The Lower Cretaceous carbonate slope-to-platform-margin succession near Khatt, United Arab Emirates: sedimentary facies and depositional geometries

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ABSTRACT

The Jurassic and Lower Cretaceous carbonate succession exposed near Khatt provides exceptional conditions for the investigation of sedimentary facies and depositional geometries in a carbonate slope-to-platform-margin setting. A coarsening-upward sequence in Lower Cretaceous limestones indicates decreasing depth of deposition and platform progradation. A pronounced shedding of sediments containing reefal fragments occurs in a slope environment with a well exposed basin-to-platform transect. The carbonate succession consists of mudstone, wackestone, grainstone, coarse rudstone with conglomerate/breccia interbeds, and framestone at the top. The depositional architecture is characterized by the abundance of massive sheet- or channel-like limestone bodies within thinly bedded and generally uniform strata. Quantitative analysis of many carbonate channel deposits and their geometries measured in outcrop led to the distinction of two major types. Type I channel deposits are thin (0.3 to 5 m) but massive, and are commonly irregularly shaped in cross-section. They are as much as 200 m wide. Type I channel deposits are characterized by a wide size range of skeletal and non-skeletal carbonate components. Type II channel deposits, by contrast, are more regularly bedded and have much larger thickness-to-width ratios, in general close to 1:10. Furthermore, they are composed of packstone to grainstone calciturbidite sediments. As with some sheet deposits, they can be correlated through most of the 5.5-km-long Khatt outcrop. Stratigraphically, however, their occurrence is very much restricted, indicating significant alternation of depositional styles as a consequence of changing carbonate platform production and changing sedimentary environments. The data presented here can serve as input for 3-D geological modeling of equivalent depositional environments in the subsurface. They can also be applied to object-based deterministic and stochastic facies modeling.

INTRODUCTION

Upper Paleozoic and Mesozoic rocks are exposed in a thrust belt in the northern part of the United Arab Emirates and in the Musandam Peninsula (Figure 1) along the western front of the Oman Mountains (Ricateau and Riché, 1980; Searle et al., 1983; Glennie, 1995). Traditionally, the Lower Cretaceous limestones are considered as equivalents of the Rayda, Salil, and Habshan formations in the subsurface of Abu Dhabi. The Jurassic-Cretaceous boundary and the Lower Cretaceous limestones are particularly well exposed in the Khatt area close to the United Arab Emirates-Oman border. The limestones may serve as an analog for the hydrocarbon-bearing units in the subsurface of Abu Dhabi and other parts of the Gulf region. The stratigraphy and lithofacies in the Khatt mapping area are shown in Figure 2.

Most of the exposed strata are in an approximately vertical position, so ensuring excellent geological exposure. The Khatt outcrops provide a rare opportunity for gathering quantitative data (for example, thickness-width relationships) on depositional geometries in a carbonate slope environment. This paper summarizes the results of a geological mapping survey of the Khatt area at 1:5,000 scale in November and December 1998. The sedimentary and depositional characteristics of massive carbonate bodies (slope-channels and overbank deposits), as well as the investigation of the tectonic setting, were of particular interest for the work presented here.
The study area is located on the western margin of the Oman (Hajar) Mountains, close to the Strait of Hormuz (Figure 1). The mapping area covers the hilly ground to the north, east, and west of the small town of Khatt, approximately 20 km southeast of Ras Al-Khaimah City in the Ras Al-Khaimah Emirate. The outcrops extend over an area of approximately 8 sq km. Morphologically, the Khatt area marks the transition from the Oman Mountains in the east, to the Jiri Plain in the west. The average elevation of the eastern part of the Jiri Plain is less than 40 m above sea level. The vertical relief of most ridges does not exceed 20 to 40 m but can be as much as 150 m near the eastern boundary of the outcrop area. The ridges typically trend parallel over several kilometers (Figure 3), although they are deeply incised and sometimes completely separated by erosion in places. The Jurassic and Lower Cretaceous succession in the Khatt area has been intensely karstified to form rugged ridge tops. On the ridge flanks, linear karst features (lapiés or karren) prevail over other denudational forms. Vegetation is scarce in this desert environment.

Structural Setting

The general strike of the Khatt outcrops is N10°E to N25°E, parallel to the western edge of the Oman Mountains and most major morphological and geological units are aligned in this direction. An exception is a large NNW-plunging syncline in the central Khatt area that, together with a minor anticline, disrupts the general geological trend. Its northern flank of the syncline is moderately (40°–60°) SSW-dipping, whereas the southern flank is only gently inclined to the NNE. Elsewhere in the area, Toland et al. (1993) described the tectonic setting of the Lower Cretaceous rocks in Wadi Haquil. The Jurassic part of the succession is strongly folded and thrusted. In the Khatt outcrops, most of the Lower Cretaceous exposures lack significant tectonic overprinting. Three major fault systems can be distinguished:
Figure 2: Outcrop characteristics of the geological mapping units, approximate thickness of the Lower Cretaceous facies (mapping units) in the central Khatt area, and stratigraphic succession of the rocks exposed in the Khatt area including the mapped lithofacies units. Total thickness of the facies units is about 625 m.

1. Large-scale faults and thrusts (10s to 100s of kilometers long) have affected the Jurassic and Lower Cretaceous rocks in this part of the United Arab Emirates and Oman. They are aligned N-S parallel to the western thrust front of the Oman Mountains. Low-angle thrust faults mark the Jurassic-Cretaceous contact at various locations, but predominantly in the northern and central mapping areas. The compressional tectonic regime within the Jurassic section of the western Oman Mountains is also shown by the presence of medium- to large-scale plunging synclines and anticlines. Parallel normal faults that occur throughout the Jurassic rocks in the Khatt outcrops, seem to be due to late-stage tectonic activity and are consistent with the idea of post-orogenic stress-relief and Cenozoic extensional tectonics (Mann et al., 1990).
2. A second generation of faults strikes in an E-W direction at right angles to the strike of the rocks, and commonly cross-cuts the thrust planes. These faults are widespread throughout the mapping area and include small- to medium-scale normal faults and fracture zones.

3. A large N-S trending dextral strike-slip fault zone affects most of the central part of the Salil Calciturbidite Facies and terminates in a complex region of thrust and normal faulting in the south. It clearly offsets several faults and fracture zones by about 100 m. Typically, intensive calcite veining, scales, druses, or tectonic breccia accompany all of the faults and fractures. Slickensides and pressure-solution features (stylolites) are common.

In the study area, the usually discordant Jurassic-Cretaceous contact shows an apparent complex thrusting relationship between slices of Jurassic rocks and rocks of the Rayda Facies. However, some authors (for example, Searle et al., 1983), have interpreted the relationship as due to slumping and not as the result of compressional tectonics. Similar structures are reported from outcrops to the north of the Khatt area in Wadi Naquab (Hulstrand and Al Matroushi, 1998).

Doubling of the sequences, indicated by lithostratigraphic reference horizons such as conglomerates, clearly suggests a major thrust-fault within the Rayda and Salil facies. The finding of a block of Jurassic and Rayda Facies rocks measuring 200 x 100 x 50 m within the lower Salil Facies in the central mapping area supports this interpretation (Figure 4). The thrust-fault itself is laterally discontinuous. High-angle back thrusting (the thrust-planes of the back-thrust and the main thrust are dipping in opposite directions) can be recognized in the southern section of the mapping area. The thrust-fault crops out as a large-scale fracture zone that has caused considerable thinning of the Salil Facies in the south so that its thickness has been decreased by approximately 50 percent to about 100 m.
Figure 4: Cross-section through the central parts of the Jurassic and Lower Cretaceous carbonate succession exposed near Khatt, UAE. j = Jurassic; r = Rayda Facies; s = Salil Facies; Sc = Salil Calciturbidite Facies; h = Habshan Facies; R = 'Reef'; F = Fanglomerates

STRATIGRAPHY

Definition of the Geological Mapping Units

Figure 2 lists the most important lithological characteristics and ages of the geological mapping units. Other distinctive criteria and wide-ranging characteristics of the local geological units are given in de Matos (1992) and in Hulstrand and Al Matroushi (1998).

There are several sedimentological markers, such as conglomerates or sheets of massive limestone, in the Khatt area. Aligned chert nodules in bands up to 50 cm thick provide the best means for the lithostratigraphic correlation of the limestone sequences. These marker units represent laterally extensive beds or double beds of chert on the same lithostratigraphic level.

Chronostratigraphy

The Lower Cretaceous units exposed at Khatt are time-equivalent to the Barremian to Aptian Kharaib and Lower Shu’aiba formations (Alsharhan, 1985). However, the depositional facies near Khatt shows striking similarities with prograding units of the Hauterivian Habshan Formation (see Aziz and Abd El-Sattar, 1997) in the subsurface of Abu Dhabi.

Based on the large-scale mapping of the Musandam Peninsula by Biehler et al. (1975) and resumed by Ricateau and Riché (1980), the pre-Rayda succession has been assigned to the Late Jurassic. Age determination of the Lower Cretaceous units (and hence stratigraphic correlation) is based on analysis of nannofossils (van Buchem et al., written communication, 1998) and caprinid rudists (Masse et al., written communication, 1998). The rudists indicated an Aptian age for the top of the Khatt Lower Cretaceous succession and the nannofossils suggested a Hauterivian age for the base. Due to the lack of diagnostic faunas in the Hauterivian and younger (Valanginian and Berriasian), a precise stratigraphic age determination is commonly difficult. As a consequence, many chronostratigraphic uncertainties exist, particularly at the base of the Khatt Lower Cretaceous succession. This, however, does not affect the main focus of this study that was the sheet and channel deposits and their geometries.

Sequence Stratigraphy

Throughout the Early Cretaceous, a relatively deep-marine shelf basin (the ‘Rayda Basin’) existed in what is today northern onshore Oman north of about 21°N (Haan et al., 1990). It was situated at the periphery of the Habshan shallow-marine, shallowing-upward shelf carbonate facies that prograded...
Figure 5: Regional sequence stratigraphic relationship for the eastward-prograding Habshan sequences (modified from Aziz and El-Sattar, 1997). The seismic and sequence stratigraphic interpretation is given according to Landmesser and Saydam (1996): Sequence I was deposited under highstand/shallowing upward conditions. Due to the lack of impedance contrast with the underlying Jurassic limestones, the base of Sequence I could not be clearly defined. The internal reflection geometry is monotonous. Sequence II is a lowstand systems tract with seismically well-defined sequence boundaries at the top and the bottom of the sequence. The internal reflection configuration is characterized by low-angle progradation. In the west, the base of Sequence III shows lagoonal onlap onto the top of the Sequence II boundary. Further east, the top of Sequence III is onlapped by younger strata from the basinal side. Seismic data indicate both, lagoonal and basinal onlap edges, which strike in a NNW–direction similar to the strike of progradation of the earlier sequences. The top of Sequence III displays a clear unconformity below steeply dipping, prograding clinoforms. Sequence IV represents a highstand/transgressive sequence tract, that flooded the entire shelf as the result of a drastic rise in sea level. In the E, the base is marked by a pronounced unconformity, while in the west, the base is not a clearly mappable seismic event. Sequence IV is overlain by younger clinoforms in the east. The Khatt outcrops are equivalent to the ‘Younger Clinoforms’ in the scheme presented in this paper.
into the basin (Landmesser and Saydam, 1996). These facies are regarded as time-equivalent of the Salil and Rayda facies that correspond to deeper marine slope and pelagic carbonate facies, respectively (Hughes Clarke, 1988; Haan et al., 1990). A detailed study of carbonate depositional sequences and the response of carbonate platforms and slopes to relative sea-level changes was made by Handford and Loucks (1993), Coniglio and Dix (1992), Schlager (1999), and Immenhauser et al. (2000).

The Lower Cretaceous succession near Khatt is defined by its third-order sequence boundaries (AP8 tectonic megasequence of Sharland et al., 2001). According to the scheme proposed by Sharland et al. (2001), the lithostratigraphic facies mapped in the Khatt outcrops are most likely limited by Maximum Flooding Surface (MFS) K10 (early Berriasian) at the base (Rayda Facies) and by MFS K80 (mid-Aptian) at the top (Habshan Facies, and 'Reef'). Because of the uncertainties in the age determinations (see above), it is difficult to relate precisely the Khatt outcrops to the regional sequence-stratigraphic framework.

In the Khatt area, as well as in eastern Abu Dhabi, the deeper marine facies (Rayda and Salil) occur within the deep basin that extended westward from Oman into Abu Dhabi (Hassan et al., 1975). These units therefore represent the eastern margin of the eastward and northeastward prograding Habshan shallow-marine limestone deposits. The stratigraphic relationship between those shallow-water and deeper marine (basinal) facies remains unclear. Aziz and Abd El-Sattar (1996, 1997) and Landmesser and Saydam (1996) developed a depositional model that related the shallow platform to the deep basin. Seismic-stratigraphic, biostratigraphic, lithostratigraphic, and wireline log data were used to identify three major carbonate sequences (Sequence I to III). The sequences document progressive sedimentation from the eastern margin of the Arabian Platform in the west toward the Rayda Basin in the east (Figure 5). In the sequence stratigraphic scheme proposed by Aziz and Abd El-Sattar (1997), the Khatt outcrops are equivalent to the so-called ‘Younger Clineforms’ (see Figure 5). The corresponding shelf edges trend north-northwest (see Aziz and Abd El-Sattar, 1997). The model is based on the Habshan and Zakum formations (Zakum Member of the Lekhwair Formation) in Abu Dhabi, as well as the Rayda and Salil formations (Berriasian to lower Hauterivian) of Abu Dhabi and Oman. Its sequence stratigraphic interpretation remains important for the understanding of similar (but younger) regional lithofacies relationships in the Arabian Platform.

RESULTS AND DISCUSSION

Sedimentary Facies

Upper Jurassic
The Upper Jurassic rocks are olive, gray, or dark-gray on fresh surfaces. They are massive in places, but elsewhere they are regularly bedded with highly continuous bed thicknesses of generally not less than 30 to 50 cm. The Upper Jurassic rocks of the northern and central parts of the mapping area consist of packstone with small (<10 cm) mudstone to wackestone intervals. Grainstones become more common southward. The packstone and grainstone beds contain pellets, coated grains, and shell-fragments (<1 mm). Coarse grainstone and floatstone with reeal fragments more than 1 cm in size only occur at the southern end of the mapping area. Intra-bed grainstone and rare floatstone intercalations have been interpreted as sedimentation from distal calciturbidite flows, as shown for instance by Reijmer and Everaars (1991) for the Triassic of the Northern Calcareous Alps in Europe.

Rayda Facies
The Rayda Facies has a characteristically light surface color that contrasts sharply with the underlying dark-colored Jurassic rocks. The rocks are almost white at the base, become light beige, and then yellow-beige toward the top of the unit and the transition into the Salil Facies. The change of surface colors may be very abrupt and is often accompanied by the emplacement of a second and third brecciated conglomerate deposit (see below). On fresh surfaces, the Rayda Facies limestone is gray to dark-gray. It is massive at the base, but beds 5 to 30 cm thick and small marly intervals of less than 3 cm thick become more abundant near the top of the unit. In addition to the conglomeratic intercalations, the facies consists of mudstone and wackestones with pellets <0.5 mm as the main components. Pelagic
and benthic foraminifera and calcified radiolarians are present. The unit contains many randomly dispersed chert nodules that are up to 30 cm in diameter.

**Conglomerates**

A total of three brecciated conglomerates (Figure 6) can be recognized in the Rayda Facies and in the Rayda/Salil facies transition zone. They are probably best characterized as debris flows, as their thickness rarely exceeds 4 to 5 m in the Khatt outcrops. The size of the conglomerate clasts decreases from as much as 1 m in diameter in the first conglomerate layer (cgl1) to about 5 cm and 3 cm in the second and third conglomerate layers (cgl2 and cgl3), respectively. Sphericity increases from angular to subrounded in cgl1, to subangular to well rounded in cgl2 and cgl3. In cgl1, dark-gray Jurassic packstone components are common, whereas white to beige wackestone and packstone clasts are dominant in cgl2 and cgl3.

The conglomerates are matrix-supported and have a wackestone, packstone and, in some cases, a grainstone matrix. They may represent poorly confined debris flows. At other locations, the conglomerates have been interpreted as submarine canyon fills (de Matos, 1992; Toland et al., 1993), petrographically similar to the conglomerate avalanche deposits or ‘exotic limestone breccias’ of Immenhauser et al. (1998) in the Batin Basin of Eastern Oman (see also Cook and Mullins, 1983). The small thickness of the conglomerates in the Khatt outcrops would seem to support the debris flow hypothesis.

**Salil Facies**

Many types of carbonates make up the Salil Facies, which is the dominant geological unit in the Khatt area. The Facies represents a succession of laterally consistent, well-bedded limestone deposits (bed thickness 10–50 cm) with marly intervals 1 to 10 cm thick. The thickness of both limestone beds and marls increases toward the top of the unit. Conglomeratic deposits are present but are restricted to the base of massive gray limestone units. The massive layers are irregularly shaped

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**Figure 6:** Schematic section through the central area of the Khatt outcrops: M = mudstone, W = wackestone, P = packstone, G = grainstone, F = framestone, R = rudstone. The change in depositional style from basin to platform is marked by an increase in grain-size upward and the increasingly frequent intercalation of massive (channel) deposits.
Figure 7: The Salil Facies in the central Khatt area. Note the abundance of prominent massive units. According to the degree of lateral consistency, they were classified as sheets or Type I channel deposits.

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ridge-forming units (Figure 7) up to 5 m thick. They are interbedded with beige to light-brown carbonates (light- to medium-gray on fresh surfaces) and show downcutting of as much as 30 cm, as well as many examples of lateral thinning and thickening. As a function of their lateral extension and thickness, they were classified as sheet and Type I channel deposits (see section on Depositional Geometries below). They consist of a wide range of carbonate facies from mudstone to coarse grainstone, with subsidiary floatstone containing oysters and rudists. The massive channel-like deposits are commonly rich in coated grains, pellets, and shell fragments whereas the well-bedded limestone units are almost entirely composed of mudstone and wackestone. Chert nodules up to 40 cm in diameter are abundant.

Salil Calciturbidite Facies
The upper part of the Salil Facies is differentiated as the ‘Salil Calciturbidite Facies’ named because of its mode of deposition (Watts and Blome, 1990). Beige to light-brown carbonates are interbedded with thin marly intervals less than 5 cm thick. The Salil Calciturbidite Facies contains dark-brown and beige laminated beds having numerous small-scale sedimentary structures such as cross-bedding, convolute bedding, dewatering structures, micro-slumps, and bioturbation. Although most of the rocks are pure carbonates (very fine packstone to grainstone), small quantities of fine detrital quartz are present within channeled units. Silt-sized quartz occurs as an accessory in some laminae that are less than 0.5 cm thick.

Habshan Facies
The base of the Habshan Facies is marked by the first appearance of ooids in massive channel deposits. There is no abrupt lithological difference between the Salil Facies and the lower Habshan Facies, but rather a gradational change. In the upper part of the Habshan Facies, well-bedded beige and massive, thickly packaged gray limestones are interbedded. The lateral thickness of the massive gray units varies considerably. Most of them represent Type I channel deposits (see section on Depositional Geometries below) and downcutting and erosional truncation are frequent. As the number of channel deposits as well as their thickness generally increase toward the top of the Habshan Facies (Figure 8), channels are commonly stacked and form massive deposits more than 5 m thick. The Habshan Facies Type I channel-fill consists of packstone and/or grainstone. A clear overall coarsening-upward trend
STACKED TYPE I CHANNELS

Figure 8: Stacked Type I channels within the Habshan Facies form the top of the main ridge in the Khatt outcrops. Lateral termination, thinning and thickening are common.

can be seen as the frequency of channel intercalations increases (Figure 8) until floatstones and rudstones replace very coarse grainstones. In the grainstones, most of the components are coated grains, shell-fragments, and some echinoids (Hulstrand and Al Matroushi, 1998). Rudstones and floatstones contain large quantities of macrofossils that may have been derived from bioherms. Due to the abundance of caprinid rudists, this part of the succession was referred to as the ‘Habshan rudistid biostromes’ (de Matos and Peebles in Alsharhan, 1997). The upper part of the Habshan Facies near Khatt also contains many benthic foraminifera.

‘Reef’
The mapping unit named ‘Reef’ consists of gray, massive grainstone, rudstone, and bafflestone with muddy packstone intercalations. The unit contains reefal fragments such as branching corals (some of them covering more than 1 sq m), stromatoporoids, rudists (including caprinids), and gastropod and shell fragments.

Except for the Quaternary fanglomerates and some small, locally very dispersed karst pocket fillings, all geological units of the Khatt area are limestones and marls. The observations indicate that the outcrops represent a slope environment with a well exposed basin-to-platform transect (see measured section Figure 6). Other slope settings have been described from the Lower Cretaceous elsewhere on the Arabian Peninsula (Pratt and Smewing, 1993; Masse et al., 1998).

**Depositional Geometries**

Many weathered-out and often massive carbonate bodies are exposed in the Khatt area. The prime objectives of their study were the investigation of depositional geometries and their classification, and an attempt at a genetic interpretation of these massive, commonly ridge-forming units. They are easily distinguishable from the very regular and well-bedded limestone matrix due to their darker weathered surfaces. Genetically, and with respect to their geometries, they can be subdivided into sheet-like deposits and two types of channel deposits. Type I channels are present in all facies of the Khatt outcrops but sheets were only identified in the Salil and the upper Salil Calciturbidite Facies.
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Sheets, and Type I and Type II channel deposits were classified according to their width, thickness, and degree of lateral thinning (Figure 10). In addition, Type I and Type II channel deposits show distinctly different lithologies. The sedimentological characteristics for the three geometry types are discussed below. Geometries are only taken into account where an overlap of the three depositional elements exists (Figure 10). This is particularly so for the sheets and Type I channels as only the ridge sections exposed in the Khatt outcrops could be studied. The real lateral extent of the sheets is probably much greater than observed.

**Sheet Deposits**

Sheets are defined as prominent, usually gray units of massive and/or very thick limestone beds with a high degree of lateral continuity (Figure 7). Lateral thinning of less than 20 percent per 100 m is tolerated by definition. Most of the sheet-like deposits, however, show thickness variations of less than 5 percent per 100 m and some are almost consistent in thickness over the entire N-S extent (about 5.5 km) of the outcrop area. The sheets are generally composed of slightly coarser material than is present in the beds above and below. The prevailing rock types are wackestone and packstone.

**Type I Channel Deposits**

Type I channels weather out as gray or dark-gray units of massive, in some cases slightly layered, channel-like limestone bodies that are laterally discontinuous (Figure 8)—some pinch out after only a few meters (Figure 11). Values of lateral thinning typically exceed 20 percent per 100 m. Downcutting, abrupt thinning, and rethickening are frequent occurrences. Type I channel fills may consist of packstone, grainstone, conglomeratic limestone, and rudstone or, with respect to some Type I channels in the Habshan Facies, floatstone as well. Hence, they consist of much coarser-grained sediments than those deposited above and below them. A clear coarsening-upward trend of Type I channel deposits toward the ‘Reef’ has been noted in the central Khatt Lower Cretaceous succession (Figure 6), but no such observations have been made everywhere in the Khatt area. This suggests that the channel sediments were derived from very localized sources and their massive character suggests that they were filled during a single depositional event, such as a gravity flow (see interpretation below). In terms of the paleoenvironment, it would have required a very well differentiated carbonate platform source area with clear-cut pathways for sediment transport; a modern analog would be the Bahamas (Westphal, 1998).

**Type II Channel Deposits**

Type II channel deposits are well bedded and form trough-like depositional structures of considerable thickness. They are defined by laterally onlapping channel fills (Figure 12) and show thickness-to-width ratios that are substantially higher (as much as 20 times more) than those observed for Type I channel deposits (Figure 10). A well-exposed Type II channel in Wadi Wid (central Khatt area) is shown in Figure 13. In an earlier study, the onlapping margin had been interpreted as an intraformational unconformity (Searle et al., 1983). Reinvestigation of the site (Grötsch, in Hulstrand and Al Matroushi, 1998) from a vantagepoint on a nearby ridge provided a complete cross-section and made visible the channel-trough structure. Typically, Type II channel fills are composed of packstone or fine grainstone. Compared to the surrounding rocks the bed thickness is increased by 10 to 30 percent. In the upper part of the Habshan Facies, Type II channels may locally incorporate other massive limestone deposits that are a maximum of 3 m wide and 0.4 m thick.

Numerous strike and dip measurements have been made for each sheet and channel. Although all sheet and channel axes trend in westerly or northwesterly directions, there are significant differences with respect to the variability of their orientation. As can be seen in Figure 14, the sheets have a definite northwesterly orientation. The Type 1 channels also have a northwesterly trend (although less constrained), but the orientation of the axes of the Type II channels are less well defined.
Figure 9: Distribution of sheet and channel-type carbonate deposits investigated in the Khatt Lower Cretaceous succession. The numbers are summarized on the basis of 25-m vertical intervals and may not include all such deposits.

Figure 10: Sheet and channel geometries as measured in the Khatt outcrops. In addition to differences in composition and texture, the analysis of thickness and width relationships reveals a distinctive pattern for the different channel/sheet types. Only the ridge sections could be considered, which are exposed in the Khatt outcrops. Therefore, the real lateral extent of the sheets is probably much larger.
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Figure 11: Cross-section of a small Type I channel in thin-bedded rocks of the Habshan Facies (h). Hammer for scale.

Numerically, the orientation of the sheets is much more uniform (azimuth variation <20°/ dip variation <15°) than for Type I channels (about 60°/70°) and Type II channels (about 80°/75°). Moreover, Type II channels are generally more gently inclined than both the sheets and Type I channels. In the upper Habshan Facies, the Type I channels define the slope orientation by massive shedding in a southwesterly direction. The general uniformity of the orientation of the sheets can be attributed to their size in covering a large slope area. By contrast, low dip angles and inconsistently oriented axes of Type II channel deposits reflect a mechanism of gradual channel fill with highly uniform sediments in a low-energy regime. Continuous but slow sediment flow is responsible for the characteristic onlap of the fill, whereas the channel margins are left intact.

Modern analog studies (for example, Einsele, 1993) suggest that the repeated sheet-like limestone deposition represents storm-triggered calciturbidite flows of unconsolidated carbonate mud and ooze from the platform, which are redistributed on the platform slope.

In contrast, the channel deposits are localized and gravity induced, and depend on the sediment load derived from the platform top or other distinct platform sources. The difference in the depositional style of the two channel types (massive for Type I channel deposits; thick, yet regularly bedded for Type II deposits) is difficult to explain. Sediment grain-size and hydrodynamic behavior, as well as the consolidation state of the underlying sediments, are thought to be the dominant parameters (see El Albani et al., 1999). The gradual deposition of the homogeneous Type II channel deposits on a semi-consolidated, yet similarly homogeneous substratum in the Salil Calciturbidite Facies, may result in the formation of relatively deep channel troughs. R.B. Davies (oral communication, 2001) suggested that the channel trough itself could have been formed by a more vigorous sediment flow. Coarse sediments are swept farther down the slope ahead of the flow, whereas the trough (formed by the flow) is subsequently filled by finer flow particles in a calm setting. This mechanism could also explain the observed fine lamination of some channel fills. In addition, low-energy transport and deposition of fine-grained sediments after a first ‘flush’, results in the well-defined bedding of the channel fill. Slope failure may also have helped in the formation of the Type II channel troughs and would have had a bearing on the observed geometries. However, no supportive evidence for slope failure was found during this study.
Figure 12: Several Type II channels within Salil Calciturbidite Facies (Sc) wackestones and packstones as defined by their onlapping margins. Note the increased bed thicknesses of the channel fills.

Figure 13: Onlapping southern flank of a Type II channel in the Salil Calciturbidite Facies (Sc). Inset: complete channel trough as seen from a nearby ridge.
Figure 14: Polar plot of the axial orientation of massive limestone deposits in the Khatt area. In contrast to the Type I channels and sheets, which trend very uniformly in WNW direction, the axes of Type II channel deposits are marked by a significantly wider orientation and inclination range.

In the case of the high-energy transport of relatively coarse materials and their deposition within weakly consolidated mud-dominated sediments, wide and comparatively shallow channel troughs are likely to be generated with original margins being eroded or leveled down. The mixing of flow deposits with carbonates of the matrix yields the massive and rather heterogeneous fills of the Type I channel. If this interpretation is correct, Type I channel fills are the result of the primary deposition of a sedimentary flow, whereas Type II channel fills are secondary and independent of the type of trough-forming mechanism. The onlapping margins of the Type II channels suggest a fill (calciturbidites) of a pre-existing feature. Type II channels may also have served as ‘line sources’ or feeder channels for either coalescent or laterally disconnected lobe systems (Betzler et al., 1999). These, however, are not exposed in the Khatt area.

Figure 10 summarizes the thickness-to-width relationship for the sheets and the two types of channels. A clear distinction between the sheets and the channel types is possible due to their different geometries. A change in lithology is not necessarily required. Combined geometrical and lithological characteristics of sheets and channels are, however, particularly informative with respect to the paleoenvironment when compared to their stratigraphic position in the Khatt limestone succession (Figure 15).
LITHOLOGY OF SHEET AND CHANNEL DEPOSITS

As many as three conglomeratic and brecciated intervals occur at the base of the Lower Cretaceous sediments and are attributed to high-energy transport from a Jurassic upland that was probably formed as a result of phases of tectonic activity (Le Métour et al., 1990). Synsedimentary tectonic uplift, for example by rifting (Immenhauser et al., 1998) during the possible long hiatus (Berriasian and Valanginian) between the Jurassic and the Lower Cretaceous Rayda Facies, could have created a steep platform escarpment and caused local erosion. The channel-derived sedimentation in the Rayda and lower Salil Facies indicates proximal high-energy transport of sediments on the upper slope (or possibly at the platform margin) and the deposition of the coarse grainstone and conglomeratic to brecciated limestone deposits.

In the upper Salil to Habshan facies, a clear basin-to-platform transition can be inferred (Figure 2). A significant change in sedimentation patterns occurred between the lower and the upper Salil Facies with respect to lithology (mudstone and wackestone replacing the predominant packstone and grainstone) and depositional style (enhanced sheet-like deposition instead of Type I channels). A Bahamian-type alternation of pelagic sediments with recommencing gravity flows (Bernoulli, 1981) indicated a newly prograding platform margin. The platform progradation was accompanied by the formation of a new sediment source in the upper Salil Facies.

Studies of similar carbonate platform environments (Haak and Schlager, 1989; Reijmer and Everaars, 1991) attributed the facies change to second- and third-order sea-level fluctuations and related lithological variations. Sea-level fluctuation and its influence on carbonate platform sedimentation has been studied at many locations (for example, Cartwright, 1985; Schlager et al., 1994; Grötsch, 1996;
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Everts et al., 1999; Westphal et al., 1999), and is important for the sequence-stratigraphic and paleoenvironmental interpretation of the Khatt Lower Cretaceous succession. The general picture of an overall second-order eustatic sea-level rise of about 80 m from the Barremian (chronostratigraphically corresponding to the Salil Facies) to the late Albian (Haq et al., 1988) may explain the observed trends for distal and proximal channel deposition. The marked third-order cycle in the late Barremian to early Aptian (about 124–120 Ma) has an amplitude of almost 80 m and could be responsible for the significant change in the channel-derived sedimentation of the upper Salil Facies. However, more-detailed stratigraphic data is required to confirm such a hypothesis.

Major calciturbidite flows occur in the Upper Barremian lower Salil Calciturbidite Facies. The switch from large-volume Type II channel to low-volume Type I channel deposition in the upper Salil Calciturbidite Facies probably reflects a decrease in platform-carbonate production. A pronounced shedding of reefal fragments from the nearby platform margin is inferred for the lower Aptian Habshan Facies. The sequence terminates with platform-top sediments and the lower Aptian ‘Reef’ Facies.

**CONCLUSIONS**

Facies analysis of the various channel fills in the Khatt Lower Cretaceous succession indicate a coarsening-upward sequence and a decrease in the depths of deposition from the upper Salil Facies to the top of the Habshan Facies and the ‘Reef’ (upper Barremian to lower Aptian). In terms of the paleoenvironment, the Khatt outcrops represent a carbonate platform slope setting with a well exposed basin-to-platform transect.

An analysis of the depositional geometries in the Khatt outcrops defines three types of sedimentary bodies distinguished by thickness-to-width relationship and lithology: they are sheets, and Type I and Type II channels. Both sheets and Type I channel deposits are characterized by low thickness-to-width ratios. In contrast to the sheets, Type I channel deposits are laterally discontinuous and show significant thinning and re-thickening. Storm-triggered flow and the shedding of fine platform-derived sediments over a wide slope area has led to the deposition of sheet-like limestone bodies, whereas Type I channel deposits represent more localized and much more vigorous gravity-induced flows of carbonate sediments. They caused downcutting into a pre-existing relief and reworking of sediments. The regular bedding and remarkably high thickness-to-width ratios of Type II channels are a consequence of the sedimentary properties of the fine-grained carbonate particles and their hydrodynamic behavior in distal turbidity flows. This hypothesis is supported by the investigation of modern calciturbidite analogs (Eberli, 1987; Eberli, 1988). The formation of troughs filled with Type II channels probably occurred independently from fill deposition, and may be due in part to slope failure.

The quantitative data presented here may serve as input for geological modeling of equivalent depositional environments as observed in the subsurface by Landmesser and Saydam (1996) and Aziz and Abd El-Sattar (1997). In addition, the data can be applied for object-based 3-D deterministic and stochastic facies modeling.

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