

Facies Analysis and Sedimentary History of the Middle Eocene Sequence of Jabal Hafit, Al Ain Area, UAE

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Received: 1/12/2001 Revised: 10/11/2002 Accepted: 1/1/2003

ABSTRACT. The Middle Eocene 270 m thick carbonate sequence of Jabal Hafit, to the south of Al Ain City, UAE is one of the thickest nummulitic buildups, not only in the Arabian Peninsula but also in the Middle East. The sequence is characterized by highly diverse and frequent faunal content. Moreover, many taxa attain gigantic sizes, e.g. *Nummulites* cf. *lyeli*, *N. maximus*, *Assilina gigantea*, gastropods, burrowing echinoids, thick-shelled oysters and others. The sequence shows very little or no lithological and/or paleontological lateral variations all over the study area, which reflects the homogeneity of the depositional environment. On the other hand, the vertical time-changes are remarkable. The rhythmic appearance of the larger foraminiferal (*Nummulites* and/or *Assilina*, *Alveolina*) buildups with one or two species of each, and the non-or poorly nummulitic zones in-between, is an indication of oscillating sea level and syntectonic sedimentation. The chrono-and biostratigraphic setting of the studied sequence confirms Lutetian age.

Introduction

Middle Eocene carbonate sediments of the Dammam Formation crop out on Jabal Hafit on the western margins of the Northern Oman Mountains. Jabal Hafit is located to the southeast of Al Ain City, at the border between Sultanate of Oman and the United Arab Emirates, Fig. 1. It is a plunging anticline trending NNW-SSE. Stratigraphically, the exposed rocks at Jabal Hafit range from Late Paleocene to Middle Oligocene, Table 1; Miocene deposits crop out on the eastern flank.

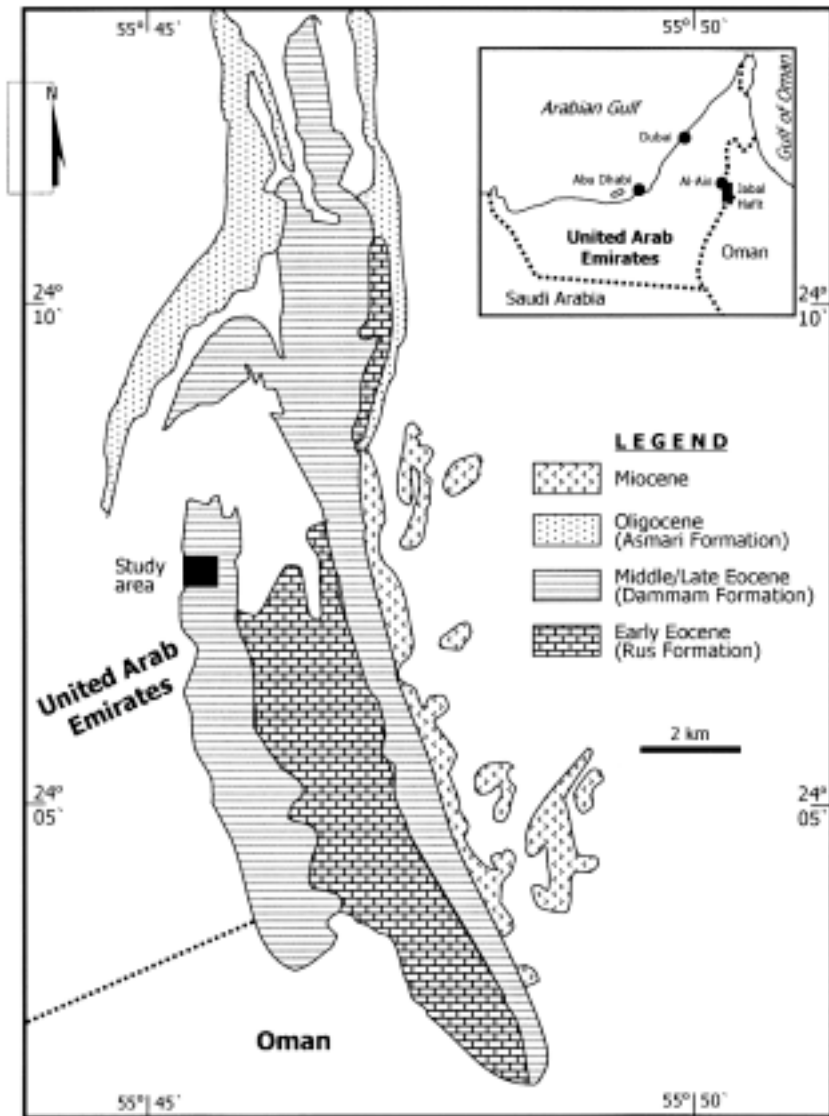


FIG. 1. Geologic map for Jebel Hafit, UAE (modified after Whittle and Alsharhan, 1994).

TABLE 1. Correlation chart for the exposed Paleogene rock-units of Jebel Hafit, U.A.E.

Epochs		Hunting (1979)	Cherif & El Deeb (1984)		Hamdan & Bahr (1992)	
Oligocene	Middle	Tlo2	Al Jaww FM	Upper member	Asmari FM	Muwaiji
		Tlo1		Lower member		Mutaredh
	Early	Tle7	Senaiya FM	Member A, B, C, D, E		Zakher
Late	Tle6	Hafit FM			Upper Member	Mazyad
	Tle5					
Eocene	Middle		Tle4	Middle Member		Dammam FM
		Tle3	Wadi Al Nahayan			
	Early	Tle2	Lower Member	Rus FM	Hili	
		Tle1			W. Tarabat	

The Eocene rocks of Jabal Hafit and the neighboring hills have attracted the attention of many workers including Glennei *et al.*, 1974, Hunting 1979, Cherif and El-Deeb 1983 & 1984, Warrak 1987, Anan *et al.*, 1992, Cherif *et al.*, 1992, Hamdan and Bahr 1992, Hamdan and Anan 1993, Whittle and Alsharhan 1994, Noweir and Eloutefi 1997 and Whittle *et al.*, 1996.

The occurrence of *Nummulites brongiartii* d' Archiac and Haime, *N. orbigni* (Galeotti), *N. perforatus* (Montfort) and *N. striatus* (Brugiere) assigned the Ain Al Faydah Member to the Middle Eocene (Lutetian) age (Cherif and El Deeb, 1983 & 1984 and Cherif *et al.*, 1992).

The present study aims to: 1) present a detailed facies analysis for the Ain Al Faydah Middle Eocene rocks of Jabal Hafit to interpret the different ecological parameters affecting their deposition; 2) present an overview of the sedimentary history of the Middle Eocene rocks of Jabal Hafit; and 3) reconstruct the ecological and sedimentological development of the Middle Eocene nummulitic build-ups of Jabal Hafit. To accomplish these aims, a detailed field study for three seasons (between 1995 and 1997) was carried out, including description, measuring and sampling of the studied section. Some 70 specimens were thin-sectioned for the microfacies study.

Description of the Studied Section

Ain Al Faydah Member of the Middle Eocene age is exposed on both limbs and on the crest of Jabal Hafit. Lithologically, it consists of a buff, gray weathered, medium-grained limestone interbedded with yellowish mar, Fig. 2. Bed-

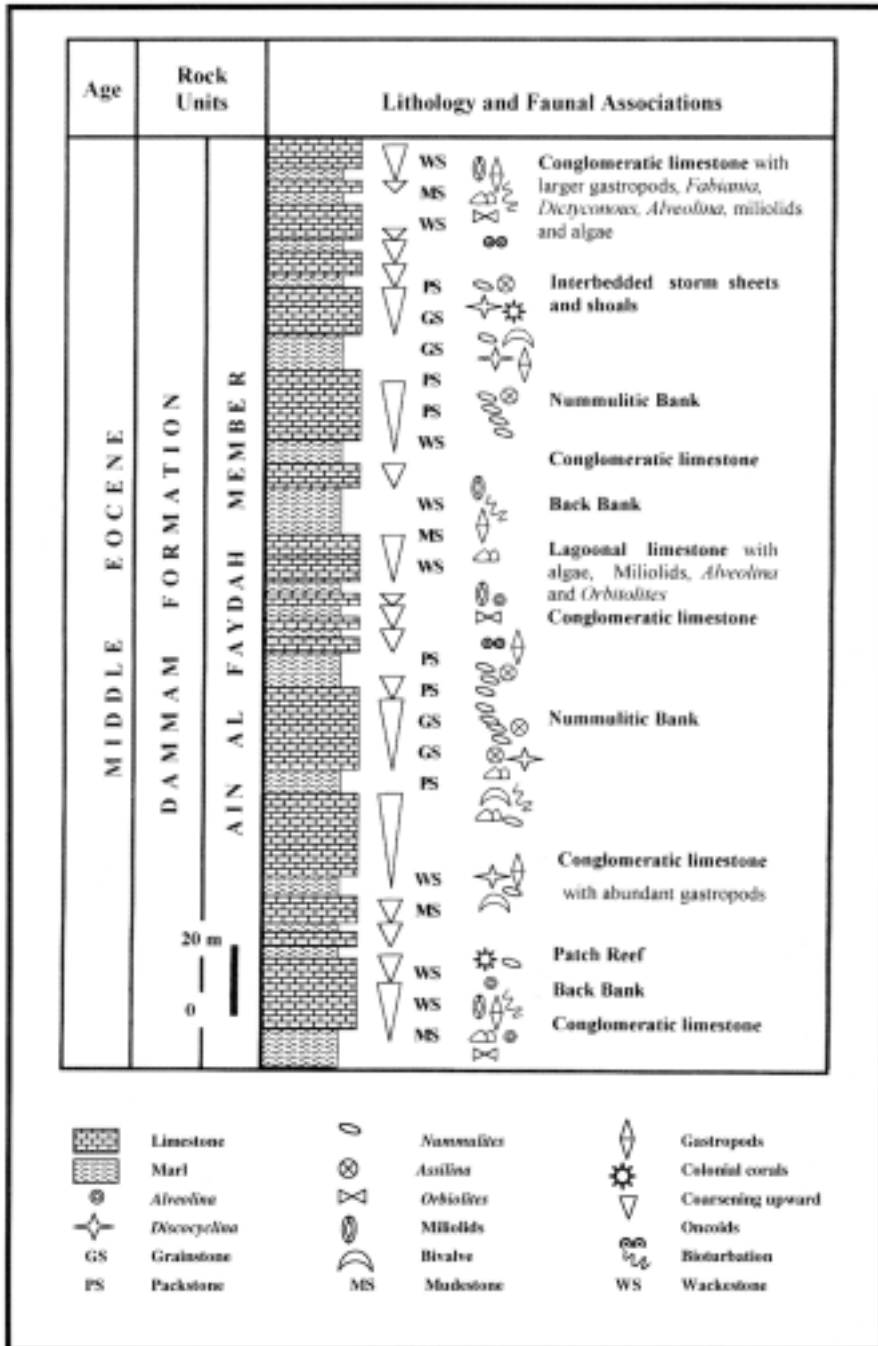


Fig. 2. Stratigraphic columnar section of the Middle Eocene, Ain Al Faydah Member, Jebel Hafit, UAE.

ding is usually distinct. Macrofossils identified include echinoderms, large and small gastropods, oysters and coarsely ribbed bivalves with abundant foraminifers especially *Nummulites*, *Assilina*, *Alveolina*, *Discocyclina* and *Orbitolites*. The contact of the Ain Al Faydah Member is conformable and gradational with the underlying Wadi Al Nahyan Member and also conformable with the overlying Mazyad Member.

At Jabal Hafit, the Ain Al Faydah Member attains a thickness of about 270 m, Fig. 2. It is described by several authors as conglomeratic or nodular limestones (Hunting, 1979; Hamdan and Bahr, 1992). The Ain Al Faydah Member, herein, can be subdivided into five limestone units of conglomeratic nature, separated by massive, hard limestones and highly weathered marly beds. The basal part is marly moderately soft yellowish limestone, fossiliferous in parts, followed by about 2 m thick of very hard nummulitic limestone, very rich in *Nummulites*, *Assilina*, *Discocyclina* and *Orbitolites*. The overall *Nummulites* size distribution is random with thin local lenses of small sized well sorted *Nummulites*, nearly oriented. The lower contact is sharp and highly nummulitic.

The first conglomeratic limestone unit is more than 25 m thick of massive, nodular, whitish-yellow limestone. It is rich in large and small gastropod moulds that give these beds the conglomeratic appearance, Pl. 1A, B. The nodular limestones are very rich in spatangoid echinoids of different sizes. The large sized echinoids are deformed and cracked in most cases. *Nummulites* are abundant, inflated and large, associated with *Assilina* (up to 3 cm in diameter). The matrix is formed of finer sediments, and the contact between the matrix and gastropod moulds is mostly filled with drusy calcite. Towards the top of the nodular limestone unit, a fine-grained very hard limestone, brownish in color in its weathered surface and yellowish color in the fresh surface, is recorded, intercalated with thin marly limestones. Small sized *Assilina* is very common.

Very thick highly bioturbated nummulitic limestones of more than 20 m thick are significant above the nodular limestone. The large forams *Nummulites*, *Assilina*, *Discocyclina*, *Alveolina*, *Dectychnoides* and *Lepidocyclina* are very abundant giving these beds the crowded appearance, Pl. 1C, D. A frequent occurrence of echinoids in living position is very characteristic to this part of the section. Large sized oysters, bryozoan fragments, together with abundant miliolid foraminifera are associated with the recorded echinoids. The bedding planes are disrupted by the infaunal lithophagid bivalves. Towards the top of that part iron concretions are recorded. Upward there are well stratified very hard yellowish white marly limestone up to 5 m thick, characterized by the presence of irregular echinoids up to 10 cm in diameter, associated with *Spondylus* and small gastropod molds.



PLATE 1. Facies units of the Middle Eocene Ain Al Faydah Member, Jabal Hafit, United Arab Emirates.

A. Back bank facies, represented by thick bedded limestones of conglomeratic appearance, intercalated with thin marly beds.



PLATE 1B. Close-up view of the conglomeratic limestone beds, showing a large sized gastropod internal mould giving these limestones their appearance.



PLATE 1C. Densely packed and edge-wise imbricated nummulite accumulation, showing enrichment of A-forms and subordinate occurrence of B-forms suggesting a relatively undisturbed assemblage fabric.



PLATE 1D. Nummulitic packstone, with *Nummulites* of the larger B-forms parallel to bedding plane, where the smaller A-forms were winnowed out suggesting residual assemblage fabric.

Above these marls the second conglomeratic limestone unit of very thick, massive and nodular white chalky limestone attains a thickness of 30 m. It is very rich in large gastropod moulds, which gives this unit its nodular appearance with scattered thick oyster shells. The large forams are scarce but frequent occurrences of *Nummulites*, *Assilina* and *Alveolina* were recorded. Towards the top of this part nummulitic marly limestones of about 8 m thick occur. They are highly weathered and characterized by very abundant and diversified *Nummulites* and *Assilina*. Solitary and colonial corals (ranging between 10-30 cm diameter), crustacean arthropods (ostracods and crabs), and gastropod moulds of *Velatus* and large turrellids (up to 30 cm long) commonly occur. These marly limestones become reddish-yellow in color and bioturbated progressively upwards. It is followed by thick very hard, massive nummulitic assilinitid limestone of yellowish color which appears to be thinly bedded from a distance.

The third grayish-white nodular limestone unit of a thickness up to 20 m is nummulitic at its base. The large gastropod molds are completely filled with fine-grained microcrystalline calcite with different degrees of recrystallization. The associated macrofossils are oyster shells, mostly fragmented with poorly preserved recrystallized coral heads. In turn, the nodular limestone is followed by whitish yellow, weathered gray nummulitic fissile marly limestone. It is free of the *Assilina*, while it is highly fossiliferous with very thin and compressed small sized *Nummulites*. These *Nummulites* are laminated and imbricated, where both the megalospheric and microspheric forms are well sorted.

The gigantic sizes of genus *Nummulites* are represented by *Nummulites maximus*, which characterize the massive, thick yellowish-white nummulitic limestone beds of about 10-m thick. These *Nummulites* are more than 10 cm in diameter mostly imbricated, oriented and closely packed. Rare gastropod moulds and oyster fragments are recorded. Progressively upward the *Nummulites maximus* decrease in abundance, to disappear completely by the appearance of a very distinctive less hard marly limestone bed (1 m thick) containing disarticulated oysters and medium sized spatangoid echinoids. Above this bed occurs a reddish yellow moderately hard, highly bioturbated marly limestone (10 m thick) highly fossiliferous with *Nummulites* and *Assilina*, *Nummulites* are very inflated and medium sized. The associated macrofossils are spatangoid echinoids in life position, *Vlusella*, *Spondylus*, *Chalamys* and different gastropod internal moulds are common, along with thick oyster shells. Above these beds, a massive, thick bedded snow-white limestone occurs. It weathers yellow to gray and is very hard nodular and bioturbated attaining a thickness of more than 20 m. *Nummulites* and *Assilina* are very abundant at the very base, but decrease gradually upwards so that the rock is an alveolinid limestone at the top. The uppermost parts are highly nodular, owing their appearance to richness in the large

to medium sized gastropod internal moulds. Coral heads of *Actinacis* are abundant characterizing the upper most part of this unit, Pl. 1E.



PLATE 1E. Close-up view of the *Actinacis* coral head embedded in muddy substrate at the top of the nummulitic banks, and representing shallow water patch reef.

Whitish-yellow weathered brownish to gray limestone, hard at the base, soft and fissile at the top follows the previous nodular beds. *Nummulites*, *Assilina*, *Fabiania*, oysters, irregular echinoids (up to 10 cm in diameter), *Velatus* and other small sized gastropods are very abundant in these limestones. They are followed by about 40 m thick of very hard, white, weathering brown, fine-grained limestone of nodular appearance, bioturbated with cylindrical vertical burrows, highly fractured and filled with large calcite crystals. *Nummulites* and *Alveolina* are very scarce.

The fifth conglomeratic unit of thickly bedded hard limestone distinguishes the topmost part of the studied section. The boulders are poorly sorted, ranging from 5 to 50 cm. It is very rich in *Alveolina* sp., *Fabiania*, miliolids, *Velatus*, small sized gastropod shells, annelids and echinoid fragments.

Microfacies Associations

The Middle Eocene rocks of Ain Al Faydah member are studied from the microfacies point of view. The distribution of the microfacies assemblages and their constituents is illustrated in Table 2. The analysis of the different microfacies types can be simplified by grouping them into associations, which represent several horizons. Four main carbonate rock types were subdivided into 11 microfacies associations, which are defined, described, illustrated and evaluated environmentally.

1 – Foraminiferal Mudstones

In the studied section, mudstones are usually recorded at the top of thick shoal beds representing small regressive events. Mud pebbles, which are properly formed by reworking of weakly consolidated lime mud, are the most common constituents. The fauna and flora is very limited, except for individual *Nummulites* and miliolids, without any other biota, Pl. 2A, B. The mudstones are intercalated with thin laminated horizons, which occasionally grade into thin pellicular layers. Fenestral fabrics, dominated by irregular voids filled with spary calcite characterize all of them. Fenestral fabrics occur preferentially in intertidal and supratidal environments, Flügel, 1982. Later dolomitization processes are recorded by very fine euhedral dolomite rhombs.

2 – Wackestones

The wackestones represent about 15% of the studied microfacies types. They are very hard, highly bioturbated and partially recrystallized limestones recorded on the lower and middle parts of the studied section. They are represented by:

TABLE 2. Frequency distribution chart of the skeletal and non-skeletal grains, including facies type, cement and micrite abundance of the Middle Eocene, Ain Al Faydah, Member, UAE.

Age	Lithology	Skeletal Grains																	Non-Skeletal Grains					Matrix		Rock Type												
		Baculata	Biomorpha	Textulariids	Milneids	Other	Rotalids	Fusulinids	Planorbis	Dryopoda	Favosites	Orthis	Alveolites	Amygdalum	Discoglypha	Astrone	Numerulites	Algae	Gastropods	Bivalves	Echinoidea	Ostracods	Ammonites	Bryozoa	Pellets		Intracasts	Quartz	Crystalline Grains	Spartite	Micrite							
MIDDLE EOCENE		F	A	F	C						A	F	C		F	C	C	A		A		A	F	C	F								A	WS				
		R	A	R	R						R	A	R			A	C							F	C	A								A	MS			
		F	A	F	C						C	C	C			R	A	A	C		C				R								F	A	WS			
		A	C								C	C	C			C	C	C																A	PS			
		C	A								A	C	A			C	A																	A	GS			
		C	A								C	A				C	A																	F	C	PS		
		C	A								A					R	C	A																F	C	PS		
		C	A								A	C	A			R	C	A																R	A	PS		
		C	A								A	C	A			R	C	A																R	A	PS		
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		C	A								A					R	C	A																	C	R	A	WS
		R	A													A																			C	A	PS	
		A	C	R												F	A																	R	A	PS		
		C	A													A	C	A	F															A	GS			
		C	A													C	A	R	C															R	GS			
	A	R													F	C	R																A	R	A	PS		
	A	R													R																			R	R	A	WS	
	A	C	R	C											F	R	C	R	R	F	R												F	R	R	A	MS	
	A	F	C												C	C	F	A																		A	WS	
	A	C	R	R											F	C	C																	F	A	WS		
	A	F													R	R	R																			A	MS	

A= Abundant; C= Common; F= Frequent; R= Rare; GR= Grainstone; PS= Packstone; WS= Wackestone; MS= Mudstone

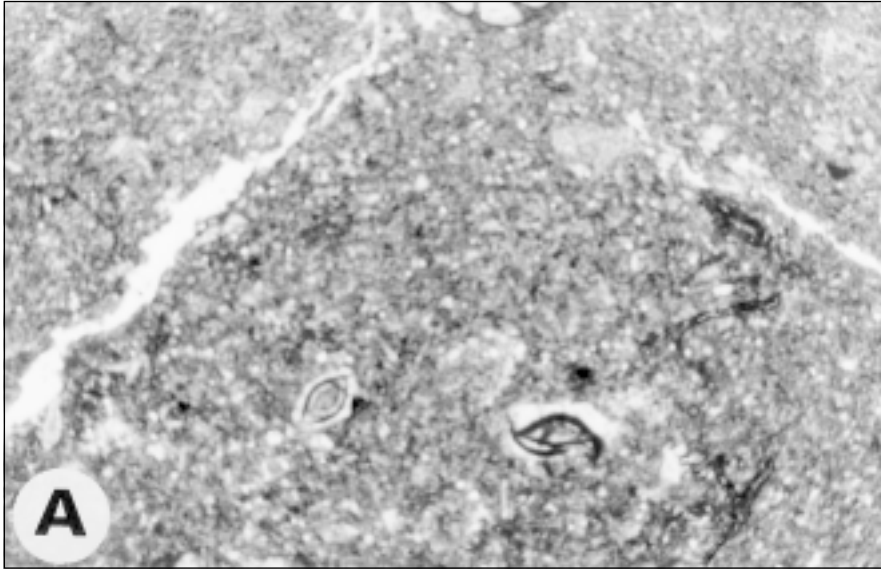


PLATE 2. Photomicrographs of different microfacies associations and diagenetic processes affecting the Middle Eocene Ain Al Faydah Member, Jabal Hafit (all figures in crossed polars).

A. Foraminiferal mudstone with miliolid foraminifers, with largely obliterated wall structure, showing channel porosity. Scale bar = 250 μm .

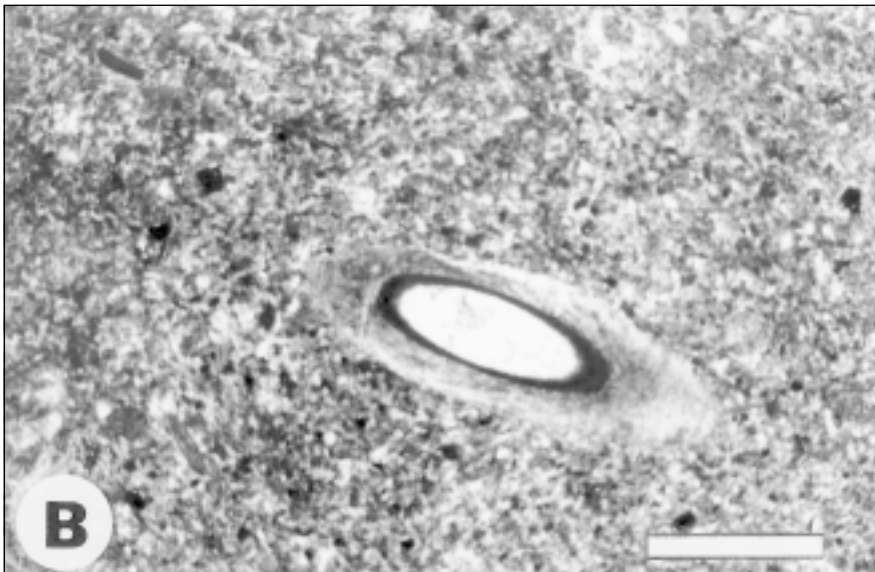


PLATE 2B. Foraminiferal mudstone, transverse section in large serpulid worm built of concentric laminae of calcite embedded in micritic matrix. Scale bar = 250 μm .

2. 1. *Bioclastic Wackestone*

Foraminiferal tests (40%), reworked bioclasts (40%), and subordinate echinoids, bivalves and algae are the most common skeletal grains of this facies type. The foraminiferal grains include *Nummulites*, *Alveolina*, oysters and some planktonic forams, mainly *Hantkenina*, Pl. 2C. Debris of mollusks are completely micritized and a micritic envelope is coating most of the bivalves. Angular quartz grains are scattered in the micritic matrix.

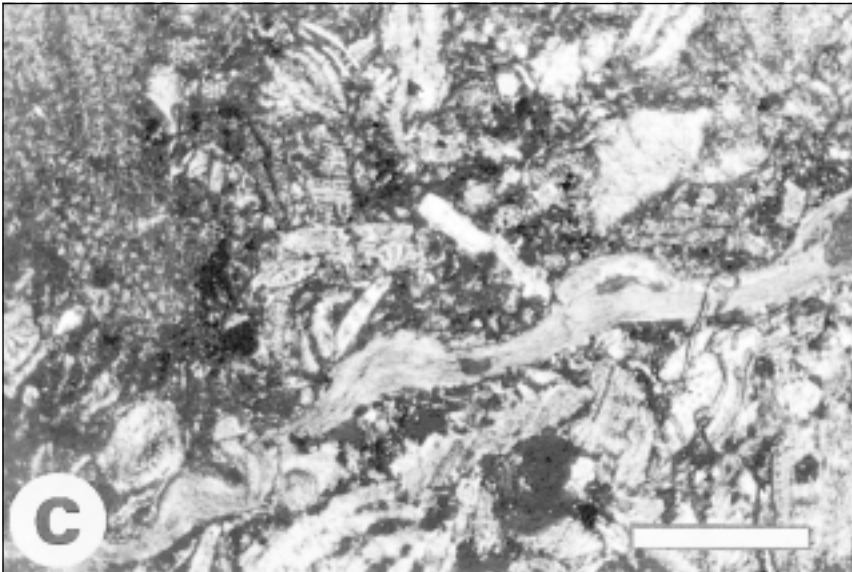


PLATE 2C. Bioclastic wackestone with different sections in oyster shell fragments exhibit the original foliated structure. Notice the different grades of neomorphic aggradation of the micritic matrix into microspar. Scale bar = 250 μm .

2. 2. *Nummulitic Wackestone*

This facies is represented by burrowed wackestones with the burrows filled with grainstone. Larger foraminifera that prevail in this association are *Nummulites*, *Discocyclusina* and *Orbitolites*, Pl. 2D, E. Other skeletal particles are miliolids, dasycladacean algal remains, bivalves and annelids. Iron oxide coats some shell fragments or is present in the matrix. Diagenetically, many calcite veins cross the micritic matrix and are filled with spary calcite. Most *Nummulites* are characterized by drusy calcite filling their chambers. An early diagenetic phase can be interpreted by the partial recrystallization of the micritic matrix into spary calcite cement.

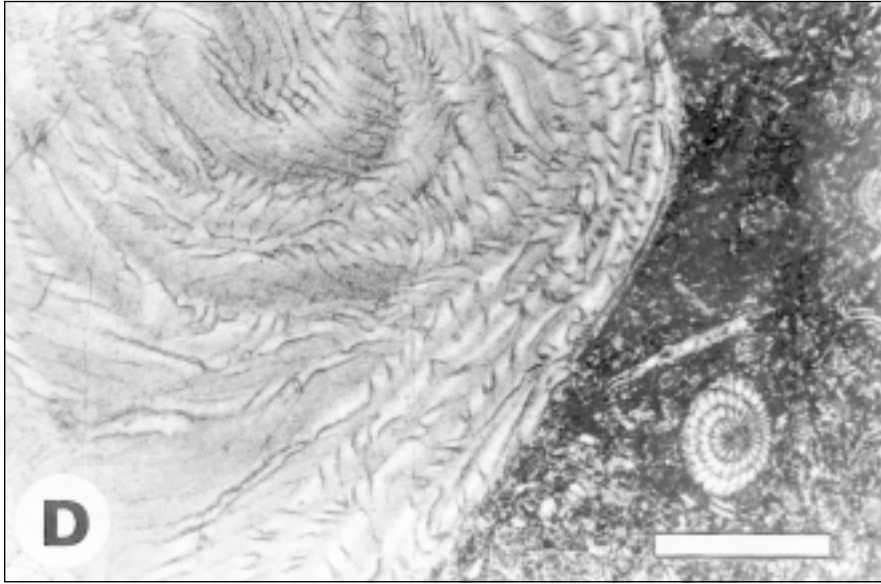


PLATE 2D. Nummulitic wackestone with two tangential sections in *Nummulites* sp.; upper B-form, lower A-form embedded in microcrystalline calcite. Scale bar = 400 μ m.

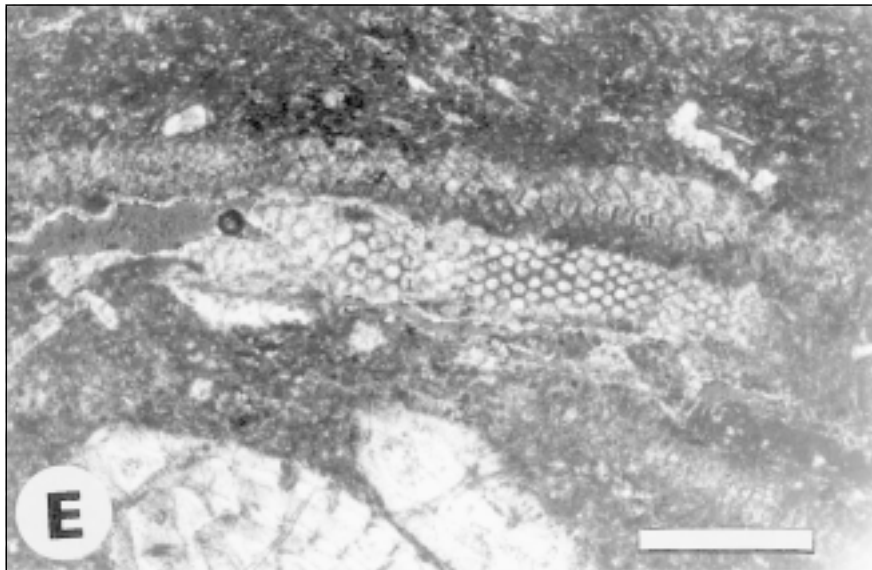


PLATE 2E. Nummulitic wackestone with long axial sections in *Orbitolites* sp. (middle), showing its chambers and internal radial structure; axial sections in *Nummulites* sp. (lower). Scale bar = 250 μ m.

3 – Packstones

Packstones represent about 36% of the studied microfacies associations. They are densely packed, fine to medium grained, thick-bedded marly limestones, distributed in second third of the lower part of the studied section.

3.1. Bioclastic Packstone

Skeletal constituents represented by *Alveolina*, *Discocyclusina*, *Fabiania*, rarely *Nummulites*, miliolids, planispiral rotalids, echinoderms, algae and oncoids characterizing this facies are densely packed to form massive layers. Most components are fragmented and abraded. Usually, the skeletal components are well-sorted. Oncoids represent about 15% of the facies constituents, with a very thick cortex and small dark micritic nuclei. The oncolites are coarse-grained, poorly-sorted, mostly broken as a result of different phases of compaction. The allochems are packed together in fine micritic matrix, recrystallized partially into microspar.

3.2. Nummulitic Packstone

Almost 50% of the total biota are made up of medium to small sized *Nummulites* and *Assilina*. Filling of most nummulitic chambers is very characteristic, with partial calcification in many grains, Pl. 2F, G. Fragments of mollusks, along with miliolids, ostracods, planktonic forams and echinoderms occur in the matrix. *Orbitolites*, *Alveolina*, textulariids and algae are less common; all are embedded in a small amount of micritic matrix recrystallized into microspar, indicating deposition in agitated water. The microcrystalline calcite fills the gastropod chambers. Both channel and intergranular porosity are recorded. Silicification is pronounced in most nummulitids.

3.3. Alveolinal Nummulitic Packstone

It is very hard highly fossiliferous, thickly bedded limestone. *Nummulites*, *Assilina*, *Alveolina*, *Asterocyclusina*, *Fasceolites* and rarely *Dictyonoids* and *Orbitolites* are the most common larger forams characterizing this microfacies association, Pl. 2H. Also, miliolids, textulariids, ostracods, and algae are abundant, along with scarce echinoid and molluscan fragments. Oncoids are common, with well developed cortex (20-25 layers) and medium-sized nucleus. Cement makes an average of 10% or higher of the rock content, which developed as a result of recrystallization of the micritic matrix after winnowing of the finer grains by wave action in the nummulitic banks. It is recorded as isopachous fibrous cement in contact with the different grains, followed by coarse granular calcite crystals up to blocky calcite cement filling the intergranular pore spaces. The granular cement indicates formation in the phreatic meteoric

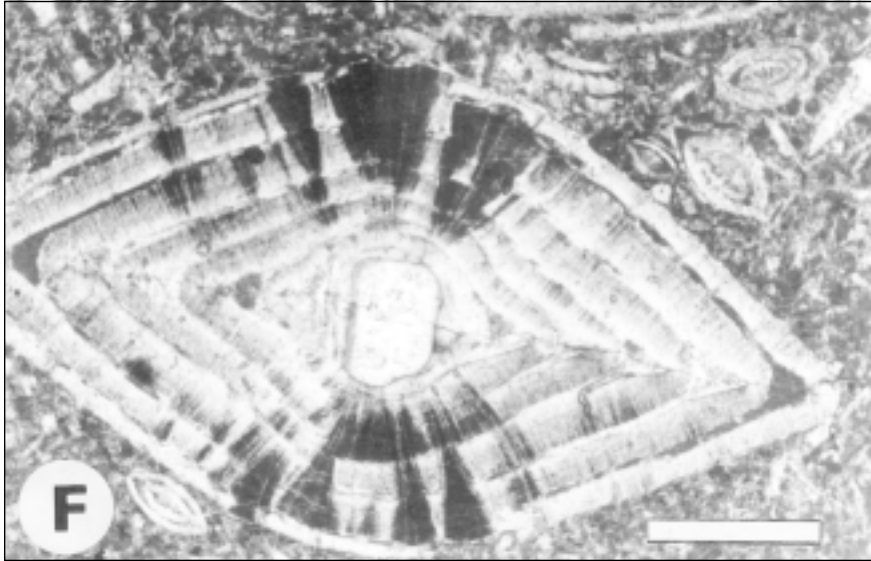


PLATE 2F. Nummulitic packstone with very large longitudinal axial section of large sized *Nummulites* sp. showing partial calcification by calcite spar precipitation in the chambers. Scale bar = 400 μm .

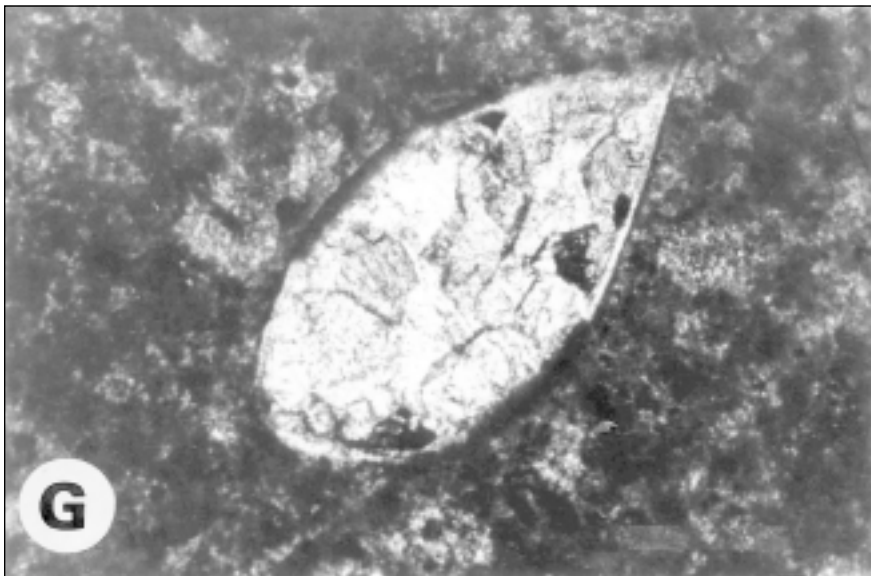


PLATE 2G. Nummulitic packstone with complete dissolution of ostracod shell, showing coarse sparry calcite cavity filling. Scale bar = 400 μm .

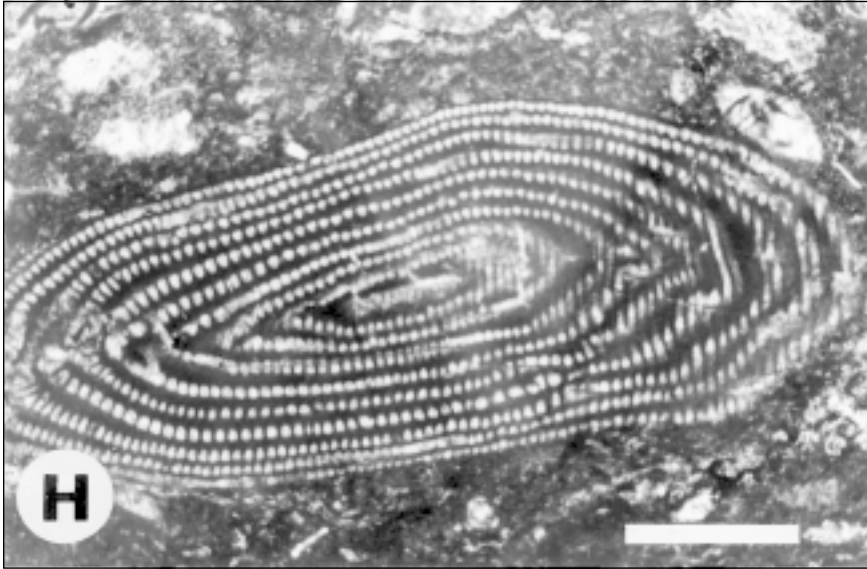


PLATE 2H. Alveolinal nummulitic packstone with longitudinal axial section of a single *Alveolina* sp. Scale bar = 250 μm .

zone, Tucker and Wright, 1990. Drusy calcite is filling most of the skeletal fragments, especially Nummulites, ostracods and gastropods. Recrystallization of some pelecypod shells has been noticed. Micrite envelopes coat most of the pelecypod shells. Geopetal filling is also characteristic to many skeletal grains

3.4. Discocyclinal Nummulitic Packstone

The common biota of this facies are *Discocyclina* and *Nummulites*, up to 3 cm in length, Pl. 3A-C. The associated fauna are *Orbitolites*, *Assilina*, dasycycladacean algae, oyster fragments and echinoderms. Most of the skeletal grains are coated with iron oxides, imbricated and disoriented. Also, the ferruginous material is observed particularly surrounding the void porosity. Medium-to coarse-grained glauconite particles are distributed in the microsparitic matrix. Both intergranular and intragranular porosity are very rare, but the vuggy and moldoic porosity is common. Pressure solution effects can be observed, where some *Discocyclina* grains truncate others to form condensed and fitted fabric, Pl. 3A.

4 – Grainstones

The grainstones represent about 40% of the studied microfacies types. They are massive, thick-bedded layers distributed along the Middle Eocene section of Jabal Hafit.

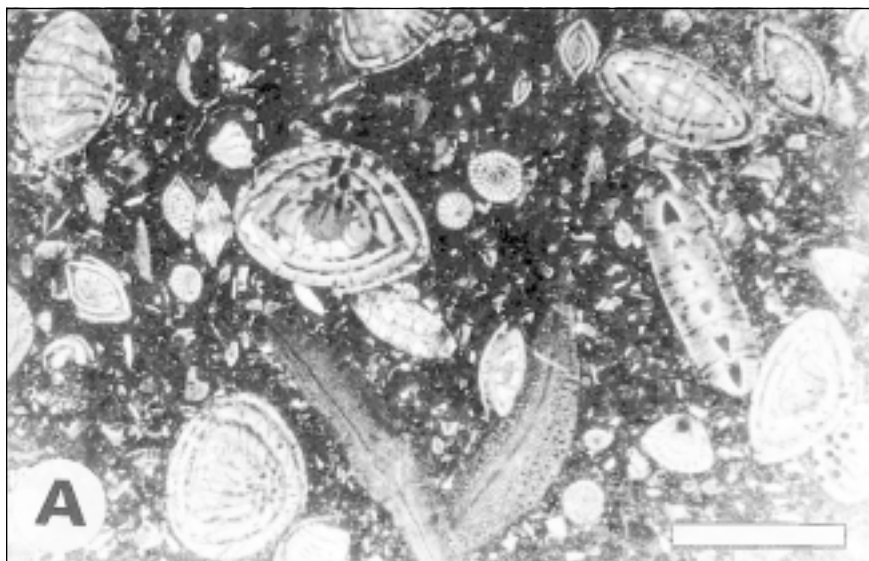


PLATE 3. Photomicrographs of different microfacies associations and the diagenetic processes affecting the Middle Eocene Ain Al Faydah Member, Jabal Hafit (all figures in crossed polars).

A. Discocyclinal nummulitic packstone showing interpenetration of two axial sections of *Discocyclina* sp. (lower middle), with several sections in *Nummulites* sp. and *Assilina* sp., all embedded in microcrystalline matrix. Scale bar = 250 μm .



PLATE 3B. Discocyclinal nummulitic packstone with different sections in *Assilina* sp. and *Nummulites* sp. Scale bar = 250 μm .



PLATE 3C. Discocyclinal nummulitic packstone with close up view of longitudinal axial section of *Assilina* sp. showing geopetal infillings. Scale bar = 250 μ m.

4.1. Bioclastic Grainstone

The main skeletal are *Fabiania*, *Alveolina*, bryozoans and algae. There is a subordinate amount of *Nummulites*, *Dictyonoids*, annelids, miliolids, echinoderms and other rotaliid forams. Oncoids are highly abundant, Pl. 3D, E. Few fecal pellets are detected, they were either formed by intense micritization or derived from organic pelleting of lime mud. Most components are micritized to variable extent, indicating shallow marine depositional environment. Cement is recorded as fibrous and bladed calcite crystals forming isopachous cement surrounding most of the particles and followed directly by granular calcite which fills the intergranular spaces.

4.2. Alveolinal Grainstone

Peloids, lumps and subordinate intraclasts are frequent together with micro- and macrofauna; all are often micritized. Besides *Alveolina*, *Fascolites*, miliolids, algae, echinoids, bryozoan and pelecypod fragments are preserved, Pl. 3F. Drusy cement, characteristic of the phreatic zone, is seen on rhombic-bladed calcite crystals formed equally around the periphery of the pore.

4.3. Discocyclinal Nummulitic Grainstone

Nummulites, *Assilina* and *Discocyclina* dominate this facies, Pl. 3G. They are imbricated and mostly oriented parallel to the bedding plane. Reworked bioclasts

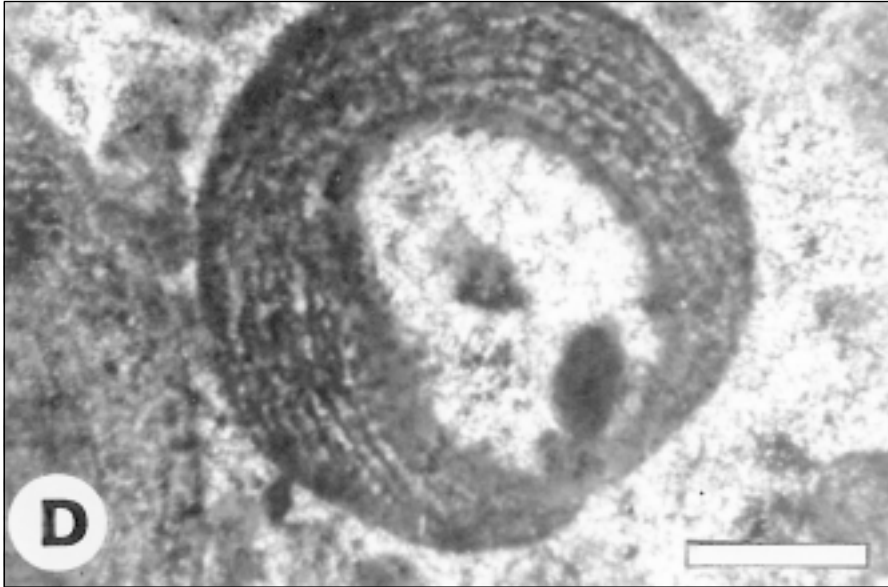


PLATE 3D. Bioclastic grainstone showing larger oncolite irregularly laminated with neomorphic replacement of the inner layers with drusy calcite. Scale bar = 400 μm .

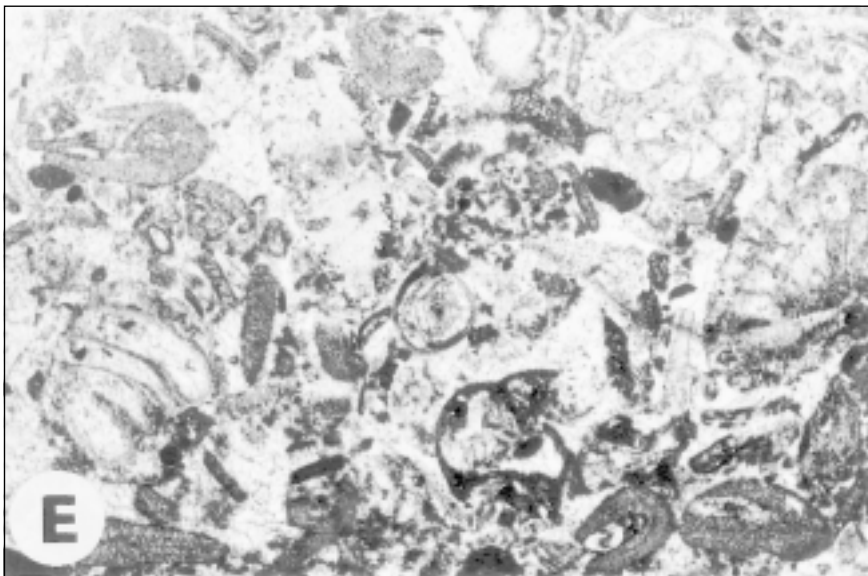


PLATE 3E. Bioclastic grainstone with different skeletal particles including miliolids (middle), planispiral rotaliid forams (upper right), *Nummulites* sp. (middle right) and oncolites (lower right) embedded in spary calcite cement. Scale bar = 250 μm with different sections in *Assilina* sp. and *Nummulites* sp. Scale bar = 250 μm .

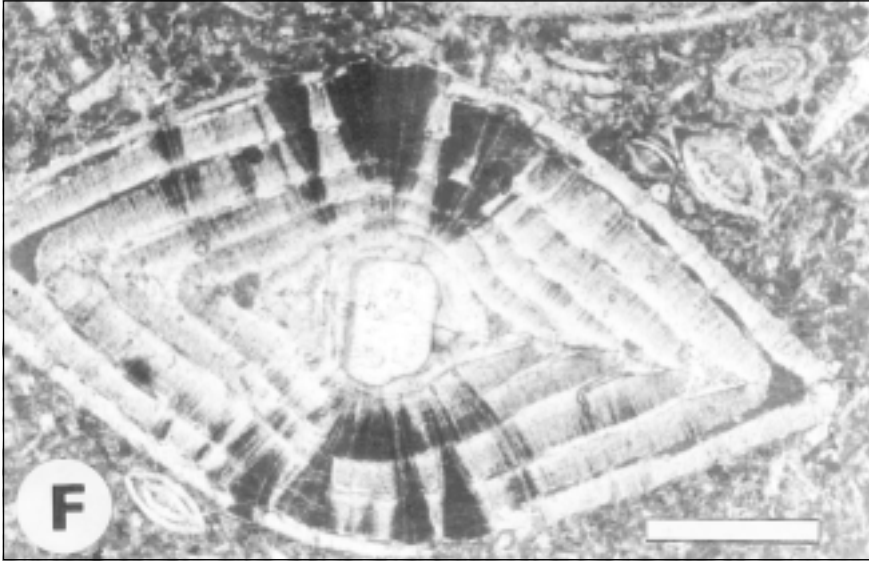


PLATE 3F. Alveolal grainstone showing moderately deformed and grain breakage of a large axial section in *Alveolina* sp. surrounded by granular calcite cement. Scale bar = 400 μ m.



PLATE 3G. Discocyclinal nummulitic grainstone with three long axial sections in *Discocyclusina* sp. parallel to the bedding plane and an axial section in *Nummulites* sp. (upper). Scale bar = 400 μ m.

of *Nummulites*, echinoid spines, pelecypods and miliolids often show conspicuous bioturbation. Cement is in the form of granular spary calcite filling the pore spaces between the different bioclasts, with remnants of microcrystalline calcite. Most of the miliolid tests and pelecypod fragments are partially micritized, with noticeable micrite envelope coating the bioclasts. Blocky spary calcite crystals are detected filling intergranular spaces and voids. Dissolution, of the sediment and shells, produced secondary vuggy, moldic and channel porosity.

4. 4. *Orbitolites* Grainstone

The larger forams which dominate this facies are mainly *Orbitolites*, *Alveolina* and *Nummulites*. The subordinate macrofauna are solitary corals, large turretted gastropods molds, bivalve shell fragments, echinoids and crabs. Miliolids frequently occur. All the skeletal grains are cemented by well-developed spary calcite crystals. Two stages of recrystallization can be observed in the present facies. First, is an initial replacement of the original microstructure starting from the outer wall, and second is coarse and equigranular drusy calcite crystals that fill the intragranular pore spaces, Pl. 3H. Impregnation by iron oxides coating many skeletal fragments is also observed.

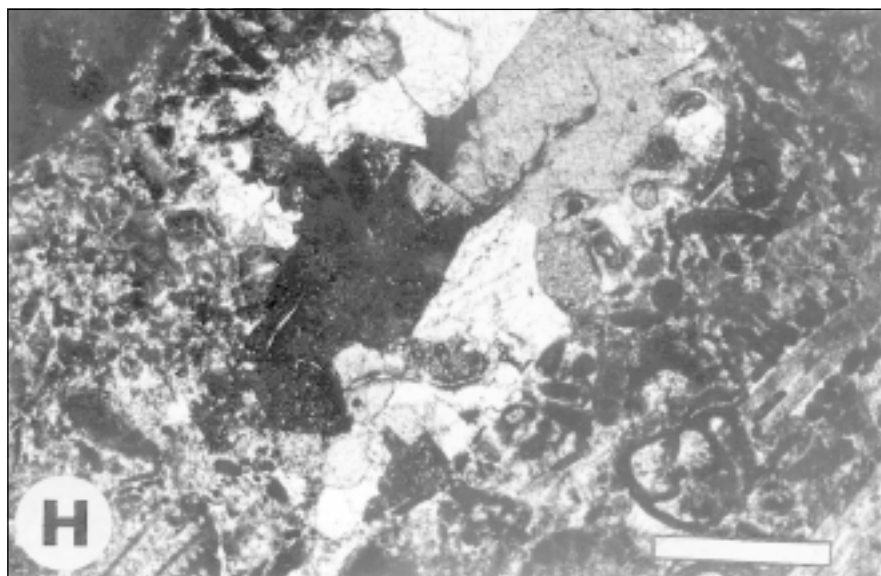


PLATE 3H. *Orbitolites* grainstone showing complete recrystallization of skeletal fragment to drusy calcite surrounded by totally micritized foraminifers. Scale bar = 400 μm .

Diagenetic History

Biogenic Alteration

Micritization of allochems is apparent in most microfacies associations commonly to the point of obliteration, Pl. 2A. Also relict marine cements and micrite envelopes are present in some bioclastic packstones and grainstones. Most of the foraminifers in the wackestones undergo micritization to the stage of becoming a lump of dark lime mud; only recognizable by the outer form. The biogenic alteration could take place on the seafloor or just below, and is considered as marine phreatic diagenesis, Bathurst, 1964; 1966 and Boggs, 1995.

Cementation

Most skeletal grains are rimmed by fibrous marine cement (isopachous rinds), which are also preserved encrusting several foraminiferal tests. Much of this early cement has been lost due to dissolution and/or recrystallization, leaving low Mg-calcite spar in place. The near surface meteoric cements which formed under the water-saturated phreatic zone are represented by isopachous, blocky and syntaxial rim. On the other hand, the drusy calcite spar which is a common deep-burial cement, is a characteristic pore filling cement in the packstone and grainstone microfacies associations of the Ain Al Faydah Member of Jabal Hafit.

Neomorphism

The micritic matrix in most mudstone and wackestone facies has undergone aggrading neomorphism and recrystallized into microspar, Pl. 2C. The recrystallization of the early fibrous marine cement coupled with subordinate leaching of allochems, suggests the influence of meteoric water on the sediments. Recrystallization of bioclasts, Pl. 3H, was much more common than leaching. Thus very limited secondary porosity was created.

Dissolution

The studied microfacies associations record different dissolution features including leached fossil allochems (mouldic porosity), vugs and micro channels, Pl. 2A, E. Boggs (1995) concluded that dissolution is relatively unimportant on the seafloor but is particularly relevant in the near-surface meteoric environments, where chemically aggressive meteoric waters percolate or flow down through the vadose zone into the phreatic zone.

Compaction

Overpacking, imbrication, interpenetration and fracturing are well observed features of compactional burial diagenetic effects, which can be interpreted as a

result of compaction/pressure solution processes, Pl. 3A, F. Both 'contact' and 'isolate' imbrication of Laming 1966, are common, especially in local concentration of the larger and flatter B-forms of *Nummulites* sp., in the nummulitic packstone and grainstone microfacies associations.

Dolomitization

Partial dolomitization is observed in the mudstone facies, represented by tiny euhedral dolomite rhombs scattered in the rock. The dolomitization process has taken place after deposition and cementation and is confined to the fine sediments indicating mixed meteoric-marine water diagenetic environments.

Depositional Model

In the Al Ain region, by the end of the Upper Cretaceous above the eastern edge of the Oman foredeep a small basin was formed including Jabal Hafit and its surrounding hills, Warrak, 1987. A thick carbonate sequence was formed ranging from Early Paleocene to Middle Eocene. Very thick Middle Eocene nummulite buildups were developed with highly abundant and diverse both micro- and macrofauna. Aigner 1983, pointed out that *Nummulites*, often associated with other "larger foraminifera", are common in neritic and shelf ramp facies in many parts of the Mediterranean Paleogene. Whittle *et al.*, 1996 mentioned that the Dammam Formation (Middle Eocene) with the grain-supported limestones rich in foraminifera and echinoderms was deposited in a restricted to open marine shallow shelf setting cycle with sparse bioclastic mud-supported limestones characteristic to quiet water deposition. They pointed out that the Dammam Formation of Jabal Hafit is considered as a transitional stage during Eocene to Oligocene shallow shelf deposition in the Arabian Gulf region. Racey 1995, concluded that the Middle Eocene nummulite buildups of the Seeb Formation of Northern Oman suggest deposition on a carbonate ramp.

The lithofacies and microfacies characteristics of the Middle Eocene Ain Al Faydah Member of Jabal Hafit represent a carbonate ramp facies *sensu* Ahr, 1973; Read, 1982; Tucker, 1985; Tucker and Wright, 1990. These characteristics are: (i) the member is widespread and shows little vertical and lateral variation in facies along Jabal Hafit, (ii) facies patterns are broadly extending in parallel bands, (iii) Major reef developments are absent, suggesting no major break in slope as occurs at a shelf margin, (iv) small patch reefs are only common, (v) storm sheets are common throughout the member whilst storm bedded facies are rarely observed. Three depositional facies associations have been recognized across the nummulite buildups of Jabal Hafit. Starting from onshore these are: back bank, nummulitic bank and fore bank facies, Fig. 3.

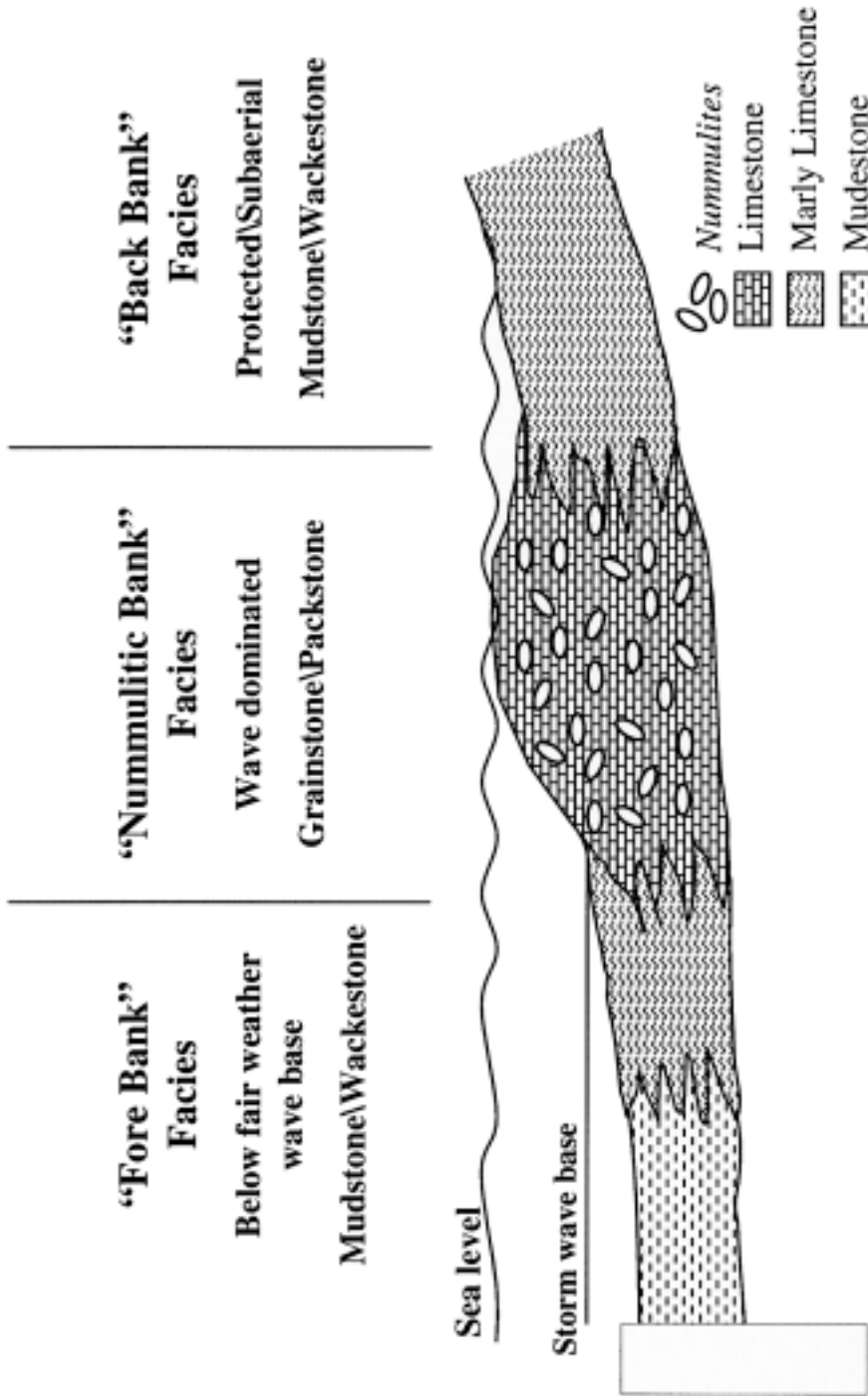


FIG. 3. Stratigraphic columnar section of the Middle Eocene, Ain Al Faydah Member, Jebel Hafit, UAE.

Back Bank Facies

Mudstones and wackestones (bioclastic and nummulitic wackestones) dominate the sequence. However, packstones (mainly bioclastic packstone) are frequently recorded in certain horizons. This facies commences with coarse, poorly-sorted bioclastic packstones containing diverse molluscan and echinoid fauna. The beds are highly bioturbated and were deposited in a protected environment below wave base, possibly in a shallow lagoonal setting. *Alveolina*, *Orbitolites* miliolids are the most abundant foraminifers characterizing this facies. Bands with a higher *Nummulites* content are dominated by A-forms, while larger B-forms are generally frequent, Pl. 1C. This represents a relatively undisturbed assemblage, that characterizes the back bank facies of the muddy substrate see Aigner, 1985. On the other hand, the coated grains are represented by very abundant oncoids in the bioclastic packstones. It is commonly thought that oncoids require frequent overturning to form, mostly inhibited in a very shallow marine environments, and common in peritidal carbonates Tucker and Wright, 1990. The occasional large compound corals near the base suggests that reefal patches developed nearby. A subsequent regressive phase led to the deposition of remarkable large sized gastropod shell-lag beds, Pl. 1A, B. These well-sorted and well-lithified beds could represent shallow platform shoals formed above active wave base. In environment terms, the associated fauna generally indicates muddy substrate conditions (dominance of burrowing molluscs and echinoids) in a relatively open lagoon behind the "barrier" formed by the nummulitic bank/shoal complex Aigner, 1983.

Nummulitic Bank Facies

This facies forms a continuous massive, well-bedded, often poorly-sorted Nummulites rich beds (up to 30 m thick), partially interrupted by marly layers. Packstone (bioclastic, nummulitic, alveolinal nummulitic and discocyclinal nummulitic) and grainstone (bioclastic, alveolinal and discocyclinal nummulitic) depositional textures are most abundant. Wackestones and mudstones are absent.

Microfauna of this facies association consists almost exclusively of nummulite tests, mainly of the *gizehensis*-group. In fact the tests of *Nummulites*, as well as all foraminifers, are present in two distinct size classes: small A-forms (megalospheric) and large B-forms (microspheric). The natural population of the larger nummulitid foraminifera are dominated by the megalospheric A-forms Blondeau, 1972; Hallock, 1982; Aigner, 1985. The residual sedimentary fabrics (residual lag) of Aigner 1985, enriched with imbricated larger accumulation of B-forms with subordinate occurrences of A-forms Pl.1D characterizes the nummulitic bank facies of Jabal Hafit. This accumulation suggests that win-

nowing of the smaller sized *Nummulites*, by wave action, caused *in situ* concentration of B-forms, and it was strong enough to transport the finer carbonate grains (A-forms) away. Storm events are considered to be very important on ramps Tucker, 1985 and Tucker and Wright, 1990 and together with normal wind-wave activity they led to the formation of beach barrier complex or banks.

Microfaunal elements other than *Nummulites* are *Assilina*, *Alveolina*, *Discocyclina*, *Orbitolites*, *Fabiania*, *Asterocyclina*, *Fascolites*, *Dictyonids* and very rare textulariids. Among the macrofauna, are burrowing echinoids, calcareous algae, byozoans, large sized gastropods, oyster fragments and few pectinid and spondolid bivalves.

Shoal reefs are recorded interfingering the nummulitic banks and consist of isolated patch reefs of less than one meter to a few meters in diameter, of colonial scleractinean corals and coral heads of *Porites*, *Actinacis* and *Goniopora*, Pl. 1E. In most cases these patch reefs are encrusted by crustose coralline algae suggesting a very shallow reef to shoal-type environment, Wray, 1972; Aigner, 1983 and Tucker and Wright, 1990.

However, the microfacies and faunal associations indicate that the nummulitic banks of the Ain Al Faydah Member were probably deposited in a shallow, subtidal shoreface setting, probably above fair weather base and may have been formed through gradual shoaling of the ramp, due to relatively strong wave-action in the shoreface-intertidal region.

Fore Bank Facies

Thin storm bedded limestones and marly limestones dominated with packstones facies usually top the nummulitic bank facies and replace them vertically. These may have been formed through reworking by storm waves and are interbedded with low energy, wackestone lithologies, which commonly develop behind such banks/shoals. In deeper areas, possibly below storm wave-base, larger foraminiferal packstones and wackestones predominate. The composition of the macrofauna and microfauna indicates gradual deepening of the environment.

Conclusion

During the Middle Eocene, very thick nummulite buildups (Ain Al Faydah Member) were formed with highly abundant micro- and macrofauna. The depositional interpretation of the Middle Eocene Ain Al Faydah Member of Jabal Hafit is based on the field observations and micro- and lithofacies characteristics of the studied section. The Middle Eocene Ain Al Faydah Member represents homoclinal ramp deposition. It was deposited in a shallow marine setting,

warm water, with high concentration of CaCO₃, in the photic zone of a submarine swell and highly agitated environments. The lower beds are dominated by packstones rich in textulariids, miliolids, large sized gastropods and calcareous algae indicating a restricted inner shelf storm-swept carbonate ramp environment. These pass upwards into limestones dominated by *Nummulites* and *Assilina* as a result of the combination between favorable ecological conditions and the repeated reworking and winnowing of the fines. It led to development of the nummulitic banks, back banks and forebank facies. The Ain Al Faydah limestones therefore records a transgressive, storm-swept sequence from shallow inner-ramp to more outer ramp conditions.

Acknowledgment

The authors are grateful to Prof. Dr. G. Philip, Geology Department, Faculty of Science, Cairo University for his valuable comments and for revising the final manuscript.

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التحليل السحني والتاريخ الرسوبي لتتابعات الإيوسين الأوسط لجبل حفيت بمدينة العين ، دولة الإمارات العربية المتحدة

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المستخلص . تعتبر تتابعات الإيوسين الأوسط بجبل حفيت، جنوب مدينة العين بدولة الإمارات العربية المتحدة والتي يصل سمكها إلى حوالي ٢٧٠ متراً، واحدة من أكبر التجمعات لصخور الحجر الجيري النيموليتي، ليس فقط في منطقة الخليج العربي ولكن في منطقة الشرق الأوسط على الإطلاق. هذا وتميز هذه التتابعات بكونها عالية التنوع من الناحية الحفرية. كما وأنها تتميز بوجود العديد من أنواع الفورامينيفرا ذات الأصداف ضخمة الحجم مثل:

(*Nummulites cf. lyeli*, *N. maximus*, *Assilina gigantea*)

بالإضافة إلى البطنقدميات والقنافذة الحفارة، وأيضاً المحاربات سميقة الأصداف (*Oysters*).

ولقد أظهرت الدراسة الحالية أن تتابعات الإيوسين الأوسط بمنطقة الدراسة تتميز بعدم وجود تغير سحني جانبي واضح للطبقات الجيرية النيموليتية وذلك سواءً من الناحية الصخرية أو من ناحية المحتوى الحفري مما يعكس التجانس الواضح في بيئات ترسيب تلك الصخور. كما استنتج الباحثون أن التوزيع المنتظم لتجمعات الفورامينيفرا الكبيرة البانية للصخور الجيرية من أجناس *Nummulites* and/or *Assilina*, *Alveo-* *loina* والتي قد يوجد كل نوع منها إما منفرداً أو بمصاحبة نوع أو أكثر من الأنواع الأخرى مع وجود طبقات جيرية متداخلة خالية في محتواها من النيموليتات، إنما يعبر بشكل واضح عن مدى تذبذب مستوى سطح

البحر والذي كان نتيجة عمليات تكتونية متزامنة مع عمليات الترسيب. وقد أظهرت الدراسة الاستراتيجرافية أن التتابعات الجيرية النيموليتية والتابعة لعضو العين الفايضة إنما يرجع عمرها إلى الفترة المبكرة من الإوسين الأوسط (الليوتيتي).