GeoArabia, Vol. 5, No. 2, 2000
Gulf PetroLink, Bahrain

Recognition and Interpretation of Polygenic Discontinuity Surfaces in the Middle Cretaceous Shu'aiba, Nahr Umr, and Natih Formations of Northern Oman

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ABSTRACT

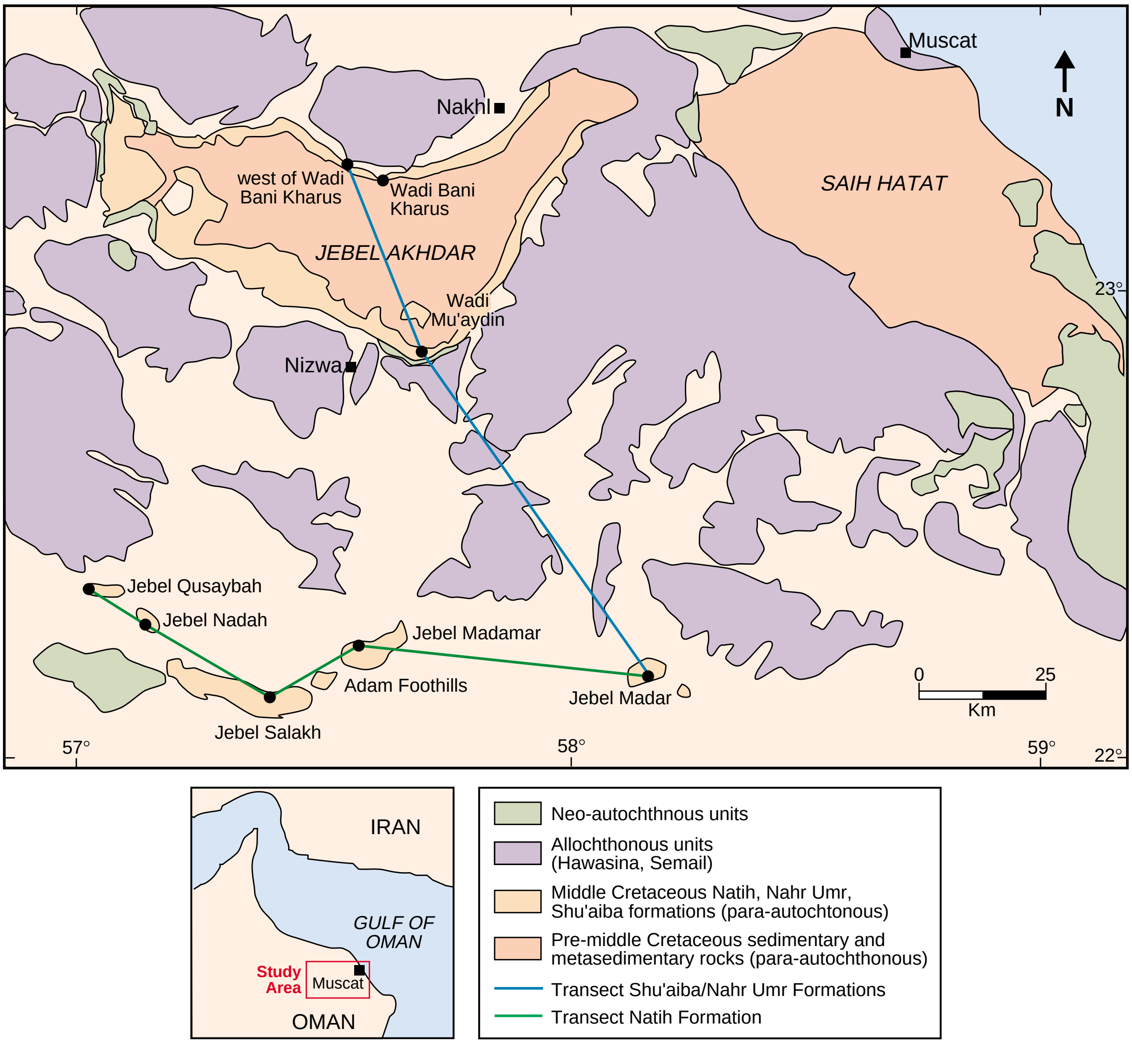
Discontinuity surfaces that recorded superposition of marine hardground and subaerial exposure stages are common in the Middle Cretaceous of northern Oman. These surfaces formed during periods of rapid sea-level drop. The marine hardground stages are dominant in the field, whereas the subaerial exposure stage is documented in circumstantial petrographic, geochemical, and biological evidence. The record of a shoaling phase prior to exposure is commonly subtle and incomplete; supratidal deposits are conspicuously absent. Porosity in the limestones underlying the discontinuities is rearranged during subaerial exposure and subsequent burial and hence the permeability of large volumes of limestone is affected at a variety of scales. During marine hardground stages, carbonate cements, iron oxides, and manganese occludes some of the existing pore space. During burial, these intervals may thus have acted as either seals or efficient conduits of fluid flow. The surfaces under study in the Shu'aiba, Nahr Umr, and Natih formations are spaced ten to few tens of meters apart and many of them were traced laterally over distances of 100 kilometers and more between sections at Jebel Akhdar and in the Foothills. This implies that they play an important, but poorly understood role in compartmentalization of carbonate reservoir rocks.

INTRODUCTION

Early lithification of marine carbonates either occurs in the subaquatic (hardground) or the subaerial realm (exposure surface). The interpretation of the nature and origin of these discontinuity surfaces, however, is not straightforward (Budd et al., 1995). Dissolution of marine carbonates associated with subaerial exposure is thought to be responsible for much of the secondary porosity in many large oil and gas fields in the Middle East and elsewhere (e.g. Wilson, 1975; Harris and Frost, 1984; Hurley et al., 1995). Synsedimentary lithification of fossil sea floors, on the other hand, may result in extensively cemented seals within carbonate units. Both, subaerial exposure surfaces and marine hardgrounds may compartmentalize reservoir rocks (Wagner et al., 1995), or form flow conduits during burial (Cander, 1995).

The processes that lead to early lithification and to rearrangement of porosity, are often complex successions of erosion, deposition, colonization, dissolution, impregnation, and cementation rather than a single event (e.g. Shinn, 1969; Kennedy and Garrison; 1975, Fürsich, 1979; Bromley and Gale, 1982; Brett and Brookfield, 1984; Clari et al., 1995; Hillgärtner, 1998; Ruffel and Watch, 1998).

We took advantage of the exceptionally well-exposed discontinuity surfaces in the Middle Cretaceous interval of northern Oman (Jebel Akhdar and Foothills) to examine processes that create and modify these features and the rocks beneath them. Many of these surfaces show clear field evidence for marine hardground stages, and within the same interval, circumstantial petrographic, geochemical, and biological evidence for subaerial exposure (Immenhauser et al., 1999). Many of the surfaces form extensive event markers that can be correlated in outcrops at Jebel Akhdar and in the Foothills over distances of 100 kilometers (km) and more. Correlation of the Nahr Umr in the field is based on three calcareous marker bed successions that are present in all sections (Immenhauser et al., in press). Correlation of the Natih Formation throughout sections in the Foothills is based on the sequence stratigraphic framework of van Buchem et al. (1996).



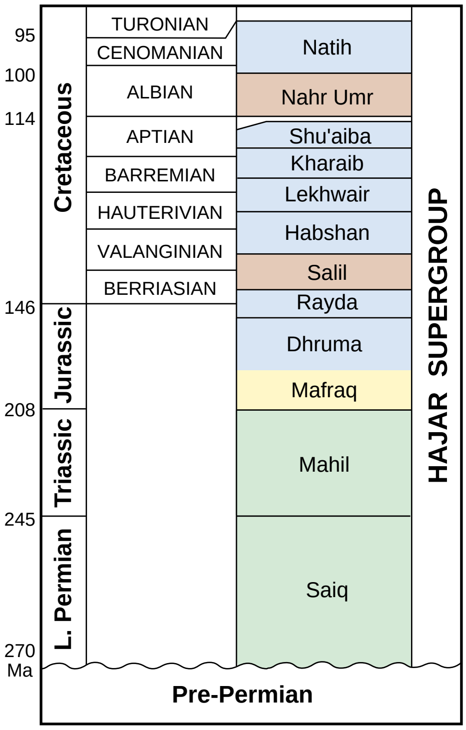


Figure 1: Geotectonic overview map of the eastern Jebel Akhdar and the Foothills to the south. The position of transects through the Shu'aiba/Nahr Umr (blue), and the Natih C formations (green) are indicated as straight lines. Black circles indicate locations of sections. The smaller map shows the location of the study area. Stratigraphic framework is shown below (time scale after Harland et al. (1990)).

The purpose and scope of this paper is to document the origin and polygenic overprinting of discontinuity surfaces in the Aptian Shu'aiba Formation, the Aptian to Albian Nahr Umr Formation, and in the middle Cenomanian C interval of the Natih Formation in northern Oman. The relevance of this type of analysis of surfaces for sequence stratigraphic interpretation is the topic of another manuscript.

METHODS

Due to the excellent exposure conditions, surfaces were investigated over many 100s to many 1,000s of square meters (sq m). Beneath surfaces, sampling focussed on the relatively rare localities where limestones showed possible pedogenic features. About 120 thin sections were made from the most promising samples. However, only about 10% of these thin sections showed petrographic evidence for subaerial exposure (i.e. *Microcodium*-like spherulitic features, incipient caliche features, meteoric cements, mixing zone dolomites, secondary porosity, etc.).

$\delta^{18}O$ and $\delta^{13}C$ analyses of micritic matrix carbonate were carried out at the Vrije University, using a Finnigan 252 mass spectrometer equipped with an automated carbonate extraction line. Samples were digested in concentrated orthophosphoric acid at a temperature of 80°C. Approximately 20 to 50 micrograms of sample were required per analyses. Data are reported versus Vienna Pee Dee Belemnite (VPDB) in permil. The NBS 19 carbonate standard was routinely monitored during sample runs. NBS 19 long term reproducibility (one standard deviation) lies within 0.08‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$. To determine trace element compositions, samples were dissolved and analyzed by ICP-AES at the facilities of the Vrije University.

EVIDENCE FOR POLYGENIC ORIGIN OF DISCONTINUITY SURFACES

The polygenic discontinuities in the middle Cretaceous of northern Oman (Figure 1) possess several distinctive characteristics. One of them is that their marine hardground stage is prominent and easily recognizable in the field. The mode of mineralization (mainly goethite) and their morphologically resistive character varies so little as to be the chief field criteria of recognition. Most discontinuities have a smooth to slightly undulating surface (Figure 2a), and only few of them show lateral changes in morphology.

A further diagnostic feature is that these surfaces show scattered but consistent geochemical, petrographic, and biologic evidence for a subaerial exposure stage (Figures 2 and 3), whereas e.g., deep-cutting karst features are absent. Based on these observations, it was concluded that both, submarine lithification and subaerial exposure stages were recorded in the same surfaces (Immenhauser et al., 1999; Immenhauser and Scott, 1999). This is the simplest interpretation of the available data sets and that are adopted in this paper.

Below we summarize features that point to submarine lithification and others that are indicative of emergence. In Figures 4 and 5 we show the distribution of exposure-related features beneath the discontinuities studied. Details of the geochemical and biological investigations of the Albian examples are given in Immenhauser et al. (1999).

Hardground Related Features

Borings

Nearly all surfaces are perforated by borings (boreholes) that clearly cut through the fabric of the underlying rock and some holes preserved the shape of the bivalves that etched them. The abundance of boreholes in more recently exposed portions of the surfaces varies between 1 and 15 per sq m. Generally, the degree of perforation is relatively insignificant when for example compared to hardgrounds from the Kimmeridgian of Poland (Goldring and Kazmierczak, 1974), or the ones from the Lower Cretaceous of the French and Swiss Jura Mountains (Hillgärtner, 1998). Cross-cutting relationships of boreholes are scarce.

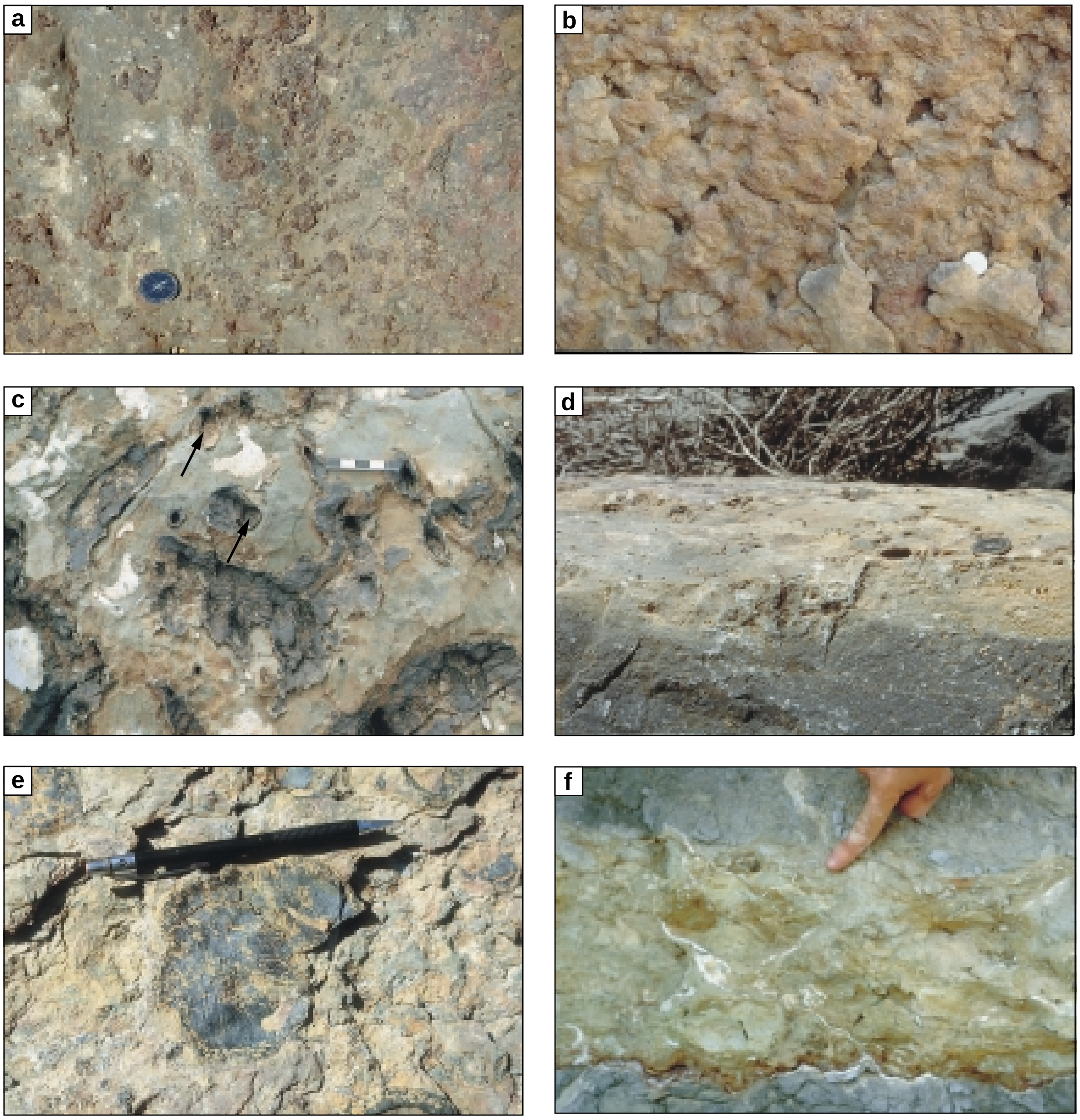
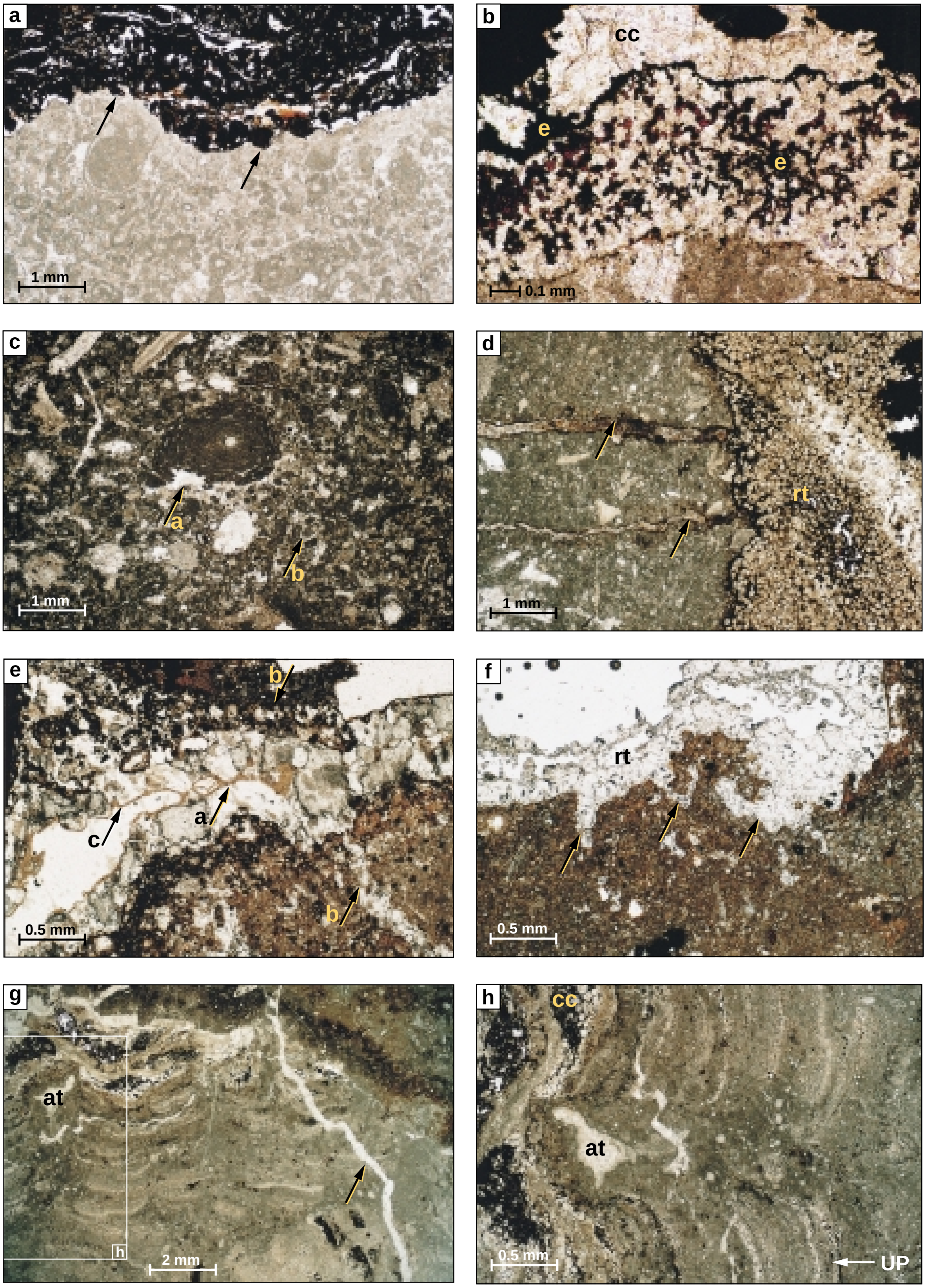


Figure 2(a): Nahr Umr Formation, Wadi Mu'aydin. Discontinuity 3 (Figure 4) has a planar surface and is strongly iron stained. Coin for scale. **(b)** Nahr Umr Formation, Jebel Madar. Discontinuity 6 (Figure 4) has an irregular, porous topography that is only slightly iron stained. Coin for scale. **(c)** Silcretes encrust the top Shu'aiba Formation and seal bore holes (white arrows), section west of Wadi Bani Kharus (Figure 4). Scale is 5 cm. **(d)** Nahr Umr Formation, Wadi Mu'aydin (Figure 4). Bleached limestones beneath discontinuity 2. Coin for scale. **(e)** Nahr Umr Formation, Wadi Bani Kharus (Figure 4). Bored, Mn-stained oysters on discontinuity 2. Pen is 15 cm long. **(f)** Natih Formation, Jebel Nadah (Figure 5). Altered paleosol atop discontinuity 8a.

FACING PAGE **- Figure 3(a):** Nahr Umr Formation, Jebel Madar. Top Shu'aiba Formation (Figure 4). Contact between marine limestone and goethite crust replacing precursor sediment. Note the sharp, scalloped contact with truncated bioclasts (arrows). **(b)** Natih Formation, Jebel Madar. Surface 6a (Figure 5). Endolithic lichens (e) growing in meteoric calcite cement (cc) that fills former root trace. **(c)** Natih Formation, Jebel Nadah. Surface 8a (Figure 8). *Praealveolina* with gravitational dissolution feature (arrow a) pointing to a vadose meteoric environment. Note also faint circumgranular cracks further below (arrow b). **(d)** Natih Formation, Jebel Madamar. Surface 6a (Figure 5). Dolomitization of a former root trace (rt). Note dolomite infilling cracks in lithified sediment to the left (arrows). **(e)** Nahr Umr Formation, Wadi Mu'aydin. Surface 4 (Figure 4). Root trace (arrow a) with rootlets (arrow b) extending from it. Root trace is



filled with meteoric cement. Note micrite coating (arrow c) of calcite crystals. **(f)** Nahr Umr Formation, Wadi Mu'aydin. Surface 6 (Figure 4). Rootlets (arrows) extending from main root trace (rt). **(g)** Nahr Umr Formation, Wadi Bani Kharus. Surface 3 (Figure 4). Caliche features with alveolar texture (at). Tertiary calcite vein (arrow) that cross-cuts caliche points to Cretaceous age of the soil feature. Note position of Figure 3h. **(h)** Detail of Figure 3g. Note laminar and alveolar (at) texture, meteoric calcite cement (cc), and goethite impregnation. Stratigraphic up is to the left.

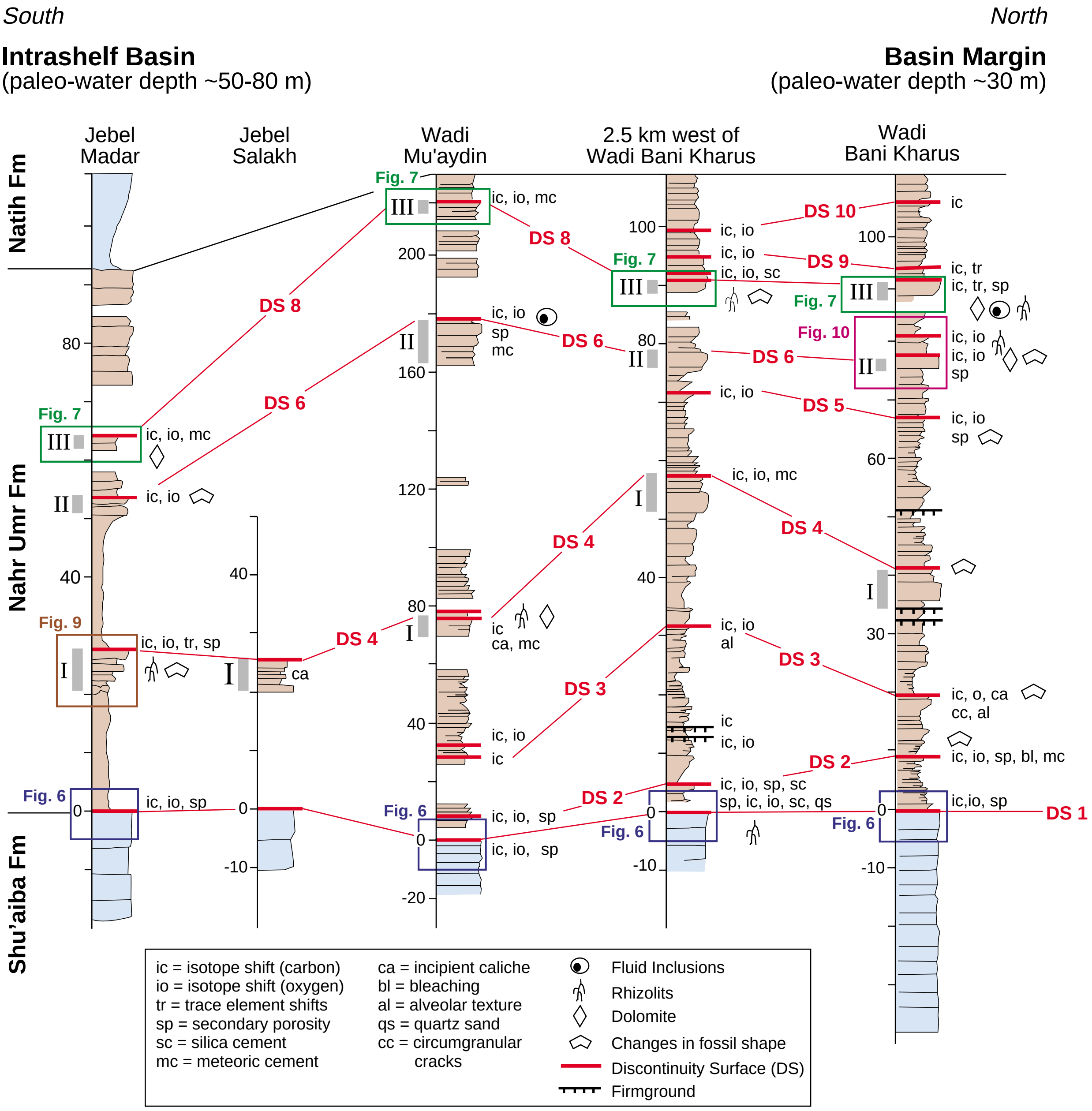


Figure 4: Sections measured in the top Shu'aiba and Nahr Umr formations. Discontinuity Surfaces are shown in red and correlated from the basin margin (northern Jebel Akhdar) into the basin (Foothills). Evidence for meteoric diagenesis is shown. I to III refers to marker bed successions. Note the different scale of the section in Wadi Mu'aydin.

Encrustation by Sessile Organisms

Encrustation by omission-related, sessile organisms is found in a number of well-preserved surfaces. Most common are oysters (Figure 2e) and serpulids, but also caprinid rudists adapted to a hard substratum (Natih Formation), or SH-type stromatolites (terminology of Logan et al., 1964), pointing to a higher hydrodynamic level are present.

Mineralization

Mineralization of sedimentary rocks and epifauna with iron and manganese oxides (Figure 2e), and phosphate impregnation is common in many of the exposures studied. This process is related to condensation and a break in sedimentation associated to the subaqueous hardground stage (Föllmi et al., 1991; Pomoni-Papaioannou, 1994). Glauconite minerals were not found.

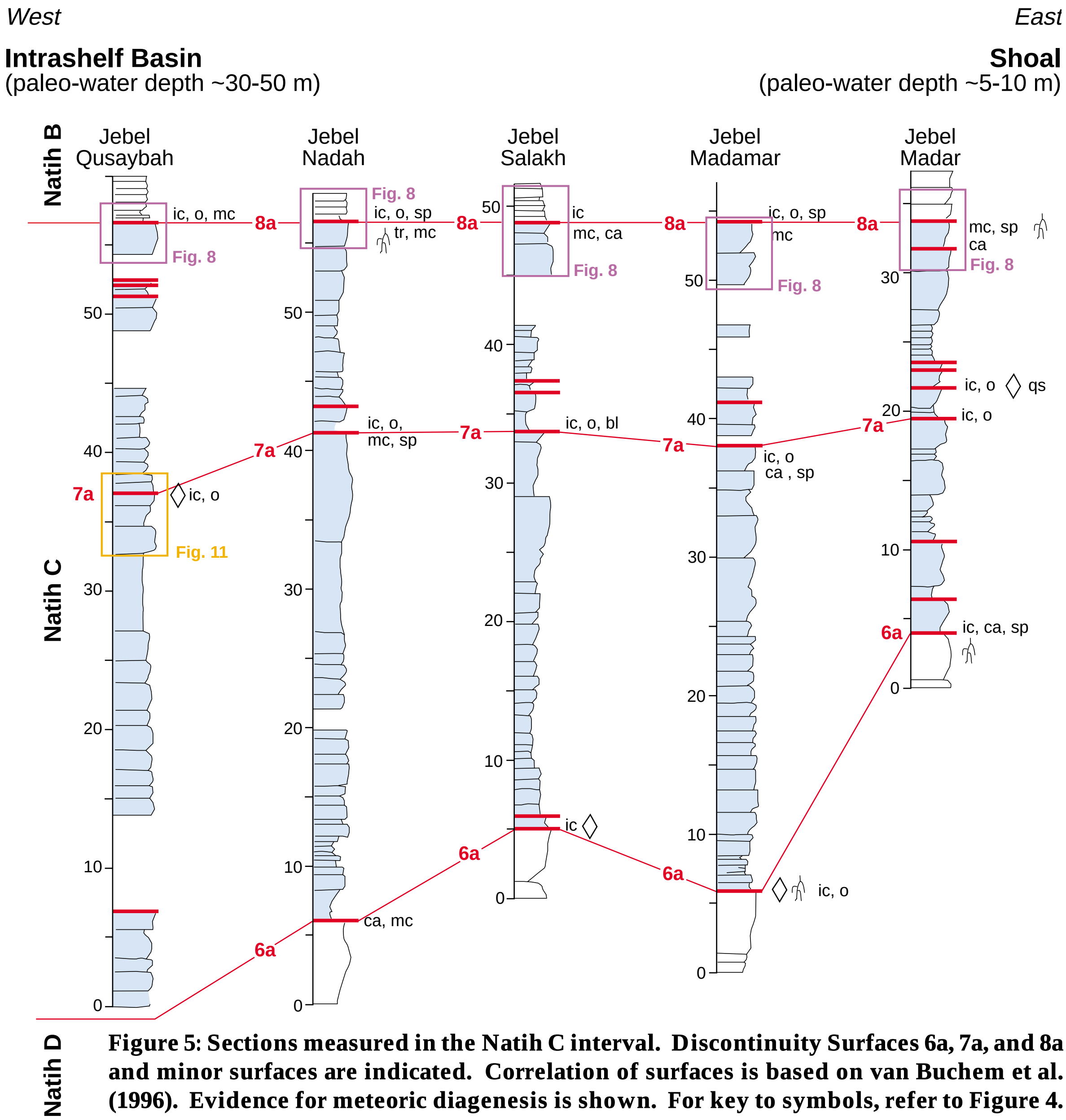


Figure 5: Sections measured in the Natih C interval. Discontinuity Surfaces 6a, 7a, and 8a and minor surfaces are indicated. Correlation of surfaces is based on van Buchem et al. (1996). Evidence for meteoric diagenesis is shown. For key to symbols, refer to Figure 4.

Early Marine Cements

Cement phases that caused early submarine lithification of the sea floor are difficult to pinpoint due to overprinting by exposure and burial diagenesis. The most obvious cases are thin ($\leq 50\ \mu m$) fringes of isopachous, bladed calcite crystals that coat components in grainstones. However, this cement phase is volumetrically insignificant.

Exposure-related Features

Micro- and Epikarst

Some of the discontinuities display an irregular, porous topography that may be the expression of micro- or epikarst (Figure 2b). However, subaqueous corrosion of carbonates (Reitner et al., 1995), or submarine erosion of patchily lithified sediments (Hillgärtner, 1998) could create a similar relief. No field evidence was found whatsoever to suggest that deep-cutting karstification may have eroded portions of the carbonate rocks.

Incipient Caliche Features and Altered Paleosols

Incipient caliche features are present in a number of thin sections. The most obvious ones are related to alternating wetting and drying of patchily lithified carbonate sediments creating a complex network of circumgranular cracks (Figure 3c). Other features that are difficult to reconcile with a submarine hardground stage are caliche-like, pendant carbonate crusts with an alveolar texture (Figures 3g-h). A heavily altered paleosol (mainly kaolinite) is present at Jebel Nadah (Figure 2f).

Rhizoturbation and Endolithic Lichen

Rhizoliths can be distinguished from animal burrows by downward bifurcation and decreasing diameters of second, and third, and lower order branches (Klappa, 1980). However, substantial rhizoturbation beneath discontinuities is rather scarce in the sections under study (Figures 3, 4 and 5). An exception is found at Jebel Nadah, where numerous rhizoliths extend from surface 8a as far as three meters into the underlying limestone (Figure 8). There, root traces are filled with an ochre, argillaceous material that also overlies the discontinuity (Figure 2f). Most rhizoliths have sharp boundaries indicative for boring through indurated rock (Klappa, 1978). Tubular colonies of "*Microcodium*-like" (Klappa, 1980) spherulitic carbonate features are found locally. Some of these root traces and corresponding rootlets were occluded by goethite and meteoric cements (Figure 3), whereas others are simple root moulds that were left empty. The later ones were not considered relevant for this study since their Cretaceous age cannot be demonstrated.

Some of the Cretaceous root traces were re-used by subrecent root systems, which led to a complex overprinting of rhizolitic features. Subrecent root traces are recognized by their cross-cutting relationship with e.g., stylolites and calcite veins that are related to Late Cretaceous and Tertiary burial and uplift of Jebel Akhdar and the Foothills. Micro-boreholes related to subrecent endolithic lichens (Figure 3b) are common in some of the root traces.

Mineralization

Iron (goethite) staining of surfaces (Figures 2a and 3a) and staining and bleaching of the underlying rocks (Figure 2d) may be the result of terra rossa formation and weathering during the exposure stage and alteration during subsequent transgression (Wright, 1994). Formation of iron nodules and iron staining of lithified sea floors are also processes that are known from marine hardgrounds. Remobilization and reprecipitation of Cretaceous goethite to form centimeter (cm)-thick, surficial Fe-crusts, however, continues to the present day. The more recent mineralization events that cut stylolites and veins should not be confused with the penetrative Cretaceous iron staining of carbonate rocks beneath the discontinuities (Figure 2a). Some of the more recent iron-oxide crusts coat fractures and karst holes at Jebel Madar that formed after Middle Miocene uplift and tilting of the strata as indicated by their oblique relationship to bedding planes. Penetrative iron-staining of limestones that border fractures or karst holes, however, was not observed. Silica encrustation of discontinuities is found in the section west of Wadi Bani Kharus (Figures 2c and 5). Silica crusts are possibly related to silcretes that commonly form under semi-arid to arid climate (Webb and Golding, 1998). These silica crusts occlude boreholes and are clearly of Cretaceous age as indicated by field relationships. Authigenic quartz minerals also intergrow with meteoric carbonate cements (Immenhauser and Scott, 1999).

Secondary Porosity

Secondary pore space in components and matrix is common beneath but rare above discontinuities. We thus assume that secondary pore space is related to meteoric diagenesis (e.g., gravitational dissolution Figure 3c) and to burial fluids trapped beneath discontinuities acting as seals. The volume of the secondary pore space varies considerably depending on the surface examined, but also on the locality sampled below an individual surface. The sizes of individual pores ranges between 0.1-0.7 millimeters (mm) and most have irregular shapes. Depending on the sample studied, pore space remained open or was occluded with goethite, meteoric phreatic, or burial (luminescent) calcite phases.

Meteoric Cements

Pendant or microstalactitic cements that are indicative for a vadose environment are present in a number of thin sections. Recognition of meteoric cements is based on textural relationships, stable isotopic composition, and investigations under a cathode luminescence microscope. Meteoric calcite cement

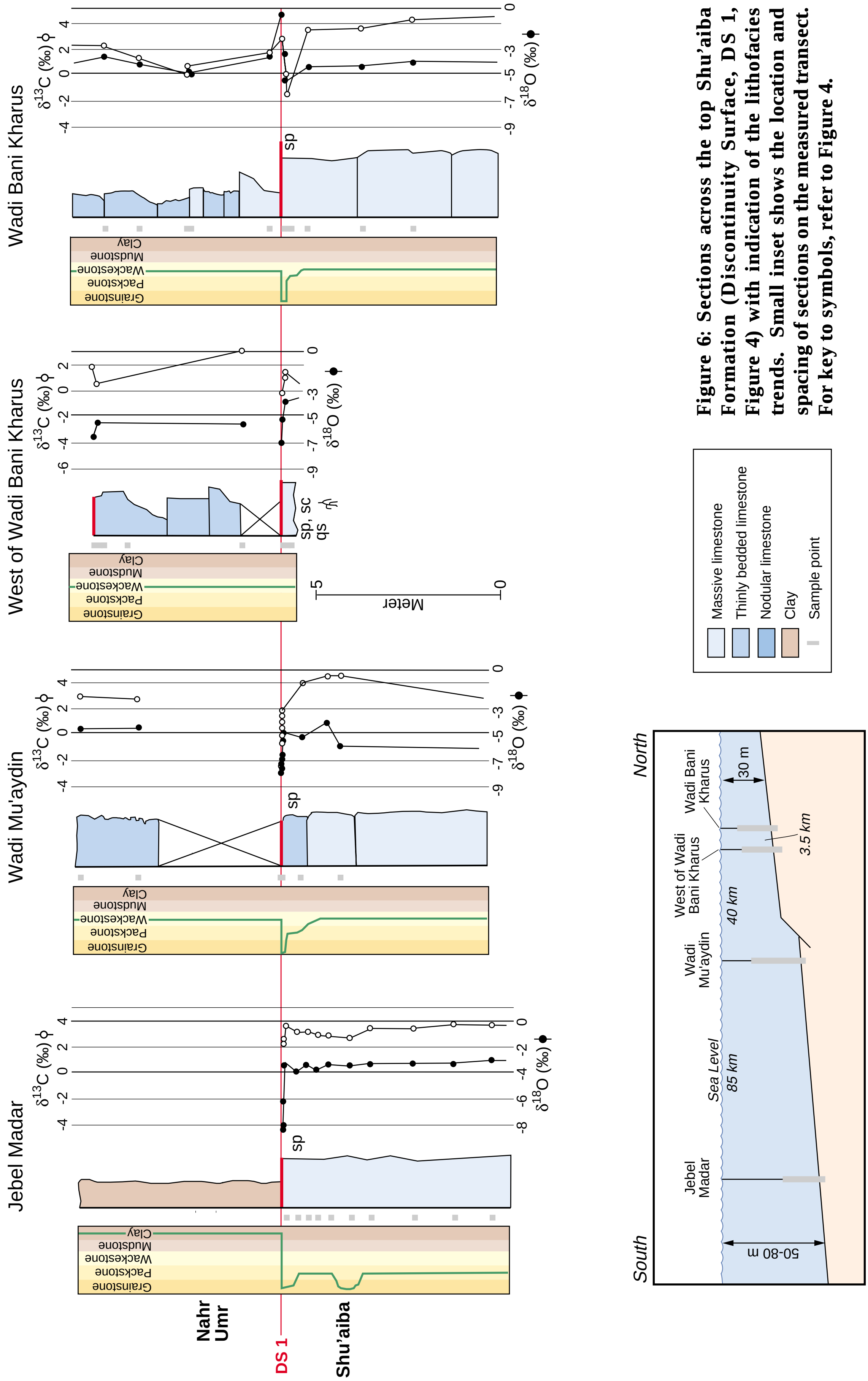


Figure 6: Sections across the top Shu'aiba Formation (Discontinuity Surface, DS 1, Figure 4) with indication of the lithofacies trends. Small inset shows the location and spacing of sections on the measured transect. For key to symbols, refer to Figure 4.

occludes circumgranular cracks (Figure 3c) related to alternative wetting and drying of nonlithified carbonates. Equant, nonluminescent sparite formed in fissures that opened due to the growth of goethite crystals within the limestone and is also considered meteoric in origin (Immenhauser et al., 1999). In some thin sections, this cement phase is overlain by fine-grained, laminated marine sediment indicative for its pre-burial origin. Stable isotopic data from meteoric phreatic cements display mean $\delta^{13}C$ values of -1.8‰ and $\delta^{18}O$ values around -6.3‰.

Dolomite

Dolomitization episodes are recorded in samples taken beneath discontinuities in the Nahr Umr and Natih formations. This cement phase is euhedral, nonluminescent, and mainly replaces portions of the fine-grained carbonate material in burrows (Figure 3d). $\delta^{13}C$ values range between +1.54 and +0.13‰, and $\delta^{18}O$ values are between -8.3 and -4.4‰ (Immenhauser et al., in press). This dolomite phase postdates iron staining and is probably related to transgression of the Cretaceous exposure surfaces. Some of the dolomites were replaced by late, luminescent calcite cement probably during burial.

Stable Isotope Shifts

The isotope curves shown are from matrix micrites but individual cement phases were also sampled (Immenhauser et al., in press). The depletion in ^{13}C beneath many surfaces under study is statistically significant (Figures 6 to 11). We follow previous authors (e.g. Allan and Matthews, 1982), and consider negative isotopic shifts as evidence for emergence, dissolution, and reprecipitation of meteoric cements that comprise isotopically light soil CO_2. In the Nahr Umr sections, the amplitude of negative carbon isotopic shifts decreases from Jebel Akhdar (basin margin) towards the Foothills in the south (intrashelf basin). This may point to shorter-lived exposure stages in the more basinal setting of the Foothills (Figures 6 and 7).

Negative shifts in oxygen isotopic composition are evidence for meteoric water depleted in ^{18}O relative to seawater. Component data from various cement phases show that many meteoric cements are isotopically light ($\delta^{13}C$ -4.4‰, $\delta^{18}O$ -7.8‰; Immenhauser et al., in press). Positive shifts in $\delta^{18}O$ in turn may point to an increase in salinity due to evaporation (e.g., Marshall, 1992).

Fluid Inclusions

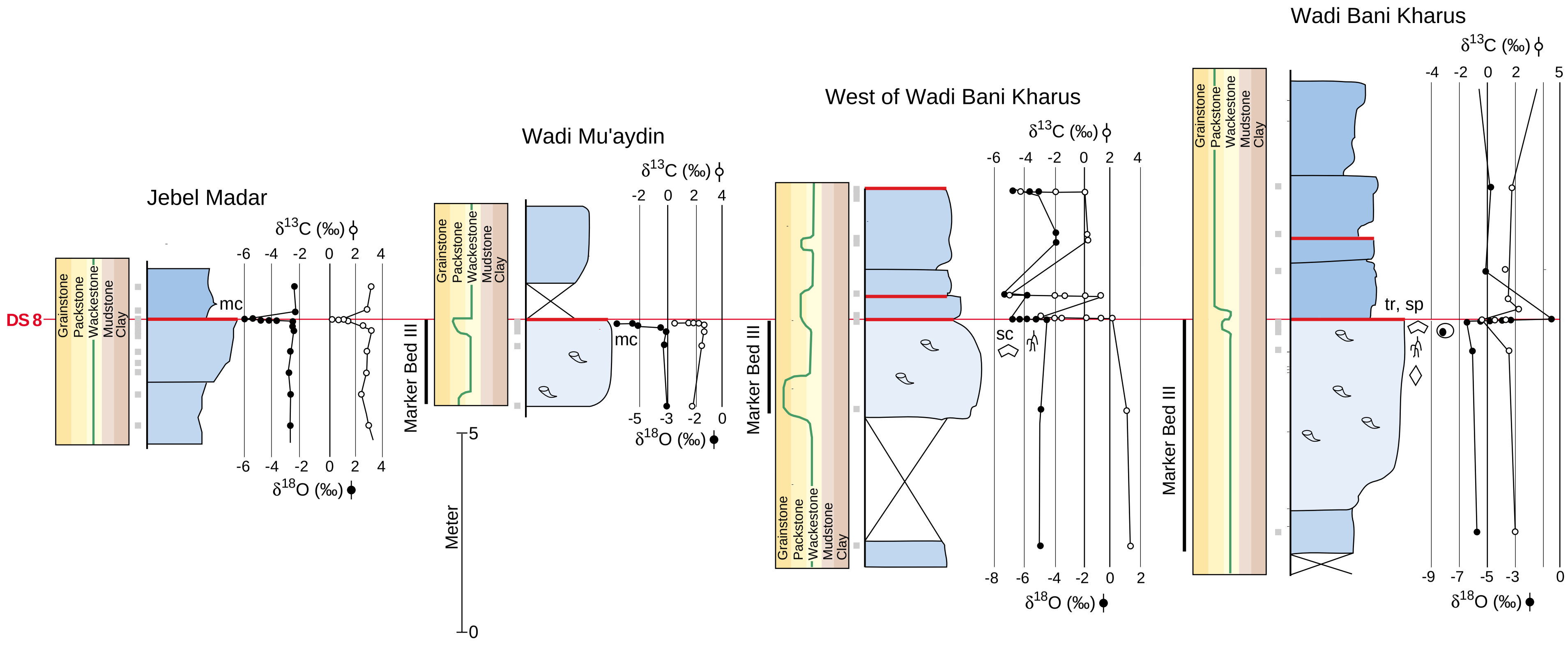
Samples from a rudist marker bed (III, Figure 4) beneath discontinuity 8 in Wadi Bani Kharus and Wadi Mu'aydin were studied for their primary liquid-vapor inclusions in meteoric calcite cements and the results are reported in Immenhauser et al. (in press). A significant number of inclusions contained brackish water of less than 28‰ salinity suggesting exposure and freshwater alteration of the overlying surfaces.

Trace Elements

Geochemical changes in carbonates beneath the discontinuities relative to the overlying rocks show an increase in Al_2O_3, Fe_2O_3, and Si, and a decrease in Mg^{2+} and Sr^{2+} (Figure 9) interpreted as the influence of pedogenesis and a meteoric phreatic paleo-environment (Beier, 1987). The magnitude of these changes is probably a function of the duration of subaerial exposure, the facies and permeability of the affected carbonate rocks, the climate during exposure, and the resultant colonization by plants and associated microflora. Trace element compositions across marine hardgrounds and firmgrounds remain largely uniform.

Statistical Changes in the Functional Morphology of Benthic Foraminifera

It has been suggested that many of the large benthic foraminifera of the Cretaceous, in analogy to their modern counterparts, lived in symbiontic relationship with photosynthetic algae (Vilas et al., 1995; Hottinger, 1997). Reiss and Hottinger (1984) and Hottinger (1997) stated that long-term changes in the degree of illumination at the sea floor are recorded in the functional morphology of orbitolinids (i.e. increase or decrease of the area of the light exposed surface). Simmons et al. (in press) similarly reported on the relation between the shape of orbitolinids and paleobathymetric change. Simmons et al. (in press) stated that orbitolinids are flattest (discoid) around the maximum flooding zones and become increasingly conical through highstands. This approach was used to document shoaling beneath and deepening above some of the discontinuities within the Nahr Umr Formation (Figure 4, Immenhauser et al., 1999).



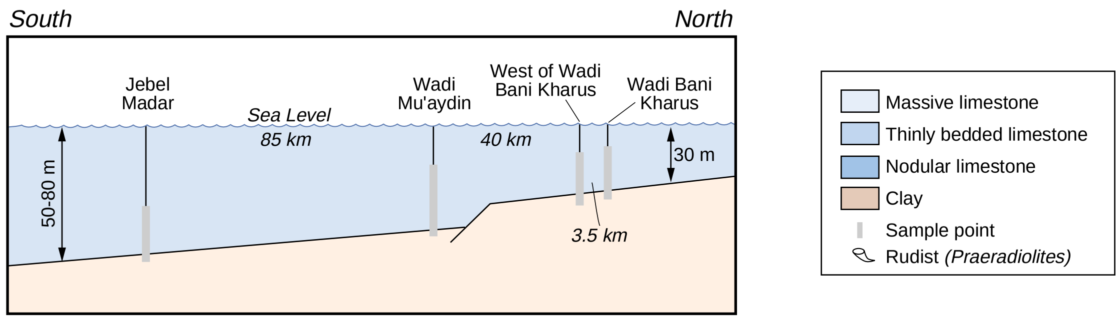


Figure 7: Sections across Discontinuity Surface, DS 8, Nahr Umr Formation with indication of the lithofacies trends. Small inset shows the location and spacing of sections on the measured transect. For key to symbols, refer to Figure 4.

EXAMPLES OF POLYGENIC DISCONTINUITIES

In this section, we describe Aptian, Albian, and Cenomanian examples of polygenetic discontinuity surfaces from northern Oman. Field evidence for a submarine hardground stage of these features are encrusting organisms, borings, truncation of shells, and finally impregnation of surface, sessile organisms, and underlying carbonate rocks with manganese oxides and phosphate. The data sets that point to emergence and subaerial exposure of the individual surfaces are shown in overview in Figures 4 and 5.

Aptian Example

Case Summary

The first example of a polyphase discontinuity is the top of the Lower Aptian Shu'aiba Formation (Figure 6). Throughout the Gulf region, the Shu'aiba is an important reservoir facies (Christian, 1997). In Oman, the Shu'aiba Formation is a thick shelf carbonate characterized by its lithologic uniformity and fossiliferous nature (Pratt and Smewing, 1993). Paleo-water depths throughout the transect under study (Figures 1 and 6) range between the shallow intertidal to the open lagoonal setting with about 20 m water depth (F. van Buchem, personal communication, 1999). It was suggested that the Shu'aiba Formation was exposed related to a combined eustatic and tectonic event (e.g., Glennie et al., 1974; Harris et al., 1984; Scott, 1990; Wagner et al., 1995; Immenhauser et al., 1999). The top Shu'aiba outcrops throughout Jebel Akhdar (Figures 1 and 6) and also at Jebel Madar and Salakh. The lateral extension of the discontinuity is considerable and can be traced laterally many 100s of km into the subsurface of northern Oman (Wagner, 1990).

In the field area studied, the surface is non-angular with respect to the underlying sedimentary rocks, whereas it is an unconformity in a regional scale (Wagner, 1990). In Wadi Bani Kharus, the age of the uppermost Shu'aiba deposits beneath the surface is 117.5 million years before present (Ma) (top Lower Aptian; Harland et al., 1990 time scale). The first deposits of the Nahr Umr above the hiatus have an age of 113.8 Ma (uppermost Aptian) according to our graphic correlation model (Immenhauser and Scott, 1999). The duration of the hiatus at northern Jebel Akhdar is thus in the order of 3.5 to 4 million years (My) but it decreases in a basin-ward (southerly and southwesterly) direction (e.g., Scott, 1990).

Characterization of the Discontinuity

In Wadi Bani Kharus and Mu'aydin (Figure 6), the surface has a sharp upper limit and is planar to gently undulating. At Jebel Madar, it shows an irregular, wavy, and porous morphology (relief ≤ 5 cm). The omission suite (terminology of Bromley, 1975) consists of boring bivalves, encrusting oysters and serpulids, and in Wadi Bani Kharus, of stromatolites.

The discontinuity is mineralized in all exposures. Impregnation with secondary iron oxides (goethite, FeO(OH)) is common, some manganese nodules and Mn-impregnation is found, whereas phosphate is relatively uncommon. The red staining is penetrative, reaching several tens of cms downwards. At Jebel Madar, some 7 to 8 goethite-enriched horizons are found in the limestone beneath the discontinuity. In Wadi Bani Kharus, the limestones are bleached from the surface some 30 to 40 cm downwards. West of Wadi Bani Kharus, silica encrusts the surface and seals boreholes (Figure 2c) and small amounts of quartz sand are preserved in depressions.

Description of Facies and Diagenetic Contrasts Across the Discontinuity

In Wadi Bani Kharus, the lithofacies beneath the disconformity is a fine-grained, graded, peloidal grainstone. In Wadi Mu'aydin, it is a coarse, skeletal rudstone, comprising rudist debris, coral fragments, oncoids, echinoderms, and reworked intraclasts. At Jebel Madar, a peloidal and bioclastic grainstone, locally with rudists debris, is present. In all sections, the grainstone interval passes downward through a number of gradual changes into the characteristic grayish, bioclastic wacke-, to packstones of the Shu'aiba Formation. The pre-omission suite is faint and only few burrows were recognized. A number of thin-sections show considerable secondary porosity and dolomitization of limestones (Jebel Madar) beneath, but not above the surface. In the section west of Wadi Bani Kharus, root casts penetrate the limestone beneath the discontinuity. However, the Lower Aptian formation age of these root traces cannot be demonstrated because they were left empty.

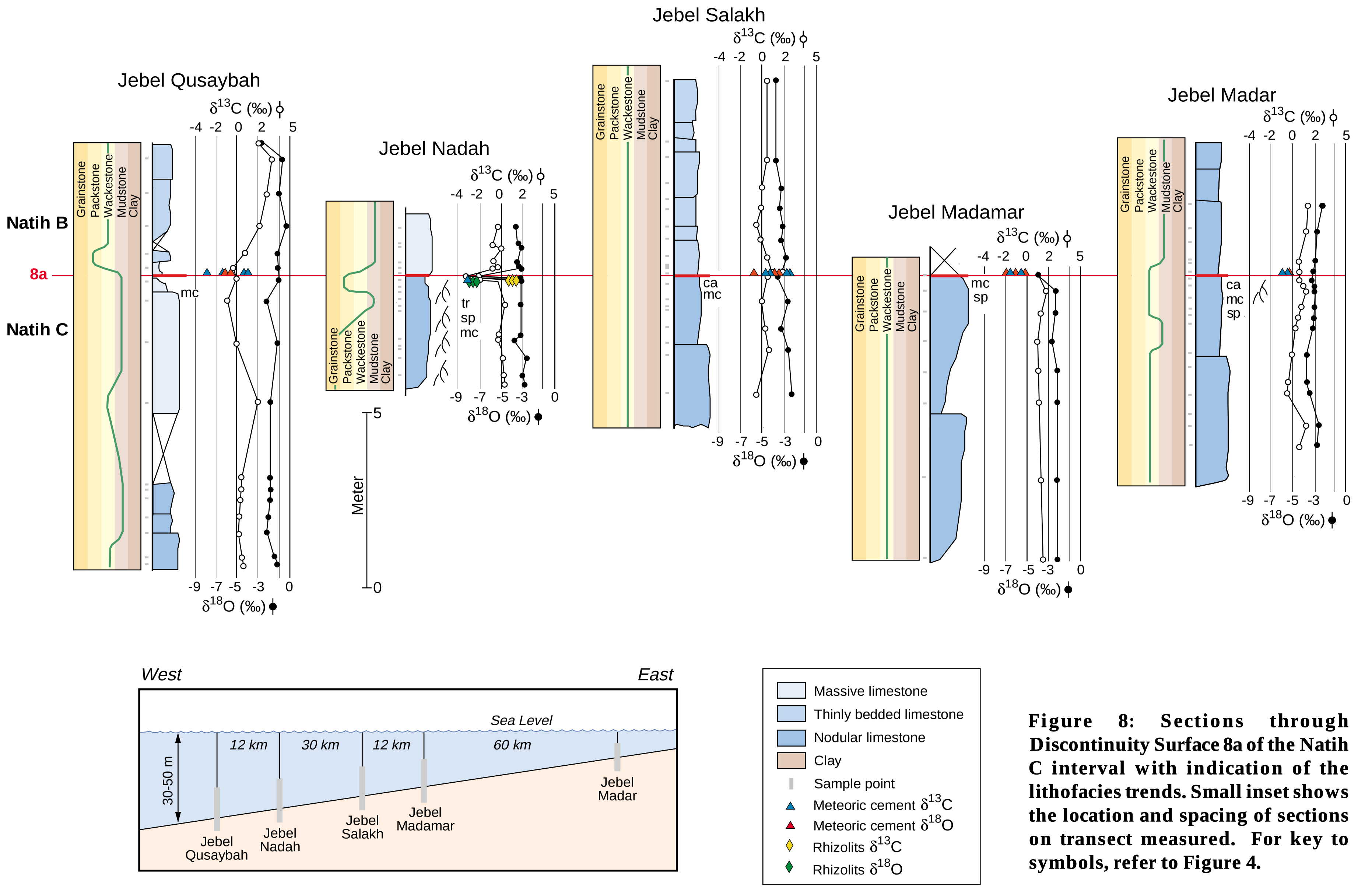


Figure 8: Sections through Discontinuity Surface 8a of the Natih C interval with indication of the lithofacies trends. Small inset shows the location and spacing of sections on transect measured. For key to symbols, refer to Figure 4.

The facies overlying the discontinuity is in sharp contrast to that underneath it. The first deposits of the Nahr Umr Formation are ochre, argillaceous packstones rich in *Orbitolina texana*. Orbitolinid foraminifera locally constitute up to 70% of the rock volume. At Jebel Madar, i.e. more basin-wards, the discontinuity is overlain by barren, greenish to ochre clays (Figure 6).

Albian Example

Case Summary

The second example is from the latest Aptian to latest Albian Nahr Umr Formation (Owen and Nasr, 1958; Murris 1980; Hughes Clarke 1988; Immenhauser et al., 1999; Figures 1 and 7). Throughout the southern Gulf, the Nahr Umr is primarily an impermeable unit of clayey facies acting as a seal for the Shu'aiba carbonate reservoir rock (Murris, 1980; Hughes Clarke, 1988). In Oman, the Nahr Umr contains three calcareous marker bed successions and some ten discontinuities, most of which are lithologically distinctive and can be traced over distances of at least 100 km in outcrop (Figure 4; Immenhauser et al., in press). Other surfaces are discontinuous and some that lie closely together (Figure 4), seem to converge and fuse laterally similar to the ones described by Bromley and Gale (1982). The discontinuities show conformable, non-truncating relationships with the underlying strata. The duration of the related time gaps is below biostratigraphic resolution.

Paleobathymetric interpretations of Nahr Umr sections are based on the analysis of microfacies and sedimentary features (Immenhauser et al., in press). A direct quantification of paleo-waterdepth in the field, however, is only possible in the northeastern Jebel Akhdar. There, the slope of the Al Hassanat Formation platform (Masse et al., 1997) grades into the sedimentary rocks of the Nahr Umr in the marginal domains of the Bab Basin.

The sections reported in this paper are from a north-south transect that reaches from the basin marginal setting (Northern Jebel Akhdar) into the basinal setting of the Foothills (Figures 1 and 4). We selected surface 8 (of Immenhauser et al., 1999; Figures 4 and 7), that rests on a rudist marker facies (Figure 7). This lithofacies is sufficiently distinctive to correlate the surface throughout Jebel Akhdar, but disappears in the Foothills.

Characterization of the Discontinuity

In most cases, the interval that shows evidence for early lithification has a sharp upper surface tinted a rusty orange-gray, but a vague lower boundary. The topography is smooth to slightly undulating. Iron staining extends downwards some 10 cm from the surface. Bore holes are relatively infrequent. In Wadi Mu'aydin manganese-stained oysters and serpulids encrust the surface.

Description of Facies and Early Diagenetic Contrasts Across the Discontinuity

The carbonate rock beneath the surface contains numerous rudists (*Prearadiolites*) in growth position. This marker bed is in its lower and middle part a dense, grayish wackestone with rudist debris and orbitolinid foraminifera. Towards the top of the bed, the facies grades into a rudist packstone indicative of a slightly higher hydrodynamic setting. The limestone beneath the discontinuity is intensely bioturbated and burrows are filled with iron-rich micrite. In Wadi Bani Kharus, the discontinuity caps a thin nodular wacke-, to packstone with recrystallized bivalve debris and orbitolinid foraminifera that overlies the rudist marker (Figure 7). Root molds filled with goethite minerals, meteoric cement, and fine-grained marine sediment were found in some samples. In Wadi Mu'aydin, the limestones beneath the surface are dolomitized. The carbonates above the unconformity are gray, commonly wacke-, to packstones, very nodular and contain diverse bivalves and orbitolinid foraminifera. Rudists or rudist fragments are scarce.

Cenomanian Example

Case Summary

The third example comes from the latest Albian to Early Turonian Natih Formation (Glennie et al., 1974). The Natih represents the last Tethyan carbonate system developed during the Permian-Turonian interval on the Arabian Platform (Murris, 1980) and is an efficient petroleum system (Terken, 1999). Van Buchem et al. (1996) published a detailed interpretation of the depositional environment and the sequence stratigraphic framework of the Natih Formation based on outcrop observations in the Foothills (Figure 1). We follow their correlation of surfaces and studied three major disconformities (surfaces 6a, 7a, and 8a of van Buchem et al., 1996; Figure 5) in the middle Cenomanian Natih C interval (Figure 5).

The above three surfaces were investigated in an east-west transect reaching from the shoal into the intrashelf basinal setting (van Buchem et al., 1996; Figure 1). The lateral extension of some surfaces is at least 100 km, others can be traced for some hundred meters only (Figures 5 and 8). The duration of the hiatus contained in these discontinuities is below biostratigraphic resolution. Overall, the Natih reflects a depositional setting ranging from the shallow intertidal to paleo-water depths in the order of 40-50 m in the intrashelf basin.

We selected the boundary between the Natih C and the Natih B interval (surface 8a of van Buchem et al., 1996) because this interface is recognized beyond doubt in all sections studied (Figure 8).

Characterization of the discontinuity

The discontinuity under study has been rendered conspicuous through intensive iron staining and its resistive character. At Jebel Madar, Madamar, and Salakh (Figures 1, 5 and 8), it is slightly undulous to nearly flat, strongly iron-encrusted with irregular concretions (few mm to 2 cm in diameter), but usually poorly phosphatized. In most localities, the discontinuity is perforated and colonized in variable degrees. Passing westwards from Jebel Salakh to Jebel Qusaybah and Nadah (Figures 1 and 8) the discontinuity fades. There, the surface is only very weakly ferruginous and less resistive.

Description of Facies and Early Diagenetic Contrasts Across the Discontinuity

Depending on the section measured, surface 8a caps a nodular to massive, bioturbated, mud-, to grainstone (Figure 8). The facies is rich in skeletal components (prae-alvelionid foraminifera, bivalves, gastropods, and echinoids; Philip et al., 1995). When traced downwards from the discontinuity, a condensed, Fe-stained facies continues unaltered some 10 to 20 cm and then relatively rapidly fades, passing through a transitional facies into apparently unaltered limestone. Over the area of fading, Fe-staining and intensity of burrowing are gradually reduced. Most burrows are filled with iron-stained, micritic material.

The carbonate rock that underlies the clay horizon at Jebel Nadah is conspicuously rhizoturbated (Figure 8). Slender root traces extend as far as three meters into the underlying limestone. They are filled with the same ochre, argillaceous material that forms a clay horizon (mainly kaolinite) above the surface (Figure 2f). The sharp boundaries of the rhizoliths points to roots penetrating a firm to lithified medium.

The facies of the limestone that overlies surface 8a varies from locality to locality (Figure 8). At Jebel Qusaybah, it is a wacke-, to packstone with numerous oysters (cerastostreon and “exogyres”) typical for the Natih B. At Jebel Nadah it is a thin clayey interval (Figure 2f) that differs due to its conspicuous ochre color and recessive nature from the beds above and below. This clay horizon is conceivably an altered paleosoil as indicated by some relicts of pedogenic features. This oyster-facies characterizes the deeper setting towards the west of the transect (van Buchem et al., 1996). At Jebel Salakh, the contrast in facies across the surface is comparably minor. The section directly above surface 8a is not exposed at Jebel Madamar pointing to a soft, muddy facies. At Jebel Madar, a bioclastic wackestone is overlain by mudstone.

Variability

In this section, we describe three other surfaces to document the overall variability of the polygenic discontinuities in northern Oman.

Discontinuity Surface 4, Jebel Madar (Nahr Umr Formation)

We selected this surface because it rests atop of a calcareous interval (Figures 4 and 9, marker bed succession I) in the otherwise argillaceous facies of the Nahr Umr at Jebel Madar. Jebel Madar represents the most basinward setting of the Nahr Umr Formation transect whereas Jebel Qusaybah is thought to represent the most basinward locality in the Natih Formation transect. The disconformity is a goethite-stained, locally bored, and somewhat nodular surface. It caps a thin ochre grainstone interval with abundant orbitolinid foraminifera. Resistive limestone beds alternate with recessive shale intervals that contain an *in situ* bivalve and echinoid fauna. The lithofacies above the discontinuity is barren, and predominately a buff-green clay with marl intercalations.

The surface shows evidence for submarine lithification due to borings that cut through burrows, foraminifera, and bivalves. Statistics on the morphology of orbitolinid foraminifera, i.e. a trend from discoidal to conical morphotypes, indicates shoaling towards the surface (Immenhauser et al., 1999). Minor negative shifts in carbon and oxygen isotopic composition point to emergence. The depletion in ^{13}C and ^{18}O is comparably weak and probably the product of only short-lived exposure, but it is present at portions of the sediment that yield secondary porosity. Emergence is also supported by trace element trends. An interval, (0.3 m thick) that lies directly beneath the surface (shaded gray in Figure 9) is enriched in Fe_2O_3, Al_2O_3, and silica pointing to pedogenesis. Conversely, depletion of Sr and Mg values is indicative for the influence of meteoric water.

Discontinuity Surfaces 6 and 7, Wadi Bani Kharus (Nahr Umr Formation)

The twin surfaces and underlying limestones at 78.5 m and 80.5 m in Wadi Bani Kharus are unusual in that they mark impressive changes in paleobathymetry within only few meters of the section (Figure 10). Their morphology and mineralization are very comparable to the discontinuity surface atop marker bed succession III (Figure 4). Field evidence for erosion of underlying strata is nil despite the laterally very continuous exposures. Statistical trends from discoidal to conical orbitolinid morphotypes point to upward shoaling (Immenhauser et al., 1999).

Discontinuity surface 6 rests on nodular wacke-, to packstone and is overlain by nodular packstone. Further upsection, a recessive, reddish shale unit with echinoids, bivalves, and the ammonite *Knemiceras*

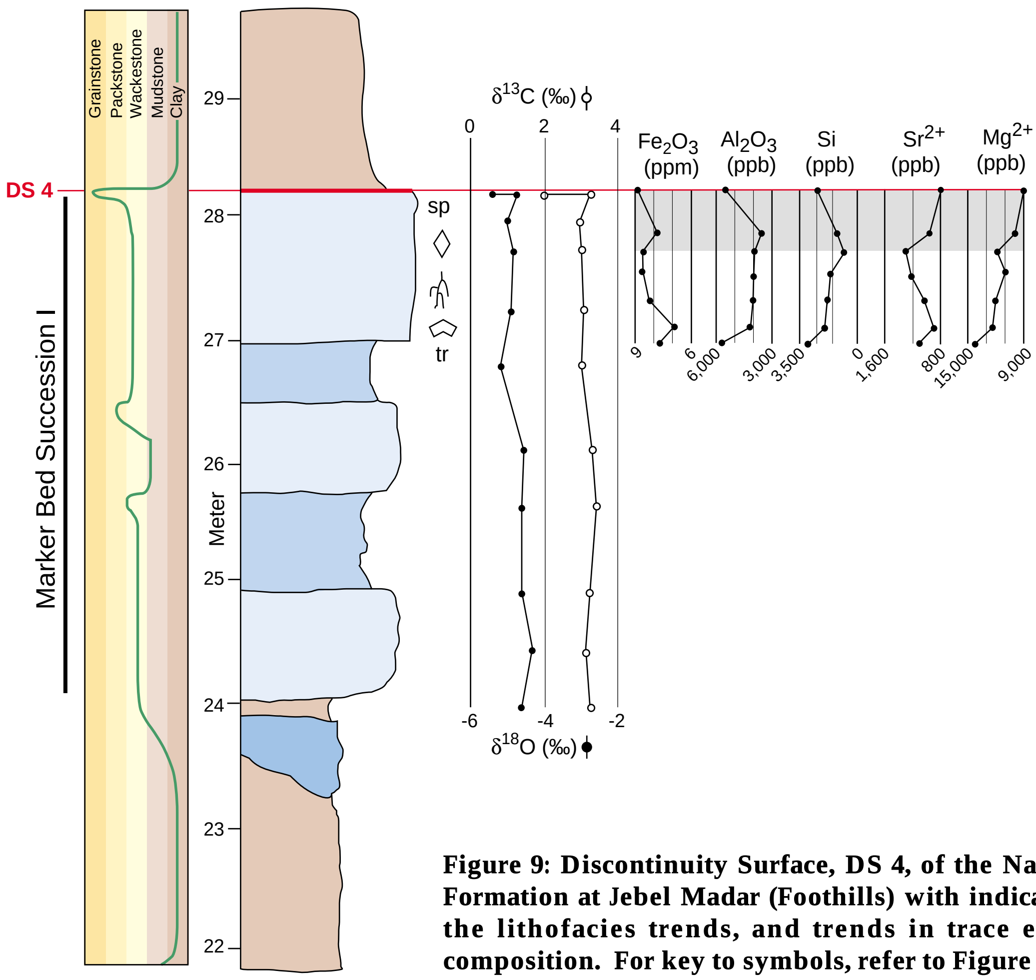


Figure 9: Discontinuity Surface, DS 4, of the Nahr Umr Formation at Jebel Madar (Foothills) with indication of the lithofacies trends, and trends in trace element composition. For key to symbols, refer to Figure 4.

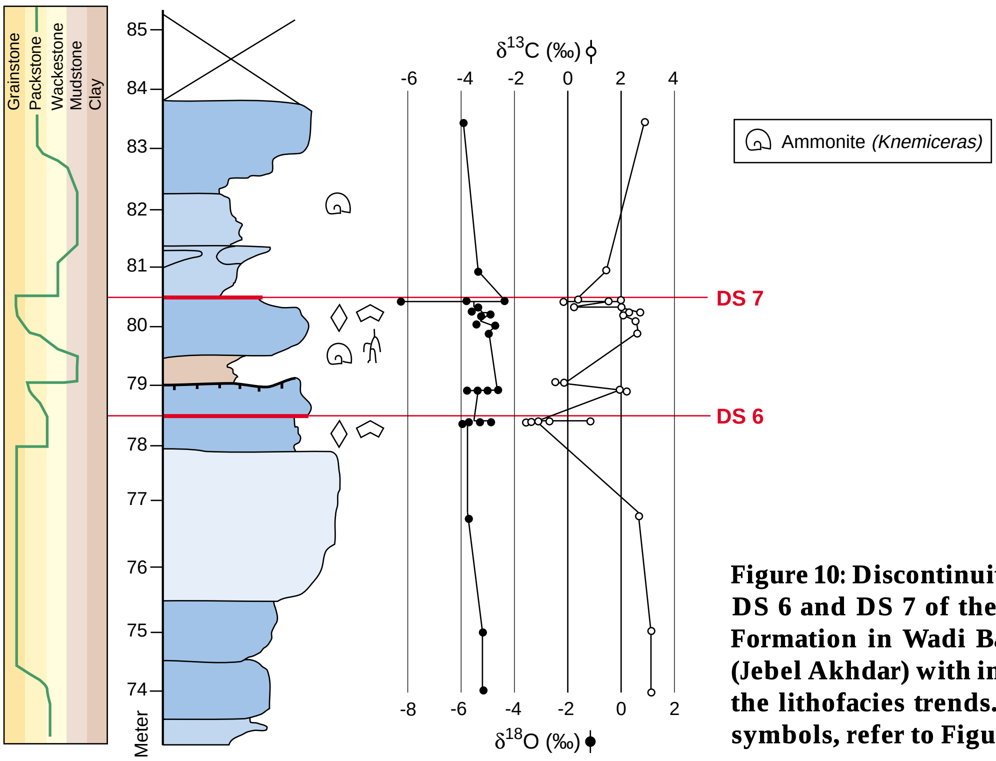


Figure 10: Discontinuity Surfaces, DS 6 and DS 7 of the Nahr Umr Formation in Wadi Bani Kharus (Jebel Akhdar) with indication of the lithofacies trends. For key to symbols, refer to Figure 4.

uhligi follows. The argillaceous lithofacies and the ammonite fauna document a deep-water environment. Towards discontinuity 7, the shale grades into a grainstone facies. A second shaley interval, also with ammonites, overlies the upper surface.

Both discontinuities are bored and encrusted and thus represent indurated fossil sea floors. Both are depleted in ^{13}C and ^{18}O (Figure 10) and show trace element trends that are comparable to those described from discontinuity surface 4 at Jebel Madar (Figure 9). The volume of secondary pore space in limestones beneath the surfaces is variable. Locally, secondary pore space reaches 15%. The limestone beneath surfaces 6 and 7 is dolomitized, that above the surface not. Root traces and weak pedogenic features are found in some samples (Immenhauser et al., 1999).

Discontinuity Surface 7a, Jebel Qusaybah (Natih Formation)

The discontinuity 7a (Figure 11) is one of the exceptional cases where evidence for meteoric diagenesis is poor. The discontinuity 7a resembles the “undercut” to “pebbly” hardgrounds of Brett and Brookfield (1984). Brett and Brookfield (1984) referred to this term for hardgrounds that are characterized by removal of unlithified sediment from burrows and between nodules leading to very irregular (undercut) surfaces, respectively to layers of lithified carbonate pebbles resting on only patchily lithified carbonate material.

In the case of discontinuity 7a, individual lithified carbonate pebbles reach 10 cm in diameter. They form an irregular layer atop of a recessive interval with wackestone nodules. Limestone pebbles are iron-impregnated, encrusted by small epibiota, and bored from all sides except where they rest on the underlying limestone. Caprinid rudists morphologically adapted to a hard substratum are present. The biota within marls and nodules is mainly thin-shelled bivalves and prae-alvelionid foraminifera. The carbonates that overlie the discontinuity are reddish, nodular wacke-, to packstones.

Evidence that might point to meteoric diagenesis is exclusively from stable isotopes. It seems intriguing, however, to assign a subaerial exposure stage to this poorly lithified surface. It is conceivable, that the sea-level drop that caused subaerial exposure of surface 7a in the other four (shallower) sections to the east was insufficient to expose the most basinal section at Jebel Qusaybah (Figure 5). In this case, depletion in ^{18}O may reflect the influx of brackish water during sea-level lowstand (Joachimski, 1994). Depletion in ^{13}C at this surface may be linked to an exposure surface that lies meters to tens of meters

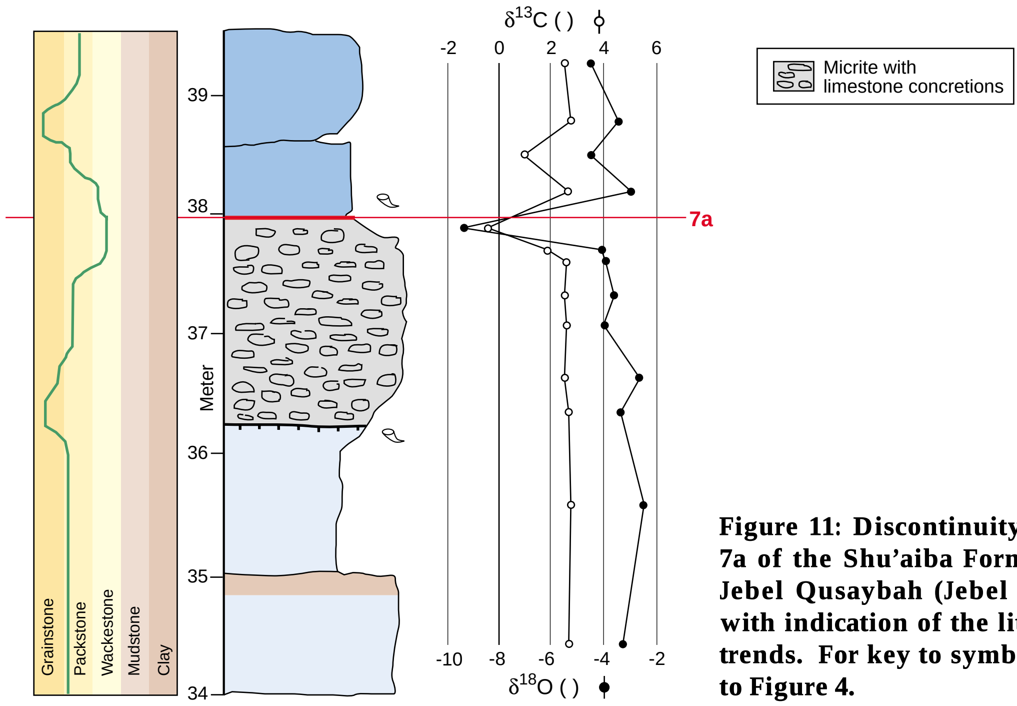


Figure 11: Discontinuity Surface 7a of the Shu'aiba Formation at Jebel Qusaybah (Jebel Akhdar) with indication of the lithofacies trends. For key to symbols, refer to Figure 4.

further upsection. Meteoric fluids percolating downwards from this surface are often trapped at an underlying seal (e.g., a marine hardground) and dissolution of the host rock and precipitation of meteoric cements just above a seal then leads to a negative shift in $\delta^{13}C$ (Matthews and Frohlich, 1998).

DISCUSSION

We have chosen six polygenic discontinuities from the Late Aptian to the Middle Cenomanian rock record to document evidence for marine hardground and subaerial exposures stages within the same surface. For many of these surfaces, it is difficult to pinpoint whether meteoric diagenesis overprinted a submarine hardground stage or vice versa. Some discontinuities, however, reveal a succession of sedimentological and diagenetic events that point to two subsequent hardground stages interrupted by a phase of emergence (e.g., discontinuity 2 in Wadi Bani Kharus cf. Figure 4, or discontinuity 7a at Jebel Madamar cf. Figure 5, and others). Based on these observations, we discuss a model for the formation of the polyphase discontinuities in Oman. Figure 12a summarizes the succession of events related to submarine hardground and subaerial exposure stages, whereas Figure 12b documents the formation model of polyphase discontinuity surfaces.

Polygenic Discontinuity Surfaces - Evidence and Model

Depending on the environment, cementation of carbonate material is a rapid process (see Grammer et al., 1999 for review). Synsedimentary or early diagenetic lithification of a carbonate sea floor occurs under a number of specific environmental conditions (Hillgärtner, 1998 and references therein). In the case of the surfaces under study, it is proposed that early lithification was either related to emergence, or more common, to periods of rapid sea-level fall. Rapid lithification of marine carbonates in the meteoric environment is a process that is relatively well understood (e.g., Wagner et al., 1995). Early marine lithification of carbonate sea floors during periods of rapid sea-level fall ("catch-down" of Soreghan and Dickinson, 1994) is probably related to the following setting. Rapid lowering of the effective wave base onto the sea floor induces winnowing and wave action and currents rapidly pump large quantities of sea water through the pore space (Tucker and Wright, 1990; Osleger and Read, 1991; Schlager et al., 1994). Consequently, submarine surficial lithification will occur. The processes of sea-floor winnowing and subaquatic lithification result in what we termed "hardground stage I" (Figure 12). There is clear petrographic evidence in several thin sections that lithification during this first hardground stage affected only the uppermost 3-5 cm of sediments beneath the paleo-sea floor.

Relative Succession of Events

(a)

OBSERVATION		INTERPRETATION
(8) Sedimentation (7) Manganese mineralization and boring of encrusters. Encrustation of surface by thin-shelled sessile biota. (6) Deposition of fine-grained marine sediment on isotopically light cements.	**Hardground Stage I I**	(8) Rise of sea-level and subsidence of sea-floor below range of effective wave base. (7) Effective wave base on sea-floor, subaqueous erosion. (6) Non-erosive transgression onto exposure surface.
(5) Precipitation of carbonate cement phase (light $\delta^{13}C$ and $\delta^{18}O$) within cracks in goethite crusts and fractures in carbonate. (4) Weak caliche features, bleaching. (3) Mineralization of surface (goethite, silica) (a) Bore holes sealed with goethite (b) Growth of large goethite crystals within carbonate rock (c) Fracturing of carbonate rock due to growth of goethite crystals.	**Subaerial exposure Stage**	(5) Meteoric cements (light soil CO_2, light $\delta^{18}O$ from meteoric source). (4) Terra rossa formation. (3) Sea-level drop, nonerosive subaerial exposure of sea-floor.
(2) Omission, submarine cementation, (a) Perforation by boring bivalves (b) Mineralization (Mn, phosphate). (1) Sedimentation, pre-omission bioturbation	**Hardground Stage I**	(2) Sea-level drop, lowering of effective wave base on sea-floor, subaqueous erosion and lithification. (1) Sea-floor below effective wave base.

Figure 12 (a): Paragenetic sequence of sedimentologic and diagenetic events as observed beneath the Discontinuity Surface, DS 2 in Wadi Bani Kharus (Figure 4). The events recorded are indicative for two hardground stages interrupted by a subaerial exposure stage.

(b)

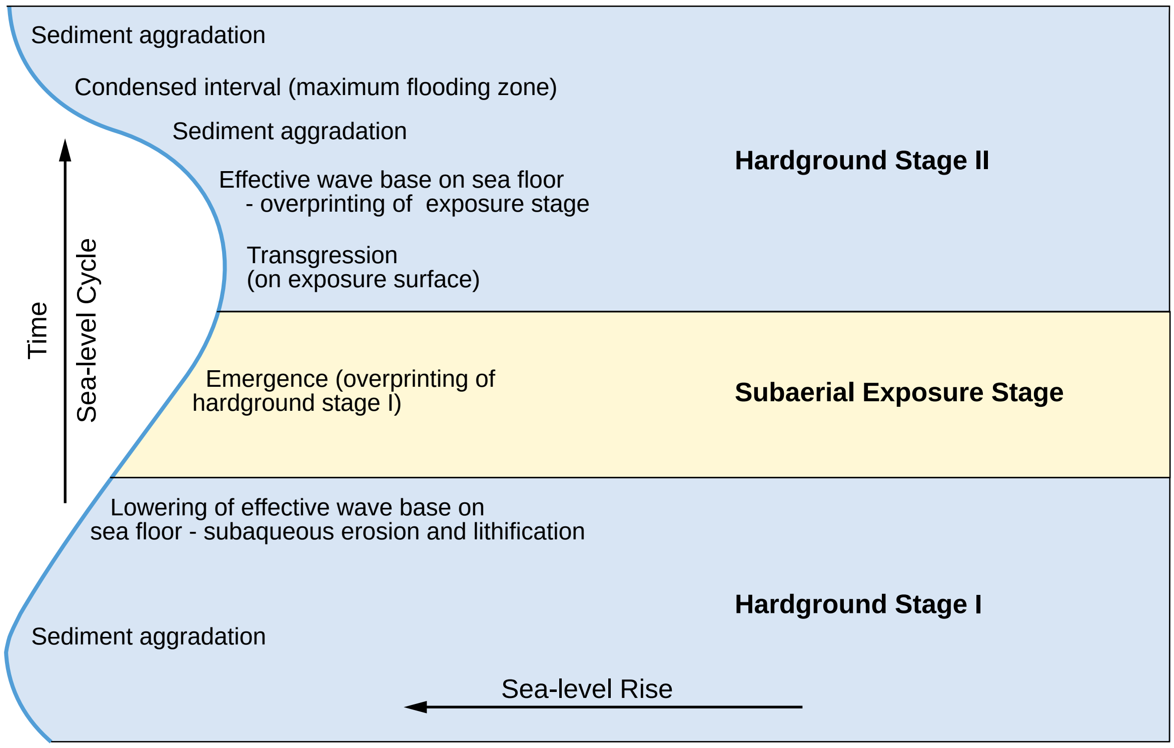


Figure 12 (b): Model for the formation of polyphase discontinuity surfaces throughout a sea-level cycle as based on the paragentic sequence indicated in (a).

Under a continuously falling sea-level, wave action and currents will constantly remove sediment from the hardground and thus prevent the formation of a shoaling cycle. This explains why many discontinuity surfaces rest directly on low-energy, subtidal sediments, or on very thin grainstone intervals.

Eventually, emergence may or may not occur ("subaerial exposure stage" in Figure 12a, b). If so, lithification in the vadose environment leads to further induration and to diagenetic and morphologic overprinting of the exposed surface. Depending on many factors, such as climate, topography, vegetation, and type of carbonate material (Immenhauser et al., 1999 and references therein), the carbonate surface will become karstified in various degrees or covered by a soil and caliche horizon only. Deep-cutting karstification will destroy most or all of the evidence for previous submarine lithification. In the case of the examples from northern Oman, the thickness of beds underneath the discontinuities is very constant when traced over distances of many hundreds of meters. This and their planar topography suggests that erosion ("top-cut-out sequences" of Soreghan and Dickinson, 1994) during subaerial exposure or renewed transgression was not substantial.

Eventually, sea-level will rise again and in most cases wave action will strip off the soil cover atop of the carbonate surface (an exception is the possible paleo-soil above discontinuity 8a at Jebel Nadah, Figure 2f). If substantial marine and biological erosion cuts into the underlying limestones, it may destroy all or large portions of the rock record that witnessed exposure. However, there is no evidence for massive submarine erosion in the surfaces under study. Similarly to hardground stage I, wave action will continuously remove sediment from the drowned exposure surface until the sea floor subsides below the effective wave base. We relate evidence for a marine hardground stage that succeeded subaerial exposure to this phase ("hardground stage II", Figure 12).

Exposure-related Features

The scattered evidence for incipient paleosol and caliche features and the absence of deep-cutting karst is characteristic for the surfaces discussed. This may point to a short-lived exposure stage (Wagner, 1990), to an arid climate, or may be related to a soil cover and seasonally humid climates (Hillgärtner, 1998). A semi-arid or arid climate is indeed indicated by Albian silica mineralization (silcretes) of two surfaces in the section west of Wadi Bani Kharus (Figure 2c; Webb and Golding, 1998). An alternative explication is that wave erosion during transgression has removed most of the former paleosols and caliche layers.

A paleosol horizon is possibly preserved above surface 8a at Jebel Nadah (Figures 2f, 5, 8) and there is circumstantial evidence for a former paleo-soil cover beneath other discontinuities. Evidence for a paleosol is rhizoturbation as found in some exposures, carbon isotope anomalies interpreted as the influence of light soil CO_2 (Allan and Matthews, 1982), and shifts in trace element composition. However, the absence of a well-developed caliche sequence and the overall scarcity of rhizoliths suggests, that an advanced stage of soil development was not reached in most cases or has been removed during transgression.

Care must be taken in distinguishing features that are related to Cretaceous subaerial exposure and such that are the result of sub-recent root traces, sub-recent endolithic lichen, and sub-recent iron-remobilization. In many cases, the two phases can be distinguished based on petrographic relationships. Root traces, for example, that cross-cut Tertiary calcite veins and stylolites are considered sub-recent in origin.

Duration of Subaquatic Omission

Physical erosion and sculpture of discontinuities is generally more or less modified or aided by biological destruction of the lithified substrate due to borers (Kennedy and Garrison, 1975). Shinn (1969) described closely spaced, superimposed bored surfaces and concluded that the number of boreholes in lithified sea floors is related to the duration of omission. The surfaces under study in Oman are rather simple and underwent relatively weak modification by scour and bioerosion, when compared for example, with the complex Upper Cretaceous hardgrounds from England described by Bromley and Gale (1982). It is thus concluded that the submarine omission stage was rather short lived, which is in agreement with the model proposed for the formation of these discontinuities ("catch-down" of sea-level).

Temporal Frequency of Discontinuity Surfaces

Based on our graphic correlation model of the Nahr Umr Formation in Wadi Bani Kharus (Immenhauser et al., 1999) and unpublished data from the Natih Formation in Wadi Mu'aydin (R.W. Scott, personal communication, 2000), the temporal frequency of discontinuity surfaces can be estimated. In the Aptian-Albian sections, these surfaces appear with a mean frequency of 1.4 My. In the Cenomanian, the temporal frequency is in the order of 0.3 My. These estimates, however, ignore periods of nonsedimentation contained in the discontinuities.

Spatial Frequency of Exposure-related Features

All of the 20 different discontinuity surfaces studied show various lines of evidence for subaerial exposure. Towards the more basinal sections, evidence for meteoric diagenesis fades for some of these surfaces or is absent (Immenhauser et al., 1999). Furthermore, some samples show incipient pedogenesis and meteoric diagenesis and whereas others sampled only few tens of centimeters aside show none. Geochemical evidence for a meteoric paleo-environment (i.e., shifts in stable isotope values, increase or decrease in trace element composition) is present in most sections. The amplitude of these shifts and the depth of penetration, however, vary strongly between different surfaces but also beneath individual discontinuities that were investigated at different localities.

The recognition of the polygenic nature of these discontinuity surfaces in the Middle Cretaceous of Oman based solely on cored drill holes appears thus difficult. The probability that the volume of carbonate rock provided in cores allows for a clear recognition of pedogenic or meteoric diagenetic features is rather small. Shifts in stable isotopes and trace elements that are related to a meteoric paleo-environment are more efficient since they might penetrate deeply into the underlying rock. Alternatively, the study of discontinuity surfaces in outcrop analogues and correlation of exposed sections in the subsurface is most promising.

SUMMARY

Discontinuity surfaces are common in the Middle Cretaceous Shu'aiba, Nahr Umr, and Natih formations of northern Oman. These surfaces formed during periods of rapid sea-level drop and many of them show evidence for two marine hardground stages interrupted by a subaerial exposure stage. The marine hardground stages are easily recognized and dominant in the field, whereas evidence for meteoric diagenesis is scattered. Direct petrographic evidence for subaerial exposure is present in about 10% of carefully screened rock samples. Circumstantial geochemical and biological data sets are more efficient in recognizing shoaling trends and the effects of meteoric diagenesis. The lithologic record of a shoaling phase prior to exposure is often incomplete due to subaquatic winnowing at the effective wave base. Supratidal deposits or paleosols were nearly always removed during transgression.

Discontinuity surfaces in the Shu'aiba, Nahr Umr, and Natih formations are spaced ten to few tens of meters apart. Many of them were correlated laterally over distances of 100 km and more between sections at Jebel Akhdar and the Foothills, respectively throughout the Foothills. This implies that cementation during phases of submarine lithification to form seals, and conversely, rearrangement of pore space, due to meteoric diagenesis and subsequent burial affected large volumes of carbonate rocks.

ACKNOWLEDGEMENTS

We gratefully acknowledge financial support from the Swiss National Science Foundation (Immenhauser) and the Vrije Universiteit Industrial Associates in sedimentology research grants held by Wolfgang Schlager. Fieldwork was possible due to the help of the Ministry of Industry and Commerce, especially Mohammed Bin Hussein Bin Kassim, Director General of Minerals, and Hilal Al Azri, Director of the Geological Survey, who provided logistical help and support. Critical comments by F. van Buchem, R.K. Matthews, W. Schlager, and an anonymous *GeoArabia* reviewer improved an earlier version of this manuscript.

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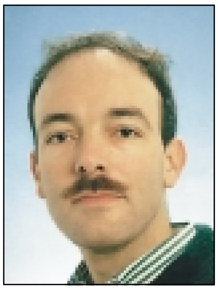

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Manuscript submitted: December 6, 1999

Revised: January 29, 2000

Accepted: February 15, 2000

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