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Aptian faulting in the Haushi-Huqf (Oman) and the tectonic evolution of the southeast Arabian platform-margin

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ABSTRACT

A major upper Aptian unconformity is recorded on the eastern Arabian Platform, between the lower Aptian Qishn limestone and the Albian Nahr Umr marls. The study of this hiatus, in the western homocline of the Haushi-Huqf Uplift (Eastern Central Oman) provides new data about the evolution of the eastern Arabian Platform during middle Cretaceous times. The limestones of the Qishn formed a shoaling sequence, mainly composed of matrix-rich, coarse-grained sediment with small rudistids and algal build-ups, that led to a subemergent environment. A third-order sequence is recognized in the Qishn platform carbonates, which is partitioned into three minor sequences. The Qishn carbonate was subjected to pre-lithification normal faulting. A thick ferrugineous crust (hardground) covered the top surface of the Qishn as well as the faultscarps before they were buried under the Albian Nahr Umr marls. The faults are dominantly NW-trending, SW-facing, normal faults. The significance of the faulting remains hypothetical. The syndiagenetic NW-SE normal faults may correspond to 'en-echelon' faults, combined with a sinistral movement of the Haushi-Nafun Fault (HNF). The HNF acted as a left-lateral, strike-slip fault during late Cretaceous, pre-Maastrichtian times. This movement possibly began earlier, during the late Aptian. It could be related to the dynamics of the eastern Arabian margin during the Cretaceous (Masirah transform margin). There are some indications testifying to the activity of the Masirah transform fault during the early-middle Cretaceous. The margin kinematics may be responsible for the reactivation of nearby large faults affecting the platform basement (for instance the HNF). A slight sinistral reactivation of the HNF may have induced the development of the Aptian NW-trending normal faults. Moreover, the occurrence of early Cretaceous strike-slip movements in the Arabian Platform have already been envisaged, at a plate-scale, as a consequence of the South Atlantic extension. On this assumption, the Aptian fault blocks may have resulted from the development of a sinistral transtension along the HNF.

INTRODUCTION

The Haushi-Huqf Uplift is located in Oman on the eastern margin of the Arabian Platform, and forms part of a NNE-trending paleohigh from Ra's Al Hadd (easternmost point of Arabia) to Marabat near Salalah in Dhofar (Figure 1). Proterozoic granitoids form the Haushi-Huqf basement and these are overlain by upper Precambrian-lower Paleozoic sedimentary and volcanic rocks. Rocks of Late Silurian-Early Carboniferous age are absent in this region due to a long period of emersion and erosion. Deposition recommenced in the Late Carboniferous-Early Permian with the clastics related to the glaciation of the southern Arabian Peninsula and parts of Gondwana (Glennie et al., 1974). The Middle Permian part of the Khuff Formation marked the start of predominantly carbonate deposition over the Arabian Platform, that endured throughout most of the Mesozoic times.

Various episodes of faulting occurred during the Permian to Jurrasic periods. These are related to the development of the Tethyan rift and the extensional tectonics that mostly affected the northeastern margin of the Arabian Platform (Béchennec et al., 1993; Pratt and Smewing, 1993; Rabu et al., 1990). During this period, the Haushi-Huqf area was an uplifted region as evident from the stratigraphic record (Dubreuilh et al., 1992). Starting with the Triassic and Lower Jurassic (Liassic) succession, the corresponding section is either absent, or consists of relatively thin terrigenous continental deposits (Minjur Formation). The Middle Jurassic (Bajocian to Callovian stages) is only represented by relatively thin, shallow-marine deposits (Mafraq and Dhruma formations); while the upper Jurassic is altogether absent.

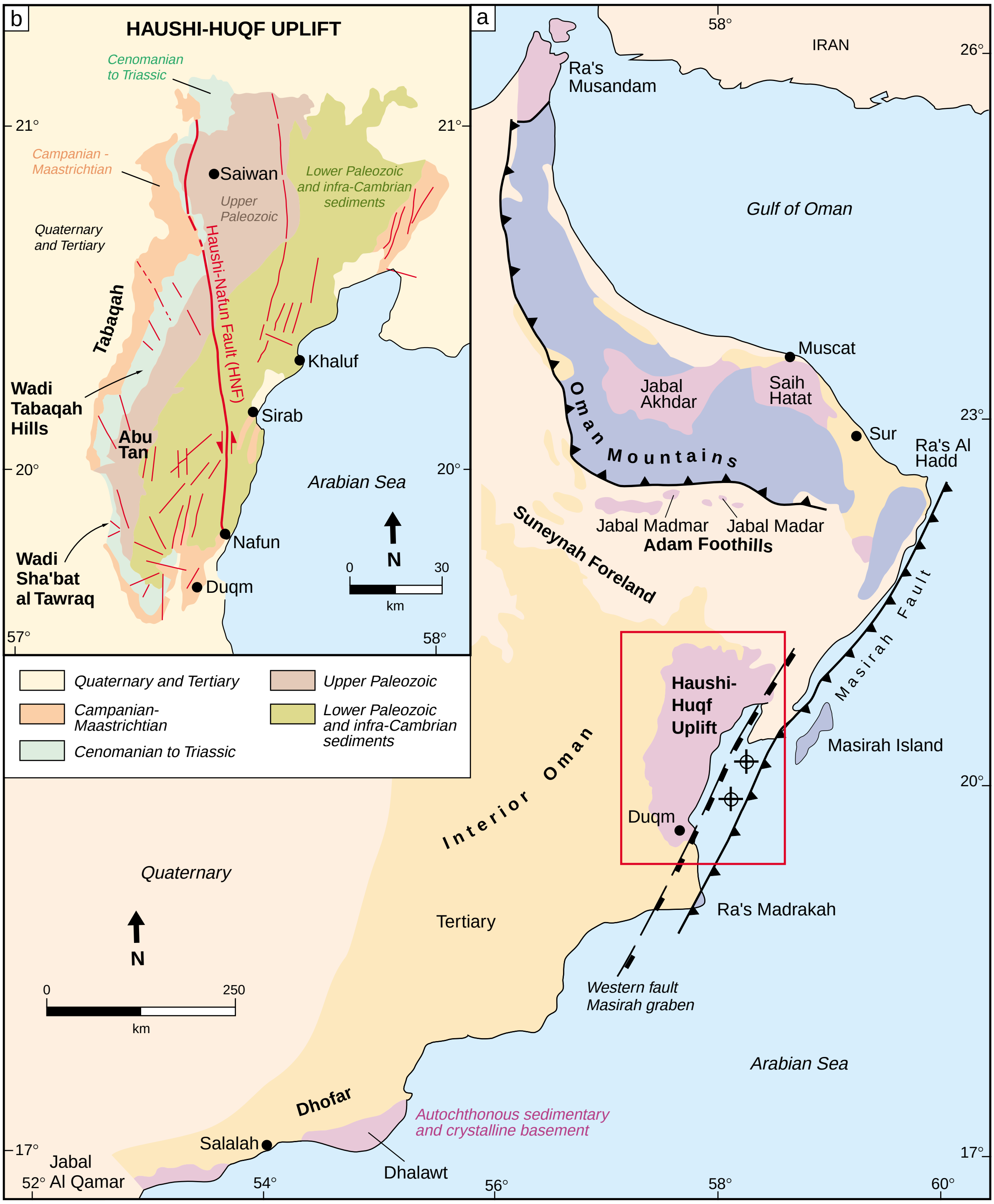

Figure 1: (a) Geological sketch map of Oman and location of the Haushi-Huqf Uplift. (b) Simplified geological map of the Haushi-Huqf, including the Haushi-Nafun Fault (HNF) (from Platel et al., 1994) and location of the studied area (Wadi Tabaqah, Abu Tan and Wadi Sha'bat al Tawraq).

The lower Cretaceous (Neocomian to Aptian) is composed of platform carbonates deposited in a shallow-marine environment (locally supratidal), and subject to notable variations in thickness. Dubreuilh et al. (1992) and Platel et al. (1992), mapped the lower Cretaceous interval as the Jurf (Neocomian-lowermost Barremian) and Qishn (upper Barremian?-lower Aptian) formations. The lower Aptian Qishn Formation in South Yemen (Cherchi et al., 1998), was also recognized and mapped in Dhofar (Platel et al., 1987), and the Haushi-Huqf area (Béchennec et al., 1993). The Qishn Formation approximately corresponds to the Kharaib and Shu'aiba formations, classically used for lithostratigraphic descriptions in other parts of Oman and in the United Arab Emirates (Alsharhan and Nairn, 1986; Hughes Clarke, 1988) (Figure 2).

According to various authors (Simmons and Hart, 1987; Scott, 1990; Hughes, 2000), the Kharaib-Shu'aiba boundary approximately corresponds to the Barremian-Aptian boundary. In the Haushi-Huqf Uplift, most of the Qishn Formation yielded a lower Aptian fossil association, and therefore most of it (about three quarters of the total thickness) could be approximately correlated with the Shu'aiba Formation. In the following description the term Qishn Formation or Qishn limestone is used to denote the Aptian limestone of the Haushi-Huqf Uplift. The lower part of the Qishn Formation (= Kharaib Formation) as the underlying Jurf Formation, is very reduced in thickness. This is consistent with wells drilled to the southwest of the Haushi-Huqf Uplift, where a thin Qishn Formation rests unconformably on pre-Mesozoic rocks (Platel et al., 1992). This paper is specifically concerned with the tectonic-sedimentary and tectonic events recorded at the top of the Qishn limestone.

In the Haushi-Huqf Uplift, the top of the lower Aptian Qishn limestone (Shu'aiba Formation) is covered with a widespread thick ferruginous hardground. The Nahr Umr Formation rests unconformably on this surface and consists of gray to yellowish silty marls, with abundant orbitolinids and epibenthic echinoids. The base of the Nahr Umr Formation is dated as early Albian, and its top as late Albian (Béchennec et al., 1993). The ferruginous surface corresponds to a late Aptian hiatus that is recorded in the eastern Arabian Platform: Dhofar, Central Oman, the Oman Mountains autochthon (Jabal Akhdar), Musandam and United Arab Emirates (Harris and Frost, 1984; Alsharhan and Nairn, 1986, 1988; Simmons and Hart, 1987; Scott 1990; Dubreuilh et al., 1992; Béchennec et al., 1993; Immenhauser et al., 2000a; Hughes, 2000; Sharland et al., 2001). The duration of this sedimentary gap is estimated to be about 1.5 to 2.0 million years (Harris et al., 1985; Pratt and Smewing, 1993).

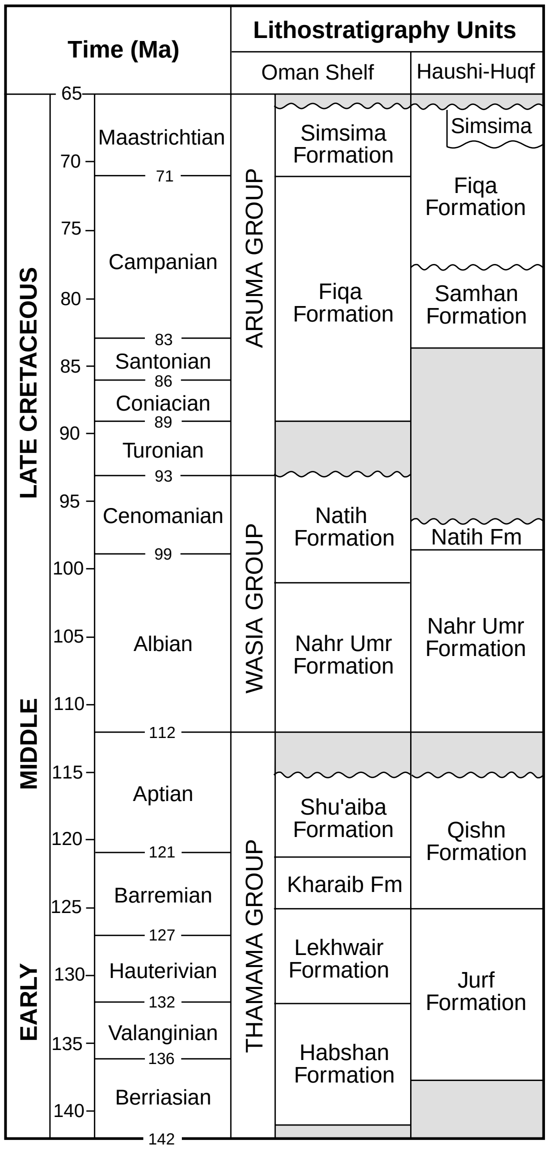

Figure 2: Cretaceous stratigraphic units of the eastern Arabian Platform. Gray intervals: regional unconformities and stratigraphic gaps. Ages in Ma, after IUGS International stratigraphic Chart (2002). (Note Boundaries of the early Cretaceous formations are subject to debate.)

In many places, the upper part of the Qishn limestone (Shu'aiba Formation) consists of rudist build-ups, and forms important reservoirs located immediately beneath the sedimentary break. The reservoir rocks display preserved primary porosity and/or solution-enhanced primary and moldic porosity. The hardground and the correlative sedimentary gap are attributed to different processes: emersion and erosion, non-deposition in a persistent marine environment, or polygenic evolution of marine hardground succeeded by subaerial exposure. Some authors (e.g. Frost et al., 1983; Harris and Frost, 1984; Harris et al., 1985; Alsharhan, 1987; Scott, 1990) attribute the porosity development to a short but pronounced late Aptian eustatic drop, during which subaerial exposure and dissolution by fresh water resulted in the leaching of rudists and other bioclasts. An alternative model attributes the development of porosity to the depletion of carbonate supply in sea water around the sequence boundary, without long-lasting emersion (Pratt and Smewing, 1993).

The ferrugineous surface (phosphatized or ferrugineous hardground in Jabal Akhdar; glauconitic level in Abu Dhabi; Alsharhan, 1987; Rabu et al., 1990) may also delineate a flooding surface related to a rapid drowning of the platform. The rapid drowning event may have been accompanied by the eastward tilting of the Arabian Platform. A tilted platform could explain the abrupt deepening recorded by the Nahr Umr deposits and the influx of terrigenous sediments that were eroded from the exposed western Arabian Platform. Scott (1990) suggests that a sea-level rise provided the major influence; while Pratt and Smewing (1993) favor the dominance of platform tilt. If platform tilting dominated, the comparison of paleodepth curves of the eastern Arabian Platform, around the Aptian unconformity, should show significant dissimilarities (see for example Pratt and Smewing, 1993).

In addition to the various interpretations outlined above, the Aptian unconformity in the Haushi-Huqf Uplift region also corresponds to an important faulting event (Montenat and Barrier, 2002). This event affected the Qishn limestone prior to lithification (synsedimentary and mainly syndiagenetic faulting). This paper focuses on describing this tectonic event.

SEDIMENTATION OF THE QISHN FORMATION LIMESTONE

In the Haushi-Huqf area, outcrops of the Qishn limestone show a succession of bright white, soft limestones, prominently exposed in cliffs and hills of the western homocline.

Facies

The studied sections (Figure 3a) are located to the west of Tabaqah (north of Abu Tan; 20°17’800 N; 57°26’800 E; Figures 4 and 5) and in the Wadi Sha’bat al Tawraq, 30 km southward (19°49’830 N; 57°22’200 E; Figures 6 to 12). They allow the main depositional features of the Qishn limestones to be identified (Figure 3b). The contact between the Qishn and the overlying Nahr Umr Formation is especially well exposed in Wadi Sha’bat al Tawraq (Section 2).

There are bioclastic limestones with a variable, often abundant micritic matrix and marly intercalations, few and far between. The northern section (Wadi Tabaqah) shows prevailing matrix-rich deposits (mudstone/wackestone) while grainstone/rudstone and floatstone are frequent to the south (Wadi Sha’bat al Tawraq). The different facies indicate an inner-shelf environment, related to a protected bay head, probably a backshoal area, with banks built by small rudistids and/or calcareous algae (*Lithocodium agregatum* and/or *Salpingoporella*) and periodically subject to storms (see below). The recorded facies range from subaerial deposits (paleosoil with root traces), to infralittoral grainstone (hydraulic dunes), and infralittoral mudstone/packstone (muddy littoral area with sponges, various mollusca, miliolids, orbitolinids, etc). Accumulations of small rudistids are frequent at the top of the Qishn limestone (Figure 7) where they form elongated, flat shell banks, somewhat like oysters. These shallow, backshoal sediments, associated with flattened rudistid/algal shoals, form the prevalent, widespread facies of the Qishn or Shu’aiba formations, in Oman and the United Arab Emirates (Alsharhan, 1987; Hughes, 2000).

Remarkable sedimentary surfaces

Various salient sedimentary surfaces have been recognized and used for correlation and sequence partitioning of the sections.

Wadi Sha’bat al Tawraq Section (Figure 3, 6 to 12)

(1) *Transgressive surfaces (TS)*: The TS_1 corresponds to the top of a yellowish dolomitic limestone, which correlates with the top boundary of the Kharaib Formation (Figure 2). TS_2 is located on the top of a paleosoil (root traces); TS_3 is located on the top of a bed bearing tidal structures (cf. above) and poorly exposed; TS_4 corresponds to an indurated and bored surface (bioerosion due to *Polydora* polychetids) bearing encrusting fauna (ostreid) and covered with a ferrugineous crust. The hardground developed contemporaneously with the faulting of the Qishn limestone (see below). It corresponds to a forced transgression surface.

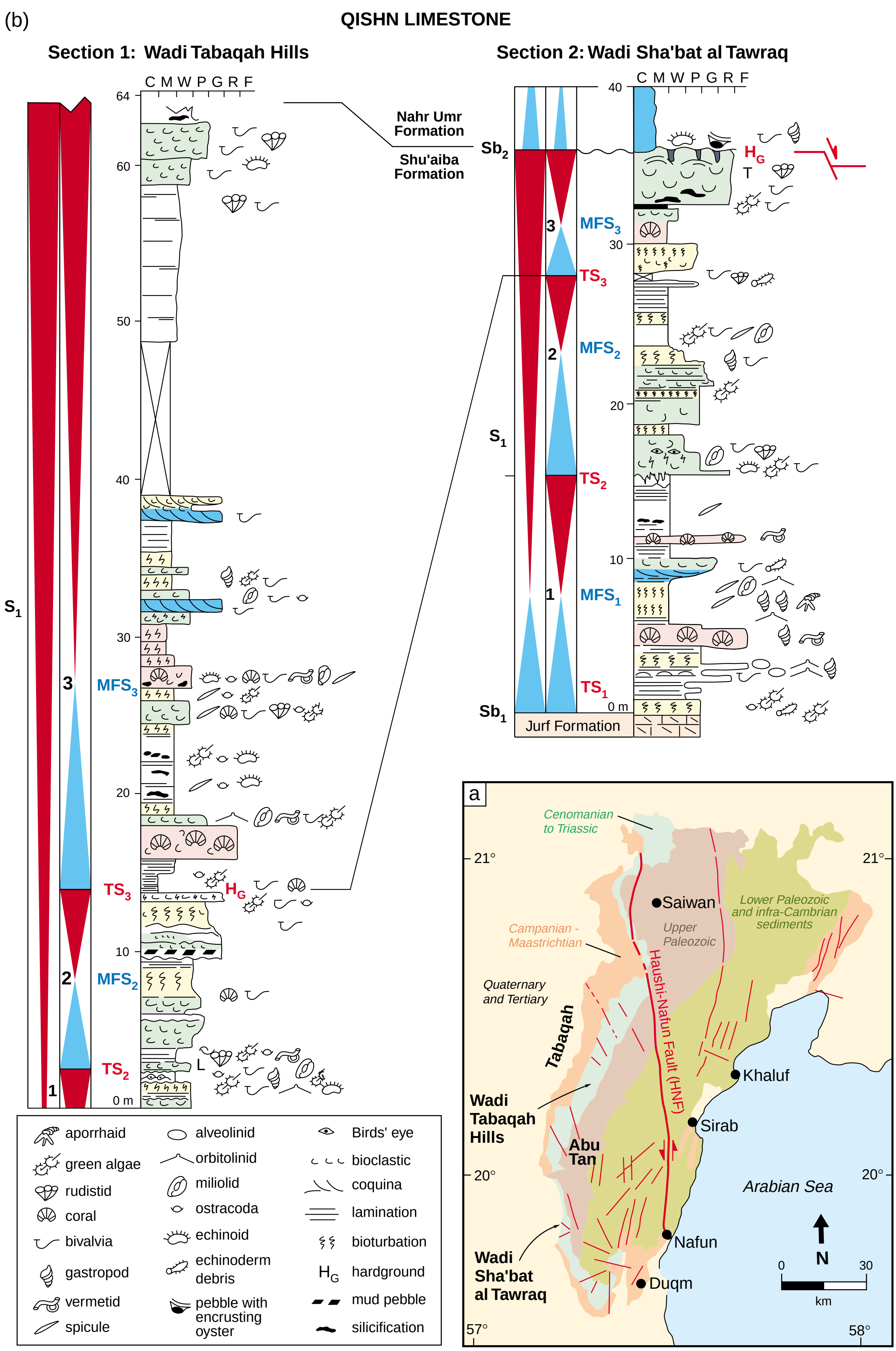

Figure 3: Sections of the Qishn limestone (early Aptian). Sedimentological characteristics and sequential units. (a) Location of sections. (b) Depositional sections: 1. Wadi Tabaqah Hills 2. Wadi Sha'bat al Tawraq.

WADI TABAQAH HILLS

Figure 4: General view of the whitish, soft Qishn limestone beds in the Tabaqah hills.

Figure 5: The Qishn limestone of Tabaqah Hills. The top of the dark limestone bed corresponds to the hardground of TS_3 in Figure 3, Section 1.

(2) *Maximum flooding surfaces (MFS)*: As mentioned above, these surfaces are defined with reference to the bathymetric data given by the faunal associations. For example, the first MFS corresponds to the deepening indicated by the fauna including turritellid-aporrhaid gastropods and an association of benthic foraminifera, orbitolinids, alveolinids and miliolids, that characterizes the transition between lower infralittoral and upper circalittoral environments (about 50 or 60 m depth).

Echinoids give interesting indications. They are represented solely by spat tests belonging to a globular *Toxaster*. The majority of the species of the *Toxaster* genus are characteristic of the upper circalittoral environment. However, during transgressive episodes (TS and MFS), they can temporarily invade the infralittoral environment, as occurs here; these *Toxaster* rapidly disappear after brief invasion periods (unpublished data from the middle Cretaceous of the Adam Foothills).

Wadi Tabaqah Section (Figures 3 to 5)

(1) *Transgressive surfaces (TS)*: The TS_1 is not visible in this section; the TS_2 is located close to the base of the section, on the top of a bed including tidal subemergent birds'eye structure; TS_3 is a ferrugineous hardground underlying gray marls that contain infralittoral organisms (ostracods, dasyclad algal and madreporaria).

(2) *Maximum flooding surfaces (MFS)*: The MFS_1 is not visible on this section; MFS_2 and MFS_3 correspond to levels that show the most abundant and diversified infralittoral faunal association, related to the deepest environment.

The upper Aptian-Albian unconformity

In the Wadi Sha'bat al Tawraq area, the unconformity between the Qishn and Nahr Umr formations is intensified and complicated as a result of an episode of faulting that occurred before the Qishn limestone was completely lithified (Figure 6). The study of the deposits located just below and above the unconformity gives interesting additional data.

The carbonates that directly underlie the hardground display two main facies:

(1) Aggradational deposits are boundstone with rudistids and *Lithocodium aggregatum* and/or floatstone with *in situ* rudistids, *Lithocodium* and few *Vermetus* debris (Figure 7). The matrix, locally developed, may include birds' eye structures with indication of an early cementation. A related facies is a packstone-wackestone with *Salpingoporella*, miliolids, textularids, *Praechrysalidina infracretacea*, various mollusc fragments and probable *Characea*; it includes a larger amount of micritic matrix with birds' eye structures. These deposits are related to a subemergent inner shelf (bay head) with a low-energy depositional environment and lagoonal influences.

WADI SHA'BAT AL TAWRAQ

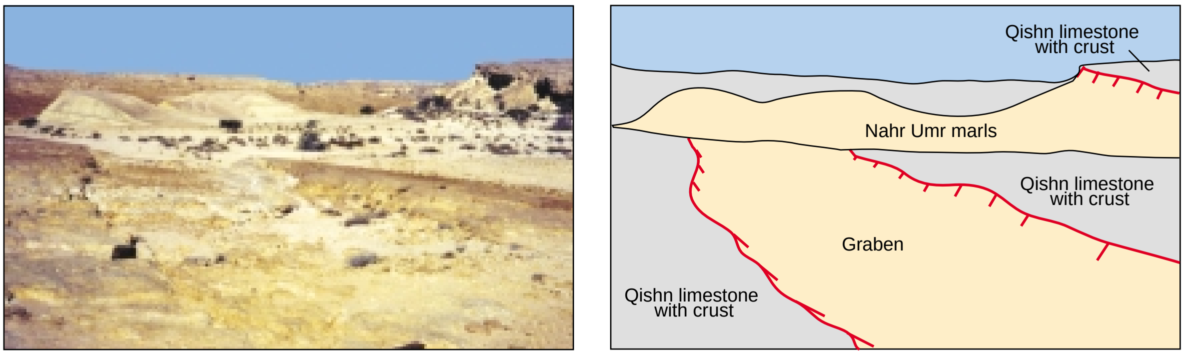

Figure 6: General view of the outcrops at Wadi Sha'bat al Tawraq. Foreground: small graben resulting from syndiagenetic NW-SE faulting of the Qishn limestone, covered with ferruginous paleo-crust. Background: the yellowish Nahr Umr marls rest on the faulted Qishn limestone. To the right: the Nahr Umr marls rest against a palaeofault scarp.

Figure 7: Small rudist and algal build-ups in the uppermost part of the Qishn limestone (Wadi Sha'bat al Tawraq).

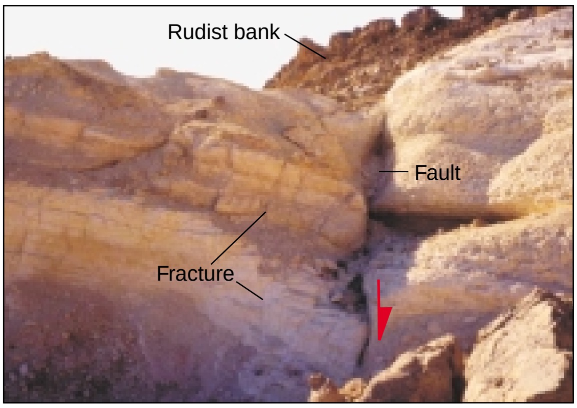

Figure 8: Upper Qishn matrix-rich calcirudites (white) and rudistid bank to the top (dark), (Wadi Sha'bat al Tawraq). The fault and associated small synthetic fractures are the continuation at depth (about 4 or 5 m) of a syndiagenetic fault which affected the top surface of the Qishn. Downthrown side is to the right.

(2) Storm-related deposits display a brecciated character with broken and reworked fossils and frequent intraclasts: floatstones and packstones with fragments of rudistids, *Lithocodium*, echinids and textularids. The intraclasts are mud balls and various reworked fragments of early lithified sediments including ooids with sparite cement of beach rock. These deposits are related to a very shallow-marine environment, and probably result from the reworking of pre-existing deposits by storms: rudistids/algal bank, beach-rocks and secondary reworking of previous storm-derived deposits.

These deposits show some evidence of early lithification, grain solution and recrystallization with local geopetal structures. There is no terrigenous influx. The limestone shows silicified and dolomitized patches. On the other hand, the Qishn carbonates were not subject to pronounced erosion and karstification processes before being capped with the ferruginous hardground. Indications of long-lasting subaerial exposures, which are shown elsewhere (for example, northern Oman; Immenhauser et al., 2000a), are not exposed here.

The ferruginous hardground resulted from two concomitant phenomena:

(1) Induration of the surface sediments; and (2) formation of the ferruginous crust. The surface sediment was at first burrowed (soft consistency of firm ground), and subsequently bored by polychetids when indurated, prior to being covered by the ferruginous crust. The different stages of bioturbation: burrowing and then bioerosion due to boring by organisms, succeeded

each other without any evidence of interruption due to a general emersion and related dissolution process. The ferrugineous crust (iron oxides), some millimeter to one centimeter thick, may include small limestone intraclasts. The oxides diffusedly penetrated and locally substituted the limestone on bed surfaces as well as on fault planes (see below). Moreover, they obliterated small holes due to previous boring by organisms.

The deposit that directly overlies the hardground (Figure 6)

This is a sandy and marly wackestone with orbitolinids, miliolids, echinid fragments and bivalves, of early Albian age (Nahr Umr Formation), related to an upper circalittoral environment (about 60-80 m depth). It is worth noting that an important terrigenous component (clay, silt and fine quartz sand) appears at the very beginning of the post-hardground sedimentation; these clastics are totally absent in the underlying Qishn limestone. However, it must be noted that an Albian fauna collected at the base of the Nahr Umr is composed of organisms that lived on a hard substratum devoid of muddy sediment. The Echinoid fauna associated with hardground is very particular. In fact, although the base of the Nahr Umr Formation is generally poor in macrofauna and comprises essentially molluscs and gravel-filtering, Echinoids (*Coenholectypus khamarensis*) together with some limivorous species (*Epiaster* sp.) and a few persistant opportunists (*Tetragramma variolare*), here it is the tests (whether whole or fragmented) and radioles of regular Echinoids which dominate: *Tetragramma variolare*, *Polydiadema tenue*, *Orthipsis aff. ruppelli*, long and fusiform radioles of the *Hemicidaridae* type which may belong to the genus *Emiratia*. These hardground forms lived in the photic zone (most likely in the upper regions) and whose diet consisted primarily of epiphytes which they ingested by grazing the sea bed. The limivore species (*Toxaster* cf. *radula*) only appear in the upper marine zones. This fauna, living on a hard substratum prior to the deposition of the Nahr Umr muddy sediment, does not provide any biostratigraphic argument for dating the base of the Nahr Umr Formation as older than the early Albian (i.e. uppermost Aptian as stated by Immenhauser et al., 2000b, for northern Oman).

Depositional sequences and high-resolution sequence stratigraphy

Facies are arranged in decimetric to metric parasequences composed of alternating muddy, bioturbated and coarse-grained, high energy sediments. These genetic units correspond to the fifth-order sequences. Their stacking forms the decametric-scale, fourth-order sequences. These combine to form the third-order depositional sequence (S_1) several tens of meters thick terminating with sequence boundary Sb_2 (Figure 3b).

The stacking facies observed in both sections indicate the same general evolutionary trend for S_1: a short transgressive interval that rapidly reached the maximum depth (MFS_1) around the infralittoral/ circalittoral boundary (about 50 m depth) and a long regressive interval. This regressive interval may be divided into two fourth-order sequences, the latter being notably thicker to the north (Figure 3b). The Jabal Mustaqbis section, located about 90 km to the south of Abu Tan (Platel et al., 1992), shows the same organization of the fourth and third-order sequences. The transition from the Qishn limestone to the Nahr Umr marl corresponds to the interruption of the general regressive trend, probably without reaching a prolonged emersion, but with the sudden flooding of the area in a circalittoral environment (about 60-80 m depth).

In the Haushi-Huqf Uplift, the lithostratigraphic units globally related to the Thamama Group include various sedimentary gaps and are not accurately defined. Therefore, general correlations based on sequence stratigraphy remain questionable.

The maximum depositional depth of the Qishn limestone was reached close to the base of the section (the MFS_1; early Aptian) (Figure 3b). It may be tentatively correlated with the MFS K70 (Sharland et al., 2001). The inferred MFS_2 and MFS_3 of the studied sections are also located in the early Aptian. Nevertheless they are poorly characterized. Thus, correlations with the MFS K80 remain hypothetical and are not proposed. It is possible that the MFS K80 is included and merged into the sedimentary hiatus that corresponds to the ferrugineous hardground overlying the top Qishn carbonates. According to Sharland et al. (2001), the MFS K90 may correspond to the contact of the hardground with the orbitolinid-rich marls of the Nahr Umr Formation (early Albian).

SYNDIAGENETIC FAULTING OF THE SHU'AIBA LIMESTONE

Various outcrops expose the Shu'aiba limestones and the overlying ferrugineous hardground, complicated by faults. The top limestone bed, the fault planes and numerous heaps of brecciated and pillowed limestone are coated with the ferrugineous crust and buried in the Nahr Umr orbitolinid-rich marls. A relevant example of the faulting that obviously occurred prior to the Albian sedimentation is exposed around the Wadi Sha'bat al Tawraq, about 20 km to the south of Abu Tan (Figure 1).

The faults are of various sizes: from one meter to hundreds of meters long; from one decimeter to ten meters of vertical throw. The faults almost exclusively trend NW-SE to WNW-ESE (N 120° to N 150°) with throws down to the SSW or SW (Figure 13a). The large range of fault plane dips (between 45° and 90°) results either:

(1) from syn- or post-faulting tilt (~20°);

(2) from the rheology of the carbonate sediment (various degrees of lithification) when subjected to faulting. Striae and grooves indicate mostly dip-slip movement (pitch between 70° and 85°). A few small transverse faults (trending N 20° to N 45°) act as a relay in the NW-SE fault system. All faults show various features that characterize early syndiagenetic fractures:

(3) the large sinuous faultscarps are usually made of coalescent step faults and scissor faults (Figure 9);

(4) numerous small, spoon-shaped, hydroplastic faults display 'soft' striae with a crumpled aspect due to secondary creeping of the incompletely lithified striated carbonate. These fault planes are devoid of striated calcite (Figure 10);

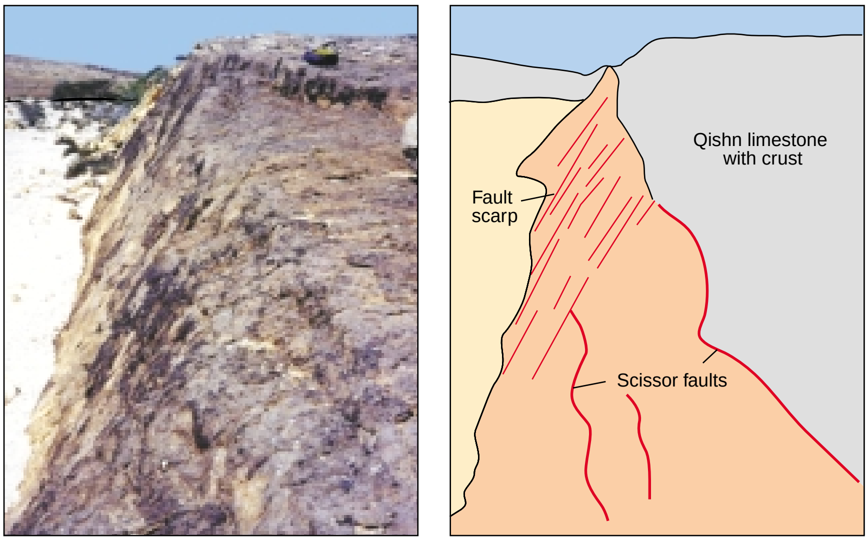

Figure 9: Syndiagenetic faulting of the Qishn limestone (Wadi Sha'bat al Tawraq). Large fault scarp with a vertical throw of over 5 m, is locally composed of smaller scissor faults (foreground). Note the slaggy aspect of the ferruginous surface (top bed of the Qishn) and the presence of ferruginous crust covering the palaeoscarps.

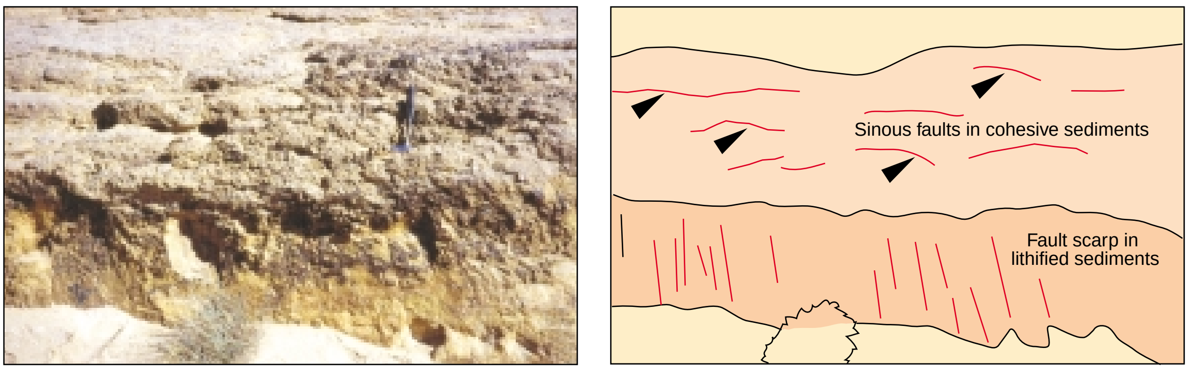

Figure 10: The lower part of a small fault scarp (about 0.6 m high) displaying a striated, planar and even surface. This indicates that the carbonate sediment was at least partly lithified during faulting. In contrast, the sediments above were not yet lithified during the faulting event. The small sinuous faults (arrows) were smoothed as a result of sediment creeping, boudinage and collapse of the cohesive muddy sediment. A ferruginous crust subsequently covered the deformed surface.

WADI SHA'BAT AL TAWRAQ

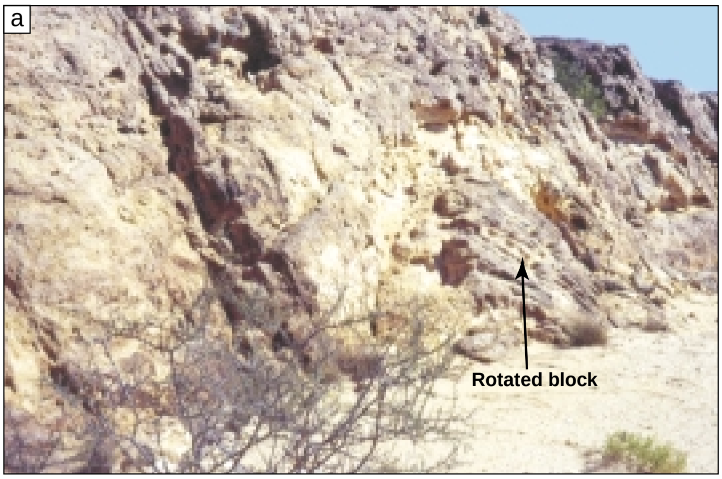

Figure 11: (a) About 5 m high palaeofault scarp covered with patches of the sedimentary breccia (for close-up see Figure 5b). Part of the faultscarp collapsed and slid down with a clockwise rotating motion (arrow) during or shortly after faulting. Both the rotated block and the related slide scars show evidence of soft sediment deformation. (b) Close-up of a large palaeofault scarp covered with a breccia composed of heterometric fragments of limestone (~0.3 m) and a carbonate matrix including gravels and bioclasts. The large limestone fragments show pre-lithification deformations, such as stretching and pillowing. The carbonate mud between the breccia clasts has a flow structure. This is attributed to syndeformational creeping of the carbonate mud on the steep surface of the fault scarp.

(5) the reaction of the carbonate deposit to faulting changes with depth: the surface carbonate often displays a jumbled deformation (boudinage, creeping, collapse) due to the softness and plasticity of the unlithified sediment. Some decimeters deeper, the fault planes show hydroplastic characteristics (i.e. soft sedimentary deformation). One to several meters beneath the surface, the carbonate reacted to the faulting as a nearly hard rock: the same fault plane that shows indications of soft deformation close to the surface, displays a plane and even surface in depth. (Figures 8 to 10);

(6) accumulations of brecciated carbonate remain stuck to the fault planes (Figure 11); the clasts show evidence of soft deformation (stretched, convoluted fragments, absence of secondary calcite between the clasts);

(7) occasionally, the large faultscarps (several meters high) collapsed. Spoon-shaped scars (one meter to over several meters) are still visible and the collapsed material rests at the foot of the faultscarp. Such accumulations are often a mixture of angular and blunt fragments, pillow-shaped blocks and matrix, that correspond to different diagenetic stages of the collapsed sediment (Figures 11).

All the above mentioned features were coated with the ferrugineous crust that developed when the faultscarps were exposed at the bottom of the sea. The limestone exposed on the fault planes does not show evidence of crushing as usually observed on post-diagenetic fractures. On the contrary, it suffered a slight ductile deformation (bending, stretching and boudinage, occasionally visible in thin section) related to the plastic state of the sediment.

There are also small synsedimentary gravity faults, some of which have listric geometry, which are recorded in the upper part of the Qishn limestones (Figures 8 and 12); they show decimetric scale throws. Nethertheless, the main faulting episode is clearly dated: it occurred after the deposition of the Qishn limestones and prior to the complete lithification of the carbonates during middle/late? Aptian times, *in any case before the early Albian*. The material of the paleoscarps, still lying under the sea, was subsequently indurated and bioeroded by boring organisms, and then covered with the hardground and drowned in deeper waters when the transgressive Nahr Umr sequence began.

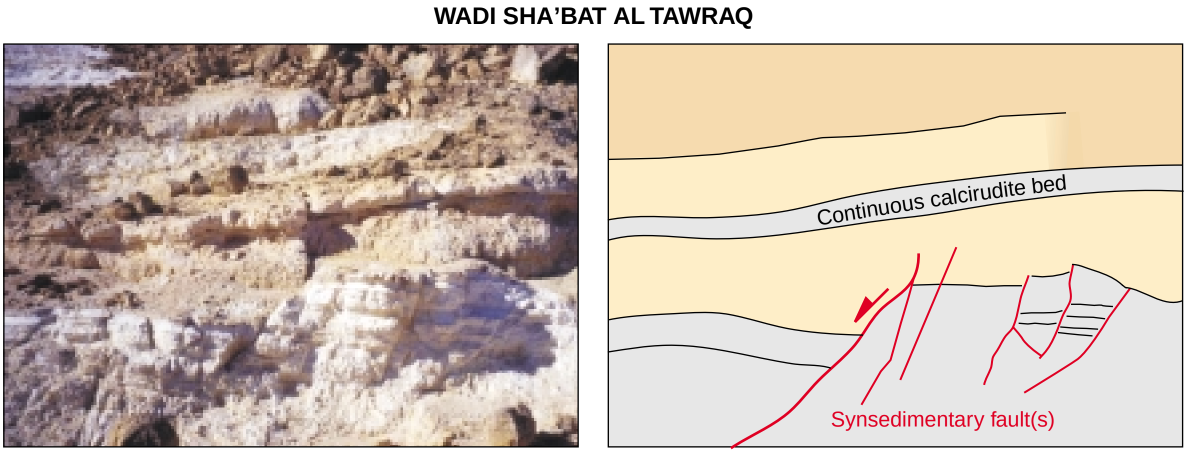

Figure 12: Upper part of the Qishn limestone (Wadi Sha'bat al Tawraq). Alternating bright whitish matrix-rich calcirudites and beige bioclastic limestone with small rudistids. A small synsedimentary listric fault (downthrown side to the left; vertical throw about 0.4 m) is covered by calcirudite beds deposited after faulting.

THE APTIAN FAULTING RELATED TO THE HAUSHI-HUQF UPLIFT TECTONIC FRAMEWORK

The regional occurrence of the Aptian faulting is not yet known. Throughout the western homocline of the Haushi-Huqf Uplift, the Cretaceous series were affected by numerous NW-trending faults and flexures, although this fault trend is almost unrepresented in the core of the Haushi-Huqf (Ries and Shackleton, 1990; Dubreuilh et al., 1992; Platel et al., 1992). A number of faults which affect the Qishn Formation and underlying Cretaceous rocks, decrease or disappear within the Nahr Umr marls. Others cut through the upper Cretaceous beds with the exception of the Fiqa Formation (Campanian-Maastrichtian deposits) that is rarely faulted and commonly seals the faults.

According to Ries and Shackleton (1990), the fault pattern of the Haushi-Huqf core is composed of prevailing NNE- and N-trending faults. The two sets are closely related; a single fault or a lineament including several fault segments may curve from one trend to the other. They acted as left-lateral, strike-slip faults during late Cretaceous, pre-Maastrichtian times. The fault segments that cross the Haushi-Huqf Uplift core from the south (Nafun near Duqm) to the north (Saiwan, Haushi Dome) (Figure 1), form the Saiwan-Nafun Fault (Gorin et al., 1982), or Saiwan-Nafun Lineament (Ries and Shackleton, 1990), or Haushi-Nafun Fault (HNF) (Dubreuilh et al., 1992). Half-domes and minor folds are associated with fault segments of the HNF. The folds are genetically related to strike-slip faulting. The folds are oblique to the faults, with NE-SW to NNE-SSW axis; they are cut by the faults. The folds involve lower to middle Cretaceous strata. They may be interpreted as drag folds that are consistent with a left-lateral motion of the HNF. These structures indicate a transpressive regime related to a NW-SE to WNW-ESE direction of compression. In accordance with this stress field, measurement of stylolites in the Permian limestones of the Haushi Dome, close to the HNF, indicate an average direction of maximum compression of N 120° (Dubreuilh et al., 1992). The strike-slip movement of the HNF and related fold structures were sealed prior to the deposition of the last Cretaceous levels (late Campanian-Maastrichtian) (Ries and Shakleton, 1990; Platel et al., 1994).

The Aptian NW-trending (N 120° to N 150°) normal faults observed in Wadi Sha'bat al Tawraq could be integrated in the above-mentioned kinematics, acting as en-echelon normal faults within the wrench fault system. Moreover, these faults do not seem to be rooted in pre-Mesozoic levels: they rarely show any continuation in the core of the Haushi-Huqf Uplift. Therefore, they could represent the response of the mid-Cretaceous sedimentary cover (not yet lithified in surface) to the motion of a nearby deep-seated wrench-fault zone. On this assumption, a transcurrent regime could have occurred as early as the middle Cretaceous. This should be compared with available tectonic data.

EARLY TO MIDDLE CRETACEOUS TECTONICS ON THE NORTHEASTERN MARGINS OF THE ARABIAN PLATFORM

During Permian-Triassic times, the eastern Arabian Platform was subject to an important extensional faulting regime related to the breakup of Gondwana and the development of the Tethyan rifting. The fault pattern is composed of major NW-trending faults that controlled the shelf margin, and of transverse NE-trending faults that acted as transform faults. This tectonic system led to the opening of the Neo-Tethys Ocean (see review in Loosveld et al., 1996). The northeastern and eastern edges of the Arabian Platform evolved into passive margins during the majority of the Mesozoic. The northeast corner of Oman in the Arabian Platform is an original feature of special interest that associates two distinct segments of the Tethyan margin: (1) a NW-trending passive margin that corresponds to the Oman Mountains area (northern margin); and (2) a NNE-trending transform margin, bounded by the Masirah Line (eastern margin) (Figure 1).

The northeast corner of Oman in the Arabian Platform evolved from a passive or transform margin into a compressional margin during late Cretaceous times as a result of the obduction of the adjacent oceanic crusts. These phenomena occurred differently on both margins.

The tectonic-sedimentary evolution of the northern margin during Mesozoic times

Previous data

The tectonic-sedimentary evolution of the northern Oman margin is well-documented. In particular, the fact that the margin was renewed with extensional tectonics during the Jurassic-earliest Cretaceous is highlighted (Pratt and Smewing, 1990; Rabu et al., 1990).

The obduction of the Semail Ophiolite and associated Hawasina and Sumeini sedimentary nappes occurred during the late Santonian-early Campanian and developed a strong compressive regime. The emplacement of the nappes was preceded, during the Turonian, by the formation of a peripheral bulge that affected a large part of the foreland platform in front (i.e. to the south) of the present-day Oman Mountains (Burchette, 1993). The formation of the forebulge was the first manifestation of a compressional regime on the northern margin. It resulted in the emersion of the platform carbonates (Natih Formation, latest Albian-Cenomanian) that were eroded, before being drowned again during the post-Turonian late Cretaceous (Van Buchem et al., 1996).

Additional data

The tectonic evolution of the northern Oman margin is poorly documented for the interval of time between the earliest Cretaceous and the Turonian. Some data concern the Adam Foothills (about 150 km to the north of the Haushi-Huqf Uplift; Figure 1) (Montenat et al., 2000 and unpublished data). In Jabal Madar, for example, the Natih carbonates were fractured when the bulge formed. The fracture network favored the development of a karst system filled with sediments when the Madar area emerged, and also when it drowned again during the Coniacian. The tectonic network includes two fault trends: (1) prevalent sub-N-S fractures (Figure 13c) may be interpreted as tension gashes related to a slight N-S compression that affected the Natih limestones when the bulge formed (Turonian); (2) subordinate NW-SE small fractures formed earlier, prior to the lithification of the Natih carbonates (syndiagenetic, late? Cenomanian faulting). In Jabal Madmar (Adam Foothills, to the east of Adam, Figure 1a) the same fractures are well-developed. Small NW- and WNW-trending, normal faults (Figure 13b) affected the Natih limestone prior to compaction and lithification (syndiagenetic, late? Cenomanian faulting). The fractured and karstified limestones were subsequently folded during late Cretaceous and Tertiary compressional stages. Thus, there are some indications of NW- and WNW-trending normal faults which affected the platform area to the north of the Haushi-Huqf Uplift (Adam Foothills) during pre-Turonian, middle Cretaceous times. In any case, they are small faults (metric scale), not yet related to a given tectonic event.

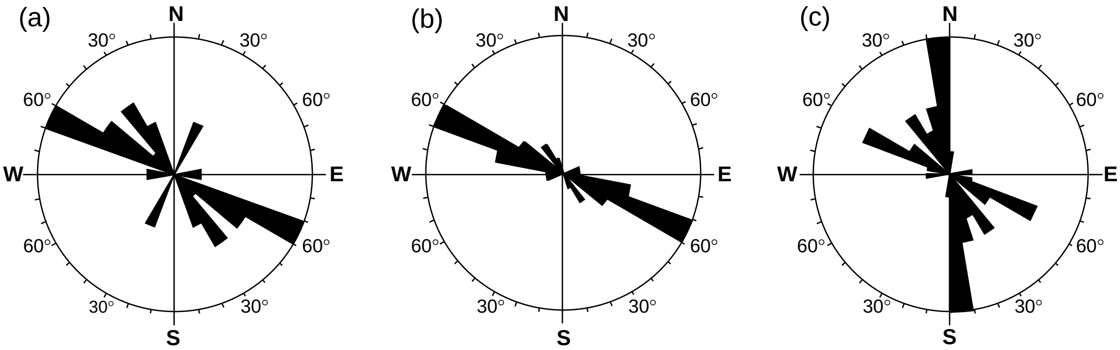

Figure 13: Rose diagrams of syndiagenetic fault directions. (a) Wadi Sha'bat al Tawraq: the normal faults affected the early Aptian Qishn limestone prior to complete lithifacation. (b) Jabal Madmar near the Adam (Adam Foothills, Figure 1). The faults affected the Cenomanian Natih limestones prior to compaction and lithification (syndiagenetic faults) (unpublished data). (c) Jabal Madar near Sanaw (Adam Foothills). The faults affected the late Cenomanian Natih limestones. They acted prior to the formation of a karst network related to the Turonian emersion (from Montenat et al., 2000). The WNW-ESE trending faults are present in the three sites and developed from Aptian (Haushi-Huqf) to Cenomanian (Adam Foothills). The N-S trending fractures (Jabal Madar) probably acted slightly later on.

Mesozoic evolution of the eastern margin

The evolution of the eastern margin is much less well known. This margin evolved as a transform margin controlled by the Masirah Line, probably as early as the Triassic (Moseley and Abbots, 1979; Moseley, 1990; Mountain and Prell, 1990; Shackelton and Ries, 1990); but it has not been possible to describe in detail the Mesozoic tectono-sedimentary evolution of this margin until now.

Nevertheless, Beauchamp et al. (1995) provided important data on the subject of the Masirah Graben (or Masirah trough) located on the eastern margin, to the east of the Haushi-Huqf Uplift. The structure is documented by subsurface data (onshore reflection seismic and well data). The eastern side of the Haushi-Huqf Uplift is bounded by an extensional NNE-trending fault system that is downthrown to the ESE, and forms the western edge of the Masirah Graben (Figures 1a and 14). The eastern border of the graben has not been identified. It is covered by a large wedge of allochthonous material that corresponds to the westward obduction of the Masirah Ophiolite and related sedimentary nappes (Shackleton et al., 1990). According to Beauchamp et al. (1995), the sedimentary sequence in the Masirah Graben, documented by oil wells, shows the following distinctive features (Figure 14):

- The rift basement is composed of infra-Cambrian sedimentary rocks (Huqf Group).
- Deposits related to Cambrian-Triassic formations are not present. Jurassic carbonates (Bathonian-Callovian) are the first deposits resting transgressively on the basement. Thus, the bottom of the graben previously belonged to an emergent and eroded uplifted block (i.e. the eastern continuation of the Haushi-Huqf). The eastern part of this block was faulted and drowned in a shallow marine environment during the Middle Jurassic.
- Platform conditions prevailed during the Cretaceous; according to Beauchamp et al. (1995), these platform deposits include the Shu'aiba limestones (Aptian), Nahr Umr marls and Natih carbonates (Albian-Cenomanian). As is the case elsewhere on the platform, the Shu'aiba and Natih shallow-marine carbonates are separated by a regional flooding episode that corresponds to the middle-late Aptian unconformity and the subsequent deposition of the Nahr Umr marls.
- A thin series (< 100 m) related to the upper Cretaceous Aruma Group rests unconformably on the Wasia Group (Natih Formation or Nahr Umr Formation to the north). Thick Paleocene-Eocene and Oligocene-Miocene deposits form the upper part of the graben fill.

From these data, the following points are emphasized. The faulting and flooding of the previously uplifted and eroded block initiated the formation of the NE-trending Masirah Graben during Middle

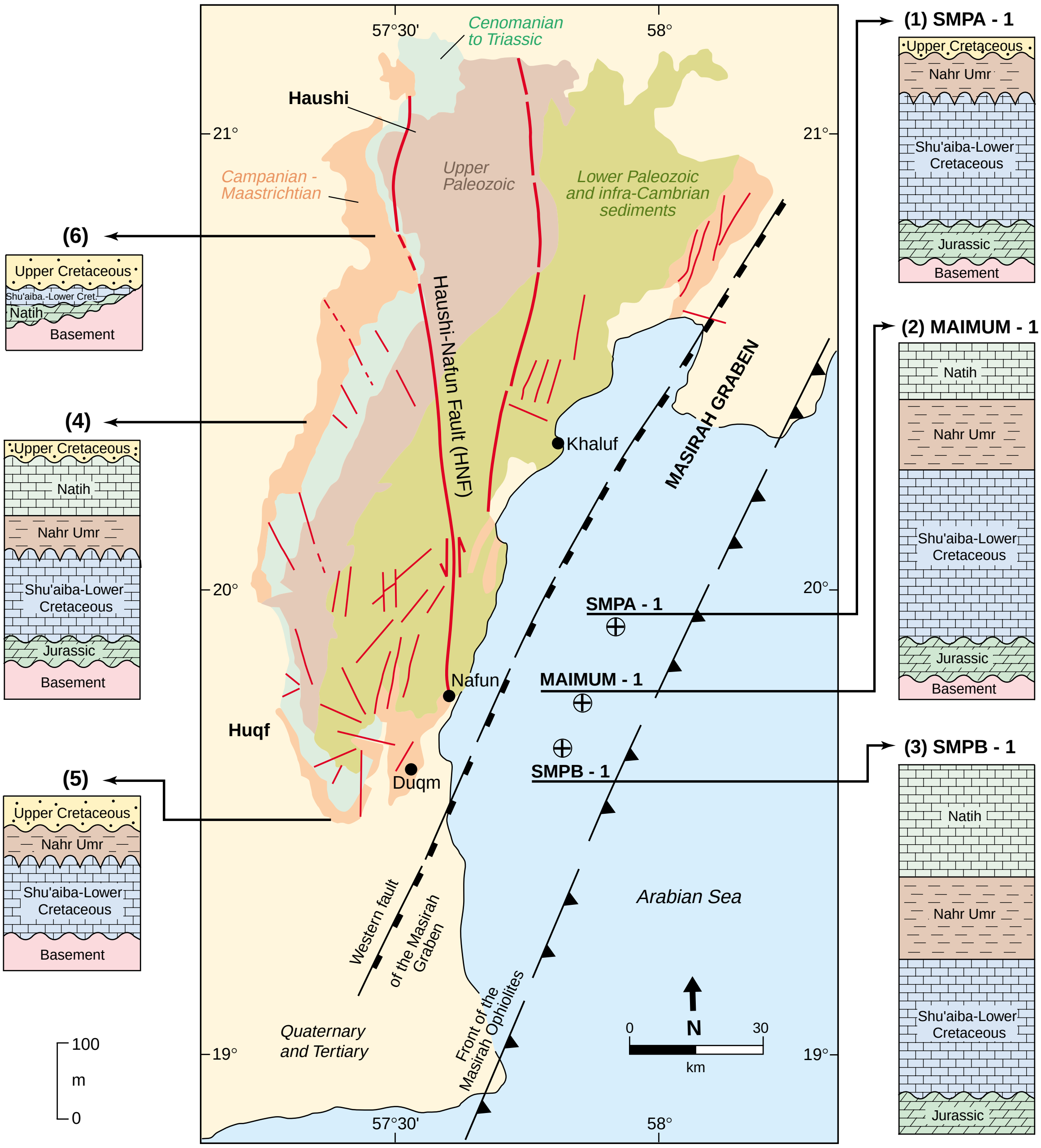

Figure 14: General sketch map of the Masirah Margin (Haushi-Huqf Uplift from Platel et al., 1994; Masirah Graben from Beauchamps et al., 1995). The correlated Shu'aiba-Lower Cretaceous units (green) mainly correspond to the Shu'aiba limestone, and clearly thicken in the Masirah Graben (Sections 1 to 3), compared with the sections of the western homocline (Section 4, west of Tabaqah; Section 5, Jabal Mustaqbis, from Platel et al. (1992). The thinning of the same unit along the HNF (Section 6, west of Saiwan) probably results from the addition of synsedimentary and post-depositional phenomena. Source of well data from Beauchamp et al. (1995).

Jurassic times. This faulting may be related to the break-up of the Arabian-African-Indian shield. The separation between the southeastern border of the Arabian Platform (Masirah edge) and northwestern India resulted in: (1) the formation of the Proto-Owen Basin including the Masirah oceanic crust (Loosveld et al., 1996); and (2) the creation of southeastern Masirah Margin. The formation of the Masirah Ophiolite occurred as early as the Late Jurassic (about 150 Ma; Smewing et al., 1991; Peters et al., 1995; Loosveld et al., 1996). The infilling of the Masirah Graben includes typical shallow water deposits, the Shu'aiba (roughly equivalent to the Qishn) and Natih carbonates. These limestones are significantly thicker than on the western homocline of the Haushi-Huqf Uplift: 200 to 280 m for the Shu'aiba (~100 m onshore); ~350 m for the Wasia Group (~100 m onshore). Obviously, the graben area experienced more subsidence; as already stated by Beauchamp et al. (1995), the fault that bordered the Masirah Graben to the west was active during the early-middle Cretaceous. The erosion of the Natih (in part or entirely), the unconformity with the overlying Aruma sequence, the thinness of the latter (< 100 m, compared to ~400 m onshore) are indicative of an important upthrust that affected the graben during the late Cretaceous (post-Cenomanian). This event may be related to the westward obduction of the Masirah ophiolitic complex onto the margin. According to Shackleton and Ries (1990), the Masirah Ophiolite uplift that preceded the obduction, began as early as the early/middle Cretaceous. In contrast, mapping data (Le Métour et al., 1992) suggest a more likely late or post-Cenomanian age for the upthrust of the Masirah Ophiolite. According to Loosveld et al. (1996), these uplift and associated intraplate deformations in the southeastern margin could be related to transpressional movements of the Indian Plate migrating northwards.

THE APTIAN FAULTING RELATED TO THE EVOLUTION OF THE MASIRAH EASTERN MARGIN

The Masirah southeastern margin is generally interpreted as a transform margin along the Masirah Line (see Sharland et al, 2001). The major structural features of the margin recognized until now (i.e. the Masirah Graben or trough) are oriented NNE-SSW, like the transform faults which affected and segmented the northeastern margin (for example the Dibba Line; Rabu et al., 1990). The strike-slip direction of the Masirah Line is disputed, and not clearly documented (Shackleton and Ries, 1990; Jorgensen et al., 1994; Marzouk and Abd El Sattar, 1994; Sharland et al., 2001). As a result of the transcurrent dynamics, the margin slope was steep and narrow, and the related slope deposits were probably of a limited extent. They correspond to the small outcrops of the Shin'zi Formation described in Masirah Island and at Ras al Madrakah (Le Métour et al., 1992; Béchennec et al., 1993). They show a volcanic-sedimentary sequence composed of alkaline basalts, clasts and large blocks of reworked lower Cretaceous shallow marine carbonate. The sequence dates from the Cenomanian and is interpreted as slope deposits sedimented below the edge of the Masirah Margin. The gravity-driven debris resulting from the disintegration of the platform carbonate, indicate the Masirah Line was still active during Cenomanian times.

Thus, there are some indications testifying to the activity of the southeastern Masirah transform margin during the early-middle Cretaceous. The margin kinematics may be responsible for the reactivation, with slight lateral movements, of nearby large faults affecting the platform basement, inherited from previous tectonic developments (for instance the HNF). Given this assumption, a limited sinistral movement of the HNF may be expected, as compatible with the development of the NW-trending Aptian normal faults (see above). Moreover, it is worth noting that the occurrence of early Cretaceous strike-slip movements in the Arabian Platform have been envisaged (Al-Fares et al., 1998; Sharland et al., 2001). This could be the result of the propagation of a sinistral transtension across Central Africa (NW-trending early Cretaceous intracratonic rift basins) as far as the Arabian Platform (Yemen grabens), as a consequence of the South Atlantic extension. In other respects, according to Marzouk and Abd El Sattar (1995) and Glennie (2000), an important geodynamic event occurred during Aptian times: (1) the start of subduction of the oceanic Hawasina Basin (forward the northeast margin); (2) the correlative up-warping of the Arabian Platform. These phenomena may have also contributed to the reactivation of basement faults.

CONCLUSION

A major middle? -upper Aptian unconformity (post-early Aptian/pre-early Albian) is recorded within the deposits of the eastern Arabian Platform. The study of this hiatus on the western homocline of the Haushi-Huqf Uplift (eastern Central Oman) provides new data that leads to the following conclusions.

- The early Aptian limestone (Qishn Formation) forms a shoaling trend that corresponds to the regressive interval of a third-order sequence (S_1). This interval is composed of fourth-order sequences that lead to temporary emersion or subemergent environments. These sequences were deposited on a relatively stable and slightly subsident shelf. Most of the sediment includes a large part of micritic matrix, indicating a low-energy depositional environment (probably a backshoal bay head). The uppermost trend, below Sb_2 is composed of matrix-rich calcirudites and small rudist banks. The top Qishn does not show evidence of a long-lasting emersion as observed in other regions (Alsharhan, 1987; Frost et al., 1983; Harris and Frost, 1984).

- Correlations of sequence boundaries remain uncertain due to the thin and probably lacunar development of the Qishn deposits. MFS_1 could be correlated with the MFS K70 (Sharland et al, 2001). MFS_2 and MFS_3 are scarcely documented and thus the correlation with MFS K80 remains open. The MFS K90 may correspond to the contact between the hardground and the early Albian Nahr Umr marls.
- The ferrugineous crust and lateral equivalent (glauconitic or phosphatic surfaces recognized in other parts of the platform) are generally considered as typical of a transgressive episode occurring when a highstand sea level is being established. The formation of indurated surfaces and authigenic minerals was favored by a relative sediment vacuity (permanency of the seawater/sediment contact and nondilution of the authigenic minerals within sediments). For a time, the submarine faultscarp pattern resulting from the Aptian faulting probably activated bottom currents (Montenat et al., 1987). During this time the normal deposition of sediments was inhibited thus favoring the development of organisms that lived on hard substrate. This was followed by the silting up of the sea bottom and faultscarp morphologies.
- The top surface of the Qishn limestone recorded the following events: (1) bioturbation (surface traces and burrows) related to the soft consistency of the sediment; (2) beginning of induration, perforation due to boring organisms, beginning of ferrugineous encrusting (hardground); (3) syndiagenetic faulting of the Qishn limestone in submarine conditions, formation of faultscarps (up to several meters high), collapse of masses of unlithified limestone; (4) lithification and ferrugineous encrusting continued to develop on the faultscarps, on the collapsed blocks of limestone and on the top bed of the Qishn.
- The normal faulting episode is clearly dated as post-early Aptian and pre-Albian. The faulting occurred before a complete lithification of the lower Aptian carbonates: i.e. not long after the sedimentation, in all likelihood during the middle (and/or?) late Aptian. As far as the Haushi-Huqf sections are concerned, the increasing depositional depth between the top Qishn limestones and the basal Nahr Umr marls is approximately 50 m.
- The Aptian faulting recognized in the Haushi-Huqf Uplift is unique in Oman. The NW-SE normal fault system cannot be related to the previously known episodes of distension which are notably older (Permian-Triassic rifting or Jurassic distensional reactivation on the northeastern margin). These syndiagenetic faults may be combined with the left-lateral movement of a large fault corridor (HNF) that was inherited from previous stages of deformation. In this model, the fault pattern may be considered as a discrete response of the sedimentary cover, not yet lithified in surface, to the reactivation of deep-rooted pre-existing faults.

The reactivation of basement faults (such as the HNF) during early-middle Cretaceous times may have resulted from various events:

- initiation of the upthrust of the Masirah Ophiolite inducing a slight compression on the southeastern margin (orientation of the maximum horizontal stress about NW-SE), as envisaged above;
- upwarping of the platform when the Hawasina Basin began to close off (northward directed subduction) the northern Oman margin (Glennie, 2000);
- propagation of a sinistral tension across Central Africa and the Arabian Platform as a consequence of South Atlantic opening (Sharland et al., 2001).

These hypotheses refer to different rearrangements of plate kinematics which were of special importance during the middle Cretaceous. On this account, one might expect a wide occurrence of the Aptian faulting on the Arabian Platform. This paper aimed at emphasizing this tectonic event and its possible extension and to propose a more suitable hypothesis.

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