BIO-LITHOFACIES AND DIAGENESIS IN THE EARLY-MIDDLE OLIGOCENE OF ABU DHABI, UNITED ARAB EMIRATES

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ABSTRACT: The Early to Middle Oligocene is missing throughout much of the Arabian Peninsula. Only in the Oman Mountains and related linear NW-SE trending mountains are these sediments found. In the United Arab Emirates shallow water carbonates of the Asmari Formation (Early to Middle Oligocene) range from 435-481 m (1427-1578 ft), cropping out at the Jabal Hafit area near Al Ain. Detailed measured sections, sampling and thin section analysis show these carbonates comprise seven distinct facies: 1) Nummulitic Packstone, 2) Foraminiferal Wackestone/Packstone (non-Nummulitic forams), 3) Echinoderm/Red Algal Packstone, 4) Coral Framestone, 5) Peloidal Packstone, 6) Mudstone/Wackestone, and 7) Dolomite.

Diagenetic events which have affected the Oligocene section include early cementation, formation of micrite envelopes, inversion of original aragonite and high Mg-calcite fabrics (i.e., biogenic tests and early marine cements) to low Mg-calcite, leaching of tests, dolomitization, stylolitization and fracturing, late diagenetic coarse calcite spar cementation, emplacement of bitumen within stylolitic seams and finally, hematite and pyrite staining.

A depositional model has been proposed based on the fossil and lithofacies assemblages which suggests that a deep, outer shelf, quiet water lagoon supplies peloids to the back-reef, reef and fore-reef facies as well as the shallow open marine facies of the inner shelf. A short-lived sea level low is believed to have occurred, where continental waters manifested their presence in rare chertification and partial to complete dolomitization of some samples.

INTRODUCTION

The Oligocene carbonates form the main reservoir unit in onshore Iran and northern Iraq. Richardson (1924) introduced the term Asmari Formation, which generally developed as a massive, dense limestone with relatively poor primary and secondary porosity. However, the Asmari is one of the most prolific reservoirs in the world, but this is basically a result of the extensive fracturing rather than the natural porosity of the formation (Setudehnia 1972). Pilgram (1908) was the first to publish the reference section of the formation in Iran, while Thomas (1950) first published in detail the type section on the southwest flank of Kuh-e-Asmari anticline at Tang-e-Gel-e Tursh in southwest Iran. The formation there consists of about 314 m (1030 ft) of cream to brown, weathered, well-jointed limestone with shaly intercalations.

During Middle and Late Eocene times, a widespread regression occurred and a large part of Arabia and Iran underwent uplift and erosion. In early Oligocene time, a marine transgression occurred in parts of Iraq, Iran and the southern Arabian Gulf. However, some areas remained emergent until late Oligocene times when a widespread marine transgression covered much of Iraq, southwest and southeast Iran and the United Arab Emirates (Murris 1980; Alsharhan and Nairn in press).

The present study focuses on Jabal Hafit (24°02'N to 24°13' N latitude, 55°44'E to 55°49'E longitude), located in Al Ain city near the border between the United Arab Emirates (U.A.E.) and Oman (Fig. 1). Jabal Hafit is an anticlinal structure plunging south in Oman and north in the United Arab Emirates. This structure is approximately 29 km long, 5 km wide, and reaches an elevation of about 1160 m above sea-level. At its northern end, the Hafit fold is symmetrical with flank dips about 10° and is cut by numerous normal and near-vertical faults and some reverse faults. Most of these faults either die out away from the core of Hafit or show reduced displacement. In the northern part of Hafit overturning toward the east is indicated as the Middle-Late Eocene carbonates dip about 10° and are overlain by Oligocene carbonates which dip steeply or are overturned in the eastern limb of the structure and dip gently in the western limb. In the central part of Hafit, there is a tightly-pinched, overturned syncline with a reverse fault in the overturned limb (see Hunting 1979; Warrak 1986; Whittle and Alsharhan 1994). The southern part is overturned at all exposed horizons and is displaced toward the east with the overturned limb being cut by a thrust.

Jabal Hafit is composed primarily of carbonate and marl, ranging in age from Early Eocene to Miocene. In the subsurface of the United Arab Emirates, the Asmari ranges in thickness from 54-108 m (177-354 ft) and can be divided into three units (Fig. 2). The lower unit is nummulitic and pellety dolomite and dolomitic limestone with silty mudstone and anhydritic nodules. The middle unit consists of intraclastic and nummulitic packstone/grainstone and calcareous mudstone. The upper unit is silty dolomite, dense and pellety in part, interbedded with pellety limestone and stringers of calcareous mudstone.

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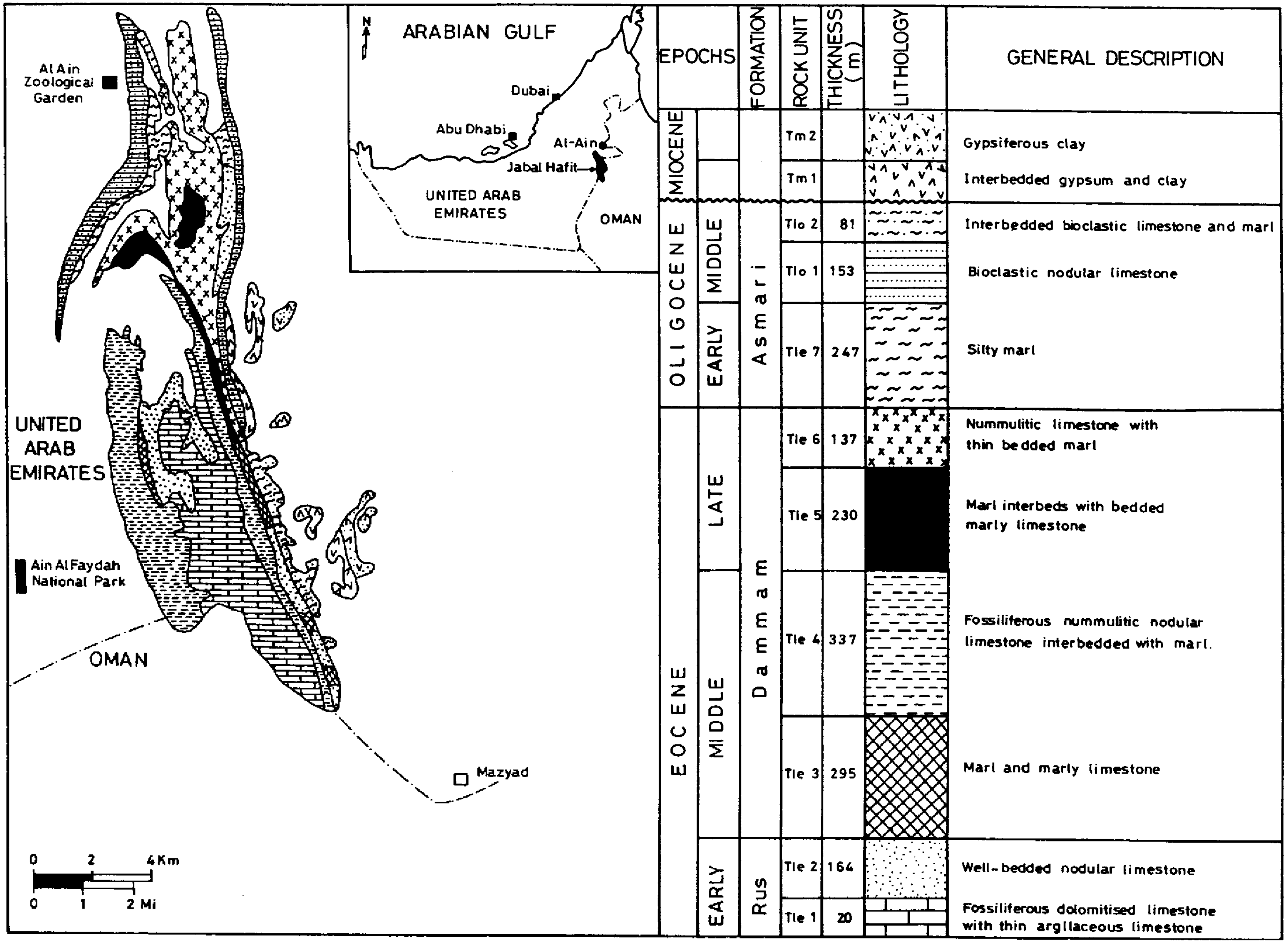

Figure 1. Lithostratigraphic and chronostratigraphic column of outcrop section of the Tertiary sediments in the United Arab Emirates associated with geologic map of Jabal Hafit (modified from Hunting 1979 and Whittle and Alsharhan 1994). Note that the lithologic pattern of the geologic map is the same as in the stratigraphic column.

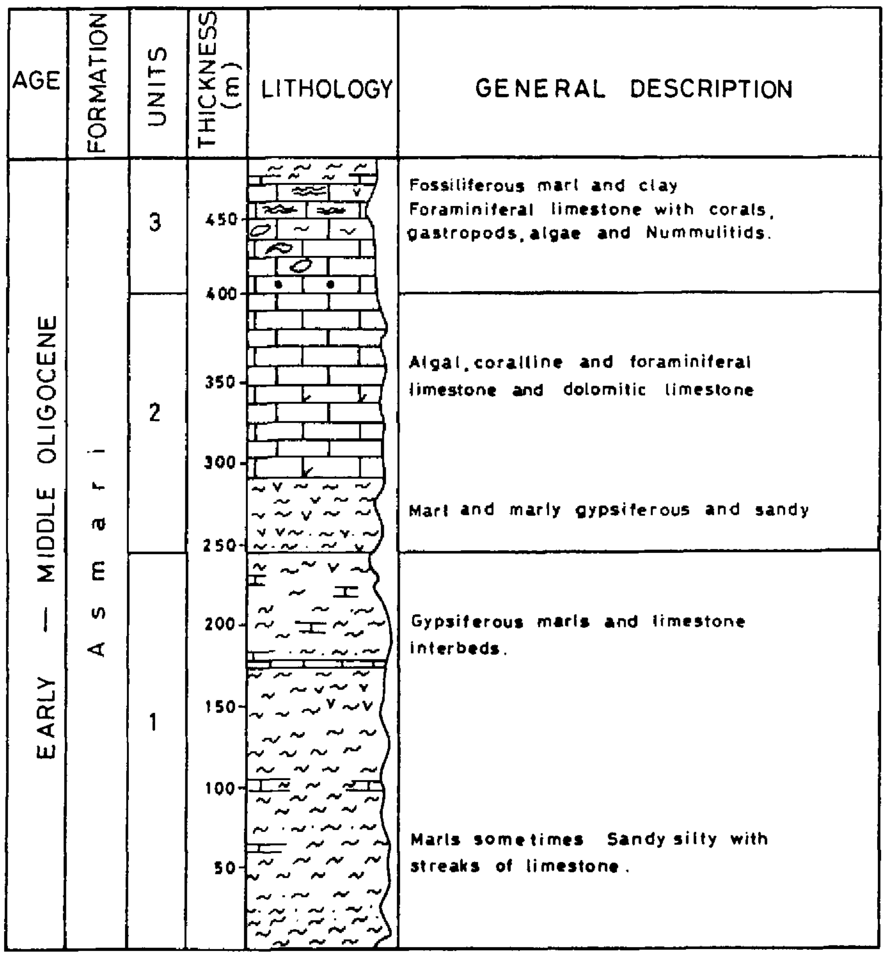

Figure 2. Detailed stratigraphic column for the Oligocene Jabal Hafit section.

LITHOSTRATIGRAPHY OF THE ASMARI FORMATION

In the study area in onshore Abu Dhabi at Jabal Hafit (Fig. 1) the Asmari Formation (Early to Middle Oligocene) has a thickness ranging from 435-481 m (1427-1578 ft). It is composed of marl with recrystallized gypsum in the lower part, grading to algal, coral and nummulitic limestone with dolomitic marly and chalky interbeds in the upper part (Fig. 2). It has different rock unit and member names (Table 1), but in this study, we divided it into three lithological units.

Unit 1: It is equivalent to Tle_7 (Hunting 1979), the upper part of the Senaiya Formation (Cherif and El Deeb 1984) and the Zakher Member of the Asmari Formation (Hamdan and Bahr 1992). The unit consists of about 247 m (810 ft) of silty marl in the lower part, grading vertically to gypsiferous marl with conglomeratic limestone. Hunting (1979) and Cherif and El Deeb (1984) assigned the age of this unit to the Lower Oligocene. Anan et al. (1992) and Hamdan and Bahr (1992) assigned an Early to early Middle Oligocene age based on microfossil study and biostratigraphy.

Unit 2: It is equivalent to the Tlo_1 (Hunting 1979), Lower Member of the Al Jaww Formation (Cherif and El Deeb 1984) and the Mutaredh Member of the Asmari Formation (Hamdan and Bahr 1992). The unit consists of about 153 m (502 ft) of thickly-bedded algal, coral and nummulitic limestone. The age of this unit was given by Hunting (1979) and Cherif and El Deeb (1984) as Middle Oligocene, while Hamdan and Bahr (1992) assigned a middle Middle Oligocene age based on planktonic foraminifera and nummulitids.

Unit 3: It is the equivalent of Tlo_2 (Hunting 1979), the Upper Member of the Al Jaww Formation (Cherif and El Deeb 1984) and the Muwaiji Member of the Asmari Formation (Hamdan and Bahr 1992). The unit ranges in thickness from 35-81 m (115-266 ft) and is composed of poorly-bedded, marly, foraminiferal limestone with coral heads, gastropods and echinoderms. It grades into an upper part of thinly bedded, marly, oolitic and bioclastic limestone, gypsiferous, richly fossiliferous marl and clay. The age of this unit was given by Hunting (1979) as Oligocene to Miocene, while Cherif and El Deeb (1984) assigned it to the Middle Oligocene. Hamdan and Bahr (1992) and Anan et al. (1992) assigned it to the late Middle Oligocene based on nummulitids.

EPOCHS		SUBSURFACE (Alsharhan, 1989)	OUTCROPS						
			HUNTING (1979)	CHERIF AND EL DEEB (1984)		HAMDAN AND BAHR (1992)		THIS STUDY	
OLIGOCENE	MIDDLE	ASMARI FORMATION	Tlo2	AL JAWW FORMATION	UPPER MEMBER	ASMARI FORMATION	MUWAIJI MEMBER	ASMARI FORMATION	UNIT 3
OLIGOCENE	MIDDLE	ASMARI FORMATION	Tlo1	AL JAWW FORMATION	LOWER MEMBER	ASMARI FORMATION	MUTAREDH MEMBER	ASMARI FORMATION	UNIT 2
OLIGOCENE	EARLY	ASMARI FORMATION	Tle7	UPPER SENAIYA	MEMBERS D AND E	ASMARI FORMATION	ZAKHER MEMBER	ASMARI FORMATION	UNIT 1

Table 1. Nomenclature for the Oligocene section in the Jabal Hafit area. Note that this study divides the Oligocene into three new units based on fossil and lithologic assemblages.

FACIES ANALYSIS OF THE ASMARI FORMATION

In onshore Abu Dhabi, seven facies have been defined in the Early-Middle Oligocene Asmari Formation. These include: 1) Nummulites Packstone, 2) Foraminiferal Wackestone/Packstone, 3) Echinoderm/Red Algal Packstone, 4) Coral Framestone, 5) Peloidal Packstone, 6) Mudstone/ Wackestone, and 7) Dolomite. These facies are described below in terms of their fossil assemblages and diagenetic modifications. There are some similarities between facies. Non-skeletal grains are subordinate in all facies save the Peloidal Packstone facies. These non-skeletal grains were usually enveloped by a micrite envelope and showed no internal structure. On rare occasions, concentric layering of ooids was observed. However, the vast majority of non-skeletal grains were elliptical in shape and are thought to have been pellets originally. Whether they are of fecal origin is difficult to impossible to determine. The term "peloidal" is used for the Peloidal Packstone facies (described below) because of the lack of hard evidence for these non-skeletal grains being pellets and because many of the grains may be highly micritized skeletal fragments. There appear to be roughly two types of peloids: 1) fine-grained (< 20 mm) peloids (Fig. 3A) which are agglutinated into aggregates, forming botryoidal grains (intraclasts which are coated; after Harris et al. 1985) on the order of 50 to 200 mm; and 2) coarser-grained (» 45 mm) peloids (Fig. 3B) which are not aggregated but are cemented within either a muddy or sparry matrix. Peloids (referring to both the non-skeletal pellets and any skeletal grains that have been micritized beyond recognition) were heavily bored throughout the section. The borings are filled by micrite and are attributed to the work of boring cyanobacteria. Compaction features were consistent throughout the Oligocene section and where filled, fractures were occluded by late-diagenetic, coarse calcite spar while stylolites were filled with a bituminous residue.

Nummulites Packstone

This facies is dominated by *Nummulites sp.* with subordinate uniserial and miliolid foraminifera (e.g., *Quinqueloculina, Triloculina*) (Fig. 3C). Echinoderm fragments and red algae (e.g., *Goniolithon, Lithothamnium*) are also common (Fig. 3D). Chertification of one *Nummulites sp.* test was recorded and staining by hematite and bitumen has occurred. Matrix cementation is primarily by early calcite spar, but some mud occurs locally. Fracturing and stylolitization are common and porosity is very low to nil in this facies due to matrix cementation and late cementation by calcite. The high concentration of *Nummulites sp.* in this facies suggests a somewhat restricted setting. However, while the number of other types of skeletal grains is small, the diversity of species is moderate. This indicates a depositional environment which is slightly restricted but proximal to an open marine setting.

Foraminiferal Wackestone/Packstone

This facies occurred near the top of the section bounded above and below by the Nummulites Packstone facies. The difference between the two is primarily less *Nummulites sp.* and more non-Nummulite foraminifera in the Foraminiferal Wackestone/Packstone (Fig. 4A and B). *Quinqueloculina sp., Triloculina sp.* as well as peneroplids, peneroplids and various uniserial forams (unidentifiable due to recrystallization) are abundant. The matrix is cemented by

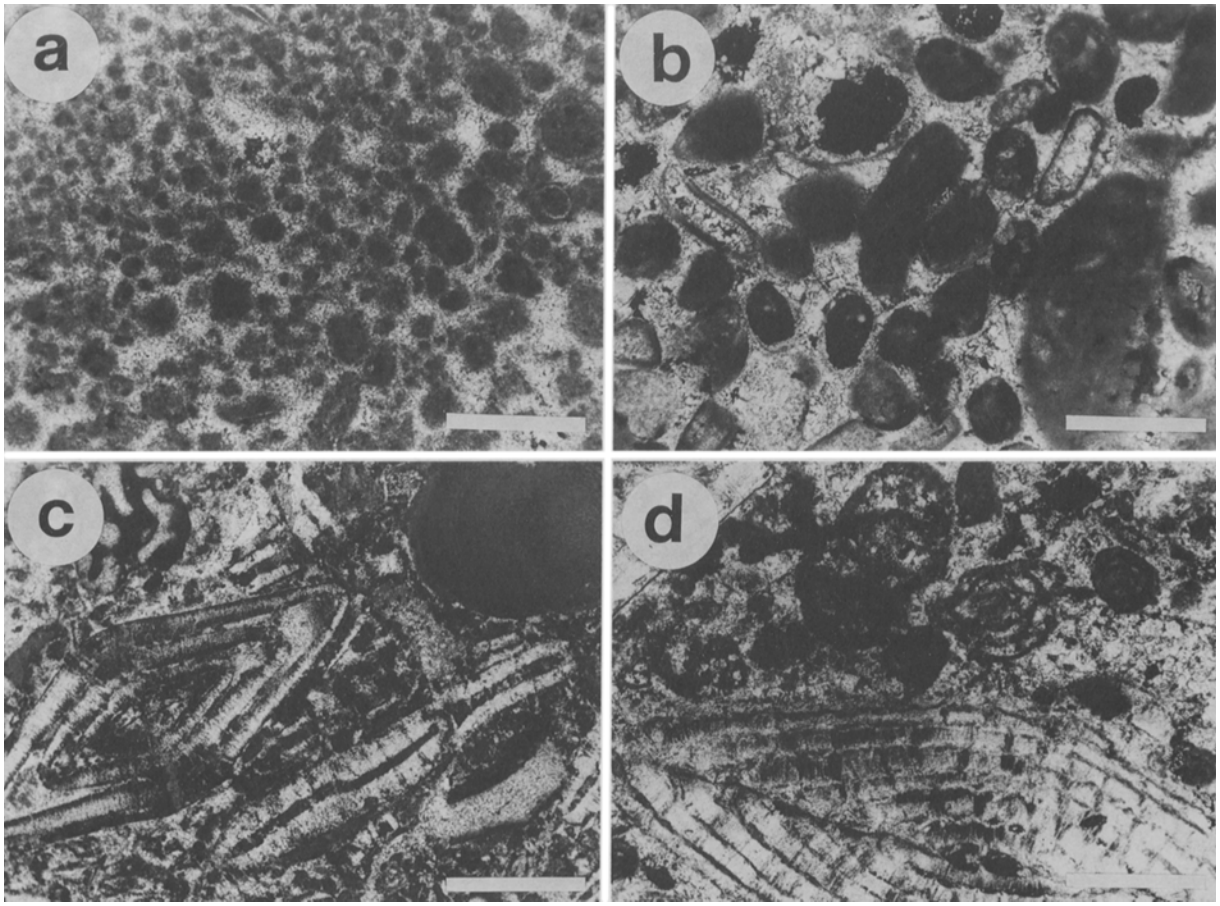

Figure 3. Two types of peloids occur in the study area: A) fine-grained peloids (<10 µm) which agglutinated into aggregates, forming botryoidal grains on the order of 50 to 200 µm (crossed nicols); and B) coarse-grained (≈ 45 µm) which do not aggregate but are cemented within either a muddy or sparry matrix (crossed nicols). C) Nummulites sp. and subordinate miliolid foraminifera compose the Nummulites Packstone (crossed nicols). D) Echinoderms (center and extreme right) and red algae (upper right) are common but subordinate skeletal grains in the Nummulites Packstone. Despite a high diversity, the overwhelming majority of the grains in this facies are Nummulites sp. (crossed nicols). Scale bar in each photomicrograph equals 500 µm.

sparry calcite (Fig. 4A) with local muddy portions at the top and bottom of the section, while the middle is predominantly muddy (Fig. 4B). No compaction-pressure solution features were observed in this facies. The muddy matrix and increase in foraminifera diversity suggest a more open marine setting than the Nummulites Packstone.

Echinoderm/Red Algal Packstone

While echinoderms and red algae are ubiquitous in the Early-Middle Oligocene section, there is a definable facies where their abundance is higher than elsewhere (Figs. 4C and D). Some echinoderms show a syntaxial calcite rim (Evamy and Shearman 1965) and all have neomorpho-sed to low Mg-calcite. On rare occasions, red algae have been partially dolomitized. *Nummulites sp*., bivalve shells and serpulid tubes occur in small amounts in this facies. The matrix was observed to be both muddy and sparry in places, probably a function of the amount of dissolution and recrystallization. Extensive hematite and bitumen staining is common. Solution vugs and enhanced molds occur occasionally, giving this facies low to moderate porosity. Solution-compaction features are common as fractures, stylolites and grain interpenetration occur frequently. Due to the high diversity and biomass of bioclasts in this facies, it is interpreted as having been deposited in a shallow open marine setting.

Coral Framestone

In addition to abundant coral fragments, this facies also is characterized by red algae, miliolid foraminifera and echinoderm fragments. Primary porosity was probably excellent prior to the formation of calcite spar, which has occluded virtually all pores (Figs. 5A and B). No cryptocrystalline cement commonly associated with reef deposits (Friedman 1985) was observed. Occasionally, samples show some solution-enhanced vugs, but the porosity created is not significant. Cryptalgal laminations are present, indicating microbes were quite active in this facies as well. The coral itself has recrys-

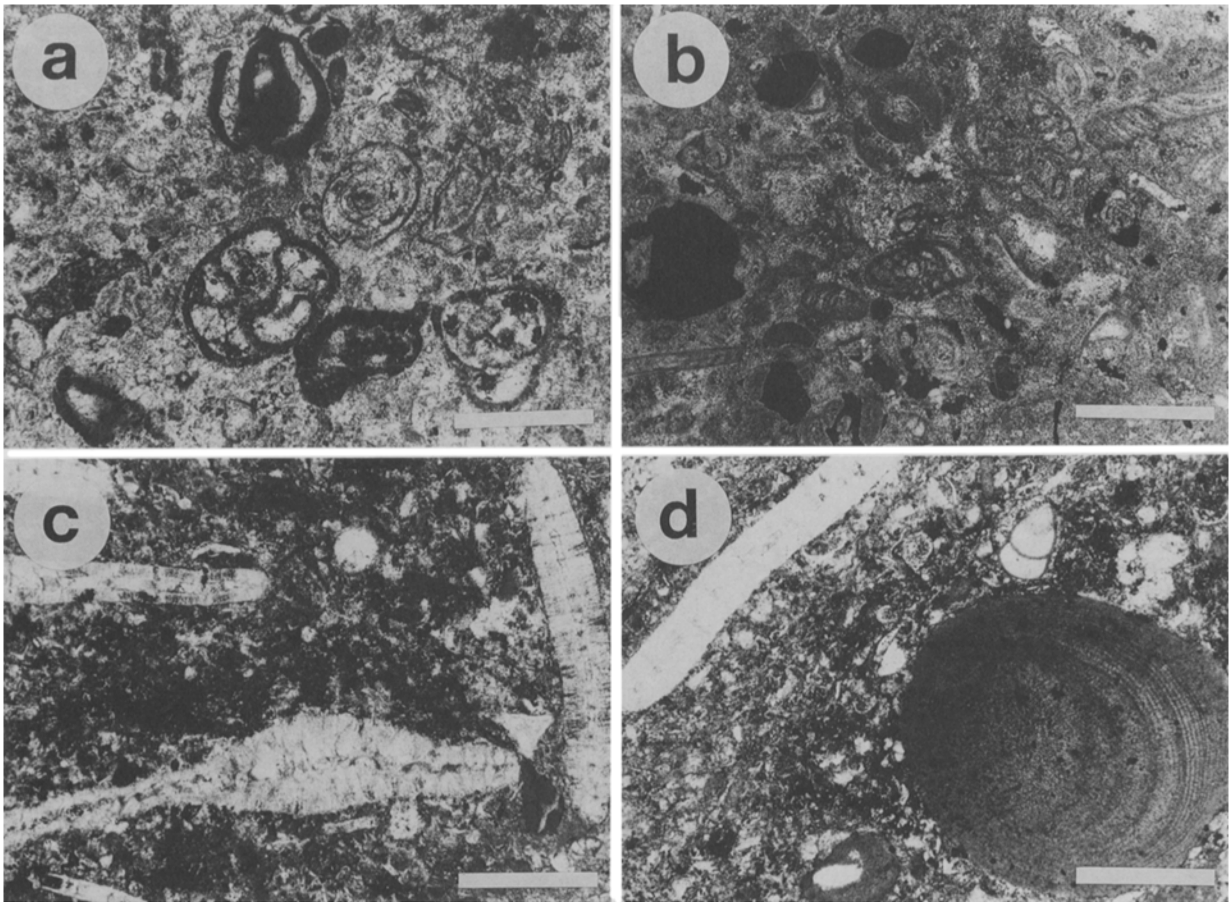

Figure 4. A) The Foraminiferal Wackestone/Packstone facies occurs toward the top of the Oligocene section and contains primarily miliolid foraminifera and is cemented by a sparry matrix at the base and top of the layer(crossed nicols). B) In the center of the layer, the matrix is muddier. Note that leaching of miliolids in this facies provided moldic porosity, but this is insignificant as far as reservoir quality (crossed nicols). C) The Echinoderm/Red Algal Packstone represents the most open water environment in the study area. While echinoderms and red algae are common in other facies in the area, they are the predominant grains in this facies (crossed nicols). D) The skeletal material in the Echinoderm/Red Algal Packstone appears to be bimodal: < 10 µm fragments and larger intact fossils (crossed nicols). Scale bar in each photomicrograph equals 500 µm.

tallized to calcite spar; if the original fabric was heavily bored (which is highly likely given the microbial activity in the other facies), then these borings were not preserved. The abundance of coral fragments suggests a reef to fore-reef depositional setting.

Peloidal Packstone

This facies is present in the lower part of the section. It is highly stylolitized and fractured; fractures are filled by late-diagenetic coarse sparry calcite ranging in size from 70 to 100 mm, which is often twinned. Peloids, defined and discussed above, are well-sorted and cemented mostly by early calcite spar and by micrite locally. Some grains are recognizable as foraminifera and echinoids as the outer wall and chambers have been preserved by recrystallization, but the species are difficult to determine due to the intensity of micritization; some of the peloids are probably highly micritized skeletal grains. Coral fragments are distinguishable within this facies, highly micritized and showing a compaction alignment, and signify proximity to a reef setting. Fine-grained pellets (Fig. 3A) aggregate into botryoidal grains cemented by lime mud and coated by a micrite envelope and sometimes include small bioclastic fragments (mostly echinoderm fragments). Because of the presence of coral fragments in some samples together with pellets (generally regarded as having a low energy environment of deposition), this facies is interpreted as a back-reef deposit, forming a reef pavement in the lee of the reef. The aggregation of these fine-grained pellets allowed them to be deposited in small quantities in higher energy shelf settings such as those of the Nummulites Packstone, Foraminiferal Wackestone/Packstone and Echinoderm/Red Algal Packstone. However, the overwhelming abundance of the pellets in the Peloidal Packstone facies suggests deposition in a lower energy setting and minor transport to higher energy regions.

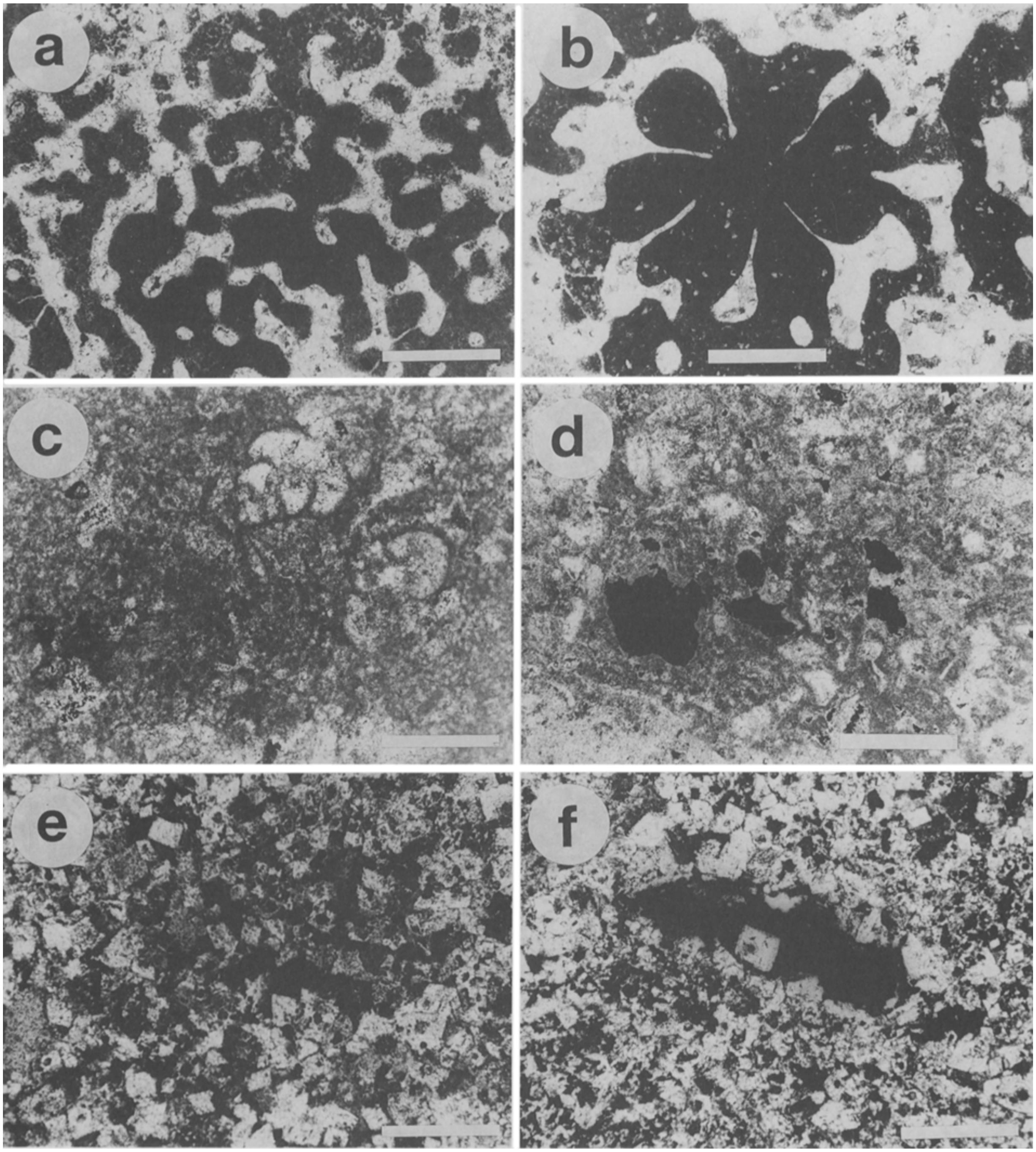

Figure 5. A) Coral fragments are by far the primary grain type in the Coral Framestone facies and these have recrystallized to low Mg-calcite (crossed nicols). B) Interparticle porosity has been virtually totally occluded by calcite spar, which is the neomorphic product of original marine cements (crossed nicols). C) The Mudstone/Wackestone facies contains the least amount of bioclastic material of any facies in the study area and has been interpreted as being deposited in quiet water (crossed nicols). D) Solution-enhanced molds of Mudstone/Wackestone sample. This facies has the highest porosity in the study area, but is considered very poor (crossed nicols). E) The dolomite facies is rare in the study area, appears to follow peloidal packstones, as rhombs occasionally engulf peloids (crossed nicols). F) The dolomite was found to have moderate intercrystalline porosity, but was probably limited in extent by a lack of diagenetic pathways (crossed nicols). Scale bar in each photomicrograph equals 500 µm.

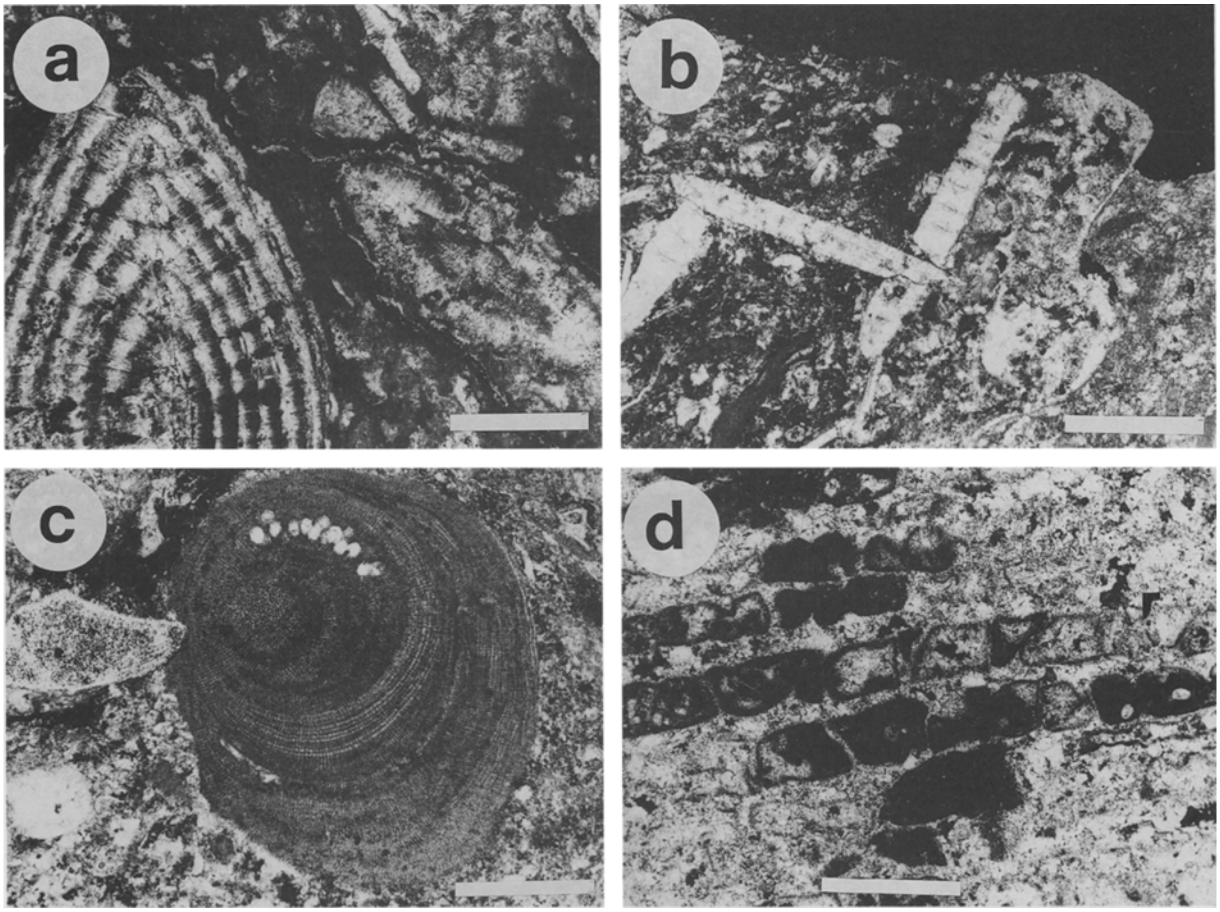

Figure 6. Compaction-pressure solution features of the Asmari: A) Fracturing of a Nummulites Packstone. Both fracturing and stylolitization were common in the Asmari and, because they occurred after dolomitization, provide moderate porosity and permeability for the formation (crossed nicols). B and C) Grain interpenetration in conjunction with fracturing in Echinoderm/Red Algal Packstone (crossed nicols). D) Alignment of skeletal grains in Coral Framestone (crossed nicols). Scale bar in each photomicrograph equals 500 μm.

Mudstone/Wackestone

This facies is virtually devoid of bioclasts except for a few miliolid foraminifera and echinoid fragments (Fig. 5C), a marked contrast from the other facies. Porosity in the form of solution-enhanced molds suggests that there may have been a greater number of allochems initially, but these have been leached out during meteoric diagenesis (Fig. 5D). Early calcite spar is also indicative of the presence of prior allochems which have now recrystallized, but original fabrics are unidentifiable. The matrix is predominantly muddy and no compaction-pressure solution features were observed in association with this facies. Pyrite staining occurs rarely, probably related to bacterial activity in a deep lagoonal environment where sedimentation rates are low (Sugden 1963, 1966). This facies is interpreted as a back-reef lagoonal deposit based on the high mud content.

Dolomite

Completely dolomitized samples are rare in the Early-Middle Oligocene section. Rhombs are euhedral and inclusion-free locally, but more often engulf fine-grained pellets (Figs. 5E and F). Intercrystalline porosity was quite good, now filled by a bituminous residue (Fig. 5F) and, less frequently, by late-diagenetic coarse calcite spar. This facies is probably a diagenetic alteration of the Peloidal Packstone facies, but low porosity due to matrix cementation by calcite has seriously inhibited migration of dolomitizing fluids.

DIAGENETIC HISTORY

The diagenetic sequence of the Early-Middle Oligocene in southwestern Arabia began in the marine phreatic diagenetic setting with secretion of micrite envelopes (Bathurst 1964, 1966; Friedman 1964; Friedman et al. 1971) and boring by microbes. Micritization of grains occurred during this stage and obliterated the original fabrics and sedimentary structures. Thus, many bioclastic grains and fragments are indistinguishable from non-skeletal pellets. Regardless, these grains may be grouped together as "peloids", the finer-grained of which agglutinated during this time period into botryoidal grains. The microbial coating around these botryoidal grains indicates their formation during this early stage of diagenesis.

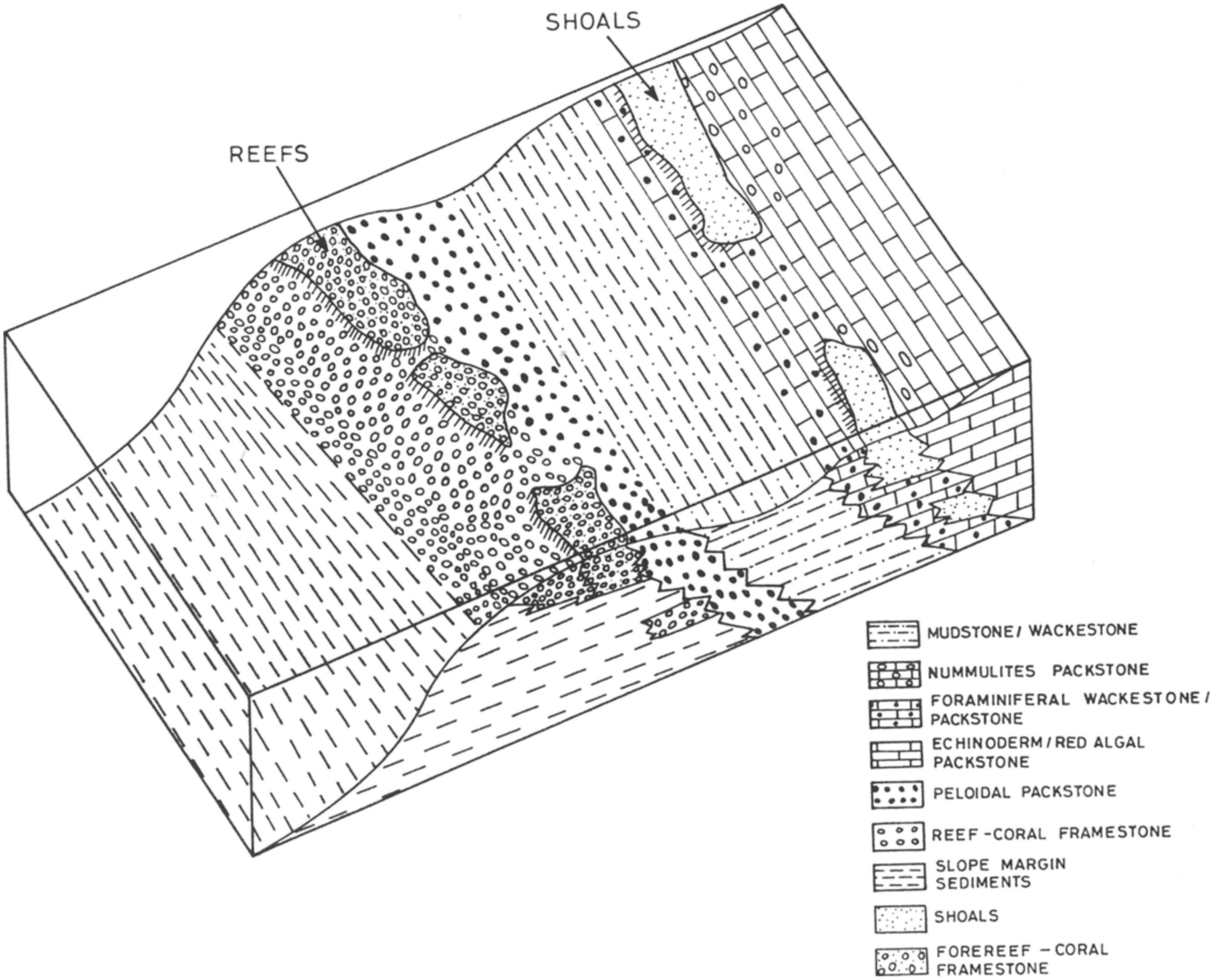

Figure 7. Depositional model for the Oligocene Jabal Hafit section. A concave shelf shape, typical of carbonate platforms, is inferred, where pellets formed in the lee of a marginal reef (Peloidal Packstone facies). Some of these pellets were redistributed both seaward (to the reef and forereef environments) and landward (to the mudstone/wackestone lagoon and shallow shelf settings).

Meteoric phreatic diagenesis is suggested by early calcite spar (James and Choquette 1990) (Figs. 3A-D, 4A, 5A and B). No relict marine cements were observed, so it was not possible to determine whether this is a neomorphic recrystallization product or a direct precipitate. Leaching occurred to some extent during this stage, removing many of the bioclastic tests from the Mudstone/Wackestone facies and providing the only noteworthy porosity in the study area. Leaching probably continued into the mixed phreatic diagenetic stage, which appears to have been very short-lived as evidenced by the rare dolomitization and chertification. The near complete dolomitization of one thin section suggests that the lack of extensive leaching of the early calcite spar inhibited dolomitization throughout most of the section despite favorable conditions for dolomite formation. *Nummulites sp.*, which was found to be very susceptible to chertification in the Lower Eocene Rus Formation of the Jabal Hafit area (Whittle and Alsharhan 1994), was only found to be chertified very rarely in the Early-Middle Oligocene. A notable absence of chert nodules or silica in any form suggests that the process was probably inhibited by a lack of porosity and permeability in a fashion similar to dolomitization.

Perhaps rapid burial interrupted the dolomitization and chertification processes. Burial diagenesis is indicated by the fractures and stylolites common in most facies (Fig. 6A) in addition to the grain interpenetration observed in the Echinoderm/Red Algal Packstone and Nummulites Packstone facies (Figs. 6B and C). Some grain alignment was found to occur in the Coral Framestone facies (Fig. 6D). Fractures tend to be completely filled throughout the section by sparry calcite. The crystal size is probably related to the size of the fracture as the spar ranges from approximately 70 mm to 100 mm. Stylolites are rarely left unfilled, usually occluded by a bituminous residue. Hematite staining is a late diagenetic feature, occurring within some stylolites and microfractures. Pyrite staining is rare and its timing is more difficult to pinpoint. It is probably a late diagenetic feature formed by the migration of hydrogen sulfide-bearing waters (Sugden 1966).

DEPOSITIONAL MODEL

The fossil and lithofacies assemblages suggest a depositional model which spreads from a deep lagoon to a reef-front margin, where local topography probably played an important role in gradation of one facies to another (Fig. 7). Mud, in the form of micrite and fine bioclastic fragments, was initially deposited in a deep, outer shelf, quiet water lagoon. The Mudstone/Wackestone facies occurs within this lagoon. Seaward, shallowing occurs associated with the typical concave shape of a carbonate shelf (Kendall and Schlager 1981), leading to a marginal reef, formed by Coral Framestone. The Peloidal Packstone facies occurs in the lee of this reef. Fine-grained pellets are deposited here and some agglutinate to form larger aggregates, some of which were cemented in place (along with unaggregated fine-grained pellets) to form the Peloidal Packstone facies, while others were washed into the back-reef lagoon and shallow shelf areas where they were incorporated into the other facies. Landward of the lagoon, the Foraminiferal Wackestone/Packstone indicates the gradation from deep water lagoonal mudstone and wackestone to the more bioclastic wackestone and packstone in a shallowing shelf environment (Fig. 7). These grade into the Nummulites Packstone, whose lower species diversity suggests local restriction, probably due to topographical changes (i.e., shoals). The Echinoderm/Red Algal Packstone, with its high biomass and species diversity, is no doubt an unrestricted open marine shallow shelf deposit. Peloids found in the Nummulites Packstone, Foraminiferal Wackestone/Packstone and Echinoderm/Red Algal Packstone were probably transported landward by storms.

CONCLUSIONS

The Early-Middle Oligocene in the southwestern Arabian Peninsula can be divided into seven distinct facies which include: 1) Nummulites Packstone, 2) Foraminiferal Wackestone/Packstone (non-Nummulites forams), 3) Echinoderm/Red Algal Packstone, 4) Coral Framestone, 5) Peloidal Packstone, 6) Mudstone/Wackestone, and 7) Dolomite. Lime mud and highly micritized biogenic fragments occur in an outer shelf, quiet water lagoon forming the Mudstone/Wackestone facies. Seaward of the lagoon, a back-reef Peloidal Packstone facies is being cemented in front of which lies the Coral Framestone facies of the reef and fore-reef. Fine-grained pellets, which are the predominant allochem in the Peloidal Packstone facies, form in the lee of the reef and some pellets agglutinate to produce larger aggregate grains which were cemented in place (i.e., in the Peloidal Packstone facies) or transported both seaward and landward, being incorporated into other facies. Landward of the Mudstone/Wackestone lagoon facies, a Foraminiferal Wackestone/Packstone facies grades into a locally restricted Nummulites Packstone facies and finally, an open marine Echinoderm/Red Algal Packstone on the shallow shelf interior.

The diagenetic path which these facies have followed includes: 1) a marine phreatic setting, where micritization of grains, secretion of micrite envelopes and boring by microbes occurred; 2) a meteoric phreatic stage, where neomorphic recrystallization to equant calcite spar and incipient leaching occurred; 3) a short-lived mixed phreatic setting, where lack of porosity/permeability, allowed only limited leaching, dolomitization and chertifi-cation to occur; and 4) a burial stage, where fractures, stylolites, grain interpenetration and grain alignment indicate compaction-pressure solution, coarse calcite spar precipitated in fractures, a bituminous residue filled stylolitic seams, and hematite and pyrite staining occurred.

The fossil and lithofacies assemblages of the Early-Middle Oligocene is suggestive of conditions similar to the Lower Eocene Rus Formation (Whittle and Alsharhan 1994). However, whereas sea level fluctuation caused shallowing and even emergence leading to the formation of extensive supratidal dolomitization and later chertifi-cation in the Rus, the Oligocene section almost completely lacks these two processes. The lack of dolomitization or chertification is attributed to the lack of porosity and permeability in the section.

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