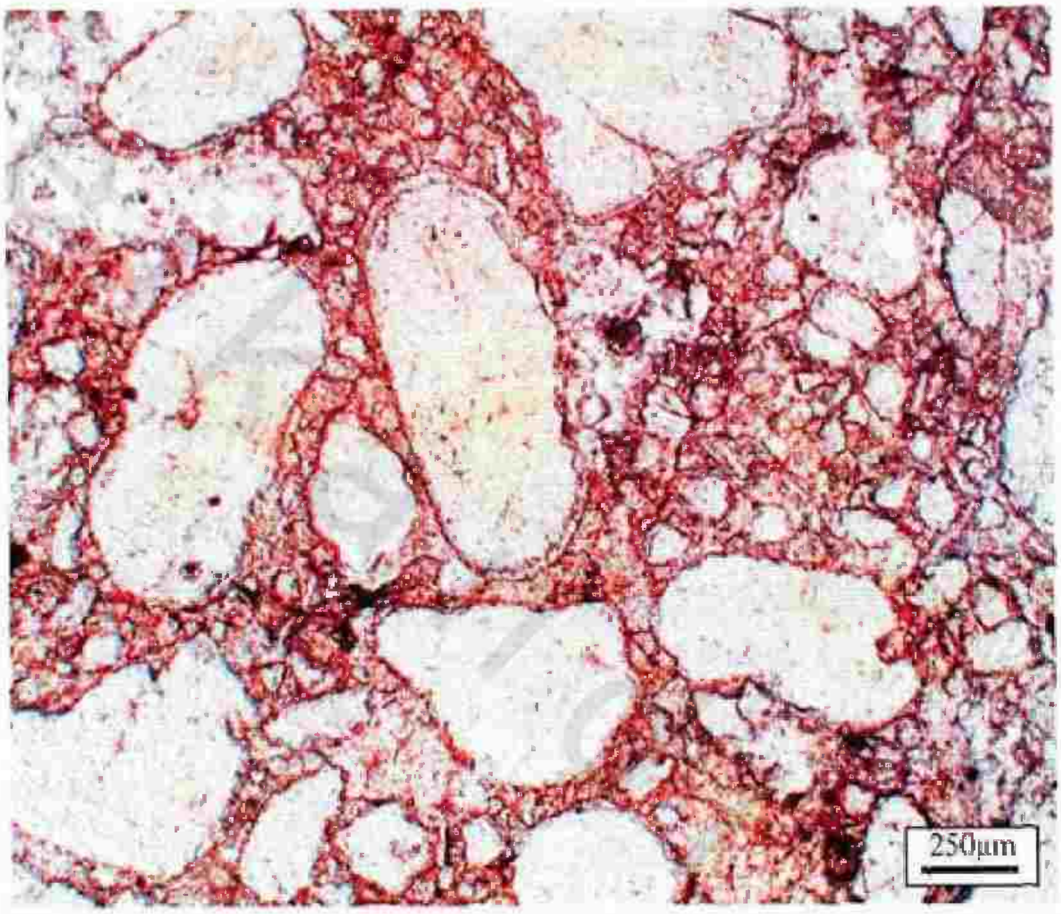


Fig. 4.28 Poorly sorted subangular to rounded quartz grains showing calcite replacement along their boundaries. Lower shoreface calcareous quartz arenite, southeast Qur Hadida, bed No. 12.

IV. 6 Ain Dalla Formation

The Ain Dalla Formation is composed of chalky limestone with dolostone interbeds in the lower part and thin-laminated chert at the top (Figs 4.29). The formation contains the following microfacies associations:

1. Deep middle/outer shelf foraminiferal wackestone
2. Lower shallow subtidal alveolinid wackestone
3. Deep subtidal calcareous shale
4. Lower intertidal sandy silicified dolostone
5. Lower intertidal lime-mudstone

The detailed facies description and interpretation of Ain Dalla microfacies types are given below:

1. Deep middle/outer shelf foraminiferal wackestone

The foraminiferal wackestone is recorded in the lower part of Ain Dalla Formation (Fig. 4.29). The rock is white to yellowish gray, massive to well-bedded and argillaceous. It is characterized by high abundance of subbotinids and morozovelliods fauna, which are loosely packed in a lime mud matrix. The common occurrence of planktics in the wackestone facies indicates deposition in a quiet-water, deep middle/outer shelf environment under open marine circulation.

2. Lower shallow subtidal alveolinid wackestone

The alveolinid wackestone is recorded as rock interbeds in the middle part of Ain Dalla Formation (Fig. 4.29). It is also recorded in the upper part of the formation, measuring about 25m thick. The rock is yellowish white, massive and compact chalky limestone.

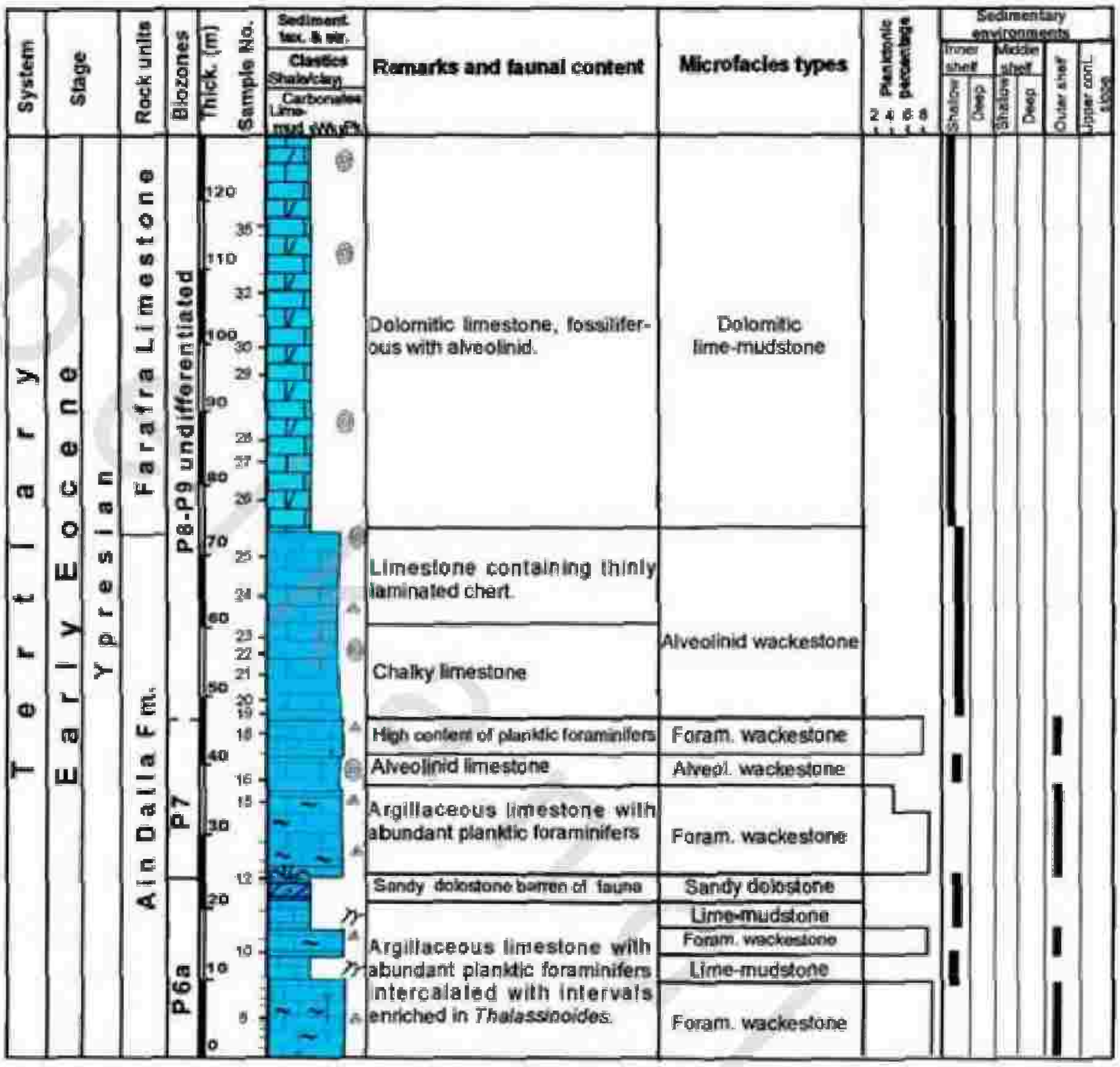


Fig. 4. 29 Representative stratigraphic section of the exposed Lower Eocene rocks in northeast Ain Dalla, west Farafra Oasis, showing their microfacies types and sedimentary environments.

Petrographically, the alveolinid wackestone is made up of well sorted larger foraminiferal and macrofaunal assemblages embedded in a partially recrystallized lime mud matrix (Fig. 4.30), these faunal assemblages form about 35% of the rock constituent. They are present in complete and fragmented manner. The bioclasts are rounded and oval in shape, variable in size and mostly derived from alveolinid, echinods, bivalves, textularia, rotallina and ostracods. The alveolines are the most common faunal content. They appear as well preserved, oval to cylindrical complete shell tests. The presence of abundant larger foraminifers in the wackestone suggests deposition under warm conditions in a lower shallow subtidal setting.

3. Deep subtidal calcareous shale

The calcareous shale is not a common facies in Ain Dalla Formation. It is found in the transitional between proper Esna and Ain Dalla formations such as in the top part of Ain Dalla Formation at Shakhs El-Obeiyid (Fig. 4.16) and at its base in Bir El-Obeiyid. The shale at the top of Ain Dalla Formation is yellowish gray, slope-forming and often associates with larger foraminifers such as nummulitids and operculinids as well as molluscan shells and echinoids. The presence of such types of fossils proves that this shale has been deposited in a deep shallow subtidal shelf setting. While, the shale recorded at the base of Ain Dalla Formation in Bir El-Obeiyid is fossiliferous with a high planktic foraminiferal content such as *Acarinina* and *Pseudohastigerina* species which suggest deposition in a middle outer shelf.

4. Lower intertidal sandy silicified dolostone

The sandy silicified dolostone is not a common microfacies type in Ain Dalla Formation, measuring about 1m thick in northeast Ain Dalla (Fig. 4.29). The rock is pale brown, hard and consolidated with chert nodules. It is consists of dolomite rhombs (70-75%) agglulinated in a pore-filling microquartz (15-20%) with some sparry calcite (<10%). It contains very small amounts of Operculina. The dolomite rhombs are coarse-crystalline, 150-200μm in grain size, hypidiotopic occasionally idiotopic and equigranular (Fig 4.31). Most of the rhombs contain dark clayey material in their cores surrounded by clear outer rims.

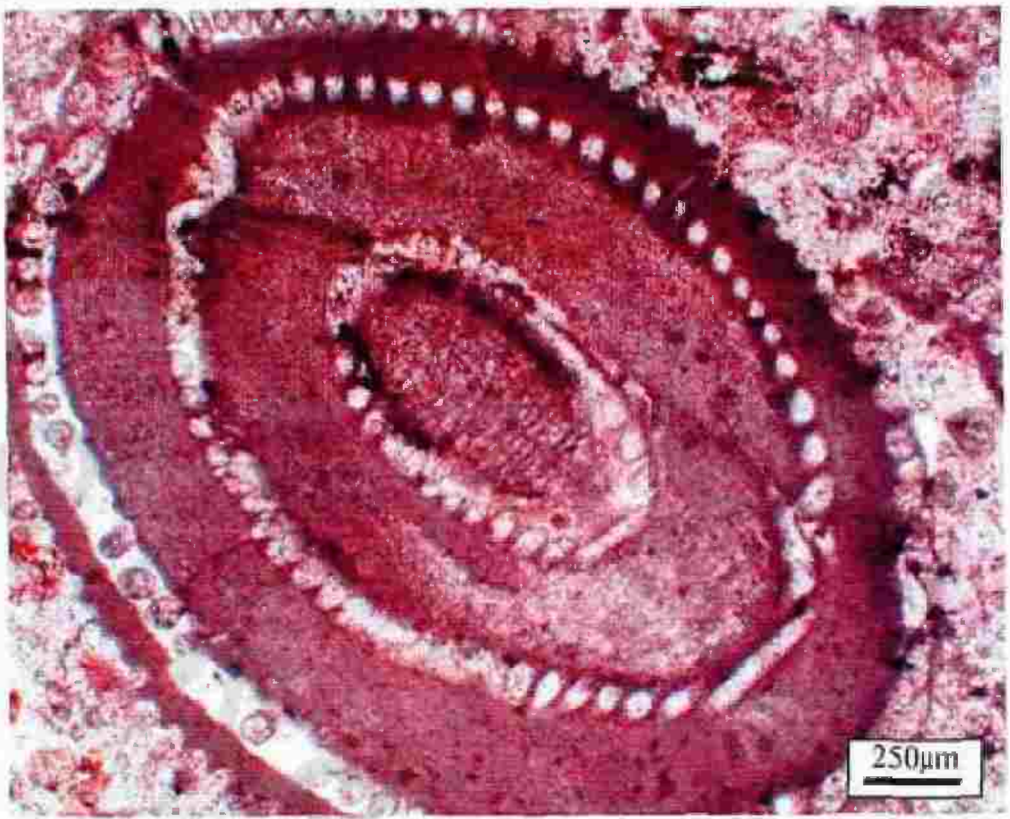


Fig. 4.30 Well preserved complete test of alveolinid embedded in a partially recrystallized lime mud matrix. Lower shallow subtidal alveolinid wackestone, Ain Dalla, bed No.16.

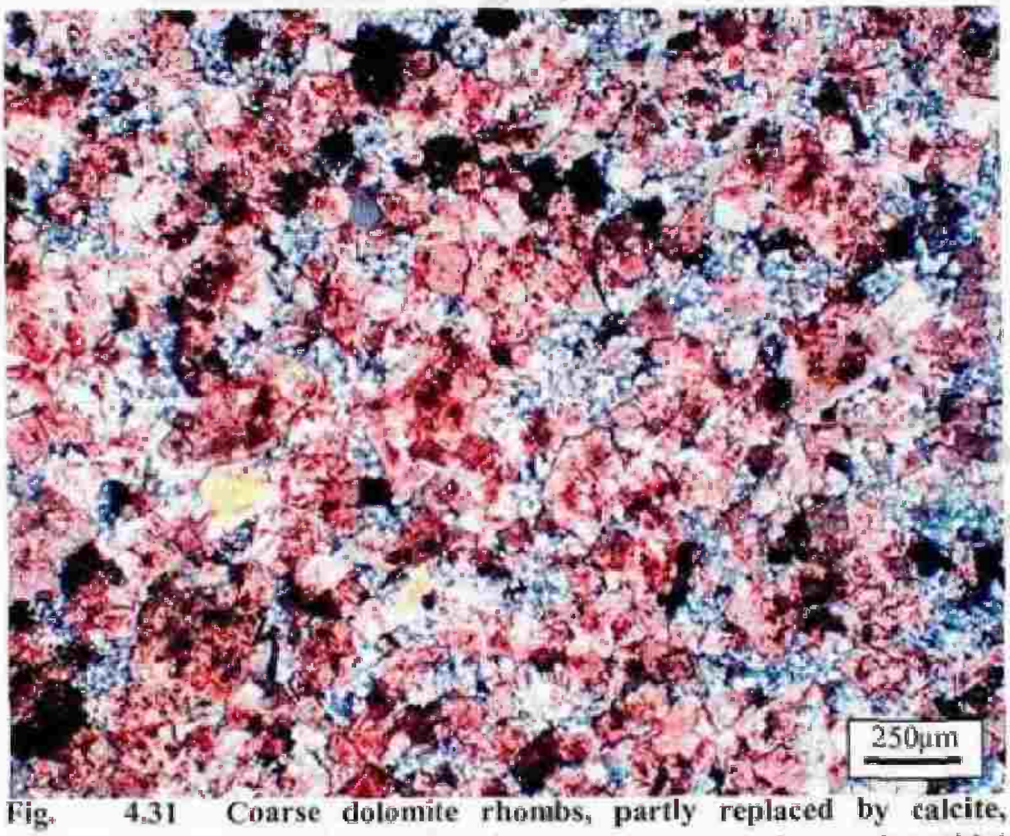


Fig. 4.31 Coarse dolomite rhombs, partly replaced by calcite, agglutinated in microquartz cement. Lower intertidal sandy silicified dolostone, Ain Dalla, bed No.12.

Some of the dolomite rhombs are replaced by calcite, but still retaining their crystal shapes. The micro quartz is formed of fine amount quartz grains, about 10-20μm in size. Some sparry calcite is observed and acts as cement between the dolomite rhombs. Vugs in the rock are also partially filled by fine amount quartz grains. The size and fabric of the dolomite rhombs, in addition to the complete distortion of the depositional fabric suggest late diagenetic dolomitization of an earlier lime-mudstone rock. The silicification and calcitization post-date dolomitization.

5. Lower intertidal lime-mudstone

The lime-mudstone rock is only recorded in the lower part of Ain Dalla Formation (Fig. 4.29). The rock is massive, fine-crystalline, argillacous limestone with *Thalassinoides* burrows.

Petrographically, the lime-mudstone is formed of a dense cloudy lime mud matrix, partially recrystallized into micro- and pseudospar. It is almost barren of any faunal content. The absence of any faunal content in the lime-mudstone strongly suggests its deposition in a protected lower intertidal environment.

In general, Ain Dalla Formation has been deposited under two main conditions:

a- Deep water conditions resulted in the deposition of its lower part (deep middle/outer shelf foraminiferal wackestone). This situation was interrupted by shallower conditions to deposit a lime-mudstone and sandy silicified dolostone of lower intertidal environment.

b- Shallow water conditions resulted in the deposition of its upper part (lower shallow subtidal alveolinid wackestone). In the upper part of Ain Dalla Formation, the planktics are nil, where as the larger foraminifers dominate indicating a regressive event.

IV. 7 Farafra Limestone

The Farafra Limestone is composed of yellowish gray, massive to thick-bedded limestone enriched in lager foraminifers (Fig. 4.32). It is intercalated with minor amount of calcareous shale. In Ain Dalla, the formation is represented by highly consolidated, massive dolomitic limestone (Fig. 4.29). The Farafra Limestone yields the following facies associations:

1. Deep subtidal calcareous shale.
2. Upper shallow subtidal nummulitic alveolinid packstone.
3. Lower shallow subtidal nummulitic wacke/packstone.
4. Lower intertidal lime-mudstone.
5. Lower intertidal dolomitic lime-mudstone.

The detailed description and interpretation of the recognized microfacies associations are given below:

1. Deep subtidal calcareous shale

The calcareous shale is not a common facies type in the Farafra Formation. The individual bed ranges in thickness from 0.5-2m. The shales are calcareous, slope-forming, compact, calcareous and fossiliferous with larger foraminifers. The faunal and lithologic characteristics of the calcareous shale suggest deposition a deep subtidal environment (inner shelf).

2. Upper shallow subtidal nummulitic alveolinid foraminiferal packstone microfacies

The nummulitic alveolinid packstone is a common facies in the lower part of the Farafra Limestone (Figs. 4.13, 4.20 &4.32).

It is made up of closely packed skeletal particles which form about 60-70% of the rock content (Fig. 4.33). The skeletal particles are represented by diverse larger foraminifers (e.g. *Nummulites*, *Alveolina*, *Assillina* and miliolids), thin-welled bivalve shells, gastropods and ostracods. They are embedded in a dense grey lime mud matrix (20%) and sparry calcite cement (10%). Some of these skeletal particles are completely filled with spary calcite.

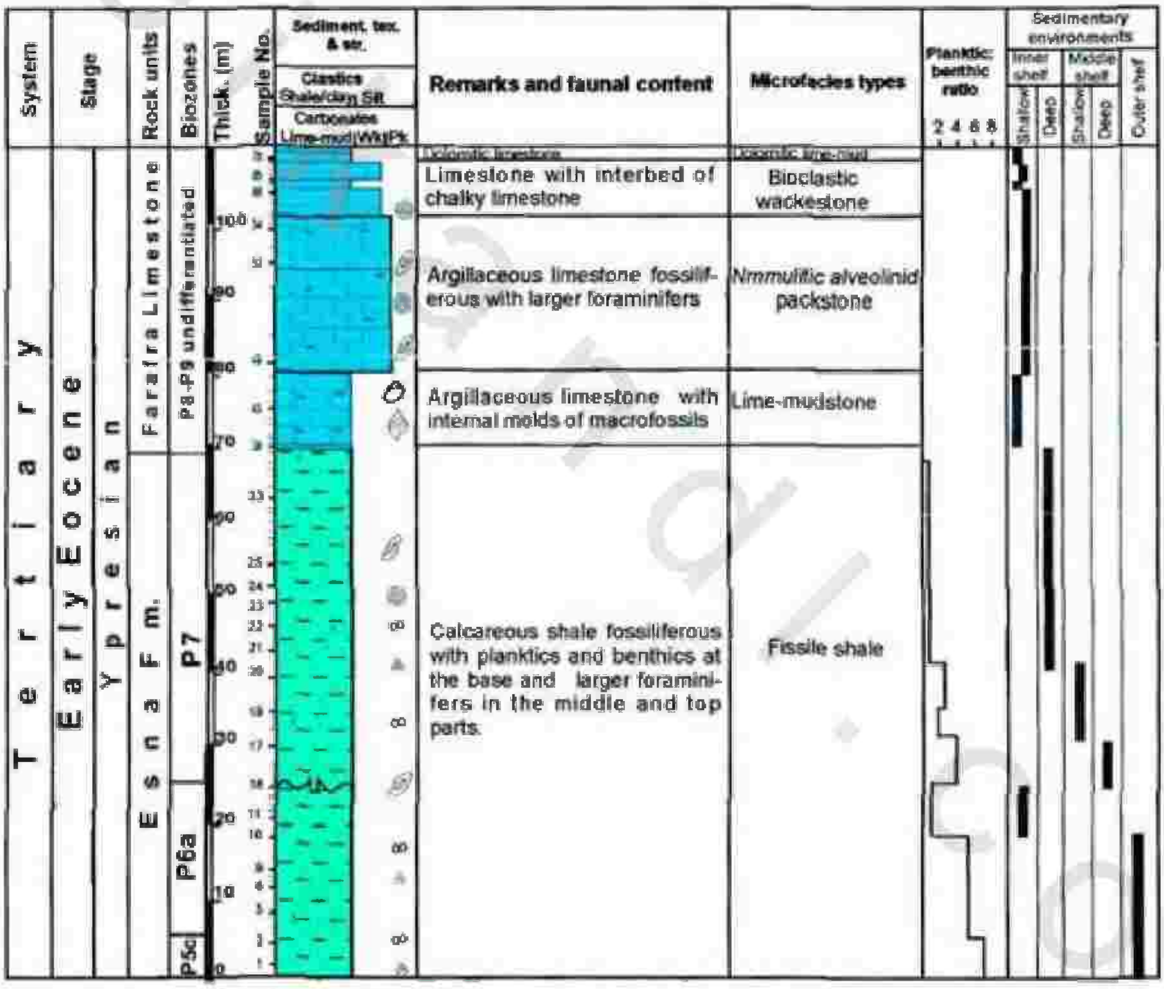


Fig. 4. 32 Representative stratigraphic section of the exposed Lower Eocene rocks in Gabal Sofra, west Ain Dalla, showing their microfacies types and sedimentary environments.

A rich bivalve assemblage is recorded in life position within the lower part of the Farafra Limestone, especially at El Quss Abu Said Plateau. This assemblage includes *Pseudomitha nokbahensis*

(Oppenheim), which is characterized by its very large size and seems to be restricted to the Farafra Oasis. Other bivalves are *"Lucina" edita* Oppenheim and *Lucina* (*Lucina*) *qurnaensis* Oppenheim, this in addition to echinoids and nautilida. The great majority of living lucinids preferentially inhabit an intertidal to shallow subtidal environment. They are deep burrowers in muddy sediments, and communicate with the water column via an anterior inhalant tube construed of sediment grains (Allen 1958).

Larger foraminiferal especially alveolinid species appear massively in repetitive banks. These probably represent shoals and bars, accumulated by waves and currents in the upper shallow subtidal regime. These reefal facies refer to moderately agitated clear water conditions with clear effect of the wave action that caused piling up of larger foraminifers forming fossil bank.

3. Lower shallow subtidal nummulitic wacke-/packstone

The nummulitic wacke-/packstone is recorded in the lower part of the Farafra Limestone at south Qaret Sheik Abd Alla (Fig. 4.14). The rock is pale orange, hard, compact limestone with many small-sized *Nummulites* sp.

The wacke-/packstone is formed of slightly packed coarse skeletal particles, which constitute about of 50-65% of the rock content, and lime mud matrix (35-50%.). The nummulites, operculines, miliolids and echinoid spines are the predominant skeletal particles (Fig. 4.34). Larger benthics are present in complete and fragmented forms. They are either affected by micritization or aggrading neomorphism. The nummulites and operculines tests are globular in shape and mostly well preserved. The chamberlets are mostly filled with granular sparry calcite. Echinoid spines often show syntaxial calcite overgrowths. miliolids may reach up to 5-8% of the rock constituent and are often filled with lime mud matrix. Also, glauconitic pellets with spherical shape are disseminated in the rock. The matrix entrapped between the particles is partially recrystallized lime mud. The wacke-/packstone facies represents a lower shallow subtidal deposit. It is known that nummulites live in tropical and subtropical shelves where the temperature ranges between 18 and 27°C. Within this range, greater amounts of $CaCo_3$ are available to the larger foraminifera for building their tests (Blondean, 1972; Ungaro, 1994).

4. Lower intertidal lime-mudstone

The lime-mudstone is a common microfacies type in the upper part of the Farafra Limestone (Figs. 4.13, 4.19, 4.20 & 4.32). It is only recorded in the basal part of the Farafra Limestone at Gabal Sofra measuring about 11m thick (Fig. 4.32). The rock is moderately consolidated, massive and partly fossiliferous.

The lime-mudstone is completely built up of dense microcrystalline calcite with grain size less than 4 µm. It contains a few randomly floating skeletal particles embedded in the lime mud matrix. The skeletal particles are mainly represented by badly preserved fauna of some ostracods, nummulites and echinoid spines (Fig. 4.35).

The coral fragments are present in some noticeable amounts in Ain Maqfi (Fig. 4.36). The well structure and septa of the corals are almost highly obliterated into microspar partly filled with granular sparry calcite due to leaching. The interseptal spaces, on the other hand, are filled with dense lime mud matrix, partly recrystallized into pseudospar (Fig. 4.37). The coral fragments account for about 2-5% of the rock content. The aggrading neomorphism is partialy affected the lime mud matrix leading to partial change into microspar and psudospar.

Fig. 4.33 Skeletal particles of larger benthics (e.g. *Assilina* sp.) closely packed in neomorphic spar and lime mud. Upper shallow subtidal nummulitic alveolinid packstone, Early Eocene, northern slope of El Quss Abu Said, bed No.50.

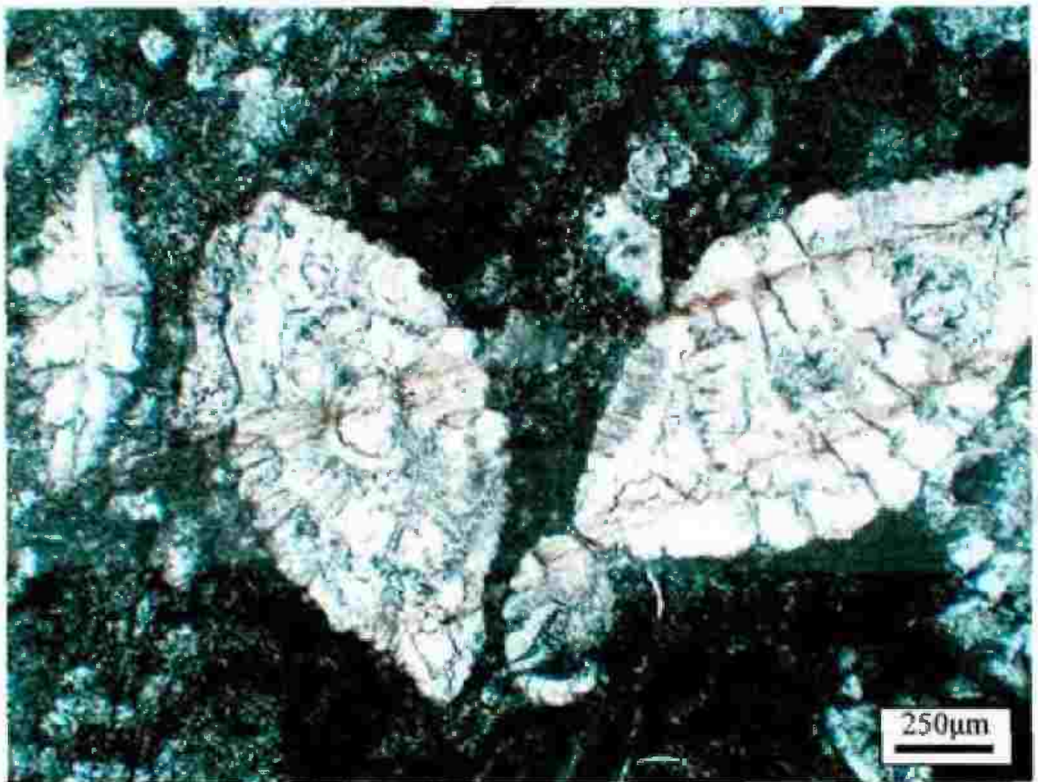


Fig. 4.34 Randamly dispersed recrystallized nummulitids and dense micritized skeletal grains in a dense lime mud. Lower shallow subtidal bioclastic nummulitic wacke-/packstone, Early Eocene, south Qaret Sheik Abd Alla, bed No. 13.

The neomorphic spars have commonly clear rounded calcite crystals with more or less uniform size. Most of them, if not all, show dark grey color on their outer borders, probably due to impurities originally associated with the lime mud. Such impurities were expelled outwards from the micrite during recrystallization. The lime-mudstone is interpreted to have been deposited in a regressive lower intertidal environment.

5. Lower intertidal dolomitic lime-mudstone

The dolomitic lime-mudstone is recorded in the upper part of the Farafra Limestone measured in Gabal Sofra and El Quss Abu Said (Figs. 4.20 and 4. 32). It forms the main part of the Farafra Limestone in Ain Dalla (Figs. 4.20 & 4.29). The rock consists of a dense cloudy lime mud matrix with abundant, randomly scattered fine diagenetic dolomite rhombs and rare benthic foraminifers. The dolomite rhombs are containing dark clayey cores and clear outer rims. They are commonly zenotopic to hypidiotopic in fabric and equigranular in texture (Fig. 4.38). The rhombs range in size from 10-20 μm. They do not show any zonal arrangement but contain, in most cases, very fine black minerals giving them cloudy appearance. The fabric, equigranular texture and unzoned habit of the dolomite rhombs are closely similar to the early diagenetic dolomite. The few benthics are present badly preserved due to aggrading neomorphism.

The virtual absence of bivalves in the Farafra Limestone of Ain Dalla suggests that this area was inhospitable to a luxuriant life; probably, it was a sheltered bay or lagoon with poor bottom circulation. This interpretation is consistent with the occurrence of alveolines, which believed to have preferentially lived in restricted shelf areas of carbonate deposition (Hottinger, 1973, Sartorio and Venturini, 1988).

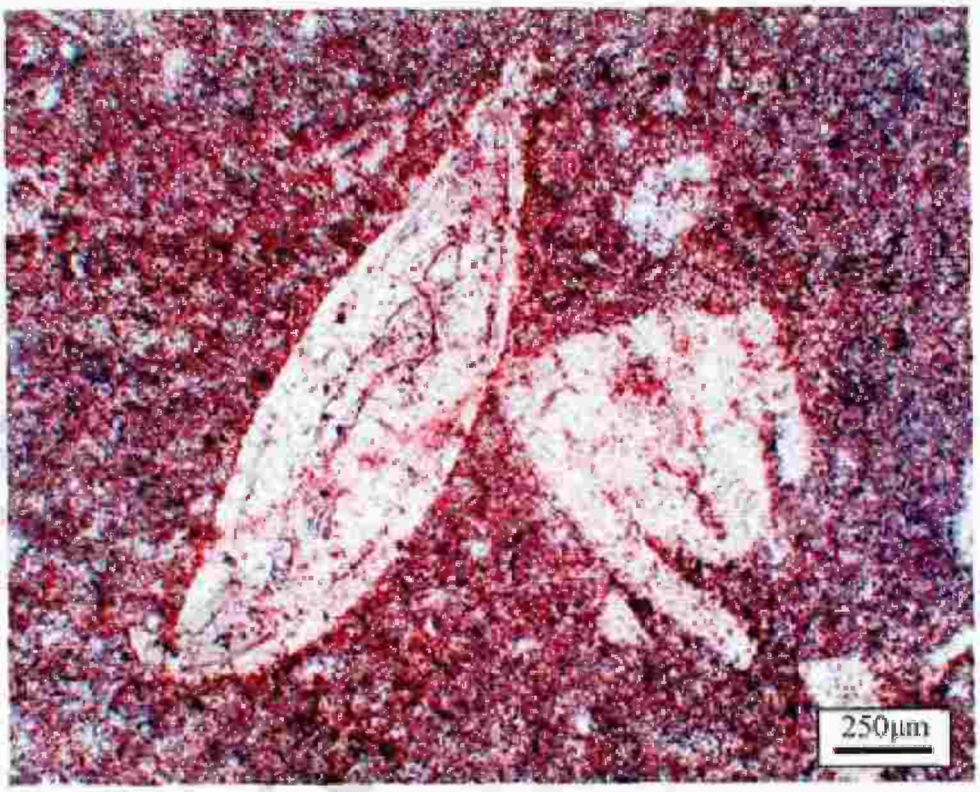


Fig. 4.35 Badly preserved nummulitids embedded in a dark cloudy lime mud matrix, partly affected by aggrading neomorphism into pseudospar. Lower intertidal nummulitic lime-mudstone, Gabal Sofra, bed No. 46.

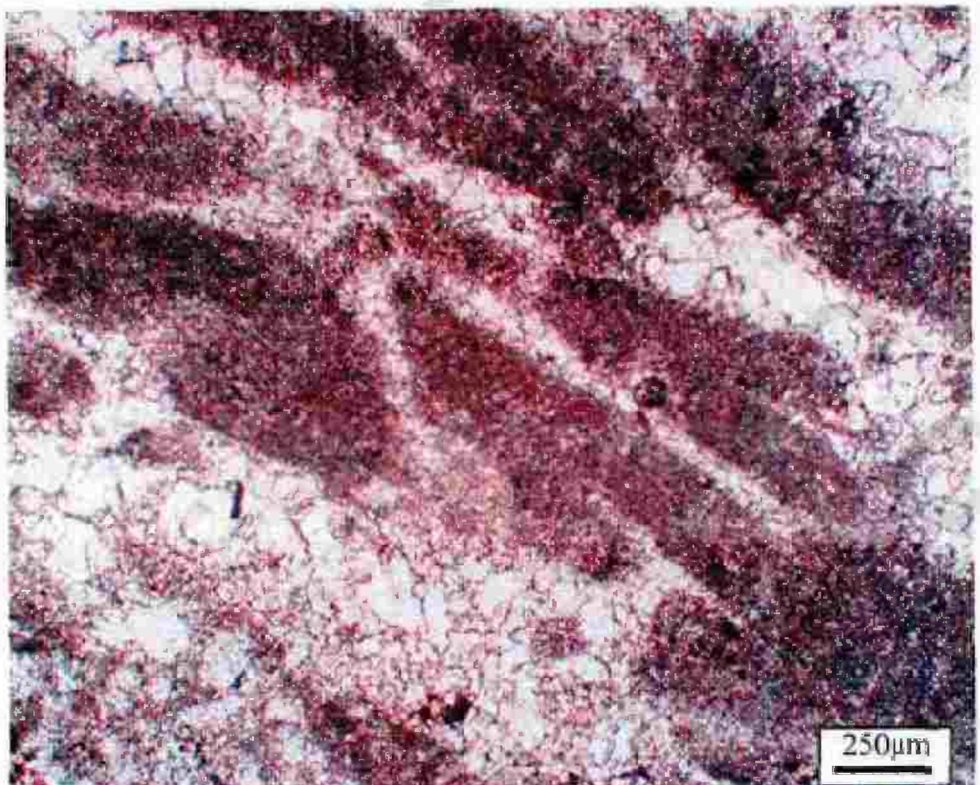
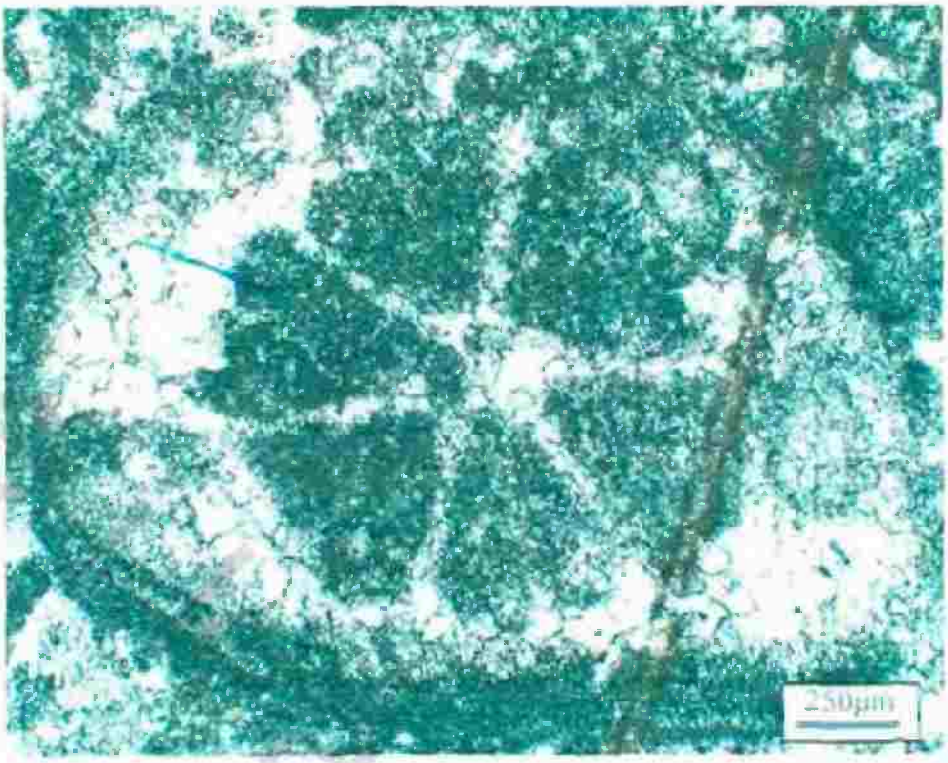


Fig. 3.36 Coral fragments disseminated in a dense lime mud matrix. Lower intertidal lime-mudstone, Ain Maqfi, bed No. 79.



[illegible] structure and septa of the corals are filled with granular sparry calcite with dense microspar filling the interseptal cavities. Lower intertidal lime-mudstone. Ain Madi, bed No. 64.

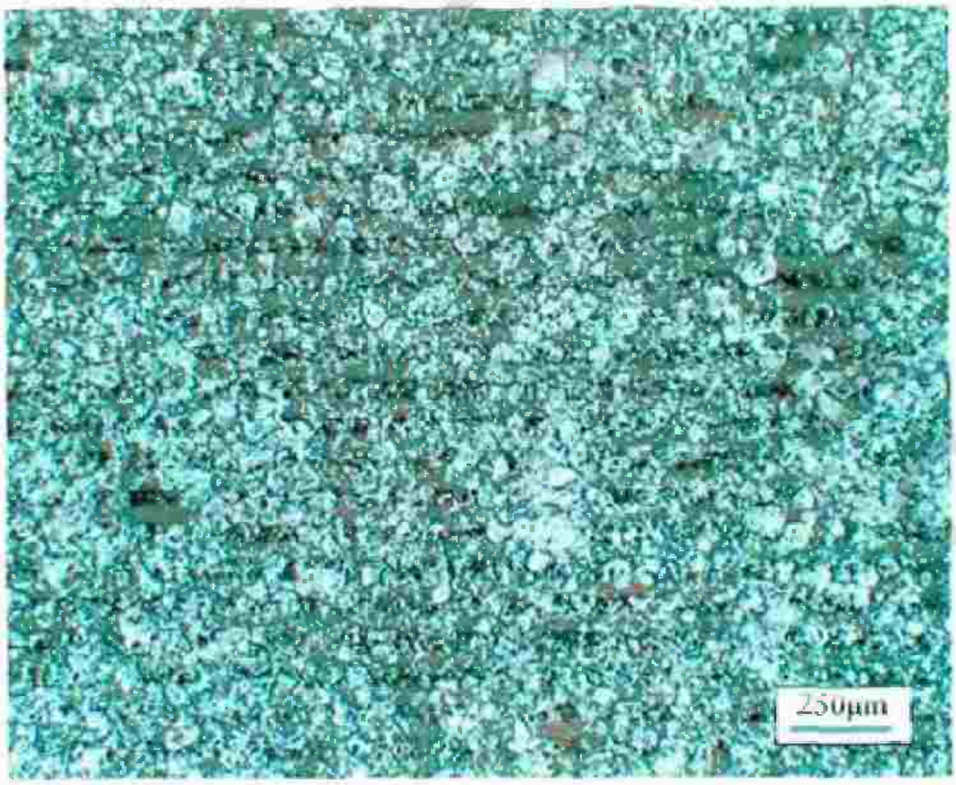


Fig. 4.58 Xenotopic to hypidiotopic fine-crystalline dolomite rhombs randomly scattered in a cloudy lime mud matrix. Lower intertidal dolomitic lime-mudstone. Ain Dalla, bed No. 32.