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Sedimentological evolution, diagenesis and hydrocarbon potentiality of Late Jurassic carbonates, Eastern Region, Yemen Arab Republic

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ABSTRACT

On the basis of the lateral and vertical distribution of the lithofacies identified within the Late Jurassic Amran sequence (Thoma Member) in Jabal Al-Balaq area, Marib, Y.A.R., three megafacies were recognized. Proceeding from the shore landwards they are: (1) Ooid bank, including barriers such as reefs and carbonate sand shoals adjacent to the margin of a shallow platform having intertidal to subtidal agitated water, the bank being composed of skeletal packstone, oolitic grainstone and oncolitic packstone; (2) Shelf lagoon, behind the shoal, characterized by less turbulent pelletoidal wackestone, sandy mudstone and algal stromatolite (boundstone); (3) Alluvial coastal plain, including tidal sand flat of the marine shoreline-intertidal area, where cross-bedded sandstone and alluvial fan toe conglomerate were deposited. The apparent small-scale facies variations which are the result of the allocyclic tectonically controlled sea level fluctuations, reflect a complex interfingering of the depositional environments and the resulting rock types.

The paragenetic sequence of the post-depositional processes within the siliciclastics inferred is: iron oxide cementation, authigenic growth of mica clays, generation of pressure solution and compaction, and generation of quartz overgrowths. It is indicated that the compaction process followed the neomorphism and cementation within the carbonates.

The best oil reservoir is the coarse grained sandstone and the oncolitic packstone, followed by the algal stromatolite. The organic-rich shelf lagoon carbonates are considered to have a good hydrocarbon source potential.

INTRODUCTION

This paper deals with sedimentological studies of the Late-Jurassic Amran sequence in the Jabal Al-Balaq-Marib area located at the eastern region of the Yemen Arab Republic (Y.A.R.) close to the southwestern edge of the Al-Jawf-Marib basin. The geology of this basin received much attention in the last few years because of its oil potential. The main aim of this study is to document and interpret the field lithological and petrographical characteristics of the various rock types to emphasize the

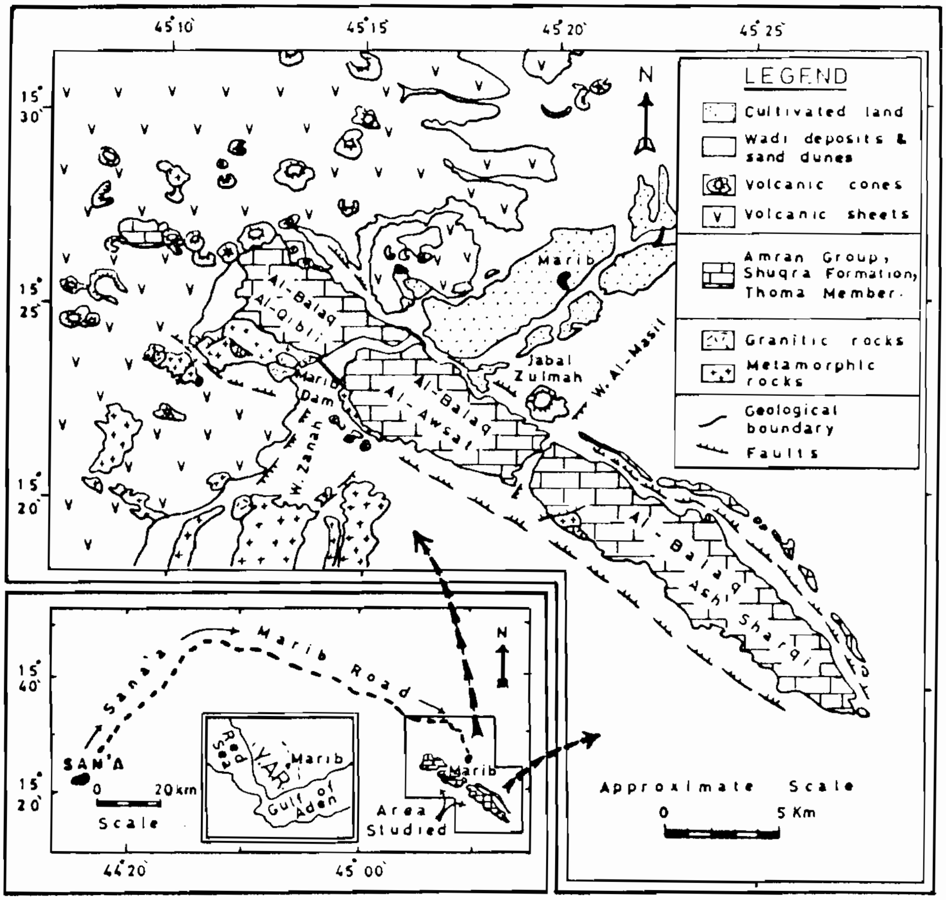


Fig. 1. Location and generalized photogeological map of Jabal Al-Balaq area, Marib, Y.A.R. (modified after Youssef *et al.* (1989)).

interrelation of the various depositional facies and diagenetic processes, and to discuss possible oil reservoir potentiality. The sedimentological evolution of the Amran sequence in Jabal Al-Balaq area is constructed based on lateral and vertical facies distribution combined with the regional geology of the Late-Jurassic sequence in the Arabian Peninsula.

Detailed sampling and field lithological examinations were carried out in eight stratigraphic sections through the various sectors of the Jabal Al-Balaq (Fig. 1). Petrographic investigations of 77 thin sections were carried out for some representative samples using the staining methods (Dickson 1965) and supported by X-ray diffraction (XRD) and scanning electron microscopy (SEM) techniques. The XRD was performed on a Philips Norelco diffractometer operated at 1° 2θ/min, Ni-filtered Cu $K\alpha$-radiation generated at 36 kV and 20 mA. The SEM was carried out on a Jeol 35SM, using gold-palladium alloy-coated samples.

REGIONAL AND FIELD STUDIES

Regionally, the Jurassic sediments are almost identical in facies on both sides of the Gulf of Aden and adjacent areas in the Arabian Peninsula. The Upper Jurassic beds are found in Somalia and Ethiopia with facies identical to those of central Arabia. This similarity is explained by the link across the Yemen between the seas covering the Arabian Peninsula and East Africa (Abdallah *et al.* 1963; Saint-Marc 1978).

The Upper Jurassic Amran sequence "series" in Y.A.R. is considered to be of Malm-Dogger age (Lamare *et al.* 1930; Geukens 1966). Grolier & Overstreet (1978) and Grolier *et al.* (1981) described the Amran Series to be composed of limestone, marl and shale, overlain by gypsum, clay, marl, shale and sandstone and underlain by the clastics of the Kohlan Series (Group) which is considered in part as Triassic in age. Abou Khadrah (1982) introduced the name "Amran Limestone" to the Middle-Late Jurassic calcareous succession. El-Anbaawy (1984) discussed the sedimentological evolution of the Amran succession in Y.A.R. He gave the Amran "Group" status and subdivided this "Group" into four distinctive formations: the Shuqra, Sabatain/Madbi, Jabal Salab and Wadi Al-Ahjur Formations. The Shuqra Formation has been further subdivided into two members: the Wadi Naham and Thoma Members.

The Shuqra Formation in Y.A.R. is equivalent partially to the Tuwaiq Limestone and probably also to the Hanifa and Jubaila Formations in central Arabia and to Behin Formation in Somalia (Table 1).

The Jabal Al-Balaq area (Fig. 1) includes Precambrian basement rocks, the Jurassic Amran Group, Quaternary volcanics and Quaternary deposits. The Amran Group in the Jabal Al-Balaq area is represented by the upper member of the Shuqra Formation which was referred to as Thoma Member by El-Anbaawy (1984). This comprises a shallow marine carbonate-clastic sequence 498 m thick. Youssef *et al.* (1989) subdivided the Thoma Member into five lithologic units arranged from base to top as follows (Fig. 2):

(1) Sandy limestone unit (110 m thick).
(2) Fossiliferous limestone unit (80 m thick).
(3) Marly laminated limestone unit (190 m thick).
(4) Chalky limestone unit (60 m thick).
(5) Stromatolitic limestone unit (58 m thick).

The basal sandy limestone unit nonconformably overlies the basement, and is made up of a dark grey to yellow sandy oolitic limestone intercalated with argillaceous and bioclastic sandstone with conglomeratic horizons. The fossiliferous limestone unit conformably overlies the sandy limestone unit and underlies the marly laminated limestone unit. This is hard, compact stylolitic oolitic-limestone interbedded with skeletal coral limestone. The marly laminated limestone unit is composed of dark grey to white and highly fractured limestone intercalated with fine sandy marl and occasionally associated with few thin fossiliferous interbeds. This conformably underlies the chalky limestone unit which is earthy brown in colour and highly rich in fossils. The stromatolitic limestone unit at the topmost part of the section is composed of biohermal stromatolitic limestone with coral and algal mounds.

Table 1. Correlation chart of the Jurassic formations of the Arabian Peninsula and Somalia.

Age	Central Arabia	Qatar	Oman		P.D.R.Y (Beydoun 1966)		Y.A.R. (Beydoun 1966)	Y.A.R. (El-Anbaawy 1984)			Somalia (Nagati 1986)
	Saint-Marc (1978)										
Berriasian M. Tithanian	Sulay Fm.	Sulay Fm.	h g	Upper Musandam Lst.	Amran Group	Naifa Fm.		W. Al-Ahjur Fm. Jabal Salab Fm.			Gawan Fm.
not dated ? Upper & Middle Kimmeridgian	Hith Fm. Arab Fm.	Hith Fm. Qatar Fm.	?			Sabatain Fm. Madbi Fm.	Transition beds	Amran Group	Sabatain Fm.	Madbi Fm.	Daghani Fm. Wanderer Fm. Gahodleh Fm.
Lower Kimmeridgian	Jubaila Fm. Hanifa Fm.	Fahalil Fm. Darb Fm.	f	Lower Musandam Lst.		Shuqra Fm.	Amran Series Shuqra Fm.		Shuqra Fm.	Thoma Mb. W. Naham Mb.	Behin Fm.
Callovian-Oxfordian	Tuwayq Lst.	Diyab Fm.	d–e			?					
Bathonian Passing to L. Callovian at top	Dhruma Fm.	Araej Fm.	c		Kohlan Fm.		Kohlan series	Kohlan Group			Adigrat Fm.

Fm. = formation, Lst. = limestone, Mb. = member, P.D.R.Y. = Peoples' Democratic Republic of Yemen.

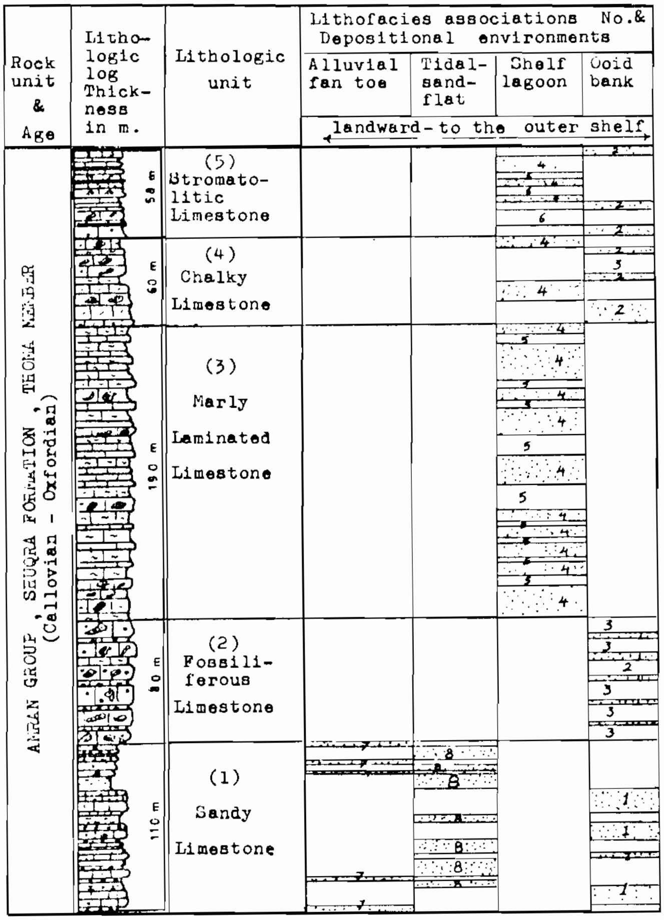


Fig. 2. Distribution of lithofacies associations and depositional environments within the lithologic units of Jabal Al-Balaq sequence.

DEPOSITIONAL ENVIRONMENTS AND FACIES

The present study reveals the identification of eight different lithofacies associations including: (1) Oolitic grainstone, (2) Oncolitic packstone, (3) Skeletal packstone, (4) Pelletoidal wackestone, (5) Sandy mudstone, (6) Algal stromatolite (boundstone), (7) Conglomerate, and (8) Sandstone.

The carbonate lithofacies associations resulted from different environments of deposition; their major characteristics correspond fairly closely to those reported in the platform carbonates, many of which were summarized by Bathurst (1975), Wilson (1975), Dahanayake (1977), Flügel (1982), Tucker (1984) and Mack & James (1986). On the basis of these studies, the pattern of the lithofacies distribution within the depositional environments suggests the distinction of three megafacies (Fig. 3). Their main characteristics are briefly discussed as follows:

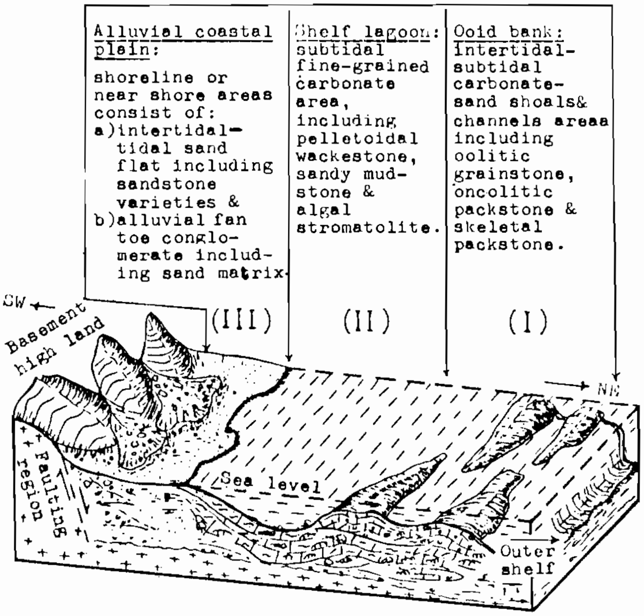


Fig. 3. Block diagram showing the depositional environments of Jabal Al-Balaq sediments and their facies characteristics.

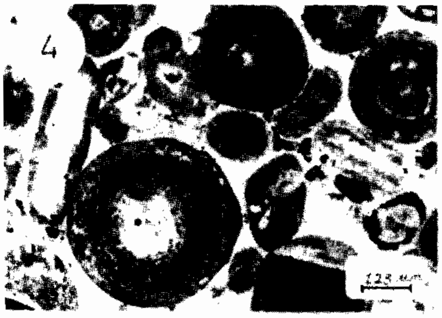
(I) OOID BANK MAGAFACIES

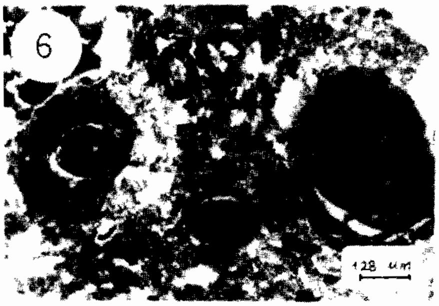
This megafacies originated in a shallow intertidal-subtidal carbonate sand shoals and channels area locally including reef-like bodies forming mobile barriers on a shelf or along the margin of a shallow platform (Fig. 3). This is characterized by regular alteration of thin beds of oolitic grainstone, oncolitic and skeletal packstone.

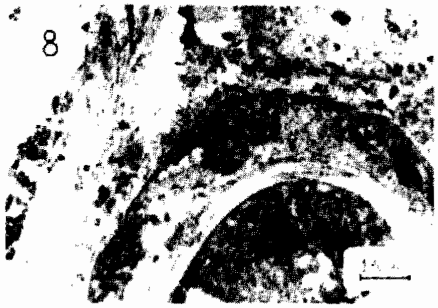
The oolitic grainstone is an oosparite essentially composed of ooids with few skeletal grains (e.g. fragments of corals and algae) and oncoids, cemented by microspar which in some parts grades into pseudospar partially filling the pore spaces. The ooids are mainly spherical-subspherical, moderately well sorted grains consisting of one or more regular tangential concentric micritized lamellae around a nucleus. However, some ooids have a radial fabric consisting of wedge-shaped fibrous crystals (Fig. 4). The majority of the ooids are simple but composite types are also observed (Fig. 5.)

The oncolitic packstone is an oncosparite (occasionally grainstone) consisting of oncoids and few peloids, bi-intraclasts or skeletal grains cemented by microspar-pseudospar or by blocky calcite. Most oncoids have concentric micritic lamination around some algal fragments forming rounded and subrounded grains (Fig.). The lamination is continuously or discontinuously developed around a nucleus of smaller oncoid or algal ball (Fig. 7).

The skeletal packstone is characterized by dark grey massive and dense appearance. In most cases it forms locally reefal limestone bodies. It is composed of skeletal organisms and subrounded interaclasts having variable sizes cemented by microsparry calcite. The skeletal grains are mainly represented by ostracods, gastro-







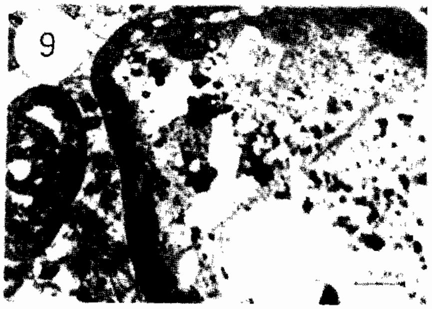


Fig. 4. Photomicrograph of oolitic grainstone showing spherical–subspherical ooids consisting of one or more regular tangential concentric micritized lamellae.

Fig. 5. Photomicrograph of oolitic grainstone showing composite ooids consisting of three nuclei with micrite lamellae.

Fig. 6. Photomicrograph of oncolitic packstone showing oncoids with micrite lamination around algal fragment forming rounded and subrounded grains.

Fig. 7. Photomicrograph of oncolitic packstone showing large oncoidal grains with continuous and discontinuous laminations.

Fig. 8. Photomicrograph of skeletal packstone showing curved and elongated calcite bivalves which invariably retain their internal structure.

Fig. 9. Photomicrograph of skeletal packstone showing drusy sparry calcite filling the voids of echinoid fragments.

pods, bivalves and echinoids. The internal structure of some bivalve shells is preserved; the calcite crystals are pseudopleochroic and lack a drusy fabric (Fig. 8) while the echinoid fragments are to a large extent preserved by drusy sparite, through solution of the original Mg-calcite (Fig. 9). However, minor amounts of Mg-calcite, dolomite and ankerite in addition to essential constituents of calcite have been detected by the X-ray diffraction analysis. The studies of skeletal material by Lippmann (1973) have demonstrated conclusively that Mg-carbonate occurs in solid solution with calcite while ankerite seems to be formed diagenetically after dolomite.

Much of the ooid bank megafacies developed in the shallowest turbulent waters on the platform where a series of mobile ooid shoals grew up (see Fig. 3). The depositional areas of the peloids, intraclasts and skeletal grains existed in less turbulent water around the migrating ooid shoals. The micritic lamination around some algal fragments as well as the presence of oncoids indicate relatively protected shallow subtidal areas within moderate-energy environment. The continuous lamination of oncoids suggests continued movement or agitated conditions which were nevertheless conducive to their growth in moderate-energy environment.

(II) SHELF LAGOON MEGAFACIES

This is a subtidal zone located behind the ooid bank barriers; it received carbonate muds (micrite), peloids and allochemical fragments. The rock types include pelletoidal wackestone, sandy mudstone and algal stromatolite (boundstone). The pelletoidal wackestone is mainly composed of micritic pellets (amorphous grains) in a matrix of micrite. The peloids are characterized by nearly spherical or ovoidal shaped grains with uniform size and homogeneous composition; occasionally some of them are welded together forming elongate and rod-like pellets (Fig. 10). The carbonate mud matrix is the original binding material showing some recrystallization to microspar and pseudospar. The sandy mudstone (micrite) lithofacies differs from the previous one in containing greater amount of equigranular floating quartz grains distributed in micritic (occasionally pelletoidal) massive groundmass (Fig. 11). The algal stromatolite (boundstone) is composed of binding algae, stromatoporid and coral colonies forming subspherical and columnar bioherms up to three meters high (Fig. 12).

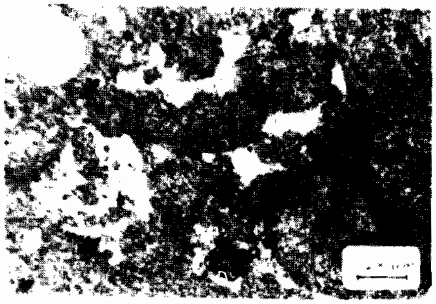
The most quiet part of the marine lagoon would have been sites for the deposition of micrite. The peloids are most common in the sediments of protected areas close to the carbonate sand shoals. The stromatolites were most probably formed in a quiet water lagoonal setting within current-swept channels behind the ooid shoals which were affected, at least intermittently, by currents. Some allochemes were probably brought in the lagoonal depositional basin by tidal and wave-generated currents or by streams. The repeated intercalation of pelletoidal wackestone and sandy mudstone beds (see Fig. 2) may indicate successive pulses of deposition of coarser sediments rich in quartz grains as a result of periodic fluvial flows.

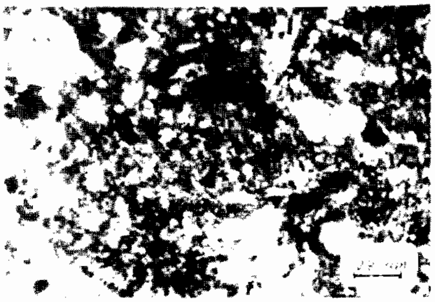
(III) ALLUVIAL COASTAL PLAIN MEGAFACIES

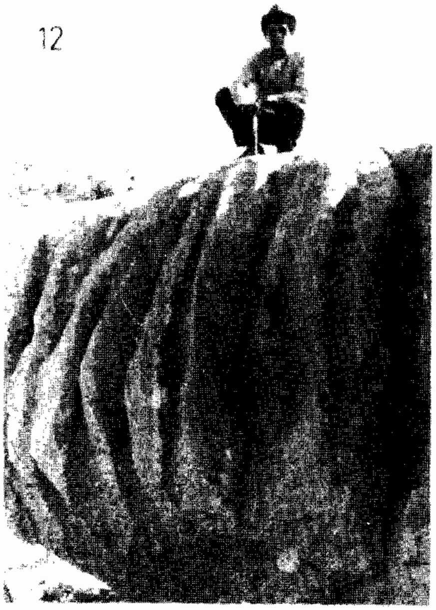
This is a shoreline or near-shore intertidal area consisting predominantly of two mixed-facies: (a) Tidal sand flat, and (b) Alluvial fan toe.

(a) *Tidal sand flat*

This consists mainly of clastic sediments ranging from coarse sandstone to argillaceous fine sandstone usually arranged in fining-upward sequences from 2 to 8 m thick. The sandstones are usually cross-bedded with all scales and types. However,







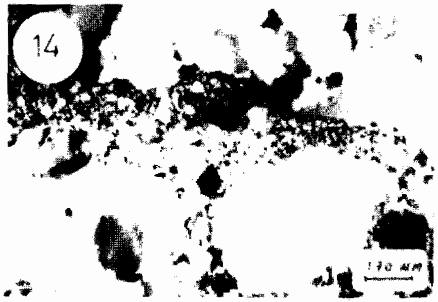


Fig. 10. Photomicrograph of pelletoidal wackestone showing nearly spherical grains of micrite in microspar (matrix).

Fig. 11. Photomicrograph of sandy mudstone (micrite) showing dense micritic calcite with small peloids and subangular quartz grains.

Fig. 12. Photograph of algal stromatolite (boundstone) showing heavily burrowed subspherical mounds composed of columnar bioherms.

Fig. 13. Photomicrograph of sandstone showing simple and composite quartz grains occasionally rimmed by fine mica matrix.

Fig. 14. Photomicrograph of conglomerate showing fine grained quartz matrix between quartz and chert pebbles.

the planar bedding with low angle and the herring-bone cross-bedding are most common. Some horizontally laminated beds with scours and channels or ripples are recorded.

Petrographically, there are three sandstone varieties within this facies, namely quartz arenite, bioclastic quartz arenite and argillaceous quartz arenite. They are almost mature to submature, moderately well-sorted sandstones composed of fine to coarse quartz grains mainly of a normal type with few feldspars, basement rock fragments and occasionally shell fragments cemented by very thin films of silica, ferruginous and mica-clayey materials (Fig. 13).

Most of the sequences assigned to this facies show many similarities to both modern and ancient siliciclastic prograding tidal flat sequences (see case histories of Ginsburg 1975). This is nearly similar to modern tidal flats along the margins of the North Sea (Evans 1965; Terwindt 1971; Van Beck & Koster 1972; Reineck 1972 & 1975) in that both display a landward decrease in grain size, which results in fining-upward progradational sequences.

(b) *Alluvial fan toe conglomerate*

The common sedimentary structures of this conglomerate facies are graded bedding and tabular cross-bedding with some syndepositional micro-faults. Petrographically, it is extraformational, matrix supported, polymicritic conglomerate. This is poorly sorted sandy conglomerate composed of subrounded to subangular quartzite pebbles in a matrix of fine grained quartz sand (Fig. 14).

Many features characterize this conglomerate facies which is assumed to be deposited from highlands (composed mainly of basement rocks) as debris (mass) flows. The facts supporting this suggestion are:

(1) Most of the conglomerates have sheet-like extensions.
(2) The conglomerate horizons lack significant basal erosion indicating deposition from alluvial fan sheet flood deposits.
(3) The matrix of these conglomerates consists mainly of sandstones and sandy mudstone of an unsorted character.
(4) Conglomerates are mainly disordered, but elongated fragments are often aligned approximately parallel to the flow surface indicating laminar flow.
(5) Sedimentary structures such as cross stratification which presumably result from more fluviatile processes are lacking. The restricted development of cross-bedded units is, however, not very persistent laterally, and these units usually taper over relatively short distances.

It is likely that this lowest conglomerate occurrence represents the distal part of an alluvial fan (fan toe sediments) because of: (1) The high sandstone/conglomerate ratio, where fluvial reworking in the upper reaches of a fan may account for an accumulation of sandstone in the distal regions (Steel 1974); and (2) the much smaller grain size (often granules), where the grain size usually decreases with distance from the apex of an alluvial fan (Bull 1972).

It is most probable that the sheet-like debris flows from which the conglomerates have been deposited reached to mean low tide level where the conglomerate horizons intercalated with thin massive sandstone or oolitic (fossiliferous) limestone beds.

From the above discussion it is concluded that the conglomerates were mainly deposited by debris flows. The stratification will hence be a product of repeated debris flows with low competence and low capacity. During certain periods there was a sufficiently high water/sediment ratio to create turbulent flows, resulting in reworking of previously deposited debris flow deposits and the deposition of other water-laid sediments, e.g. the sandstone intervals which were not deposited in tidal flat environment. It is likely that each conglomerate-sandstone interval within the sandy limestone unit in Jabal Al-Balaq represents the most distal parts of a large alluvial fan system where reworking by fluvial and tidal processes are common.

The apparent small-scale vertical fluctuations of the facies described in the Thoma Member (Fig. 2) most probably reflect the complex interfingering of the depositional environments within the lithologic units. This may be summarized as follows: (1) The sandy limestone unit consists mainly of shoal oolitic grainstone interbedded with tidal sand flats and alluvial fan toe conglomerate; (2) The fossiliferous limestone unit is characterized by the first appearance of the reefal skeletal packstone interbedded with intertidal-subtidal oolitic grainstone and oncolitic packstone of the ooid bank megafacies; (3) The marly laminated limestone unit consists of shelf lagoonal pelletoidal wackestone and sandy mudstone; (4) The chalky limestone unit consists of ooid bank interbedded with shelf lagoonal sediments; and (5) The stromatolitic limestone unit consists of lagoonal sediments that received coarse skeletal debris from the mobile ooid shoals.

DEPOSITIONAL CYCLES

The geometry of the depositional environments identified enabled the occurrence of relatively short-lived transgression-regression cycles of deposition to be recognized (Fig. 2). These cycles can be understood within the context of the depositional model (Fig. 3).

It is suggested here that the allocyclic variables were probably more important than the autocyclic variables as controls on the depositional cycles of the Jabal Al-Balaq section (Mack & James 1986) for the following reasons: (1) The regularities in the boundaries between facies zones of siliciclastics and carbonates could result in vertical facies changes dependent on outside variables; (2) The vertical facies changes involving three or more lithofacies, e.g. oncolitic packstone, pelletoidal wackestone and algal stromatolite (boundstone), are less likely to be autocyclic because of the significant change in the elevation and water depth implied by the facies changes; and (3) An autocyclic origin for deposition of the oolitic grainstone seems unlikely because of the exclusion of the intermediate lagoonal megafacies. The grainstone was deposited as an ooid bank above the sandy conglomerate, which itself originated in the alluvial coastal plain.

An absolute change in the sea level appears to be necessary to explain these cycles. The resultant depositional cycles are probably due to the tectonically-controlled sea level fluctuations where Jabal Al-Balaq depositional basin was an area of tectonic instability during the Late Jurassic time (El-Anbaawy 1984; Youssef *et al.* 1989). The tectonic history in the Late Jurassic time is well expressed in thickness and facies variations of these marine sediments.

DISCUSSION OF PALEOGEOGRAPHY

Regionally, it seems that during the Late Jurassic time the Tethys was a broad shallow sea depositing clastic limestones from the central Arabian Peninsula east to Iran and Oman and south across Yemen where it was in continuity with the East African Sea (Powers *et al.* 1966). The principal feature of the Jurassic was a transgression from the Tethys which began in Callovian times and reached its maximum during the Kimmeridgian (Abdallah *et al.* 1963). The transgression was more extensive in the east than in the west.

According to a tentative comparison with the general framework of the Arabian Peninsula, it seems that the transgressive facies of the uppermost Kohlan Group correspond to the transgressive facies of Late Jurassic age in the central Arabian Peninsula (Tuwayq Limestone, Table 1). There is, however, one difference for in the Yemen the transgression came from the south or southeast (Saint-Marc 1978). The uppermost Kohlan marine horizons appear to represent gradational passage to the Upper Jurassic Shuqra Formation. However, in the study area, on the basis of regional correlation and following the lithostratigraphic subdivision of El-Anbaawy (1984), these marine horizons are stratigraphically equivalent to the basal part of the Thoma Member which corresponds to the lowest lithologic unit of the Jabal Al-Balaq section.

El-Anbaawy (1984) concluded that a general subsidence of the Upper Jurassic basin floor in Y.A.R. seems to have been followed up by intermittent gentle tectonic uplift which consequently led to a continuous north and south repetitive gradual transgression and regression of the sea during the deposition of the Shuqra Formation.

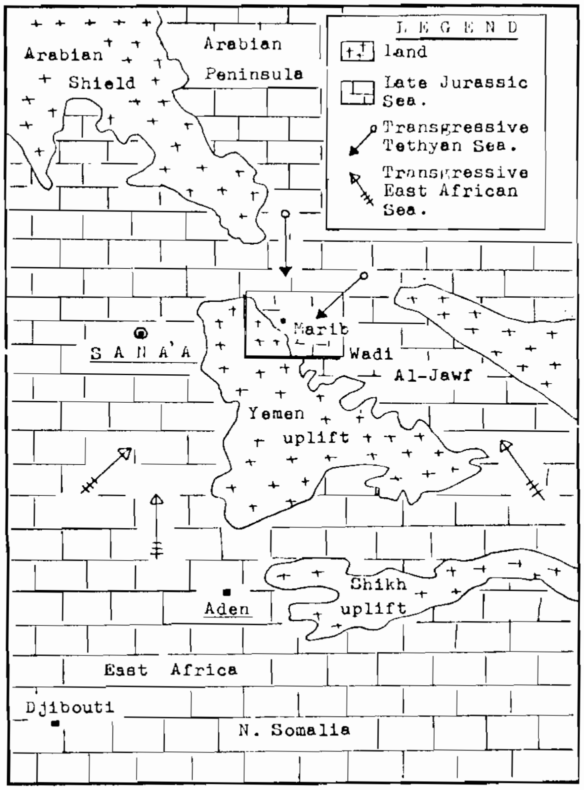


Fig. 15. Postulated reconstruction of paleogeography of Jabal Al-Balaq-Wadi Al-Jawf basin during the Late Jurassic time.

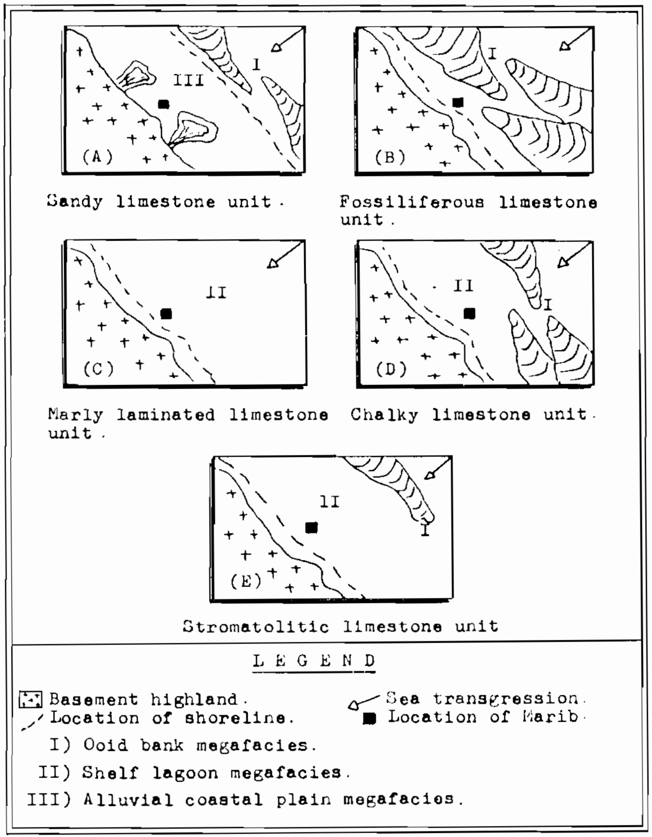


Fig. 16. Postulated sedimentological evolution of different lithologic units of Jabal Al-Balaq.

From the above discussion it is concluded that the Shuqra Formation in Y.A.R. represents the depositional connections which probably occurred north-northeastwards of Tethys across the Arabian plate and south-southwestwards of the East African Sea across the African plate (Fig. 15). It is suggested here that during the Callovian-Oxfordian interval the Thoma Member represents the first main transgression and was probably connected to Tethys from the northeast through the Wadi Al-Jawf basin (Fig. 15).

The appearance of the Thoma Member with its increasing coarse texture and clastic characters in a southwesterly direction suggests proximity to a highland and a shoreline in that direction (Fig. 16).

As previously mentioned, the lithologic units of the Thoma Member lie discordantly upon the basement rocks. This discordance is probably due either to non-deposition or erosion of both the older Kohlan Group and the Wadi Naham Member (the lower member of the Shuqra Formation). However, the former is more likely since the area did not receive the sediments of the Kohlan and Wadi Naham rock units as the basement blocks were high all the time during their deposition.

The absence of carbonate rock fragments from older sediments and the predominance of pebbles of basement composition in the basal conglomeratic horizon within the sandy limestone unit in the Jabal Al-Balaq may support the suggestion of this depositional break.

In summary the paleogeographic evolutionary steps can be briefly described as follows:

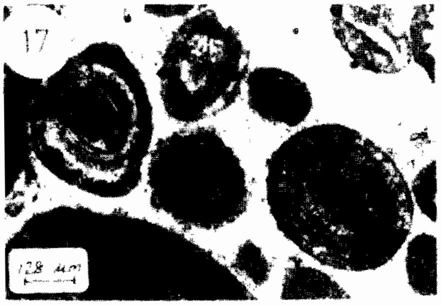
(1) After the termination of the orogenic phase, the uplifted and emergent basement rocks located to the southwest of the Jabal Al-Balaq area (Fig. 16) were subjected to deep weathering and intense erosion. The products of this erosion provided the material for the discordant clastic sediments of the sandy limestone unit (Fig. 16-A).
(2) Subsidence, and shallow and marginal shelf environments resulted in the deposition of the fossiliferous limestone unit (Fig. 16-B).
(3) As the sea level rises resulting in landward migration of depositional belts, the development of the deeper water facies of the marly laminated limestone unit took place (Fig. 16-C).
(4) The tectonically-controlled sea level fluctuations led to the deposition of the succeeding two units: the chalky limestone unit (Fig. 16-D) and the stromatolitic limestone unit (Fig. 16-E).
(5) By the end of the Jurassic, following uplift, the sea regressed and erosion of the younger Jurassic beds resulted.

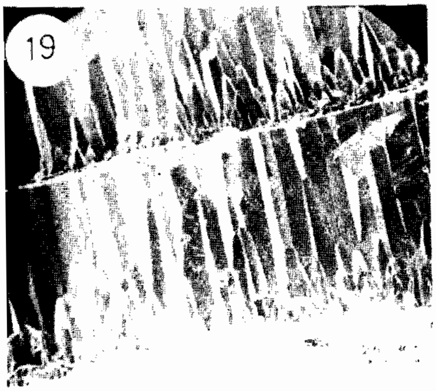
DIAGENETIC PROCESSES

The principal diagenetic processes affecting the sediments of Jabal Al-Balaq are cementation, neomorphism, compaction and pressure solution. Two types of calcite cement can be recognized in the carbonate sediments; the first is drusy calcite being perpendicular to the outer borders of oncoids or ooids (eosparry calcite) and the second type (neosparry calcite) is blocky and massive sparry calcite which represents a second phase of cementation filling the pore spaces between the first type (Fig. 17). Some parts of the lime mud show signs of aggrading neomorphism producing microspar and part of the occasionally present radial and concentric micritized lamellae of an ooid is obliterated (Fig. 18). Also, some oncoids are partially aggraded and their algal micrite envelope is converted to microspar and pseudospar (see Fig. 6) by the action of percolating fresh water in subaerial environment (Friedman 1969) resulting in a mottling appearance of the rock. Folk (1974) maintains that neomorphism of lime mud to microspar and pseudospar is probably related to loss in Mg^{++} ion either by the influence of low-Mg fresh water or the seizure of Mg^{++} by clay minerals.

Some authigenic clay minerals are developed upon the fibrous calcite cementation which in turn authigenically developed particularly in large cavities in coral and algal mounds (Figs 19 & 20). The X-ray diffraction analysis proved that these clay minerals are mainly mixed-layer illite/smectite, degraded illite and kaolinite.

The compaction processes are represented by flattened ooid grains and their concave-convex contacts (Fig. 21). The observation that some fractures (or microstylolitic contacts) affect the microspar matrix (or cement) indicates that the compaction followed the neomorphism and cementation of the carbonates. Some of





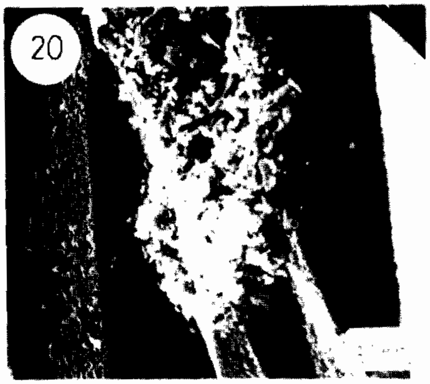


Fig. 17. Photomicrograph of oolitic grainstone showing drusy calcite perpendicular to the outer border of ooids or oncoids, and blocky and massive sparry calcite filling the pore spaces.

Fig. 18. Photomicrograph of sandy mudstone showing an individual ooid with radial fabric floating in microspar groundmass including voids and fenestral vugs.

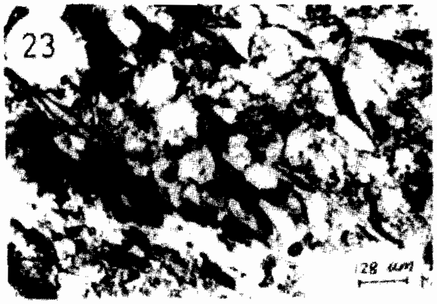
Fig. 19 & 20. Scanning electron micrographs showing authigenic calcite crystals developing perpendicular to the cavity wall, with some authigenic clay minerals.

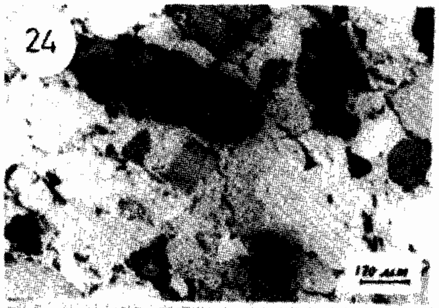
Fig. 21. Photomicrograph of oolitic grainstone showing flattened ooid and oncoid grains with concave-convex and sutured contacts.

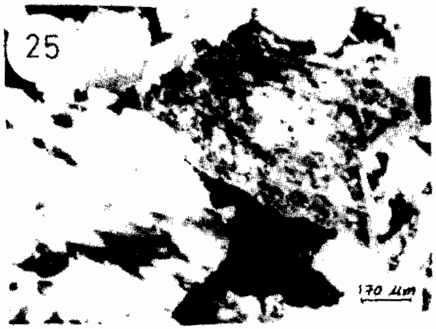
Fig. 22. Photomicrograph of pelletoidal wackestone showing algal grains and pellets dissected by fractures (or microstylolite).

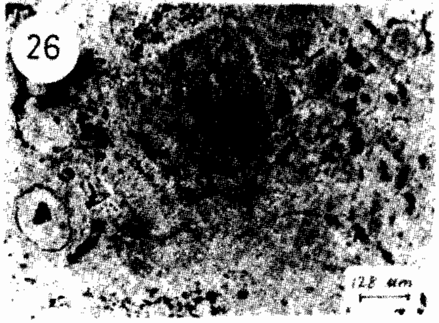
these fractures are filled with sparry calcite (Fig. 22) suggesting that the calcium carbonate which has been dissolved due to pressure solution could be the source for the late stage of calcite cementation (Youssef & El-Anbaawy 1989).

The compaction and pressure-solution processes are more effective than cementation in the siliciclastics of the Jabal Al-Balaq. The early stage of compaction









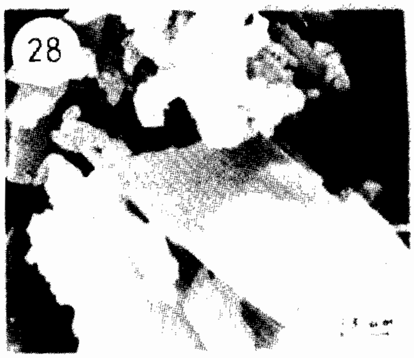


Fig. 23. Photomicrograph of sandstone showing subangular to angular quartz grains with muscovite flakes exhibiting preferred orientation. Some of these flakes show gentle bending through compaction.

Fig. 24. Photomicrograph of sandstone showing concave-convex and sutured contacts of quartz grains.

Fig. 25. Photomicrograph of conglomerate showing relatively moderate sorting and high porosity (the black spots represent the pore spaces).

Fig. 26. Photomicrograph of oncolitic packstone showing relatively high porosity (the black spots and patches represent pore spaces, some of which are stained with iron oxides).

Fig. 27. Scanning electron micrograph showing authigenic clays developed on calcite crystal. The clay minerals exhibit a delicate and fragile nature and partially reduce porosity.

Fig. 28. Scanning electron micrograph showing authigenic kaolinite pore fillings.

involves dewatering and closer packing of grains (Fig. 13). Occasionally, further compaction through excessive pressure results in local fracturing and deformation (bending) of the flexible mica flakes (Fig. 23).

The pressure-solution at the quartz grain contacts took place representing a further stage of compaction through excessive pressure and resulted in concave-convex and straight contacts (Fig. 24). The presence of the early iron oxide cementation of the argillaceous quartz-arenite variety (Fig. 23) inhibited the quartz pressure-solution effects and further quartz overgrowths. In this case, the pressure-solution can take place, producing stylolite (microstylolite) or crosscut grains (Fig. 23). This iron oxide cementation was precipitated immediately after deposition of the quartz grains depending on the pH and the primary porosity of the sediments. This early iron oxide cementation is widely distributed through bedding planes, cross-laminae and ripples.

It is suggested that the pressure-solution is probably important as a source of silica. The pressure-solution arising at contact points of detrital grains increases the relative solubility of the quartz grains. The silica thus released is transferred to points of lower pressure where it crystallized in optical continuity with the host grains (Fig. 24).

It is evident that most of the clay minerals surrounding the detrital grains as cement material or clay rim, are considered authigenic in origin due to their coarse grain, well developed crystalline structure and delicate fragile fibrous appearance (Fig. 13). These clay minerals are mainly mica clays as revealed by the X-ray diffraction analysis. The clay cementation is considered partially, as phyllomorphic change (Dapples 1967). However, the precipitation of clay rims is usually an early diagenetic event, often predating the quartz overgrowths (Tucker 1984).

HYDROCARBON POTENTIAL

OIL DISCOVERY IN WADI AL-JAWF-MARIB BASIN

The discovery of major oil reserves in Y.A.R. in 1984 has revived the oil exploration industry and renewed interest in the Jurassic Wadi Al-Jawf-Marib basin where the structural and facies characteristics are suitable for the generation of hydrocarbons.

To the east of Marib several salt plugs, dated as ?Tithanian (Nagati 1986), are considered as the seal to the reservoir of the oil field (called Alef field) in Wadi Al-Jawf basin. The Alef field is approximately 40 km ENE of Marib. Industry and government sources of Y.A.R. estimate the recoverable reserves in Alef field to be 400–500 million barrels of oil. This field produces from Cretaceous and Jurassic Formations, the same formations that produce so abundantly along the Arabian Gulf in Abu Dhabi, Dubai and Oman. The producing zone (about 1500–1800 m deep in Alef field) has 20–24 percent porosity and permeability of one to 10 darcies. Deltaic or near-shore sandstone of the topmost Jurassic Amran sequence is believed to be the main reservoir in the Alef field. This fluviomarine sandstone facies is most probably equivalent to the topmost formation of the Amran Group referred to by El-Anbaawy (1984) as Wadi Al-Ahjur Formation (? latest Jurassic–Early Cretaceous).

Although insufficient subsurface data are available on the Wadi Al-Jawf-Marib basin, it is still possible to postulate that the basin should contain approximately 1200 m of sediments at the location of the Alef field (Nagati 1986), where Well Alef No. 1 reached granite at 4180 m. Therefore, the study of the reservoir potential of the southwestern sedimentary exposures of the Wadi Al-Jawf-Marib basin (which includes Jabal Al-Balaq) is important from the oil economics point of view.

FACTORS CONTROLLING RESERVOIR POTENTIAL OF JABAL AL-BALAQ

Both depositional and postdepositional (diagenetic) factors are important in studying the reservoir potential of the Late Jurassic Thoma Member from Jabal Al-Balaq. It was found that grain size distribution, sorting, and sedimentary structure which are functions of the depositional environment may all affect porosity and permeability properties and consequently the reservoir potential of the given sediments. More or less similar conclusions were reached by Trevena & Clark (1986), namely that the coarse grained and relatively better sorted conglomerates generally have higher porosity and permeability (Fig. 25) than finer grained sandstones (Fig. 24).

Primary porosity, and often the secondary too, are commonly facies-controlled. The reefal carbonates have high primary porosity, while the lagoonal micrites have low porosity, unless affected by the diagenetic-tectonic processes leading to porosity development. However, the alluvial fan toe conglomerate (Fig. 25) as well as the carbonate sand shoal with barrier-like reefs and the oncolitic packstone (Fig. 26) generally have relatively high porosities. On the other hand, the shelf lagoon wackestone and mudstone may be considered as good oil and gas sources where they are closely associated with organic-rich muds (Fig. 18) to act as source rocks and seals. On the other hand, the compaction process produces changes in the packing of the framework grains with a corresponding loss of primary porosity and permeability. With increasing compaction the grain contacts become concave-convex and sutured (Figs 21 & 24) while the ductile and labile grains (e.g. mica flakes) are plastically deformed (see Fig. 23) producing pseudomatrix material and reducing the reservoir properties.

Cementation is the principal process of porosity loss in the siliciclastics studied where quartz grains come in contact with one another through their overgrowth, forming patches of interlocking aggregates of anhedral grains (Fig. 24). The clay minerals (mainly anthigenic kaolinite) are of particular importance in partially reducing the original porosity where these occur as pore-lining (Fig. 27) or pore filling (Fig. 28).

Secondary porosity is a common diagenetic feature in the carbonates of the Jabal Al-Balaq. Some voids and fenestral vugs in the micrite were observed (Figs 18 & 26). The irregular fenestral vugs indicate the effect of supratidal environment during lithification of sediments (Shinn 1983). Accordingly, the best reservoir of the siliciclastic sediments of Jabal Al-Balaq is the coarse grained sandstone and conglomerate. On the other hand, the oncolitic packstone followed by the algal stromatolite prove to be the best reservoir carbonate rocks.

SUMMARY AND CONCLUSIONS

Field and petrographic studies of the Thoma Member (Shuqra Formation, Amran Group) in Jabal Al-Balaq led to the identification of eight lithofacies associations and three depositional megafacies distributed within the lithologic units (Table 2). During the Callovian-Oxfordian the Thoma Member which lies discordantly upon the basement rocks, indicating a depositional break, represents the first marine transgression in Jabal Al-Balaq area, most probably connected to the Tethys to the northeast through the Wadi Al-Jawf basin. The basement blocks located to the

Table 2. Distribution of the lithofacies associations within the lithologic units of Jabel Al-Balaq

Depositional megafacies	Name and number of lithofacies associations	Lithologic units: Sandy limestone	Fossiliferous limestone	Marly laminated limestone	Chalky limestone	Stromatolitic limestone
	Carbonates					
Ooid bank	(1) Oolitic grainstone	*	*	—	—	—
	(2) Oncolitic packstone	—	*	—	*	*
	(3) Skeletal packstone	—	*	—	*	—
Shelf-lagoon	(4) Pelletoidal wackestone	—	—	*	*	*
	(5) Sandy mudstone	—	—	*	—	—
	(6) Algal stromatolite (boundstone)	—	—	—	—	*
	Siliciclastics					
Alluvial coastal plain	(7) Conglomerate	*	—	—	—	—
	(8) Sandstone	*	—	—	—	—

(—) = not represented; (*) represented.

southwest, act as source area providing material for the siliciclastic sediments. The relatively short-lived transgression–regression depositional cycles resulted from tectonically-controlled sea level fluctuations which led to the deposition of the platform carbonates of the various lithologic units.

The facies factors are important for studying the hydrocarbon potential as indicated from the following: (1) The coarse grained and relatively better sorted alluvial coastal plain sandstone and conglomerate generally have higher porosity and permeability than the finer grained ones; (2) The reefal and ooid shoal limestones have higher primary porosity than the shelf lagoonal mudstones and wackestones; and (3) The organic rich carbonate mud may be considered to have good oil and gas source potential.

The conjunction of both petrographic and scanning electron microscopic studies led to the identification of several post-depositional (diagenetic) processes such as compaction, pressure solution, cementation and neomorphism. The occurrence of fractures (or the microstylolitic contact) in the microspar matrix (or cement) of the carbonates indicates that compaction followed neomorphism and cementation. The most common diagenetic events within the siliciclastics can be arranged according to their order of formation as follows: (1) iron oxide cementation, (2) authigenic growth of mica clays, (3) generation of pressure solution, and (4) generation of quartz overgrowths.

Compaction and cementation are the most important diagenetic processes leading to the reduction of the original porosity and permeability and consequently affecting reservoir quality. The secondary porosity represented by voids and fenestral vugs in the carbonate mud rocks produced by dissolution of carbonate grains obviously improves the reservoir characteristics.

The best reservoir of the siliciclastic sediments is the coarse grained sandstone and also the conglomerate. The oncolitic packstone followed by algal stromatolite constitute the best carbonate reservoir.

REFERENCES

Abdallah, A.M., El-Addanani, A. & Fahmy, N. 1963. Stratigraphy of the Lower Mesozoic rocks, western side of the Gulf of Suez, Egypt. Geological Survey and Mineral Resources Department, Cairo, Paper 27, 23 pp.

Abou-Khadrah, A.M. 1982. A review of the sedimentological evolution of Yemen Arab Republic. Faculty of Science Bulletin, Sana'a University **2**: 39–55.

Bathurst, R.G.C. 1975. Carbonate sediments and their diagenesis. Elsevier, Amsterdam, 658 pp.

Bull, W.B. 1972. Recognition of alluvial fan deposits in the stratigraphic record. In: **Rigby, J.K. & Hambin, W.K. (Eds).** Recognition of ancient sedimentary environment. Society for Economists, Paleontologists and Mineralogists Special Publication **16**: 63–83.

Dahanayake, K. 1977. Classification of oncoids from the Upper Jurassic carbonates of the French Jura. Sedimentary Geology **18**: 337–53.

Dapples, E.C. 1967. Diagenesis of sandstones. In: **Larsen, G. & Chilingar, G.V. (Eds).** Diagenesis in sediments. Developments in Sedimentology **8**: 91–126.

Dickson, J.A.D. 1965. A modified staining technique for carbonate in thin section. Nature **205**: 287.

El-Anbaawy, M.I. 1984. Contribution to the lithostratigraphic subdivisions of the Amran sequence in the Y.A.R. Faculty of Science Bulletin, Sana'a University **4**: 65–84.

Evans, G. 1965. Intertidal flat sediments and their environments of deposition in the Wash. Journal of the Geological Society, London **121**: 209–45.

Flügel, E. 1982. Microfacies analysis of limestone. Springer, Berlin, 633 pp.

Folk, R.L. 1974. Petrology of sedimentary rocks. Hemphill, Austin, Texas, 159 pp.

Friedman, G.M. 1969. Depositional environment in carbonate rocks. Special Publication in Sedimentary Petrology **35**: 643–55.

Geukens, F. 1966. Geology of the Arabian Peninsula (Yemen). Geological Survey Professional Paper 560-H, United States Government Printing Office, Washington, 23 pp.

Ginsburg, R.N. 1975. Tidal deposits. Springer, New York, 428 pp.

Grolier, M.G. & Overstreet, W.C. 1978. Geologic map of the Yemen Arab Republic. United States Geological Survey, Miscellaneous Geological Investigations Series Map 1-1143-B.

Grolier, M.G., Tibbitts, G.C. & Ibrahim, M.M. 1981. A qualitative appraisal of the hydrology of the Yemen Arab Republic. Geological Survey Open File Report 80-565, U.S. Reston, Virginia, U.S.A.

Lamare, P., Basse, E., Maurice, L., Teilhard de Chardin, P. 1930. Études géologique en Ethiopie, Somalie, et Arabie meridionale. Société Géologique de France, New Series **6**: 1–83.

Lippmann, F. 1973. Sedimentary carbonate minerals. Springer, Berlin.

Mack, G.H. & James, W.C. 1986. Cyclic sedimentation in the mixed siliciclastic–carbonate Abo-Hueco transitional zone (Lower Permian), southwestern New Mexico. Journal of Sedimentary Petrology **58**: 635–47.

Nagati, M. 1986. Possible Mesozoic rifts in Upper Egypt, an anology with the geology of Yemen–Somalia Rift Basins. Eighth Exploration Seminar, The Egyptian General Petroleum Company, Cairo.

Powers, R.W., Ramirez, L.F., Redmond, C.D. & Elberg, J.E.L. 1966. Geology of the Arabian Peninsula (Sedimentary geology of Saudi Arabia). Geological Survey Professional Paper 560-D, US Government Printing Office, Washington: 1–147.

Reineck, H.E. 1972. Tidal-flats. Society for Economists, Paleontologists and Mineralogists Special Publication **16**: 146–59.

Reineck, H.E. 1975. German North Sea tidal flats. In: **Ginsburg, R.N. (Ed.).** Tidal deposits, pp. 5–12. Springer, Berlin.

Saint-Marc, P. 1978. Arabian Peninsula. In: **Moullade, M. & Nairn, A.E.M. (Eds).** The Phanerozoic geology of the world, No. 2. The Mesozoic, A, pp. 434–62. Elsevier, Amsterdam.

Shinn, E.A. 1983. Birdseges, fenestrae, shrinkage pores and loferites: a re-evaluation. Journal of Sedimentary Petrology **52**(2): 619–28.

Steel, R.J. 1974. New red standstone floodplain and piedmont sedimentation in the Hebridean Province, Scotland. Journal of Sedimentary Petrology **44**(2): 336–57.

Terwindt, J.H.J. 1971. Litho-facies of inshore, estuarine and tidal inlet deposits. Geological Mijnbouw **50**: 515–26.

Trevena, A.S. & Clark, R.A. 1986. Diagenesis of the sandstone reservoir of the Pattani Basin, Gulf of Thailand. American Association of Petroleum Geologists **3**: 299–308.

Tucker, M.E. 1984. Sedimentary petrology, an introduction. Blackwell, Oxford, 252 pp.

Van Beck, J.L. & Koster, E.A. 1972. Fluvial and estuarine sediments exposed along the Oude Maas (the Netherlands). Sedimentology **19**: 237–56.

Wilson, J.L. 1975. Carbonate facies in geologic history. Springer, Berlin, 471 pp.

Youssef, S.A.A. & El-Anbaawy, M.I. 1989. Petrography and diagenesis of some Jurassic oncolitic limestone in Y.A.R. Arab Gulf Journal for Scientific Research, Riyadh (in press).

Youssef, M.M., El-Anbaawy, M.I. & Al-Thour, K.A.A. 1989. Geology of Jabal Al-Balaq-Marib area. Faculty of Science Bulletin, Sana'a University **7**.

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التطور الترسيبي وعمليات ما بعد الترسيب والاحتمالات البترولية لكربونات الجوراسي المتأخر في المنطقة الشرقية للجمهورية العربية اليمنية

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خلاصة

أدت الدراسات الحقلية والپتروجرافية لصخور « عضو ثوما » التابع « لمجموعة عمران » بمنطقة جبل البلق ـ مأرب إلى التعرف على ثلاث مناطق ترسيبية عامة ، مرتبة حسب بعدها عن اليابسة كما يأتي :

١ ـ منطقة الشعاب البطروخية الضحلة : وهي منطقة حواجز شبه مرجانية قريبة من البحر المفتوح وبعيدة نسبيا عن اليابسة ، وتشمل مناطق ضحلة هائجة متاخمة لحافة الرصيف القاري ، وتتميز بانتشار صخور الپاكستون الهيكلي وصخور الستروماتوليت الطحلبي والجرانستون البطروخي والپاكستون الأنكوليتي .

٢ ـ منطقة البحيرات الجرفية : وهي منطقة بحيرات بينية تتكون خلف الحواجز الشعابية البطروخية وتنتشر بينها ، وهي عميقة نسبيا ، وحركة المياه فيها هادئة بوجه عام تتخللها فترات هائجة ، وتتميز بانتشار صخور الواكستون الحبيبي وصخور الطمي الجيري الرملي .

٣ ـ منطقة السهول الساحلية الغرينية : وهي منطقة مختلطة البيئات تشتمل على رواسب رملية ذات تطابق كاذب ترسبت في منطقة مد وجزر ساحلية متداخلة مع رواسب كونجلومرات نهرية منبسطة على أطراف مراوح غرينية منحدرة من مناطق صخور القاعدة المرتفعة على حافة حوض الترسيب .

ويعزى التداخل والتنوع في بيئات الترسيب المحلية والتذبذب الدوري لأنواع سحنات رواسب « عضو ثوما » في منطقة جبل البلق إلى تذبذب قاع حوض الترسيب ارتفاعا وانخفاضا في تلك المنطقة نتيجة لعدم الاستقرار التكتوني أثناء الترسيب .

وقد أسفرت الدراسات التي استخدم فيها المجهر البتروجرافي والمجهر الالكتروني الماسح عن العديد من النتائج أهمها أن رواسب الحجر الرملي كبيرة الحجم المصاحبة للكونجلومرات لها درجة مسامية ونفاذية أعلى من رواسب الحجر الرملي الطينية الأقل حجما ، وأن رواسب الحجر الجيري الشعابية البطروخية لها درجة مسامية أعلى من الرواسب الجيرية الطينية والواكستون التي ترسبت في بيئات بحيرية جرفية ، وأن الرواسب الجيرية الغنية بالمواد العضوية مثل الپاكستون الحبيبي والحجر الجيري الطيني المنتشرة في وحدة الحجر الجيري المارلي تعتبر من الرواسب المناسبة لتكوين صخور مصدر للمواد البترولية .

وقد تبين أن من أهم العمليات الطارئة التي أثرت على الرواسب بعد تكونها عمليات التضاغط والتلاصق في الصخور الكربوناتية ، وعمليات التلاصق بأكاسيد الحديد ونمو معادن الطين في الفراغات البينية ، وعمليات التضاغط والإذابة ، ونمو طبقات من السيليكا حول حبيبات الكوارتز . كما وجد أن هذه العمليات من أهم العوامل التي تؤثر في درجة نفاذية ومسامية الرواسب المدروسة ، وبالتالي في نوعية صخور الخزانات البترولية المحتمل تواجدها في الصخور المقابلة تحت السطح .

هذا وتعتبر صفات المسامية والنفاذية لصخور الپاكستون الأونكوليتي ، تليها (في الأهمية) صخور البوندستون الستروماتوليتي الطحلبي ، من أحسن الصفات التي تناسب تكوّن صخور خزانات البترول .