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Lithofacies Attributes of a Transgressive Carbonate System : The Middle Eocence Seeb Formation, Al Khoud Area, Muscat, Oman.

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خصائص ومميزات السحنات الصخرية في فترة طغيان البحر : دراسة تكوين السيب في منطقة الخوض بسلطنة عمان كمثال لهذا النظام الكربوناتي

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خلاصة: تبلغ سماكة تكوين السيب حوالي 600م، و الذي تكوّن في عهد الإيوسين الأوسط أثناء فترة طغيان البحر، حيث ترسبت هذه السحنات الصخرية الجيرية على الإمتداد الساحلي لمنطقة الباطنة و محافظة مسقط. يتالف تكوين السيب من خمس وحدات متراصة تمثل بنية تراكمية للسحنات الجيرية المترسبة في المياه البحرية الضحلة من الجرف القاري. تتميز هذه الطبقات بإحتوائها على ترسبات تمثل إزدياداً مطرداً في عمق المياه مع الطبقات الاقل عمرا، بمعنى ان الطبقات الأقدم تكونت في مياه ضحلة جدًا بينما الاحدث ترسبت في مياه أعمق. *الوحدة الاولى* وهي الأقدم تمثل تراكمات يكثر فيها التقاطع الطبقي و تتكون من طبقات جيرية غنية بالاحافير و قليلة النسيج الطيني (packstones) او منعدم تماما (grainstones) مما يوحي ان هذه الوحدة تكونت في بيئة شاطئية ذات طاقة هيدروليكية عالية بسبب حركات المد والجزر. *الوحدة الثانية* تتكون من طبقات غير متمايزة تكثر فيها المنخربات الكبيرة و العقد الكلسية و تحتوي على النسيج الطيني بدرجات متفاوتة دالة على ترسيب في بيئة الخيران ذات طاقة هيدروليكية متوسطة. *الوحدة الثالثة* تتكون من طبقات جيرية ذات سماكة متوسطة الى كبيرة و هي غنية بالاحافير و قليلة النسيج الطيني (packstones) او منعدم تماما (grainstones) و توجد بهذه الوحدة عدسات من الكونجلومرات محصورة أفقيا في نطاقات معينة. و يكثر فيها التقاطع الطبقي و البنيات الرسوبية المقعرة و المحدبة (hummocky and swaley cross-stratificiation) مما يدل دلالة قاطعة على انها تكونت في الاجزاء الضحلة من الجرف القاري والذي كانت تعتريه فترات تمتاز بشدة الاعاصير. أما *الوحدة الرابعة* فهي شبيهة بالوحدة الثانية من حيث السحنة الا انها ترسبت في نطاق أعمق من الجرف القاري. و اخيرا *الوحدة الخامسة* فهي عبارة عن سحنات جيرية يغلب عليها النسيج الطيني وبها نسبة قليلة من المنخربات مع وجود كميات من حبيبات الكورتزمما يعطي مؤشرا على زيادة كبيرة في عمق مياه الجرف القاري. إن تتابع الوحدات الأنفة الذكر بالطريقة المذكورة أعلاه يؤكد أن ترسيب تكوين السيب بدأ من بيئة شاطئية ضحلة إلى مناطق عميقة في الجرف القاري في فترة طغيان البحر.

ABSTRACT: The Seeb Formation (Middle Eocene) is an about 600 m thick transgressive carbonate succession deposited in the Batina and Muscat coastal region of Oman. The formation consists of five informal, but distinct units, and their stacking architecture suggests a deepening-upward, shallow marine depositional setting. Unit I is characterized by cross-bedded, sandy, bioclastic packstones to grainstones deposited in a high energy beach-tointertidal environment. Unit II consists of indistinctly bedded, nodular, bioclastic (mainly larger foraminifera) packstones and wackestones deposited in a lagoonal environment. Unit III is defined by medium to thickly bedded, bioclastic packstones to grainstones and subordinate, laterally confined conglomerates. Prominent sedimentary structures in Unit III include hummocky and swaly cross-stratificiation, erosional surfaces, dewatering-induced deformations and laterally amalgamating beds. This unit represents sub-tidal sand shoals deposited in a storm-dominated shelf (between the fair-weather wave-base and storm-base). Unit IV is extensively burrowed, nodular, bioclastic wackestone to rudstone which is similar to Unit II in many aspects. Unit IV was deposited on the basinward side of the Unit III sand shoals below the reach of the storm-generated waves and currents. The uppermost Unit V is characterized by poorly-cemented bioclastic (large foraminiferal) rudstones with clay and silt-size quartz matrix. Bioclasts are generally intact with no apparent reworking. Deposition of Unit V is also envisaged as a low-energy, outershelf environment.

KEYWORDS: Seeb formation, Middle eocene, Carbonate platform, Muscat and Lithofacies.

1. Introduction

The Seeb Formation belongs to the Tertiary sequence of Northern Oman and is well exposed along the eastern coastal strip of the Batina Region and the Governorate of Muscat, Oman. Nolan *et al*. (1990) have proposed the name Seeb Formation for a thick carbonate sequence previously correlated with the Dammam Formation that occur in much of the Arabian Peninsula (Steineke *et al*, 1958). However, the Batina coast (including the Muscat region) where the formation is best developed appears to have been separated from the main Arabian carbonate platform during deposition of the coeval Dammam Formation by the uplifted hinterland of Omani Mountains. A recent publication by Beavington-Penney *et al*. (2006) has made further biostratigraphic dating, mainly based on larger foraminifera of the formation, confirming its Middle Eocene age. However, the sedimentological attributes and the stacking nature of the various lithostratigraphic units of the formation need further consideration in order to better understand the interplay between the sedimentation and relative sea level changes. Spectacular outcrop exposures occur within a few kilometers of the campus of Sultan Qaboos University (SQU, Figure 1) and recent geological visits to the area acknowledged new sedimentologic attributes and lithostratigraphic architecture for the Seeb Formation. This work presents the preliminary results on the lithostratigraphic evolution of the Seeb Formation based mainly on field observations.

1.1 Previous work

The earliest works on the Tertiary sequence of the Batina coast include Powers *et al*. (1966), Glennie *et al*. (1974), Racz (1979), Warrak (1986) and Hughes-clarke (1988). These authors commonly adopted a stratigraphic nomenclature imported from coeval sedimentary sequences in Saudi Arabia (i.e., Umm Radhuma, Russ and Dammam formations. A stratigraphic revision by Nolan *et al*. (1990) has changed this practice by proposing new stratigraphic terms of Jafnayn, Rusayl and Seeb formations, in ascending order, for the lower Tertiary strata of the Batina & Muscat coastal regions (Figure 2). Later researchers have adopted this new nomenclature (e.g., Béchennec, 1992; Racey, 2001; Beavington-Penney, 2002; Beavington-Penney *et al*, 2006). The type section documented by Nolan *et al*. (1990, p. 507) is a "roadside section along the main Nizwa to Muscat road through Wadi Rusayl …". Despite the proximity and easy access of the section, Nolan *et al*. (1990) apparently reiterated a description given by Crawford (1982) in an unpublished report. Nolan *et al*. (1990) stated that at the type locality, the formation is 356 m thick, including a middle 145 m-thick portion concealed. Thus, descriptions given by the proponents of the type section are insufficient and incomplete. The most recent work on the Seeb Formation is a PhD thesis by Beavington-Penney (2002); this work has been summarized in a publication by Beavington-Penney *et al*. (2006). The latter work gives a fair description of the various lithofacies attributes of the formation and effect of intensive bioturbation on the cyclicity of these shallow marine carbonates. The major theme of Beavington-Penney *et al.* (2006) work is obliteration of cyclic sedimentation by the then marauding organisms (bioretexturing) and creating acyclicity in the major central portion of the formation. A recent abstract by Salad Hersi *et al*. (2008) has, however, claimed that, although intense bioturbation is common in significant portions of the formation, the original cyclicity is still preserved and discernible. This point is further discussed in this paper.

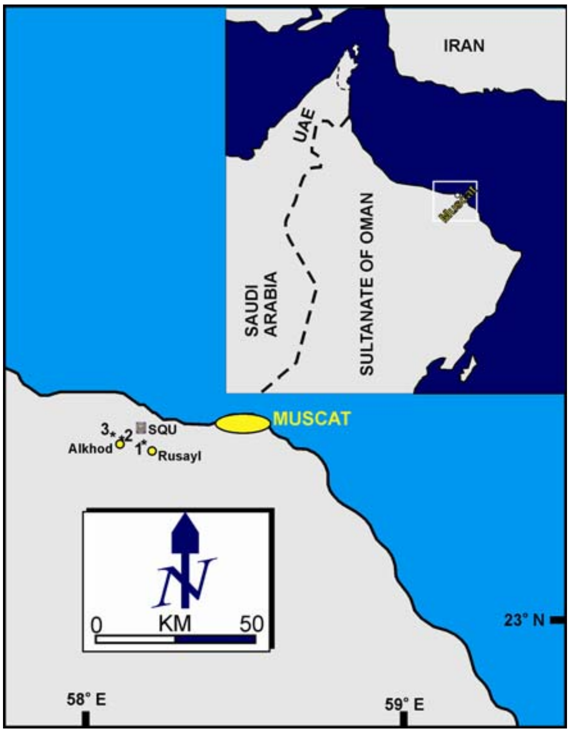

Figure 1. Location of the studied area and sections (1, 2 and 3). Section 1 lies along the SQU-Waha Al Ma'rifah Institute, Section 2 is the Al-Khoud road-cut and Section 3 is the along Wadi Al-Khoud, north of Al-Khoud village.

2. Geologic background

The Batina-Muscat coast lies on the eastern coastal margin of the North Oman mountains. The geological evolution of the sedimentary cover of north Oman is well preserved and exposed in this region. The exposed rock succession spans from Precambrian to Recent. The pre-Tertiary rocks are well exposed along deeply cut wadis occurring on the flanks of the mountains (e.g., Jabal Akhdar). The oldest rocks in the area include a slightly metamorphosed, thick (>1.8 km) sequence of Precambrian age (e.g., Mistal, Hajir, Mu'aidin and Kharous formations, (Mann and Hanna, 1990)). A long period of tectonic disturbances, erosion and non-deposition elapsed before the onset of deposition of a very thick, carbonate-dominated succession of late Paleozoic (Permian) to late Cretaceous age (the Arabian carbonate platform associated with the Tethys Ocean, (Robertson and Searle, 1990)). These platformal sediments, commonly called as Hajar Supergroup, are punctuated by prominent stratigraphic breaks and further subdivided into groups (e.g., Akhdar, Sahtan, Kahman, Wasia and Aruma groups, (see for instance Figure 4 of Robertson and Searle, 1990, p. 9)). Convergent plate tectonic movement and closure of the Tethys Ocean in Late Cretaceous heralded obduction of the oceanic crust

(Semail Ophiolites) onto the platform carbonates (Michard *et al*., 1989). Following the orogenic upheaval related to the emplacement of the Semail Ophiolite in the Campanian, widespread deposition of Maastrichtian to Tertiary dominantly marine sediments occurred over much of Northern Oman. However, presence of autochthonous iron-stained conglomerates (Al-Khod Conglomerates) and laterites that occur below these marine sediments suggest that some areas were raised above sea-level and exposed to subaerial weathering. By Late Maastrichtian to Eocene times, the Batina-Muscat coastal region lying east of the Oman Mountains was largely submerged under shallow sea (Nolan *et al*. 1990, Béchennec, 1992). The region was later (Miocene and afterwards, i.e., post-late Alpine culmination collapse, (Hanna, 1992)) affected by uplifting of the Paleogene to ?Oligocene sedimentary sequence of the region.

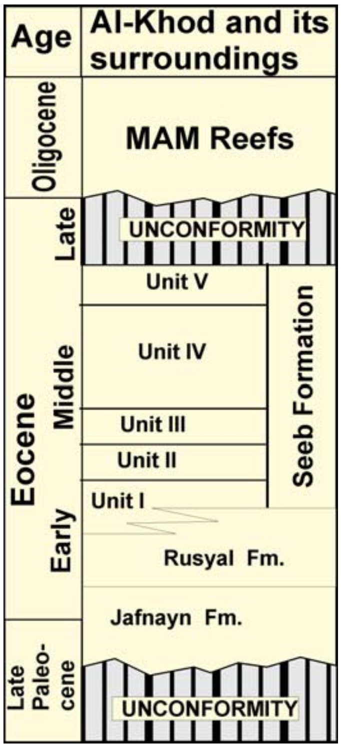

Figure 2. Stratigraphic chart showing the various late Paleocene to Oligocene lithostratigraphic units in the study area. Note the interfingering nature of the Rusayl – Seeb contact. The Seeb Formation is divided into five informal units (I to V) and it is unconformably overlain by the MAM (Muaskar Al Murtafa' reefs).

3. Lithostratigraphic attributes of the Seeb Formation

The Seeb Formation conformably overlies the Rusayl Formation but is unconformably overlain by the informal unit of Mu'askar Al Murtafa' ("MAM") Reefs (Figures 2 and 3). Although there is no section that shows a complete sequence of the formation, its thickness is conservatively estimated to about 600 m. This thickness is much more than that proposed by Nolan *et al* (1990) from the type section but comparable to that reported by Beavington-Penney (2002) and Beavington-Penney *et al* (2006). The formation can be lithostratigraphically divided into five units (I to V, Figures 2 and 3). These units can be easily traced in the study area south of Sultan Qaboos University but may be promoted to formal members if they prove to be regionally mappable. This is part of the objectives of a longer term research program but we present here a preliminary and brief description that highlights the internal lithostratigraphic subdivision and attributes of the formation.

3.1 Contacts of the formation

The Seeb Formation conformably overlies the Middle Eocene Rusayl Formation. The contact between the two formations is well exposed in Section 2 (Figures 1, 4 and 5a). The uppermost portion of the Rusayl Formation consists of bioclastic wackestone interbedded within the dominant shaly facies of the formation. This interbedding suggests recurring changes in the depositional environment until it became dominated by the marine realm that deposited the basal beds of the Seeb Formation. Moreover, the lower part of the Seeb Formation consists of shale horizons that are lithologically similar to the shales of the Rusayl Formation. Thus, the contact separating the two formations is considered conformable. Based on field observations close to the type section of the formation, the lowermost part of the Seeb Formation appears to laterally merge with the uppermost beds of the Rusayl Formation.

The upper contact of the formation is not exposed in any of the studied sections. However, the small hills just south of the Sultan Qaboos University (in close proximity of locality 1) terminate with a recessive area filled by poorly cemented foraminiferal rudstone (Unit V, as defined here) capped by a ferruginous hardground surface (Figure 5b) and overlain (within a sand-covered flat area about 50 meters wide) by massive coral framestones of the Oligocene MAM reefs.

3.2 Lithostratigraphic units

3.2.1 Unit I

Unit I is the lowest lithologic unit of the formation overlying the Rusayl Formation. It is well exposed in sections 2 and 3 where it is about 50 m thick in Section 2. The unit may be thicker than that since it is dissected (at locality 2) by a fault (Figure 4). At locality 3, about 40 meters constituting the upper part of the unit are exposed; the lower part and lower contact are concealed under the bed of the stream of Wadi Al-Khod. The upper boundary of the unit is sharp (Figure 5c and 5d) and erosional to irregular. Unit I is characterized by light yellowish brown (beige), sandy, bioclastic packstone to grainstone. These Rusayl-like shales are present (Figure 5c). The unit is thick to medium beds, cross-bedded and locally vertically burrowed. The cross beds include low angle, trough, tabular and bipolar (herringbone) sets (Figure 6a, b). Dewatering structures that disrupt the bedding are present in the unit (Figure 6c). Rare, poorly preserved desiccation cracks are observed in fine-grained packstone lithofacies in section 3. Pebble size vein quartz clasts are disseminated in the lower part of the unit but rare in its upper part. The framework grains are dominated by biocalsts that include larger foraminifera (e.g., *Nummulites, Alveolina*, miliolids and rotalids), gastropods, bivalves, algae and echinoids (Figure 6d). Intraclasts and peloids (most likely micritized bioclasts) are also present. The mollusk clasts are commonly leached-out and replaced by calcite spar; however, their original occurrence is preserved by micrite envelopes (Figure 6d). A thin (~15 cm thick), laterally discontinuous layer of rhodolithic bindstone lies at the top of the unit; this is particularly well exposed in Loc. 3. Its lateral discontinuity is mainly due to erosion. The rhodolith is formed by encrusting, calcareous red algae.

3.2.2 Unit II

Unit II is well exposed with a complete thickness of about 40 m in sections 2 and 3. The upper contact of the unit is sharp and abrupt as exposed in Loc. 3 and (Figure 7a). The unit is characterized by light brown to light pink, indistinctly bedded, nodular, bioclastic packstones and wackestones. Prominent sedimentary structures include intense bioturbation obliterating all pre-existing structures (Figure 7b). This intense bioturbation (or ‘bioretexturing’, the term of Beavington-Penney *et al*, 2006) is responsible for the amalgamation of the beds. Such amalgamation has resulted in the massive and indistinct bedding (Figure 5d) that characterizes the unit.

Unit II is highly fossiliferous (Figure 7c) with *Nummulites* (Figure 7d), *Alveolina* and coralline red algae being the most common fossils. Other fossils include miliolids, gastropods, bivalves and echinoids with less than 2% quartz grains scattered in the unit.

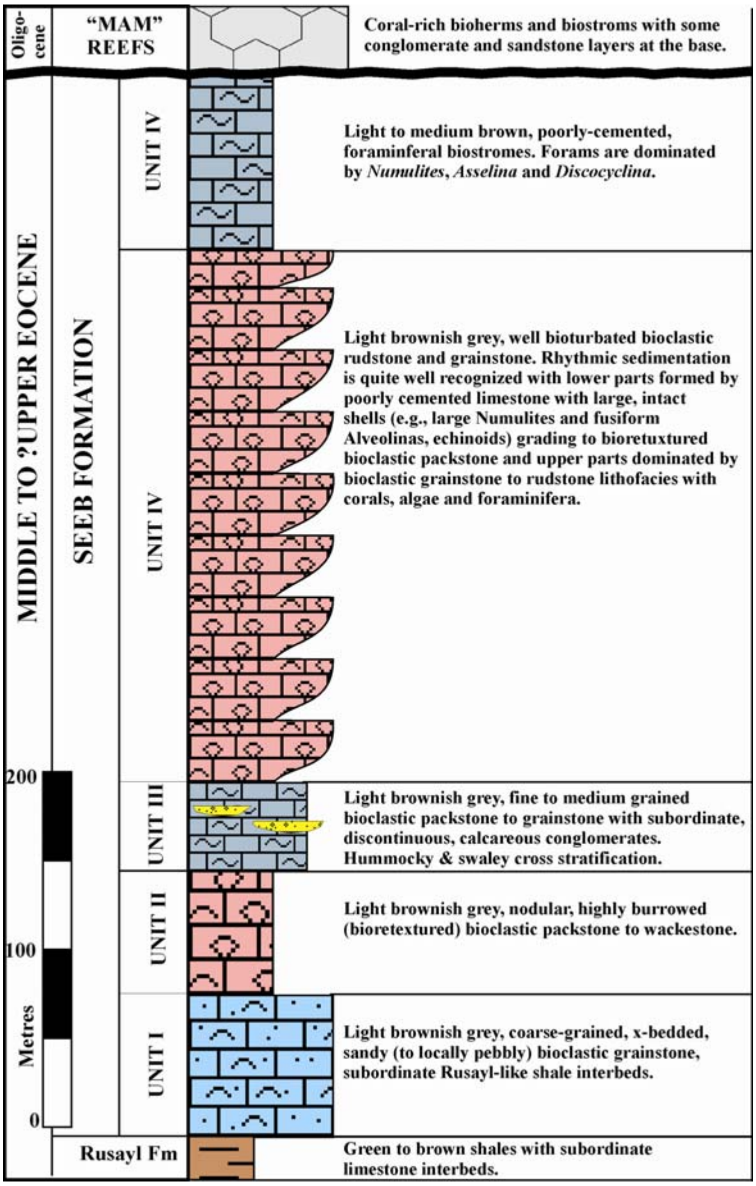

Figure 3. Hypothetical stratigraphic log for the Seeb Formation with lithologic descriptions of the five units that constitute the formation. The cycles shown for Unit IV are not to their actual scale.

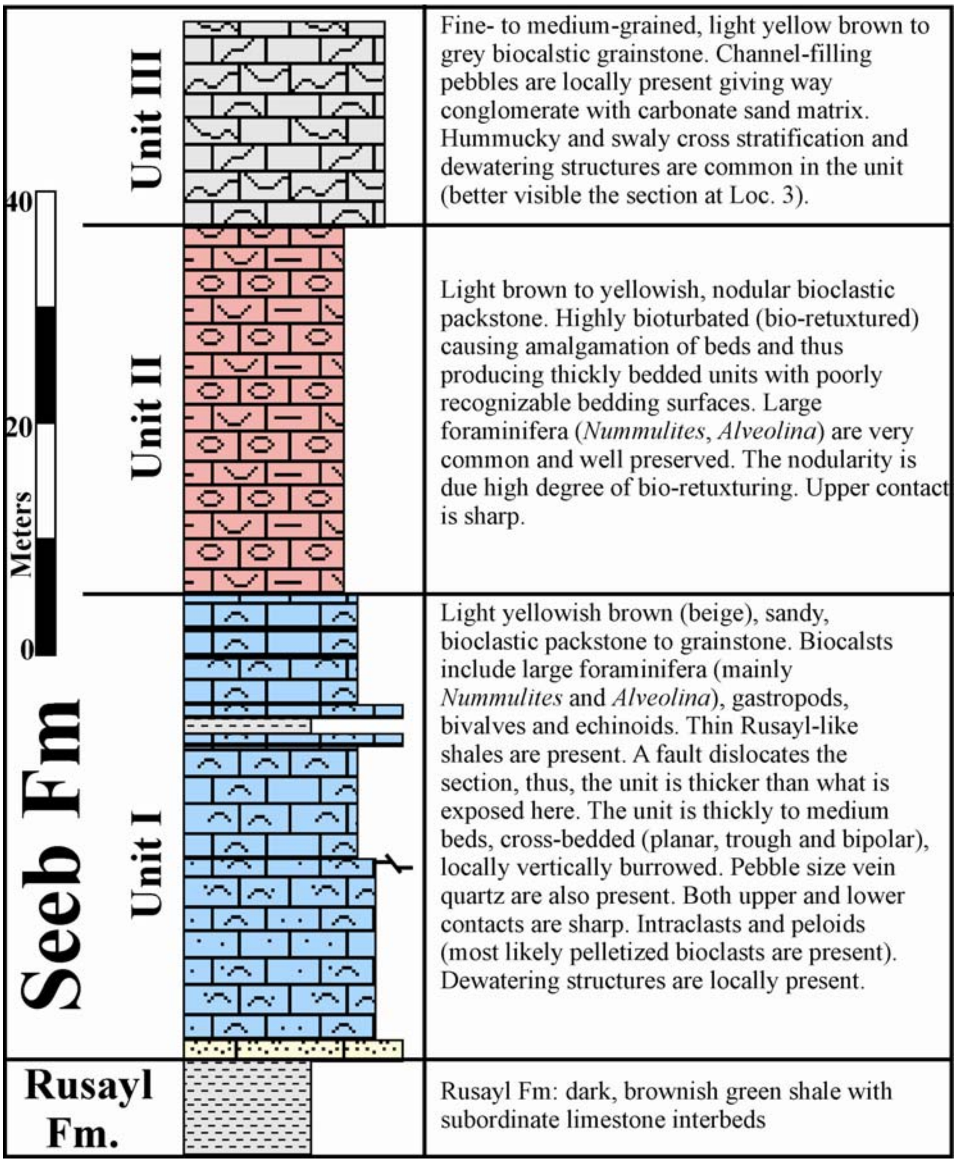

Figure 4. Stratigraphic log of Section 2 (Al-Khoud Road-cut) showing the Rusayl – Seeb contact and descriptions of the lower three units that are exposed along the section. Note the fault that lies within Unit I. The upper contact of Unit III is not exposed.

3.2.3 Unit III

Unit III is exposed in sections 2 and 3 although its upper contact is covered. The exposed thickness is in the range of 40 to 50 m thick. The lower contact is sharp with an abrupt lithofacies change from the burrowed packstones of Unit II to the well-bedded, non-burrowed facies of Unit III (Figure 8a). Unit III is dominated by thin, medium and thick bedded, medium-grained, bioclastic packstone to grainstone lithofacies. Subordinate, laterally confined, quartz-rich (vein quartz) conglomerates are also present in the unit. The lateral extension of the conglomeratic layers is in the range of a meter to 10-m scale with a thickness of a few tens of centimeters. Their matrix is calcareous sand similar to the most common packstone / grainstone lithofacies. Sand- and pebble-size extraclasts (quartz) are also locally disseminated in the unit. Moreover, intervals of burrowed bioclastic packstones are seldom interbedded with the dominant packstone / grainstone facies. Bioclasts present in the unit include broken pieces of foraminifera, mollusk and algae. Prominent sedimentary structures in the unit include hummocky and swaly cross-stratificiation, erosional surfaces, dewatering-induced internal deformation, amalgamation and lenticular bedding (Figure 8b and 8c).

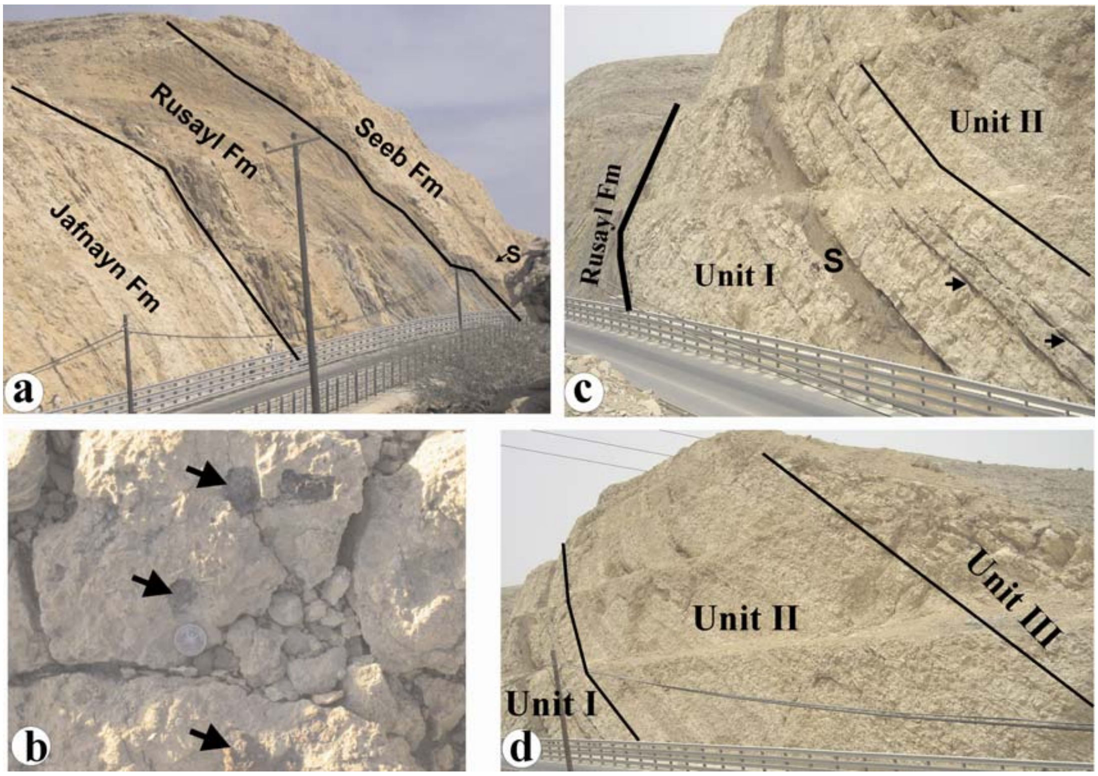

Figure 5. Outcrop exposures showing (a) the Jafnayn – Rusayl – Seeb sequence with formational boundaries demarcated with thick black lines (Loc. 2); (b) a hardground surface with ferruginous nodules (arrows) replacing bioclasts. This surface most likely indicates the top of the Seeb Formation (~ 250m northwest of Loc. 1, close to SQU); (c) Unit I of the Seeb Fm. Exposed in Loc. 2. Note the Rusayl-like layers (S & arrow heads) with the unit; (d) Unit II of the Seeb Fm. also exposed in Loc. 2. The upper contact with Unit III is also exposed here.

3.2.4 Unit IV

Unit IV is the thickest unit and constitutes the bulk of the formation. Although a complete thickness of the unit has not been observed, it is estimated to be in the range of 300 m thick. It is widely exposed in a roughly east-west oriented strip along Rusayl Industrial zone, Wahat Al-Ma’rifa Technical Institute and the hilly terrain lying north of localities Al-Khod road-cut (Loc. 2) and Wadi Al-Khod (Loc. 3).

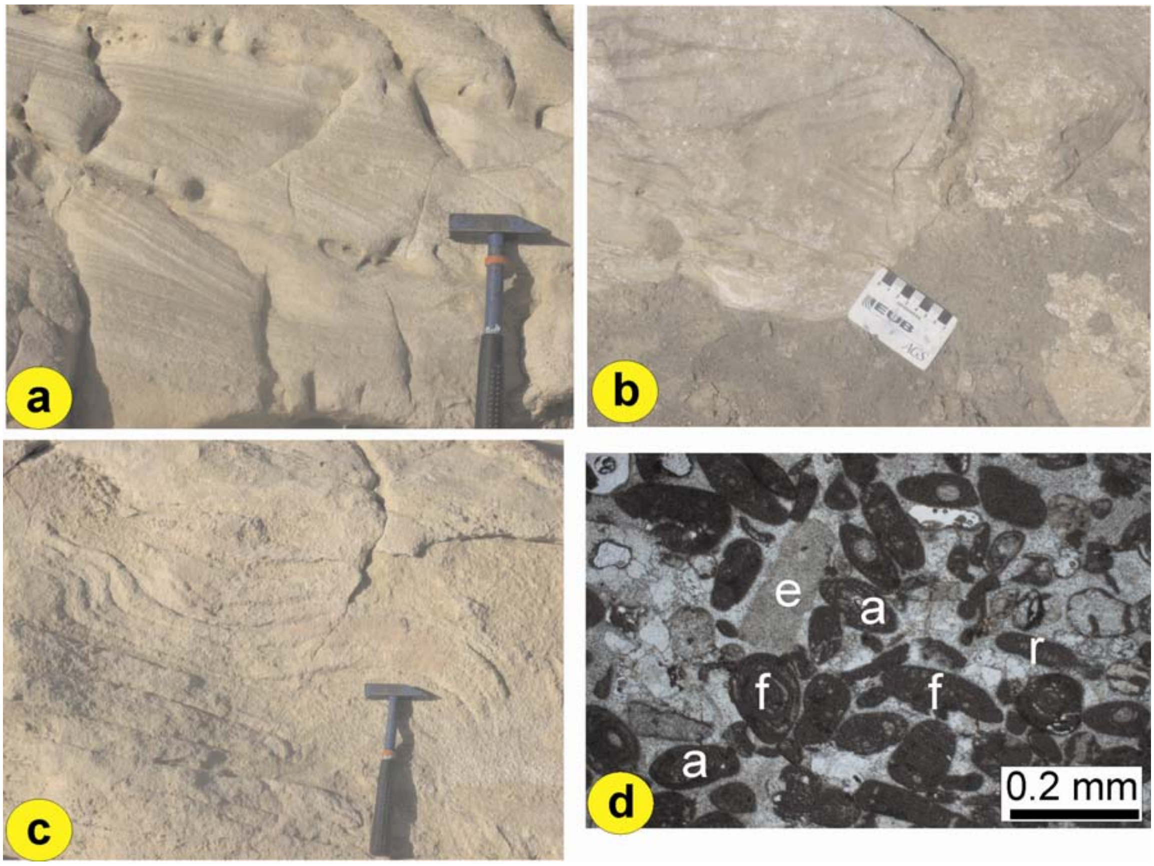

Figure 6: Sedimentary structures and microfacies attributes of Unit I. (a) Tabular x-bedding; (b) bidirectional, tabular x-bedding (herringbone x-bedding); (c) deformation of the layers due to dewatering (hammer = 33 cm, pencil ~ 10 cm), and the bars on the card in c are in cm); (d) thin section photomicrograph showing bioclastic grainstone (f = foraminifera, e = echinoid, a = Alveolina, r = red algae).

The unit is dominated by grey-weathering, light yellowish brown, thickly to massively bedded, extensively burrowed, nodular, bioclastic wackestone, floatstone to rudstone. It is lithologically similar to Unit II in terms of color, nodularity, fossil content and intense bioturbation. Bioclasts include larger foraminifers, gastropods, echinoids, algae, corals and bivalves. This unit has been discussed in great detail in the work of Beavington-Penney (2002) and Beavington-Penney *et al* (2006). The intense bioturbation that had obliterated almost all of the previously existing textures and structures led Beavington-Penney *et al* (2006) to conclude that the unit lacks the rhythmic sedimentation common in shallow marine carbonates. They documented that this “thick package of nodular, indistinctly bedded lagoonal sediments, which consists largely of one facies type, shows no evidence of hiatus surfaces (such as hardgrounds and subaerial exposure) or cyclicity (i.e., shallowing upward cyclothems)(see Beavington-Penney *et al* 2006, p. 1155). Contrary to these authors’ assertion of acyclic package for this part of the formation, this study documents that the unit is indeed cyclic with meter-scale rhythmic sedimentation. The thorough bioturbation which revamped the original sediments destroyed most of the internal texture and structure within each cycle and Beavington-Penney *et al*’s (2006) bio-retexturing is confined within the limits of individual cycles. Each cycle is commonly characterized by (i) a basal, poorly cemented, burrowed, clay-rich, bioclastic rudstone, (ii) a middle part (the thickest within a cycle) of highly bioturbated (typical bioretexturing), bioclastic packstone and (iii) an upper part of bioclastic packstone, grainstone or rudstone lithofacies (Figures 8d and 8e). The clay content decreases from the base to the top. Such stacked cycles form the bulk of the unit and are well exposed in the study area. Fossils in the basal part are commonly intact, large foraminifers, including long (> 1 cm) fusiform *Alveolina* and discoidal *Nummulites*. The top of each cycle forms a resistant ledge above its lower more recessive portion (Figure 8d). The bioclasts within these cap rocks are dominated by crustose red algae with common mollusk fragments and foraminifers are also common. Figure 9a shows the contact between Unit IV and Unit V which is irregular to wavy at this locality 1. The bed below the contact is the uppermost biclastic grainstone bed which defines the top of Unit IV. However, the overall contact with Unit V is of transitional nature, marked by interbedding of nodular bio-retextured facies with typical Unit V facies (see below).

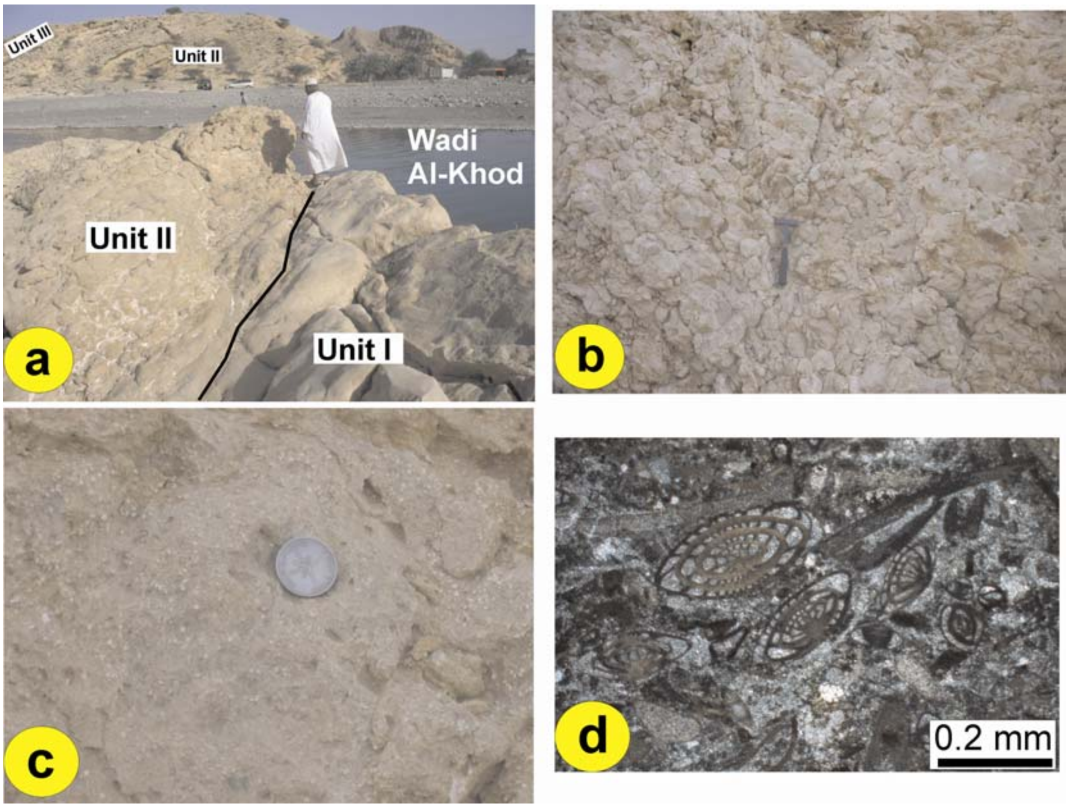

Figure 7. (a) Outcrop exposure showing the sharp contact between Unit I and Unit II (Loc. 3). (b) A view highlighting the nodular texture of Unit II (hammer = 33 cm). (c) Close-up view of Unit II showing scattered larger foraminifera tests in the unit (coin is ~1.5 cm in diameter). (d) Thin section photomicrograph of Unit II showing a grainstone lithofacies rich in Nummulites and other fossil fragments.

3.2.5 Unit V

Unit V defines the highest lithofacies of the Seeb Formation and ranges about 100 m in thickness. It is characterized by thickly bedded, light to medium brown, poorly-cemented, clay-rich bioclastic rudstones (marls with excessively abundant foraminifera, Figure 9b). Due to their recessive nature, they commonly occur the east-west trending lowland area between the MAM reefs and the Seeb Industrial Zone. The dominant larger foraminifera shells are commonly intact and imbricated; they are represented by *Nummulites*, *Discocyclina* and

Asselina. Besides high clay content, the matrix also contains silt-size quartz grains (Figure 9c). The road-cut at the northern entrance of the road to Wahat Al-Ma'rifah is an excellent reference example for this unit. Its upper boundary is not exposed and a ferruginous hardground surface close to Loc. 1 (Figure 5b) marks the top of the unit (and of the formation). Above this unit, there is a short covered zone which is followed by sandy conglomerate lithofacies which becomes interbedded with the Oligocene "MAM" reefs.

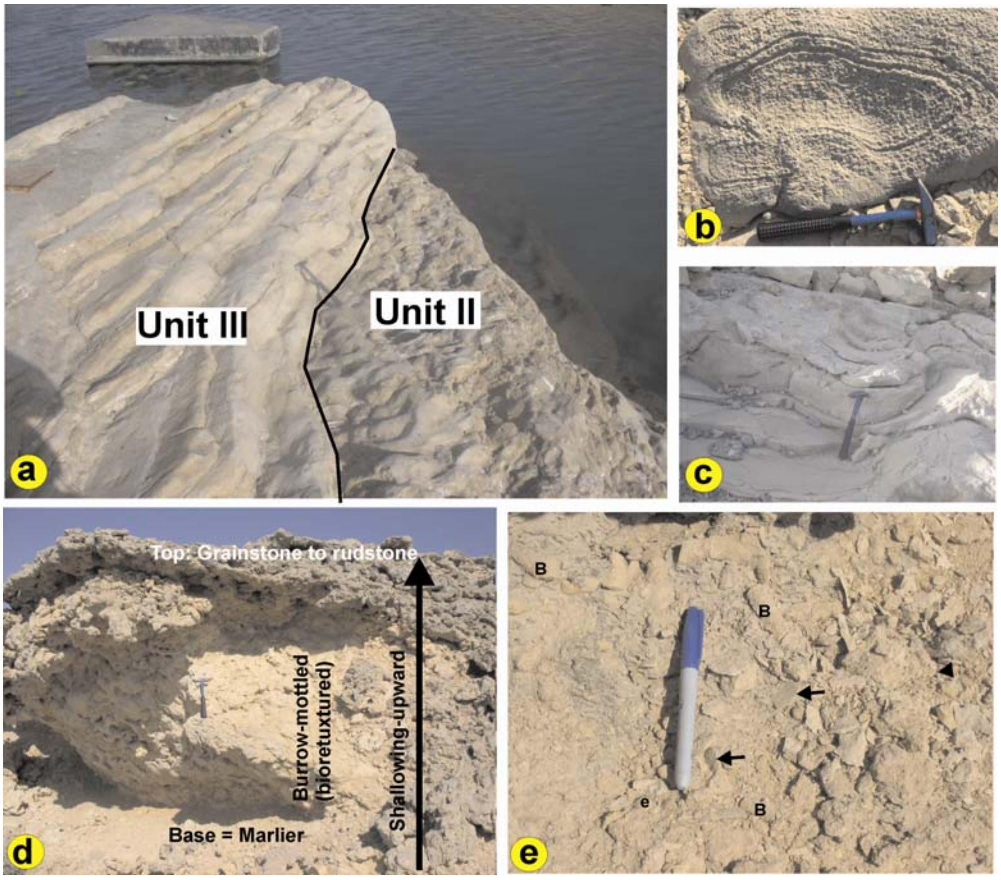

Figure 8. (a) Field view of the sharp contact separating Unit II from Unit III (Loc. 3). (b) Hummocky cross stratification that commonly occurs within Unit III (Loc. 3). Hammer (in all pictures) is 33 cm. Photos d & e are from Unit IV and show textural appearance of the unit. The unit is the thickest among all units of the formation and is characterized by rhythmically stacked cycles. (d) Single cycle defined by a basal, recessive, muddy / marly rudstone to flaostone lithofacies followed by highly burrowed (bio-retextured) packstone grading into more resistant, cleaner bioclastic packstone / grainstone / rudstone lithofacies. (e) Close-up view of the basal burrowed facies with significant amount of larger foraminifera (arrows) including Nummulites and fusiform Alveolina.

4. Depositional setting

The Lithofacies attributes and vertical succession of various units that constitute the Seeb Formation suggest that deposition took place in a rising relative sea level scenario on a ramp carbonate platform. The lowest

Unit I is envisaged to have accumulated in a transgressive (retrograding), high energy, shallow marine setting, particularly a beach environment. This is indicated by the presence of low-angle and bipolar cross stratifications, and the absence of mud and vertical burrows in the lithofacies (Jones and Desrochers, 1992; Pemberton and McEwan, 1992). The overlying Unit II was deposited in a lagoonal environment where deposit feeding organisms produced intensive mixing of the sediments, thus producing this uniform package of sediments. The lagoon was sheltered from wave energy by being deep on one hand and by basin-ward sub-tidal sand shoals that have produced Unit III. The latter accumulated between a fair-weather wave base and storm wave base as suggested by the dominant HSC and SCS structures (Tucker and Wright, 1990). Local tidal channels connected to the shallower parts of the platform may have transported the clastic pebbles associated with unit III during occasional stormy events. The fore-shoal (basin-ward) depositional site was a quiet zone, allowing accumulation of the very thick, cyclic Unit IV (mid shelf). Occurrence of the fusiform *Alveolina* and discoidal *Nummulites* at the base of the cycles suggests a depth increase (Racey, 2001; Beavington-Penney *et al*. 2006) whereas the top-cycle packstone / grainstone lithofacies indicates gradual shallowing. The packstone / grainstone lithofacies may either be due to basin-ward extension of Unit III (sand flats) during relative sea level drop or simple shoaling due to increased in-situ carbonate productivity. This unit gave way to an outer-shelf setting where deposition of the topmost Unit V took place. The presence and proliferation of intact, larger foraminiferal tests and the high clay / silt content underscores a low energy depositional environment (Racey, 2001). The Late Eocene was a period of sea level fall in Arabia in which many parts of the Arabian shelf was exposed, developing an unconformity at the Eocene – Oligocene contact (Nolan *et al*., 1990; Haq and Al-Qahtani, 2005). Such an unconformity most likely separates the Middle Eocene Seeb Formation from the Oligocene “MAM” reef deposits of the region.

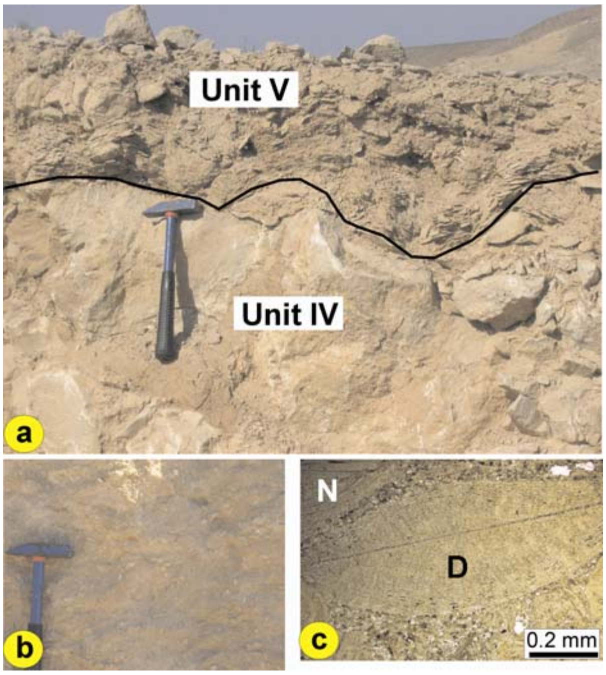

Figure 9. (a) Outcrop exposure showing the contact between Unit IV and Unit V (Loc. 1). The contact is irregular with clear lithologic change across it. The lower part of Unit V consists of interbeds of Unit IV and Unit V lithofacies (Salad Hersi *et al*., 2008). (b) Close-up view of Unit V showing prolific larger foraminifera tests (Nummulites, Asselinas and Discocyclinas) commonly dispersed throughout the unit (hammer in both a and b is 33 cm long). (c) a thin section photomicrograph showing larger Discocyclina (D) and Nummulites (N) tests.

5. Conclusions

The Seeb Formation is a Middle Eocene sedimentary succession deposited in a shallow marine setting along the eastern margin of the Oman Mountains. It is very thick (up to 600 m) and well exposed in the Muscat-Batina coast region. The lower contact of the formation is conformable with the underlying Rusayl Formation. Presence of limestone beds in the upper part of the Rusayl Formation and Rusayl-like shale beds within the lower part of the Seeb Formation suggest temporal alternations of the Rusayl and Seeb depositional environments. Field study of the formation (supported by petrographic analysis) allowed recognition of five units that constitute the formation. Unit I consists of medium to coarse-grained, sandy, bioclastic packstone to grainstone with well preserved low angle, trough, tabular and bipolar cross bedding. This is followed by thickly bedded, extensively burrowed, bio-retextured bioclastic packstone (Unit II). The bioturbation obliterated most of the original sedimentary structures, as well as depostional textures. The third unit (Unit III) is characterized by well-bedded, medium grained, sandy, bioclastic packstone to grainstone with hummocky and swaly cross stratification. Subordinate pebble-size vein quartz conglomerates locally occur, occupying meter- to decameter-long channelized zones. Minor burrowed intervals also occur. The fourth unit is the thickest of all units reaching as high as 300 m thick. Its lithology is more or less similar to that of Unit II, but shows prominent rhythmic sedimentation. However, the bio-retexturing has obliterated any pre-existing sedimentary structures within the boundaries of each cycle. The last and the fifth unit (Unit V) of the formation is defined by poorly cemented, foraminiferal rudstone. It can be simplified as marls teaming with larger foraminifera tests dominated by *Nummulites*, *Discocyclina* and *Asselina*. The upper contact of the formation with the overlying Oligocene “MAM” reefs is not exposed. However, a hardground surface with ferruginous infillings below the MAM reef outcrops is considered to represent the upper surface of the Seeb Formation. The sedimentologic attributes and the stacking nature of the various units of the formation indicate that deposition took place in a deepening-upward shallow marine basin. Unit I represents sandy shoreline deposits that pass basinward into a protected lagoonal deposits of Unit II. The latter was protected by subtidal sand shoals of Unit III lying seaward that accumulated between the fair-weather wave-base and storm base. Unit IV was deposited below the storm base allowing deposit feeders to flourish and rampage the sediments, producing the extensive bioturbation that characterizes this unit. The uppermost unit V was deposited in an outershelf setting as suggested by the dominance of flat foraminifers (e.g., *Nummulites*, *Discocyclina* and *Asselina*).

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