

High Resolution Sequence Stratigraphy of the Natih Formation (Cenomanian/Turonian) in Northern Oman: Distribution of Source Rocks and Reservoir Facies

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ABSTRACT

The Cenomanian of the Arabian Peninsula comprises a carbonate platform setting with rudists, characterized by gradual lateral facies changes including the interfingering of carbonate reservoirs (Natih and Mishrif formations) and source rocks. In order to be more predictive with regard to the distribution and the geometrical aspects of the reservoirs and source rocks, a high resolution sequence stratigraphic study has been carried out in the Adam Foothills of Northern Oman.

Based on detailed field sections a correlation scheme covering a transect of 100 kilometers (km) has been established. Three orders of stacked depositional sequences have been found based on the reoccurrence of facies. During long-term increase of accommodation the depositional environment was separated in basinal and platform facies. In contrast, during longer term sea level fall, i.e. long-term decrease of accommodation space, prograding shelfal units extended platform facies over a large part of the basin. The most heterogeneous facies associations are found in times of minimal accommodation space, when incisions and subaerial exposure produce lateral variable strata (e.g. top Natih E). The organic matter is found at the base of two of the three longer term (3rd order) depositional sequences. The organic carbon is contained in marl-limestone couplets (small-scale cyclicity) with a high abundance of oysters and monospecific brachiopod faunas (coquinas). Rudists are found in the progradational part of these sequences, and occur mostly as reworked rudstone layers in meter to decimeter scale, high frequency cycles. The detailed regional correlation depends on the identification of medium- to small-scale (4th to 5th order) depositional sequences which are bounded by regional shifts of the facies belts.

The distinct hierarchical organization of the depositional sequences in the Cenomanian, and the relative stability at that time of the Arabian Peninsula, implies a strong correlation potential and thus a broad regional similarity of the architecture of the petroleum systems at that time.

INTRODUCTION

The Cenomanian and Early Turonian stages (Upper Cretaceous) are one of the principal carbonate petroleum systems in the Gulf Region with proven hydrocarbon accumulations in Oman, United Arab Emirates, Qatar and Iraq. The reservoir facies are formed by the rudist-bearing shallow water carbonates of the Natih and Mishrif formations (Harris and Frost, 1984; Jordan et al., 1985; Burchette, 1993; Alsharhan, 1995), while time equivalent source rocks were deposited in the adjacent intrashelf basins (Natih Formation and Shilaif/Khatiyah Formation: Harris and Frost, 1984; Grantham et al., 1987; Alsharhan, 1995). The regionally deposited shales of the Laffan and Muti formations are the seal of this system (Grantham et al., 1987; Alsharhan, 1995).

Both reservoir and source rock facies have been the subject of detailed analyses and environmental interpretations (see reviews by Burchette, 1993; Alsharhan, 1995). However, as most of these are

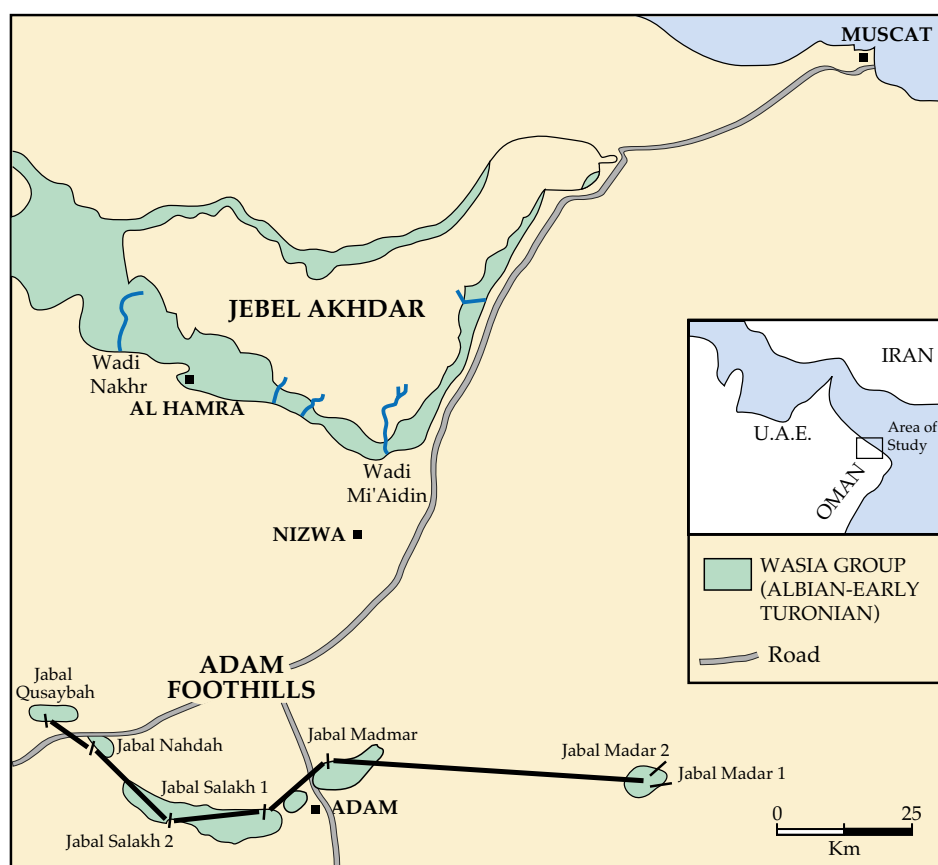


Figure 1: Geographical map of Northern Oman showing outcrops of the Wasia Group. Studied sections and correlation profile in the Adam Foothills are indicated.

sedimentological studies, primarily based on subsurface data sets, they rarely include high resolution stratigraphic correlations (at the meter scale) and a quantification of the reservoir geometries.

The establishment of a high resolution sequence stratigraphic model improves predictivity of: (1) the distribution of reservoir and source rocks, (2) their geometrical characteristics and internal heterogeneities, and (3) the diagenetic alteration patterns. The application of this model (or elements of it) to the subsurface is supported by the generally stable platform conditions during the Cenomanian in the Gulf Region (e.g. Murris, 1980), and the suggested dominant control of eustasy and climate on the sedimentation pattern (Harris et al., 1985; Philip et al., 1995).

The excellent outcrops of the Natih Formation in the Oman Mountains offer the unique opportunity to study the stratigraphic architecture of this interval both at the reservoir and exploration scale. The Jabals in the Adam Foothills provide continuous outcrops at the kilometer-scale documenting lateral facies changes, while the outcrops in the wadis of the southern flank of Jabal Akhdar provide the necessary data to construct a regional (75 by 100 km) high resolution stratigraphic framework (Figure 1). Few outcrop studies have been published, and these normally consider only one or two of the sections (Glennie et al., 1974; Harris and Frost, 1984; Rabu, 1987; Simmons and Hart, 1987; Hughes-Clark, 1988; Smith et al., 1990; Kennedy and Simmons, 1991). The first comprehensive study of these outcrops is by Philip et al. (1995). It provides a detailed biostratigraphical and paleoecological analysis of the Natih carbonates and time equivalent basinal Fitri facies.

The purpose of the present study is twofold. Firstly, to obtain a higher degree of stratigraphic resolution by studying the different scales of depositional sequences and their lateral continuity. Secondly, to define the geometrical aspects of the Natih carbonate system within this fine stratigraphic framework. This paper presents the preliminary results of the detailed sedimentological outcrop study, and is based on macroscopic outcrop observations, together with the analysis of a limited number of thin sections. The principles of high resolution sequence stratigraphy are explained and illustrated with a 100 km long correlation profile of the Natih Formation (members A to F) in the Foothills of northern Oman.

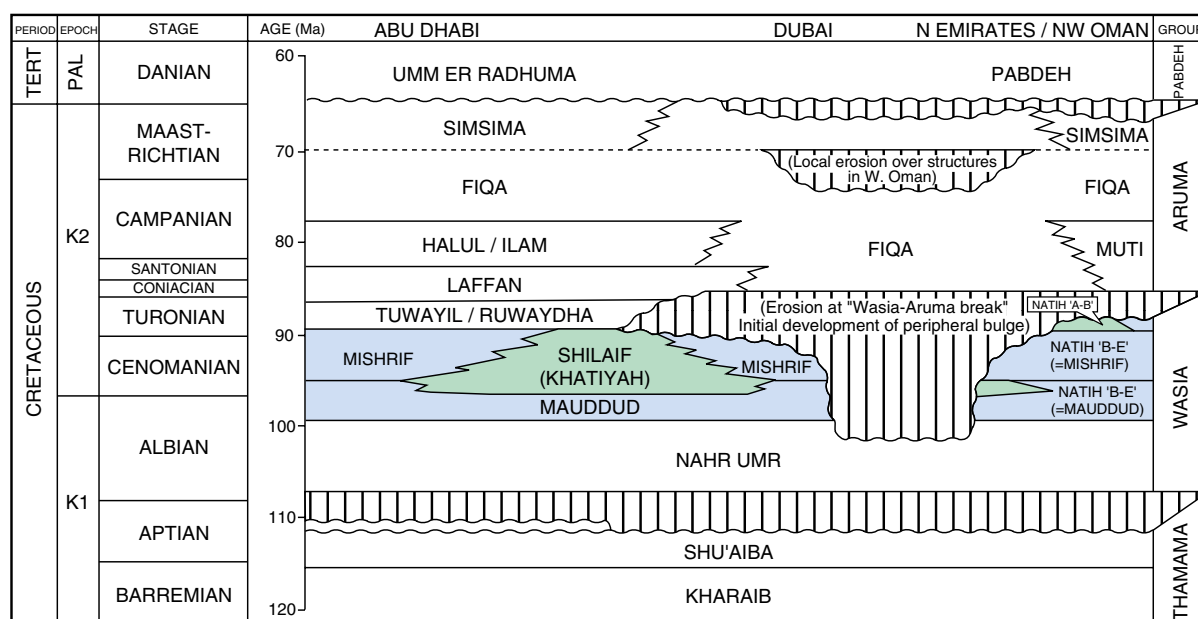


Figure 2: Chronostratigraphy of the southern Arabian Gulf and Oman showing locations, distribution and duration of the major stratigraphic breaks (vertical hatching). The studied stratigraphic interval is indicated. Blue: shallow water platform deposits. Green: intra-shelf basinal deposits. (After Burchette, 1993; time-scale for Middle Cretaceous after Haq et al., 1988)

REGIONAL GEOLOGICAL SETTING

The Natih Formation outcrops in the southern flank of the Jabal Akhdar and in the Adam Foothills in northern Oman, where it forms the upper part of the autochthonous of the Arabian Platform (Wyns et al., 1992). It is part of a major thrust unit emplaced during the Late Cretaceous compressional history of the eastern passive margin of the Arabian craton. In response to the growth of the Oman and Zagros mountains, a linear foreland basin developed along the margin of the craton in the Late Cretaceous (Murriss, 1980; Searle et al., 1983; Patton and O'Connor, 1988). Several large, restricted basins developed within the Middle Cretaceous Arabian Shelf (Murriss, 1980).

The Natih Formation is of Latest Albian to Early Turonian age (Simmons and Hart, 1987; Smith et al., 1990; Kennedy and Simmons, 1991; Philip et al., 1995). It forms part of the Wasia Group, and lateral age-equivalent formations in the Gulf Region are the Mishrif Formation, Muddud Formation, and Shilaif / Khadiyah Formation (Figure 2). In the subsurface, the Natih Formation is subdivided into seven informal members designated by the letters A to G from top to base (Hughes-Clarke, 1988; Scott, 1990). Philip et al. (1995) proposed a correlation of these informal members to the outcrop sections.

A paleogeographic picture of Cenomanian times shows the permanent presence of a shallow carbonate platform to the northeast of the studied area, and the development over the course of the Cenomanian of an intra-shelf basin in the west and north (e.g. Murriss, 1980; Burchette, 1993). The paleontological and paleoecological aspects of the outcrops of the Natih Formation in Oman have recently been studied by Philip et al. (1995).

METHODOLOGY

The high resolution sequence stratigraphic approach is a powerful methodology to unravel the fine scale stratigraphic architecture of sedimentary systems. This approach has found widespread application in siliciclastic systems (e.g. van Wagoner et al., 1988; Wilgus et al., 1988; Homewood et al., 1992), and more recently, also in shallow water carbonates (e.g. Goldhammer et al., 1990; Pomar, 1991; Loucks and Sarg, 1993). The best results are obtained in outcrop studies where the variability of surfaces and facies can be controlled laterally. The validity of this type of outcrop studies for the interpretation of subsurface equivalents is clearly demonstrated in the literature (e.g. van Wagoner et al., 1990; Eschard et al., 1993; Kerans et al., 1994; Grammer et al., 1995; van Buchem et al., 1995a).

The approach is based on four steps. The first step is the detailed description (decimeter-scale = 10 centimeter) of the different facies types and their interpretation in terms of depositional environments. In particular the estimation of the paleo-bathymetry is important in order to recognize the trends of increase or decrease in accommodation space (e.g. Jervey, 1988; McDonough and Cross, 1991; Homewood et al., 1992). In this paper the term accommodation cycle is applied.

The second step is the identification of special surfaces (e.g. subaerial exposure surfaces, ravinement surfaces, flooding surfaces, hardgrounds, firmgrounds) and their sequence stratigraphic interpretation in terms of sequence boundaries, flooding surfaces and maximum flooding surfaces.

The third step is the correlation and hierarchisation of depositional sequences. The correlations are based on the identification of sedimentary surfaces and volumes which have a stratigraphic significance (i.e. which represent time units or surfaces). Based on the environmental or bathymetric changes across limiting surfaces, the transgressive or regressive character of the depositional sequences is determined. The *amount of shift* of the facies belts along the surfaces, in combination with the character of the surface (e.g. stratigraphic hiatus, flooding surface, short-term emersion surface), determines the order (and therefore importance) of the depositional sequence.

Vail et al. (1991) and Haq et al. (1988) proposed a subdivision of depositional sequences into cycles from a 1st to 6th order, which are primarily based on time. The following orders are of relevance for this study: 2nd order (3 to 50 Million years = My); 3rd order (0.5 to 3 My); 4th order, also referred to as high frequency cycles, para-sequences or genetic sequences (0.08 to 0.5 My); and the 5th order (0.03 to 0.08 My).

The final step is the construction of a (high resolution) sequence stratigraphic model based on the correlation of cycles of increasing and decreasing accommodation potential across the different environments. This confirms the different orders of depositional sequences, and in particular the importance of their bounding surfaces. The surfaces are the time lines, and the model shows the (predictable) variability of the facies in between them, and accurately reflects the geometrical relationships of the various sediment packages. By constraining the geometrical relationships in this manner, predictions can also be made about the diagenetic alteration patterns.

The resulting model can then be tested, and possibly refined or changed, when more data become available such as additional outcrop sections (or wells), or new data sets such as geochemical, paleontological and mineralogical observations.

FACIES AND SURFACES

The detailed stratigraphic correlation of the area is based on the observed stacking of facies. Thus a short description of the facies is given below. Detailed facies descriptions of the Mishrif and Natih formations can be found in a number of recent publications, e.g. Jordan et al. (1985), Burchette and Britton (1985), Burchette (1993), Alsharhan (1995) and Philip et al. (1995). The general characterization of the intra-shelf environments encountered in the Natih and Mishrif formations as given by these authors is followed in this paper.

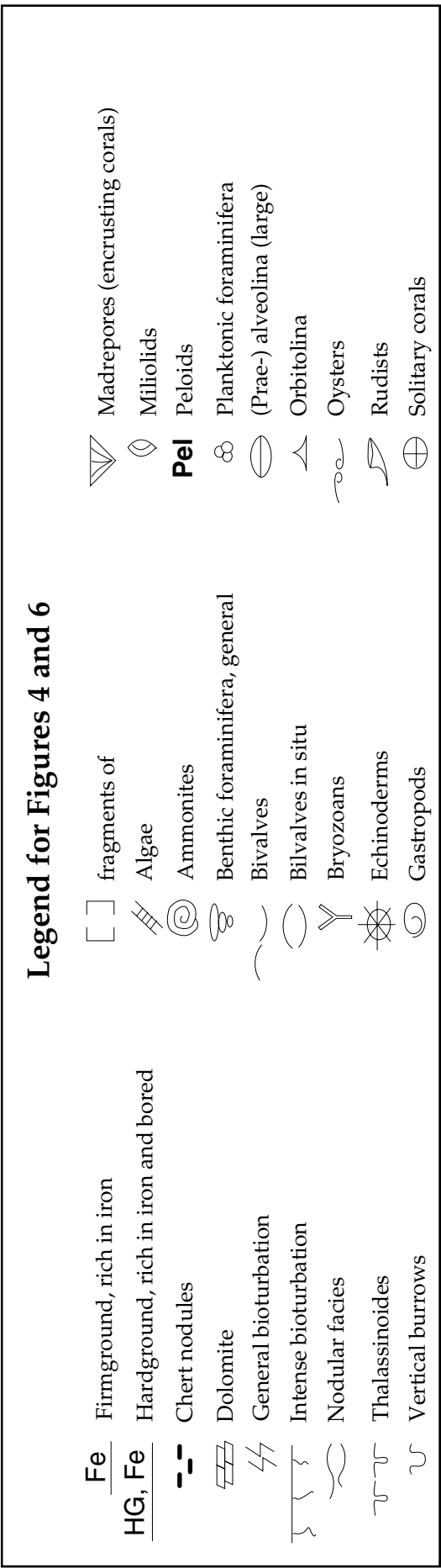
Figures 3, 4, 5 and 6 present outcrop photos and lithological logs of two key vertical stratigraphic sections in the Foothills area, at Jabal Madar and Jabal Salakh (Figure 1). The composite logs provide lithological and sedimentological information, as well as the main paleontological assemblages and biostratigraphic datum references.

Facies Associations

Eight facies types are distinguished, seven of which correspond to the intra-shelf carbonate setting and one of which corresponds to a siliciclastic coastal plain which overlays the Natih Formation in Jabal Madar. In the intra-shelf carbonate setting four main environments are distinguished: (1) basin, (2) distal shoal margin, (3) proximal shoal margin, and (4) shoal.



Figure 3: Outcrop picture of the Jabal Madar 1 section in the Adam Foothills. 4th order sequences are indicated. From left to right: the Natih E Member forms the white, bedded limestone cliff, sequence 4 is the rudist-rich upper part; Natih D (sequence 5); Natih C (sequences 6 and 7); Natih B (sequence 8). See Figure 4 for lithological log.



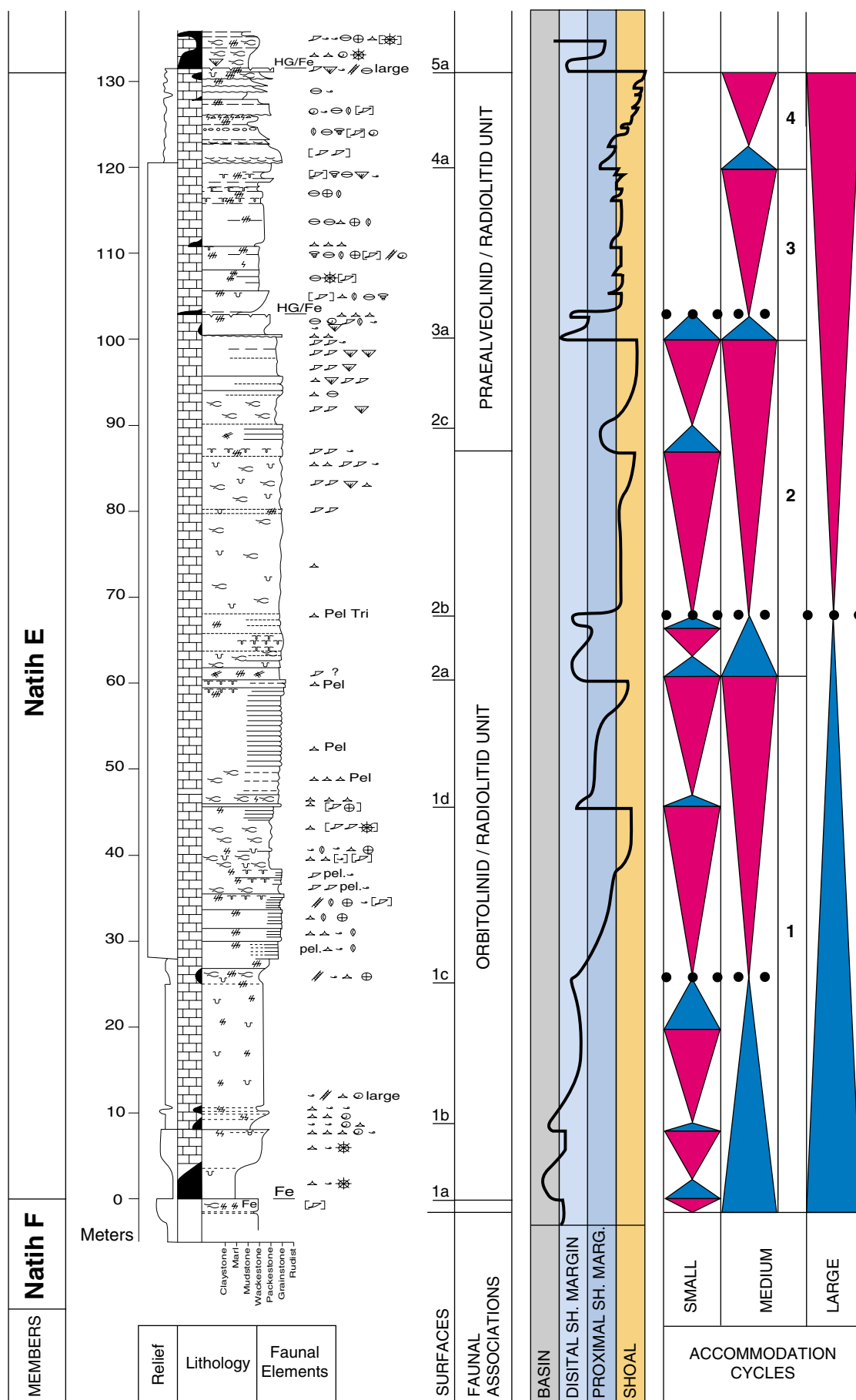


Figure 4a: Lithological log of Jabal Madar 1 section: lower part (Natih E).



Figure 4b: Lithological log of Jabal Madar 1 section: upper part (Natih D/B).



Figure 5a: Outcrop picture of the lower part of the section in the core of Jabal Salakh (section 1) in the Adam Foothills. From right to left the Nahr Umr, Natih G, F and E members are exposed. Note the fine bedding at the base of sequence 1 of the Natih E Member.



Figure 5b: The upper part of the section, showing exposure of the Natih B (sequence 8), C (sequences 6 and 7) and D (sequence 5) members.

Figure 7 shows a schematic diagram of the distribution of the various facies along a paleo-bathymetric profile. It depends mainly on physical sedimentological features such as horizontal bedding pattern, clinoforms, cross-bedding and grain size, combined with faunal associations from Philip et al. (1995). Each main environment is represented by several facies which show lateral transitions. Vertical transitions are normally more abrupt, and are bounded by surfaces (see below). Estimation of the exact paleo-bathymetry of the individual facies is complicated due to the combined influence of sediment supply / production, faunal response, and physical conditions. These aspects will be dealt with in detail in a paper elsewhere. For variations of faunal associations along a paleo-bathymetric profile see Philip et al. (1995).

The Intra-shelf Basin

Two main types of intra-shelf basinal deposits are distinguished: decimeter-bedded, oyster-bearing, organic-rich, limestone / shale couplets, and a clayey-marl facies with some limestone beds.

The limestone layers in the limestone / shale couplets vary in thickness from 5 centimeters (cm) to more than 1 meter (m). They consist of mudstone, wackestone or packstone and are often bioturbated. The bioclasts are mostly well-preserved oysters (*cerastostreon* and '*exogyres*'), and monospecific bivalves (often in, or close to life position). Some beds are particularly enriched in solitary corals. The clayey interbeds are thinner (several cms to 40 cm) and often laminated. They contain a poor fauna and can be organic-rich. First Rock-Eval results have given maximum values of 1.50%, with low Hydrogen Index values (<110), suggesting an over-mature organic facies. Pelagic elements are common in these couplets, with reported occurrences of planktonic foraminifera, planktonic echinoderms (*Saccocoma*), planktonic bivalves ("filaments") and calcispheres (Philip et al., 1995). This type of facies occurs in the Natih E and Natih B members (sequences 1 and 8 in Figure 8).

The second type of intra-shelf basinal deposits are clayey, yellow to green marls without any bedding pattern. When more clay-rich, they contain a poor fauna (large gastropods, bivalves), but when more carbonate-rich they contain a more diverse fauna (including echinoids, gastropods, etc.). They grade into bioclastic wackestones to packstones capped by iron-rich hardgrounds. This facies only occurs in the Natih D Member and at the top of the Natih C Member (Figure 8b).

The Distal Shoal Margin

This environment shows a strong lateral variability in the bedding pattern, which may vary from well-bedded at the decimeter-scale in the relatively distal position, to meter-scale bedded in the more bioturbated proximal position. Facies is dominantly mudstone with a generally scarce fauna (some gastropods), but meter-scale beds may contain more fossil debris and (prae-) alveolinids, and classify as wackestones. The decimeter-scale bedded facies can be very rich in chert, which normally follows the bedding planes and occurs either as semi-continuous blankets, or as isolated nodules. Microscopic observations of this facies showed the presence of sponge spicules, echinoids, red algae, annelids and small benthic foraminifera (Philip et al., 1995).

The decimeter-scale bedded, fossil poor mud- to wackestones show basinward transitions into either the decimeter-scale bedded, oyster-bearing limestone / shale couplets (lower part of the Natih E Member and Natih B Member; Figure 8), or transitions into the decimeter-scale bedded, chert-rich facies (the middle part of Natih E Member and the Natih A Member; Figure 8).

The Proximal Shoal Margin

In the proximal margin two facies types are distinguished, a low energy one, which is relatively muddier and bioturbated, and a high energy one, which is clean, coarse-grained bioclastic and cross-bedded.

The low energy facies consists of wackestone to packstone, comprising bioclastic debris, peloids, benthic foraminifera (*Orbitolina*, miliolids), and rudist and oyster fragments. Decimeter-scale bedding is rarely preserved and bioturbation is common. This facies is found in the relatively deeper position. The high energy facies consists of well-sorted, fine to coarse bioclastic grainstone. Small- to medium-scale cross-bedding features are normal, bedsets vary from one decimeter to up to a meter. Sigmoidal cross-bedding has been observed, suggesting tidal influences. This facies is found in the relatively shallower position.

At a larger scale (hundreds of meters) the proximal shoal margin facies are organized in low angle clinoforms, which show a basinward transition from the cross-bedded high energy facies to the bioturbated low energy facies.



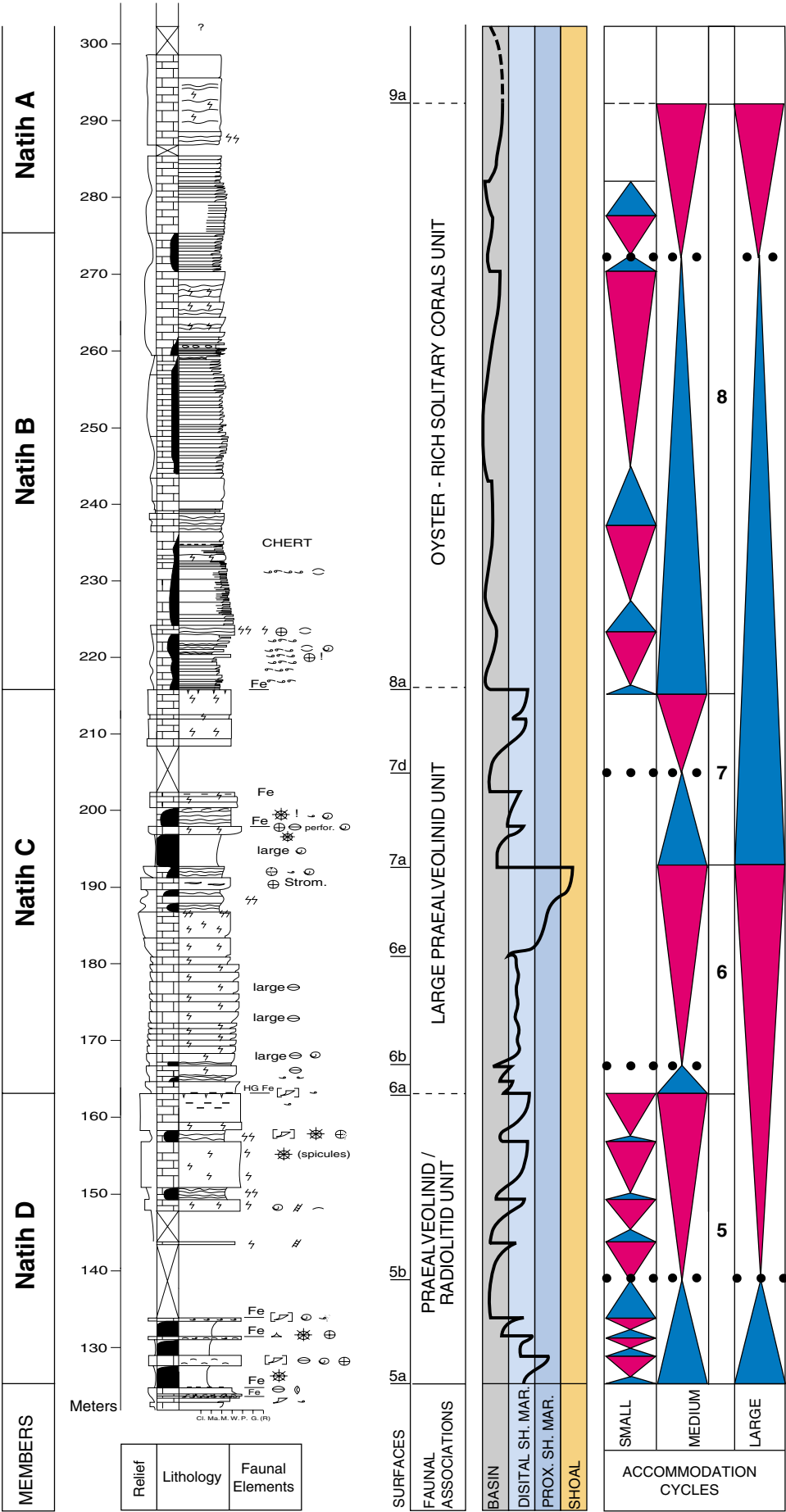


Figure 6b: Lithological log of the Jabal Salakh 1 section: upper part (Natih D/A).

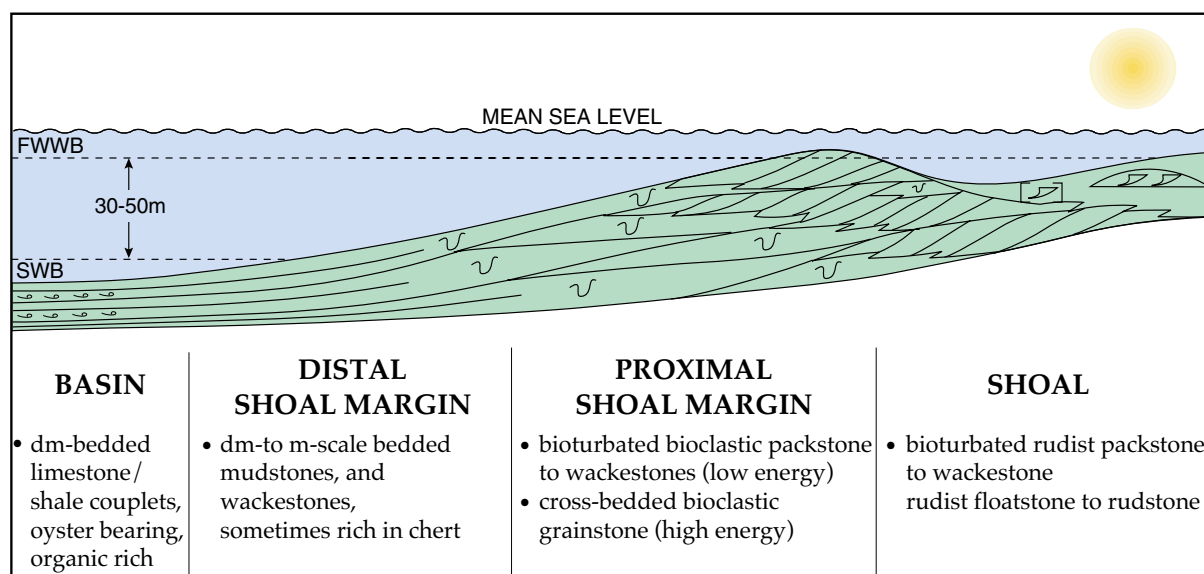


Figure 7: Schematic figure of the intra-shelf environments encountered in the Natih Formation. (FWWB=Fair weather wave base; SWB=Storm wave base)

The Shoal

The shoal environment consists of wackestones to packstones with a rich faunal association dominated by rudists (Philip et al., 1995). It is organized in several-decimeter shoaling upward cycles, marked at the top by bioturbated levels, and locally mudcracks have been observed. *Thalassinoides* ichnofacies are common. Burrows are often dolomitised, and sometimes filled with sparry calcite. Locally flat, several-decimeter thick rudist-coral biostromes occur. The faunal association is dominated by rudists (*Radiolitidae*, *Caprinidae*, *Ichtyosarcolithes*) with an admixture of benthic foraminifera (praealveolinids, miliolids, *Chrysalidina*), echinoids, various types of corals (solitary, encrusting), gastropods, oysters and other bivalves.

The Siliciclastic Coastal Plain

An interval with siliciclastic mudstones, siltstones and sandstones overlays the Natih Formation. Sandstones are organized in cross-bedded channel deposits. A coastal plain setting is inferred. The change from the coastal plain deposits to the pelagic Muti marls is marked by a several-decimeter thick package of iron-ooliths.

Surfaces

Major Stratigraphic Hiatus

A major subaerial erosional surface marks the top of the Natih Formation in the Jabal Madar area (Figure 8b; surface 12). Here the open marine limestones, dated as upper Cenomanian (Philip et al., 1995) are unconformably overlain by a 9 m thick package of siliciclastic coastal plain deposits of Turonian to Coniacian age (Rabu, 1987). The origin of this surface is related to the large-scale tectonic reorganization of the area at that time (e.g. Patton and O'Connor, 1988; Burchette, 1993).

Subaerial Erosional Surfaces

Subaerial exposure probably occurred locally at the top of the Natih E Member in Oman. In outcrop, sparite-filled burrow systems, micro-breccia structures and mudcracks are evidence for at least short-term emersion. Wagner (1990) reported evidence for local meteoric diagenesis at this level in the subsurface of central Oman. Although no evidence for important karst-related erosion has been found at the top of the Natih E Member in the studied sections, local incision of the platform top has been observed at Jabal Madar. Erosional surfaces were found at two levels, down cutting for several meters (maximum of 7 m) into the platform top. They have the shape of a shallow channel, and are filled with several phases of hummocky cross-bedded fine-grained grainstones alternating with burrow-mottled mudstones to wackestones.

Bioturbated Horizons

Carbonate packages or beds are often topped by intensely bioturbated horizons varying in thickness from one decimeter to a meter. Burrows are often dolomitised, sometimes enriched in iron, and occasionally filled with calcite spar. Thus these horizons are associated with surfaces at the top of packages which mark a temporary stop of sedimentation allowing their intense bioturbation, and the downward transportation of iron concentrated at the surface. In case of continuous submarine conditions, iron can be concentrated at the surface. When exposed, sparry calcite may form in the burrows, and subsequent flooding may enhance dolomitisation.

Transgressive Ravinement Surfaces

Ravinement surfaces indicate erosional or non-erosional marine flooding events, and are characterized by the (abrupt) deepening of the sedimentary environment across these surfaces. Surfaces are not marked by important iron-concentration, but may be brought out by locally more bioturbated levels. They occur at the scale of the high frequency, small-scale depositional sequences.

Hardground Surfaces

Hardground surfaces are marked by varying degrees of boring and bioturbation, and a concentration of iron on the surface and/or in the burrows. The amount of iron concentrated in and just below these surfaces varies from a several centimeter thick continuous crust to small, scattered nodules. The hardgrounds are a typical feature of the middle part of the succession, the Natih C and D members. Particularly well expressed are hardgrounds corresponding to surfaces 5a, 6a, 7a and 8a (Figure 8b), which can be followed in all the sections. In the lower part of the Natih D Member two hardgrounds occur which cap beds that are particularly enriched in iron. They are also correlatable in all the Foothills sections. The hardgrounds are interpreted as important flooding surfaces indicating deepening and a temporary starvation of sediment.

Maximum Flooding Surfaces

Maximum flooding surfaces are characterised by an increase in the clay content and a maximum of the transgressive shift of the facies belts. They do not show a condensed nature in the studied area, since the entire succession stays in the carbonate shelf domain. Faunal elements indicating a deepening of the environment, such as ammonites and abundant echinoids, are often associated with these surfaces.

Paleo-bathymetric Curves and Accommodation Cycles

Based on the facies interpretation and identification of surfaces paleo-bathymetric curves have been constructed for the studied sections. Figures 4 and 6 show these curves for the Jabal Madar and Salakh sections. They are an essential step for the determination of the increase and decrease of accommodation space, and the establishment of an hierarchical order in the depositional sequences. Three-dimensional information of the paleo-bathymetric evolution is one of the key sources of information in shallow carbonate platforms.

SEQUENCE STRATIGRAPHIC MODEL

The sequence stratigraphic model for the Natih Formation in the Foothills area is presented in Figure 8. The informal lithostratigraphic nomenclature of members as defined for the subsurface by Gigon (1967; internal company report), Tschoop (1967), Hughes-Clarke (1988), Scott (1990) and for the outcrop by Philip et al. (1995) has been adapted here. The model is divided into two parts, the first covering the upper Natih F Member and the Natih E Member, datumed on the top of the Natih F Member (surface 1a; Figure 8a); and the second covering the Natih A to D members, and datumed on the top of the Natih C Member (surface 8a; Figure 8b). The biostratigraphic dating is based on Smith et al. (1990), Kennedy and Simmons (1991), Philip et al. (1995) and some new finds. Three orders of depositional sequences are distinguished.

Large-scale Depositional Sequences (3rd Order)

The organization of the Natih Formation in longer term shoaling upward sequences has been described in several studies (e.g. Harris and Frost, 1984; Scott, 1990; Burchette, 1993; Philip et al., 1995). Generally

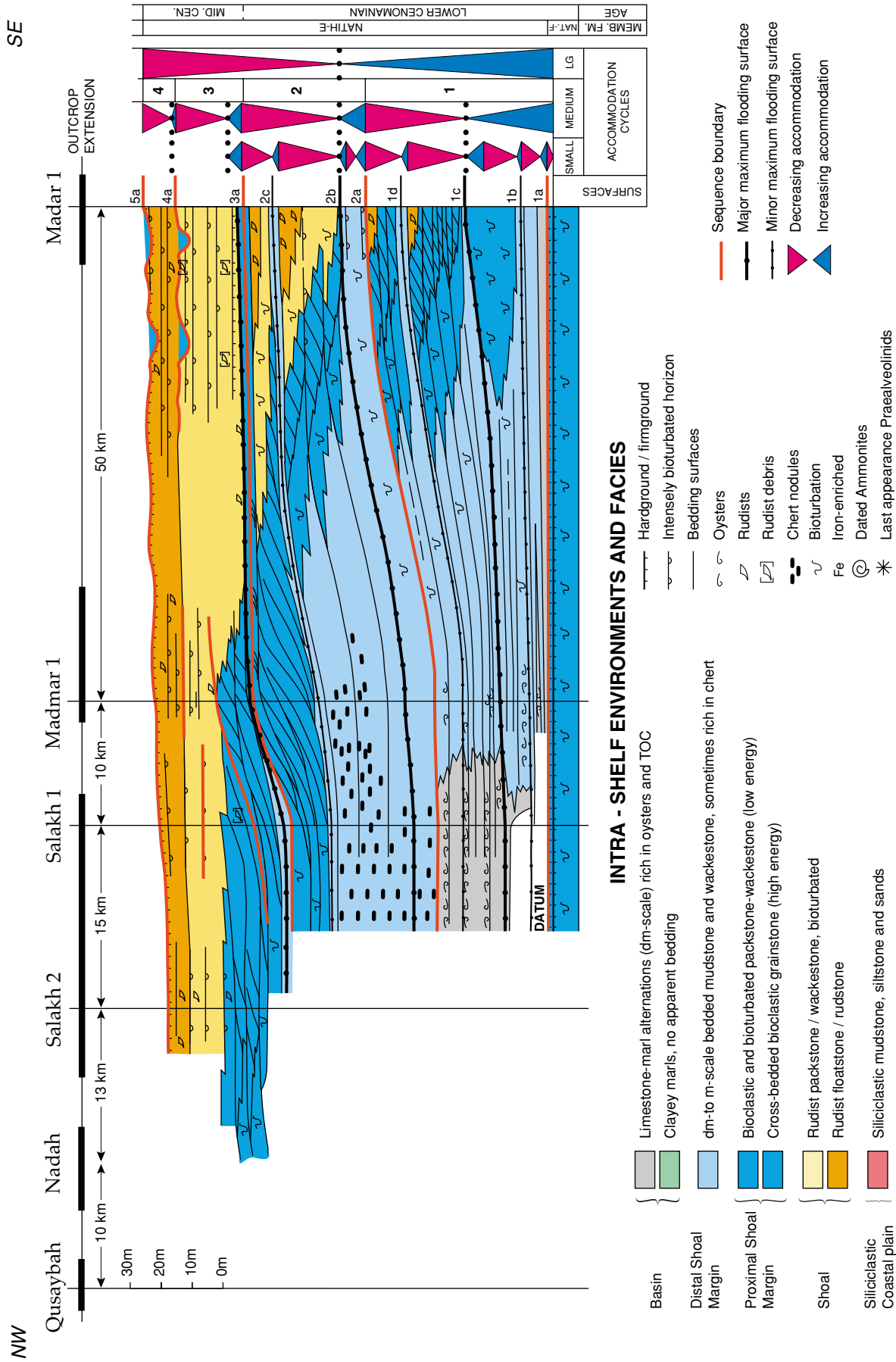


Figure 8a: Outcrop correlation scheme for the Natih E Member in the Foothills area.



two main sequences are recognized: one corresponding to the Natih E Member, and a second covering the Natih A, B, C and D members. Here we follow a subdivision in three longer term (3rd order deepening-shallowing) sequences, corresponding to the Natih E Member, the Natih C and D members and the Natih A and B members (see also Scott, 1990).

The lower boundary of the Natih E sequence is formed by the top of the Natih F Member, which marks the end of a shallowing-up trend in the Nahr Umr Formation. This trend is characterized at the top by bioturbated wackestones, interpreted as an inner-ramp to lagoonal environment. This same facies is found in the Salakh, Madmar, and Madar sections (Figure 8a), indicating relatively uniform shallow water conditions at that time in the Foothills area. The boundary is represented by iron-enriched, bored surfaces which overlay intensely bioturbated horizons. The upper boundary of this sequence is the top of the Natih E Member. The top is marked by a major hardground with a thick iron crust (1 decimeter). In the subsurface, geochemical analysis indicates local (!), longer term, exposure of the Natih E platform (Wagner, 1990). The upper part of the Natih E in outcrop is characterized by meter-scale shallowing-up cycles, with evidence for only temporary subaerial exposure (mudcracks, sparite-filled burrow systems).

During transgression of the Natih E sequence an aggradational trend develops, with the construction of a shallow water carbonate platform and the deposition of oyster-bearing, organic-rich limestone / shale couplets in the adjacent intra-shelf basin (upto surface 2b in Figure 8a). Maximum topography reached in the Foothills area is in the order of 25 to 30 m over a distance of 75 km (without correction for compaction). This is followed during regression by a strong progradational pattern, bringing shallow water carbonate platform deposits at least as far as 80 km out into the basin. The long-term transgressive / regressive trend shows a distinct pulsed character, of three to four, lower order, smaller scale, sequences superimposed on the overall trend.

The facies show compositional and geometrical characteristics directly related to their depositional environments. The basinal deposits are fine-grained, well-bedded (decimeter-scale) and very continuous; the platform slope and margin deposits are coarser grained, bioturbated or cross-bedded, laterally discontinuous and organized in clinoforms; while the platform interior deposits are both coarse and fine-grained, organized in meter-scale shallowing-up sequences, which have at least a kilometer-scale lateral continuity.

The lower boundary of the Natih C/D sequence is the top of the Natih E Member as described above. Its upper boundary is a clear hardground surface, enriched in iron (surface 7a; Figure 8b), which marks a distinct environmental change from rudist biostromes, to intra-shelf basinal marls.

During deposition of the Natih C/D sequence there was little topography in the Foothills area, and facies are laterally very continuous. The environment varies from the intra-shelf basin to proximal shoal setting. The main deepening phase of this sequence occurs in sequence 5 (Natih D Member) which is very clayey, contains very iron-rich hardground surfaces and a deeper water faunal association (reappearance of orbitolinids, echinoids). In the upper part of this sequence a distinct rudist-coral biostrome unit developed.

The lower boundary of the Natih A/B sequence is formed by the above described hardground surface (surface 7a, Figure 8b). The upper boundary of this sequence is much more complicated, and represents a multi-phased erosional surface in Oman. It cuts deep in the Natih Formation at Jabal Madar, where probably all of the Natih A Member is missing, and corresponds to a hiatus of the Late Cenomanian and Early Turonian (Figure 8b). This surface is overlain here by siliciclastic coastal plain deposits and iron-ooliths of Turonian-Coniacian age. Further to the northwest, in Jabal Salakh 2, Jabal Nadah and Jabal Qusaybah, the Natih A Member is preserved as deeper water intra-shelf basinal facies, and has been dated as Early Turonian by ammonites (Kennedy and Simmons, 1991). The complex nature of this boundary is ascribed to the flexuring of the foreland bulge in the Turonian (Patton and O'Connor, 1988; Scott, 1990; Burchette, 1993; Pascoe et al., 1994). The surface is regionally overlain by the Muti marls, which are of Santonian age and mark a widespread regional transgression (Robertson, 1987).

The first transgressive phase of the Natih A/B sequence is represented by a marly facies (sequence 7) containing a deeper water fauna of ammonites and the abundant occurrence of a number of echinoid species (Smith et al., 1990). The sequence becomes richer in carbonate and very well-bedded in the

Natih A and B members. Individual decimeter-thick beds can be followed laterally for tens of kilometers, which become oyster-bearing and organic-rich in the basinward direction (similar facies as observed at the base of Natih E; Figure 8a). The regressive trend is only preserved in the northwestern part of the Foothills where decimeter-bedded cherty mudstones and wackestones coarsen up into grainstone units (compare with upper part Natih E). The grainstones indicate the progradation of the platform coming from the northeast (in Wadi Nakhr large-scale cross-bedded grainstones are found at the top of the Natih Formation: Philip et al., 1995).

Medium-scale Depositional Sequences (4th Order)

Ten medium-scale depositional sequences have been distinguished in the Natih Formation, of which four occur in the Natih E sequence, two in the Natih C/D sequence, and four in the Natih A/B sequence. They are bounded by major shifts of the facies belts either in a landward or a seaward direction.

Sequence 1 (Lower Natih E)

Sequence 1 represents the transgressive phase of the Natih E sequence. The flooding caused a major landward shift of the facies belts introducing intra-shelf basin conditions in the Foothills area. Over the course of sequence 1 a topographic relief of about 20 to 30 m is established between Jabal Madar and Jabal Salakh (uncorrected for compaction). The Jabal Madar section (Figure 4) is dominated by shoal margin and shoal facies with bioturbated packstones, cross-bedded grainstones and rudist wackestones. The faunal association is the orbitolinid/radiolitid unit (Figure 4). The Jabal Salakh section (Figure 6) consists of deeper water oyster-bearing limestone/shale couplets, enriched in organic matter (upto 1.50% TOC). This basinal facies is one of the source rocks for the Natih/Mishrif reservoirs, and has been recognized in the subsurface of Northwest Oman (Connally and Scott, 1987; Grantham et al., 1987; Scott, 1990). The faunal association is oyster-rich. The Jabal Madmar section takes an intermediate position, it is generally well-bedded, but with bioturbated intervals and is carbonate rich, with very little organic matter.

Sequence 2 (Middle Natih E)

The second sequence is characterized by a general increase of the carbonate content (no shaly interbeds remain), and at the top by a very strong progradational trend whereby thick grainstone deposits prograde 50 to 60 kms into the intra-shelf basin. Surface 2c (Figure 8a) is a downlap surface over which the clino-stratified grainstones prograded. The Jabal Madar section is again dominated by the platform slope to interior platform facies, with increasingly abundant presence of rudistids (orbitolinid/radiolitid and praealveolinid/radiolitid units). In the Salakh and Madmar sections the base of this sequence is represented by the abrupt change from oyster-bearing limestone/shale couplets to fossil-poor, cherty mudstones (the cherty/sponge spicule-rich unit). The thick interval of cherty mudstones corresponds to an aggradational phase, which is abruptly terminated by the clino-stratified, cross-bedded packstones and grainstones prograding over the downlap surface (surface 2a).

Sequences 3 and 4 (Upper Natih E)

The upper two sequences are taken together here, since their distinction and interpretation is not equally straightforward in all the sections. Sequences 3 and 4 consist mostly of shallow water carbonates and represent the shallowest water conditions on top of the carbonate platform in protected environments (the shoal). Many bioturbated horizons are present, sometimes with evidence for temporal exposure (mudcracks, dissolution micro-breccias, sparry calcite-filled burrow systems). These surfaces are at least continuous at the km-scale. The faunal association in these sequences consists of different rudist species (*Radiolitidae*, *Caprinidae*), benthic foraminifera (*Praealveolina*, *Oalveolina*, miliolids), corals, oysters, echinoids, bivalves and algae. Sequence 3 is less muddy, and mostly represented by rudist packstones to grainstones. Sequence 4 is characterized by a more muddy facies, with locally developed biostromes of rudist/coral floatstones to rudstones.

Towards the platform top evidence for erosion has been found locally (surfaces 4a and 5a). Shallow channel shaped features (tens of meters in width) cut upto 7 m deep into the shallow water platform cycles. These incisions are filled with multiple short-term cycles consisting of an alternation of very well-sorted, fine-grained grainstones displaying hummocky cross-stratification, and fossil-poor, burrow-mottled mudstones and wackestones. Two interpretations of these incisions are possible. The first option is that they are produced by high frequency sea level changes during a longer term turnaround

(change from lowstand to early transgression), when accommodation was minimal at the platform top. This would imply that the incisions are local features, not necessarily related to deposits along the platform margin. The long-term sequence boundary can in this case be placed at surface 4a. In the second option, the incisions are interpreted as lowstand erosion caused by marked eustatic falls in sea level. As a consequence these surfaces would represent medium-scale sequence boundaries, and may correspond to lowstand wedges at the platform margin. The shallowing up cycles at the platform top are in this case deposited during increasing accommodation. Additional data in a basinward direction is needed to choose between the two options. The top of Natih E is formed by a very well-developed hardground (see above), and sometimes overlain by fine-grained storm deposits.

Sequence 5 (Natih D)

This sequence is the first deepening pulse on top of the Natih E platform, with the introduction of a high amount of fine-grained siliciclastics (clayey marls) and the reappearance of deeper water faunal associations (orbitolinids, abundant echinoids). In the lower part a rudist-rich horizon (*Radiolitidae*) is found from Madar to Salakh, indicating a short-lived return of shallower water conditions. The two following beds are equally continuous, and have iron-rich hardground tops. They are interpreted as a progressive deepening to the maximum flooding surface (surface 5b, Figure 8b). In the upper part of this sequence a thickening upward trend of echinoid rich (spicules) wacke- to packstone beds occurs. These are a characteristic feature in outcrop and are easily followed from the Salakh 2 to the Madar 1 section ("Barre blonde"). They amalgamate towards Jabal Madar, suggesting a reduction of accommodation space in that direction. The top of this sequence is marked by an iron-rich hardground.

Sequence 6 (Lower Natih C)

The carbonate content is higher in this sequence. Only at the base, in the thin deepening interval, clay-rich interbeds are found in between hardground-capped wackestone beds (Figures 3 and 5). The middle part is formed by about 10 thick-bedded (several-decimeter), grey / brown weathered mud- to wackestone beds. They contain a faunal association of large praealveolinids, gastropods and bivalves in the northwest sections, and praealveolinids, oysters, echinoids and sparse rudist fragments in the Madar section. These beds are a characteristic feature in outcrop (Figure 6). The upper part of this sequence starts with an intensely bioturbated interval recognized in all sections (bed above surface 6c; Figure 8b). The top of the sequence shows rather significant lateral variations both in thickness and in composition. In Jabal Madar the bioturbated interval is directly overlain by an iron-rich hardground marking the upper boundary. From Jabal Madmar to Jabal Nadah a gradual thickening occurs of a very fossil-rich interval, which locally forms biostromes consisting of well-preserved rudists (*Radiolitidae*, *Caprinidae*, *Ichtyosarcolithes*), corals and stromatoporoids. Towards the top big oysters are found. At Jabal Qusaybah this unit not only comprises biostromes, but also high energy deposits (3 m thick, large-scale cross-bedded grainstone). These facies represent very shallow water conditions, and mark the top of the Natih C/D sequence. The upper boundary of the sequence is an iron-rich hardground surface recognized in all sections.

Sequence 7 (Upper Natih C)

Sequence seven is again clay-rich, with some meter-thick green to yellow marl beds. Echinoids can be particularly abundant, and in the lower part ammonites are common. Corals, perforated praealveolinids, oysters and fragments of rudists also occur. The echinoid marker bed defined by Smith et al. (1990) is probably located in this interval. In the deepening part of the sequence hardgrounds cap the limestone beds. Bioturbated mud- to wackestone beds form the upper part. The sequence terminates with an iron-rich hardground in all sections.

Sequence 8 (Natih B)

The boundary between sequences 7 and 8 marks a significant deepening, and transgressive shift of the facies belts. The sequence is on the whole carbonate richer, and marks a change in the sedimentary system. The decimeter-scale bedded, oyster-bearing, and TOC-rich limestone-shale couplets which were found at the base of the succession, in the lower Natih E Member (sequence 1), reappear here. Besides oysters, they locally contain abundant solitary corals and in situ bivalves. Laterally, in the direction of the shoal (southeast), they change to well-bedded, fossil-poor carbonate mudstones. The lateral continuity of the decimeter-thick beds is striking, and individual layers can be followed for several tens of kilometers. Also in a vertical sense this oyster-rich unit (Natih B) is very uniform, and represents a vertical stack. The Natih B Member has been informally described in the literature as the Fitri Formation (Rabu, 1987).

Philip et al. (1995) demonstrated that these beds are basinal equivalents of shallow water carbonates in the Jabal Akhdar sections. They are considered to be a major source rock for the Natih reservoirs in the subsurface (Connally and Scott, 1987; Grantham et al., 1987; Scott, 1990). Towards the top of this sequence the shaly interbeds disappear, and the system becomes almost entirely carbonate dominated. A package of eight carbonate mudstone beds (decimeter-scale bedding) can be followed bed by bed from Jabal Qusaybah to Jabal Madmar 1 (above surface 8a, Figure 8b), which suggests uniform environmental conditions prevailed at that time in all of the Foothills region. The boundary between the Natih B and Natih A members is put at the base of these beds, taking the decrease of the clay content as the discriminating criterion (cf. Scott, 1990).

Sequences 9 and 10 (Natih A)

The boundary between sequences 8 and 9 is not as sharp and well-defined as the previous ones. The limit is put at the top of a thick-bedded, bioturbated mud- to wackestone interval, which is overlain by thinner-bedded carbonate mudstones. They contain few fossils. Towards the maximum flooding surface these beds develop bioturbated firmgrounds marking the bedding planes (below surface 9b). They are abruptly overlain by nodular to wavy-bedded cherty packstones. Ammonites have been found in these facies, both in Jabal Salakh and Jabal Nadah. At Jabal Salakh, *Pseudospidoceras flexuosum* Powell (determination: G Thomel) of earliest Turonian age occurs at the base of the cherty limestones (Figure 8b). The cherty facies fines upward into wackestones and mudstones.

The boundary between sequences 9 and 10 in Jabal Qusaybah is put at the middle of a grainstone interval. In Jabal Nadah grainstones have also been found at the top of the section. In the Jabal Salakh 2 section a gradually developing coarsening-up trend has been observed. The interpretation of these sequences is complicated by the substantial removal of section during the Turonian, and by the present day erosion.

Siliciclastic Coastal Plain Deposits and Muti Marls

The surface at the top of the Natih Formation is a diachronous surface related to uplift of the initial peripheral bulge (Patton and O'Connor, 1988; Scott, 1990; Burchette, 1993). It corresponds to an angular unconformity in the Madar section, where an important part of the stratigraphic section is missing. Towards the south the erosional surface resolves in the continuous deposits of the intra-shelf basin (Burchette, 1993). Overlaying this surface are siliciclastic coastal plain deposits which contain in the upper part lenses of iron oolitic deposits. They are inferred to be of Turonian-Coniacian age. The system is sealed off by the major regional transgression in the Santonian, when the pelagic Muti marls were deposited regionally (Robertson, 1987).

Small-scale Depositional Sequences (4th to 5th Order)

Two types of small-scale depositional sequences have been found throughout the Natih Formation: (1) meter- to decameter-scale (10 m) shallowing up cycles, and (2) decimeter-scale (10 cm), high frequency cycles. The smallest scale sequences are best developed and preserved in open marine, low-energy environments, which do not suffer from regular erosional activity, and where continuous sedimentation prevails. These conditions are found in the intra-shelf basins, where even the decimeter-scale bedded mudstones and limestone/shale couplets are well preserved and can be followed individually for tens of kilometers. The slope and margin of the platform are less favorable environments for the preservation of the decimeter-scale sequences due to the high degree of bioturbation. Only the more significant changes in environment are recorded here (e.g. the medium-scale sequence boundaries). The interior platform setting is characterized by meter-scale shallowing upward cycles, sometimes with evidence for temporary subaerial exposure. They are less continuous laterally than the basinal cycles, but can still be followed for several kilometers.

DISCUSSION

The high resolution stratigraphic correlation of sections in the Foothills area allows the stratigraphic architecture of the Natih Formation to be established. An important observation is that there is an hierarchy of depositional sequences at several scales. At the large-scale, three longer term sequences are distinguished. Comparing the organization of these sequences, the similarity in facies order and geometrical aspects is apparent between the Natih E sequence, and the Natih B/A sequence. The second sequence, Natih D/C, is different in nature from the other two, in that it is generally much poorer in carbonate, and no topography is present in the Foothills area.

The lower part of the Natih E and Natih B/A sequences are carbonate-rich, and show decimeter-scale bedded mudstones which become oyster-bearing, clay and organic richer (intra-shelf basin). In the upper part an aggradational to progradational trend is observed in the Natih E Member. Present day erosion of the Foothills sections removed most of the upper part of Natih B/A sequence, only leaving some grainstone units to testify of the progradational trend. Better evidence for aggradation and progradation in this sequence is found in the sections along the northern flank of the Jabal Akhdar (Wadi Mi'Aidin to Wadi Nakhr: Figure 1), where platform interior and margin carbonates are found in the Natih A and Natih B members (Philip et al., 1995).

The question then arises in regards to the significance of the organic-rich intervals. These can be interpreted either as two individual events favorable for the production and preservation of organic matter (probably related to the global occurrence of black shales around the Cenomanian/Turonian boundary; e.g. Arthur et al., 1987), or the indication of seaward and landward migration of a specific environment continuously present in the intra-shelf basin during deposition of the Natih Formation. Regional correlation of the outcrop sections to the subsurface is required to determine the correct interpretation.

The boundaries of the medium, and a number of the small-scale depositional sequences, mark important lateral shifts of the facies belts, which can be clearly identified in the intra-shelf basinal, and shoal-margin deposits. These shifts are less easy to identify in the shoal environments itself, where the lack of accommodation space may have caused erosion and 'missed sequences'. However, based on the medium- and small-scale sequences, a stratigraphic framework has been constructed with a higher resolution than possible with classic biostratigraphic zonation.

Following the time-scale by Harland et al. (1990), the Cenomanian has a duration of 6.6 My and the Turonian a duration of 1.9 My. The three longer term sequences thus represent together about 8.5 My, suggesting that they are 3rd order depositional sequences (sensu Vail et al., 1991). A total of ten medium-scale sequences (accommodation cycles) were identified, implying an average duration of about 800,000 years. This characterizes them as very short 3rd order, or long 4th order sequences (sensu Vail et al., 1991). The small-scale sequences, such as the limestone-marl cycles, may go down to the 5th order sequences (Vail et al., 1991). These approximate calculations give a general estimate of the period involved in the deposition of the different sequences. Further detailed biostratigraphic work is required to refine these estimates.

Compared to the chronostratigraphic scheme for the Gulf Region presented by Burchette (1994; Figure 2) and the lithostratigraphy presented by Alsharhan and Nairn (1988) the three longer term sequences described in this paper correspond to the Wara-Mishrif Cycle. The lower boundary is formed by the top of the Natih F Member, which makes it an equivalent to the top of the Mauddud Formation in the Gulf Region. The regionally extensive Mauddud carbonate platform is overlain in Iraq, Kuwait and Saudi Arabia by fluvial and alluvial deposits, while in Qatar and the United Arab Emirates it is terminated by shallow marine, mixed carbonate-siliciclastic deposits. Biostratigraphic data is needed to determine the reliability of this correlation.

To assess the relative influence of tectonism, eustasy and climate on the sedimentation pattern in the Natih Formation a three-dimensional data set is ideally required. However some general conclusions can be drawn considering the Foothills area. The Natih E sequence shows remarkably little change in thickness between Jabal Madar and Jabal Salakh (131 and 126 m, respectively). This suggests that the depositional profiles observed in the Foothills area are purely the result of stratigraphic infill, where all geometries are created by the dynamics of the carbonate depositional system. In the Natih D/C sequence, the Natih D does not vary much in thickness (32 to 28 m), whereas the lower part of the Natih C Member (sequence 6) shows a considerable increase in thickness towards the northwest (36 to 66 m). This suggests that differential subsidence influenced sedimentation during deposition of sequence 6 in the Natih C Member. Variations of the total thickness of the Natih A/B sequence are difficult to evaluate due to the incompleteness of the succession (Figure 8b). Individual sequences show, however, some variations in thickness which may also be due to a differential subsidence of the intra-shelf basin. Sequence 7 (top of Member C) shows a thickness increase towards the northwest (13 to 26 m), sequence 8 (Natih B) shows some variation in thickness (58 to 71 m), while the Natih A Member is very incomplete.

The Cenomanian-Turonian stages are characterized worldwide by distinct eustatic sea level changes (Haq et al., 1988). In the absence of indications for major tectonic control, an influence of the eustatic variations in sea level can be expected on the Arabian platform. It is thus assumed that the top of the Natih E platform corresponds to the major mid-Cenomanian sea level drop, the Natih C/D cycle to a somewhat less dramatic, but equally well preserved eustatic variation and the transgressive trend observed in the third cycle to the Late Cenomanian/Turonian sea level rise. This trend characterized the sedimentation pattern all around the Tethys (Philip and Airaud-Crumière, 1991; Philip et al., 1989; Philip, 1994; Philip et al., 1995), which supports its eustatic origin. The regressive trend at the top of the studied sequence is interrupted by the flexuring of the foreland basin bulge causing local uplift and erosion (Patton and O'Connor, 1988; Scott, 1990).

So far we have no data to contribute to the debate on the role of longer term and short-term climatic variations influencing the sedimentation pattern in the Cenomanian.

The Natih Formation contains three main mineralogical facies, the dominantly carbonate-rich facies which are most common, the clayey-marl facies which are associated with iron-enriched hardgrounds and are characteristic of the Natih D and C members, and thirdly the organic-rich facies which is found at the base of the Natih E and in the Natih B Member. The increase of the clay or organic matter content can be either due to a decrease of carbonate production and a constant flux of organic matter and clay fractions, or an increase in organic matter productivity and clay influx at a constant production of carbonate. The interaction of the carbonate carbon and organic carbon producing organisms may have played a role in shifting from one to the other. Especially seen within the light of the globally enhanced organic carbon storage around the Cenomanian/Turonian boundary (e.g. Arthur et al., 1987) which seemed to develop gradually over the course of the Cenomanian (Herbin et al., 1987; van Buchem et al., 1995b), and caused a change in many biological communities, including the rudists (Philip and Airaud-Crumière, 1991; Ross and Skelton, 1993).

The consequences of this outcrop study for subsurface studies are:

- (1) a model for the Cenomanian carbonate system is provided which is predictive with regard to the distribution of reservoir and source rock facies. For example the source rock facies has been found in the lower part of two of the three long-term (3rd order) sequences, in an intra-shelf basinal position where it interfingers with normally tight mudstones and wackestones. In case of fracturing however, the mudstones and wackestones have reservoir quality, and are directly filled by the source system with which it interfingers (e.g. Natih Field: Whyte, 1995);
- (2) the high resolution framework permits the more precise definition of the lateral extent of facies, their geometries, width and heterogeneities, as well as the direction of facies belt shifts across surfaces; and
- (3) the sequence stratigraphic correlation provides a conceptual model to guide the correlations of the subsurface data, both with regard to the confidence level of the correlation surfaces, as well as the geometrical constraints.

Low angle margin geometries have been documented in the outcrop, including important lateral facies variations therein. Potential reservoir facies are found in the proximal shoal and shoal environments. Geometries of the higher energy coarse grainstone facies developed during deposition of the Natih E sequence from smaller scale (tens to hundreds of meters) sedimentary bodies during aggradation, to several kilometer long, decametric thick packages during progradation (Figure 8a). This type of facies represents the principal reservoir in the Mishrif fields in Dubai and Abu Dhabi (Jordan et al., 1985; Burchette and Britton, 1985; Pascoe et al., 1994). The meter-scale shallowing-up cycles at the top of Natih E, represent a much more discontinuous potential reservoir facies. In particular (meteoric) dissolution of the bioclasts, and notably of the aragonitic *Caprinidae*, may enhance reservoir quality. The organic-rich facies occur at two places in the Natih Formation (Natih E and Natih B) in an identical facies of decimeter-bedded, oyster-bearing limestone/shale cycles. It is presumed that these facies sourced part of the Natih reservoirs (Jordan et al., 1985; Connally and Scott, 1987; Grantham et al., 1987; Scott, 1990).

CONCLUSIONS

The stratigraphic architecture of the Natih carbonate system shows a strict organization in depositional sequences at different scales (hierarchy). Three longer term sequences are distinguished (3rd order), two of which show a remarkable similarity in the type, distribution and geometry of the facies (Natih E

and Natih B/A). They both contain source rock facies (decimeter-bedded, oyster-bearing, limestone/shale cycles) in the transgressive part of the 3rd order cycle, and potential reservoir facies (coarse-grained, cross-bedded, grainstones; shallow rudist floatstones and rudstones) in the progradational part of the cycle.

The Natih C/D cycle differs in that it is significantly more clay-rich and there is little depositional topography present (in the Foothills area). At the medium-scale, 4th order sequences are bounded by regionally correlatable surfaces marking lateral shifts of the facies belts. These surfaces, and those at an even finer scale (5th order) subdivide the system at a higher resolution than classical biostratigraphy.

Eustatic control is invoked as the main control mechanism for the 3rd order sequences. The development of intra-shelf basins and the complex, multi-storey erosional surface, at the top of the Natih Formation, are induced by the Cenomanian/Turonian compressional phase of the eastern passive margin of the Arabian craton.

The consequences of this study are that the subsurface distribution of reservoir and source rock facies can be predicted with a conceptual model. It increases the confidence level for correlation surfaces, allows geometrical relationships to be constrained, and quantifies the lateral extent, width and internal heterogeneities of both reservoir and source rock facies.

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