Paper 1

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The development of Middle Cretaceous carbonate platforms, Persian Gulf, Iran: constraints from seismic stratigraphy, well and biostratigraphy

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ABSTRACT: In the Iranian Persian Gulf several fields have been producing oil from Middle Cretaceous carbonates. Geological studies of these fields (limited to industry reports) describe the subsurface using lithostratigraphic principles. Lithological boundaries are obvious and are the focus for the correlation of the interwell areas. Most of the structural highs, which were easily found, have been drilled. The lack of a sufficiently detailed seismic sequence stratigraphic analysis has precluded the definition of reliable models at both regional and field scales.

The development of many oil and gas fields requires seismic sequence stratigraphy as a predictive technique, particularly in areas between drilled structures. This study aims to re-evaluate the field-scale stratigraphy in an oil field in the southern Persian Gulf using these techniques. The high quality seismic and well data from this field form one of the first datasets of this kind presented in the literature. High-resolution seismic data reveal the internal complexity of carbonates. The Cenomanian carbonate systems of the southeastern Persian Gulf reveal internal architecture and subsurface variability that neither seismic nor well data alone can provide. This paper analyses the seismic character of the Cenomanian Khatiyah and Mishrif formations and discusses how, even after more than 25 years of production, application of sequence stratigraphic principles can improve the understanding of an oil field. For this oil field, the combination of seismic, wireline logs and biostratigraphy has allowed a better understanding of the internal heterogeneity of the Mishrif reservoir. Understanding the successive stages of drowning and back-stepping of a carbonate platform within this reservoir unit has important implications for well planning and further reservoir development.

Important new information on the depositional geometries has also been obtained from within the Khatiyah Formation (the regional source rock) which leads to exploration targets in the interwell area. This information gives new insights as to the stratigraphic distribution and internal variability of the carbonate platforms and isolated build-up geometries. The insights gained are important to the estimation of reservoir volume, connectivity and variability.

KEYWORDS: *Persian Gulf, sequence stratigraphy, late growth build-up, Middle Cretaceous, Carbonate platform*

INTRODUCTION

During the Middle Cretaceous, extensive carbonate platforms covered the eastern part of the Arabian plate, including the eastern Persian Gulf. Many of the major hydrocarbon accumulations are found in the Middle Cretaceous reservoir rocks, which developed as the carbonate platforms evolved. The stratigraphy and development of laterally equivalent reservoirs are well documented in the Arabian Peninsula (e.g. Loutfi *et al.* 1987; Alsharhan & Narin 1988; Alsharhan 1989; Alsharhan & Kendall 1991; Alsharhan 1995; Pascoe *et al.* 1995; Philip *et al.* 1995), particularly in the UAE and Oman (Jordan *et al.* 1985; Pascoe *et al.* 1995; Philip *et al.* 1995; Van Buchem *et al.* 1996, 2002*a*, *b*; Terken 1999).

A basin-wide, transgressive, shallow-water carbonate system was deposited from the Late Albian to the Turonian (Burchette 1993; Van Buchem *et al.* 1996; Terken 1999). The platforms started to grow in areas with relatively low subsidence rates, such as basement highs and salt domes, following a regional rise in sea-level (Droste & Van Steenwinkel 2004). The complex internal geometry of the platforms has been described in the Cenomanian Natih Formation (Van Buchem *et al.* 1996, 2002*a*) in Oman and in the Upper Cenomanian Mishrif Formation (Burchette 1993; Pascoe *et al.* 1995) in the UAE.

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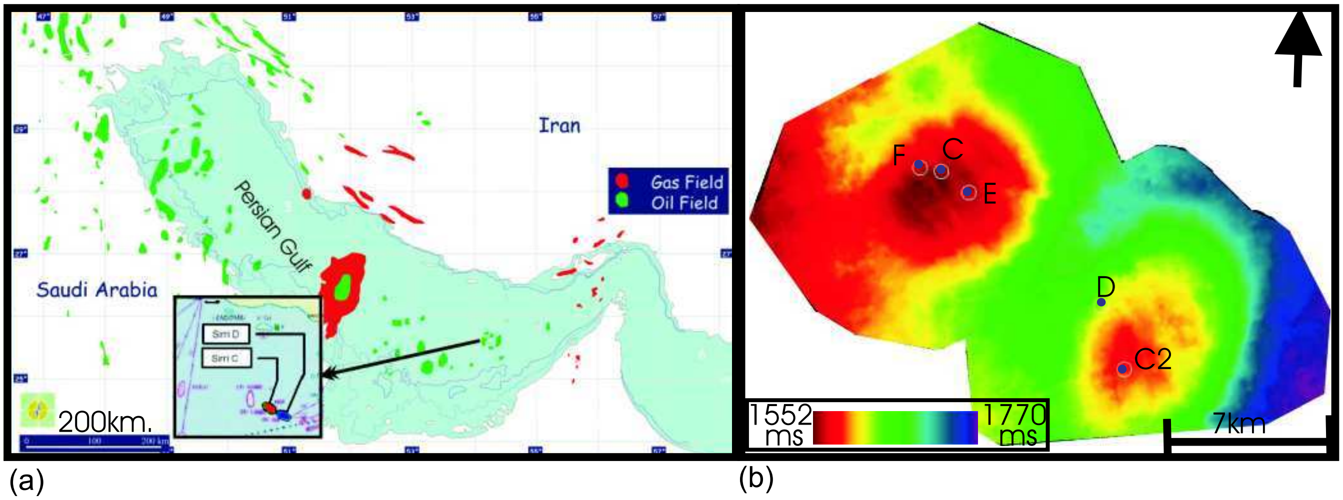

Fig. 1. (**a**) Location map showing the study area in the southeastern Persian Gulf. The study area consists of two adjacent, salt-driven domal structures. (**b**) A time-structure map on top of the Lower Cenomanian Khatiyah Formation shows the position of the structures.

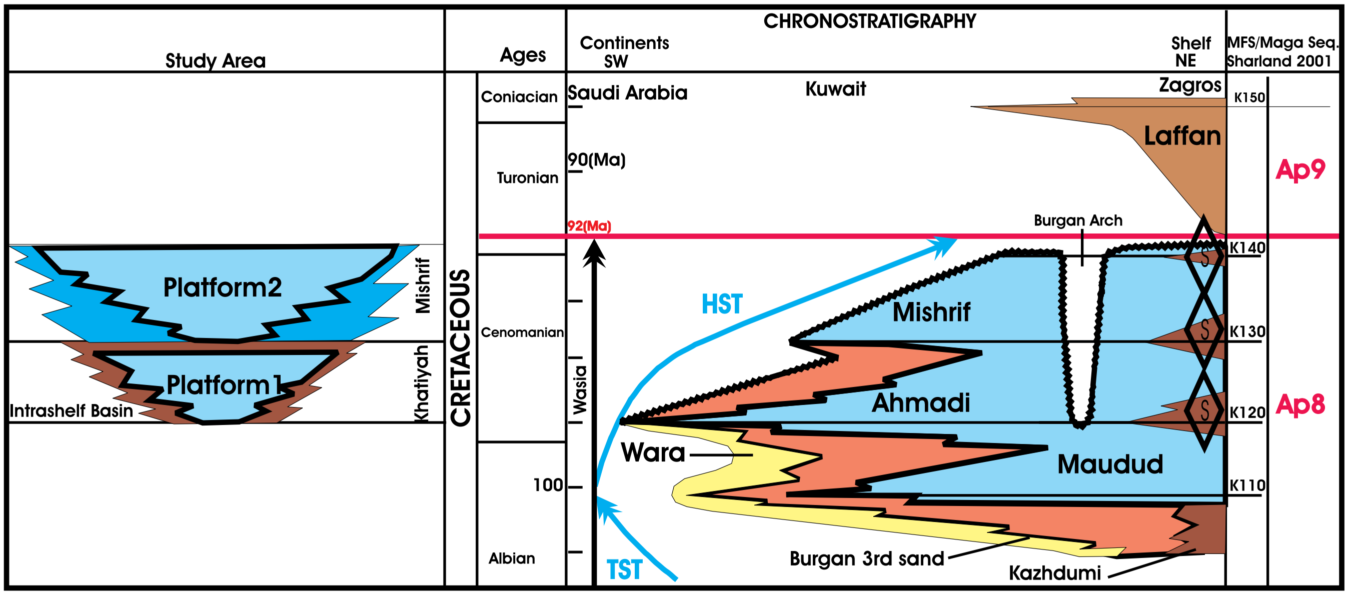

Fig. 2. Schematic chronostratigraphic section (adapted with permission from Sharland *et al.* (2001)). The studied interval (left) consists of two vertically stacked carbonate platforms above maximum flooding surfaces (k120 and k130). This interval corresponds with the upper portion of Arabian plate mega-sequence AP8, as defined by Sharland *et al.* (2001).

This study focuses on similar complexities within the platforms developed in the Cenomanian of the southeastern Persian Gulf in Iranian territorial waters (Fig. 1). The Cenomanian of the studied area consists of intrashelf basin carbonates (organic-rich mudstones and wackstones) of the Khatiyah Formation (Lower Cenomanian; Ahmadi in the Zagros) overlain by rudist-rich limestones (packstones and grainstones) of the Mishrif Formation (Upper Cenomanian–Turonian; Sarvak in the Zagros) (Fig. 2). An unconformity forms a boundary between this succession and the overlying deep-marine shales of the Laffan Formation (James & Wynd 1965). The Mishrif Formation is the main oil producer in the studied area. Primary depositional facies variability linked to secondary overprint of the Turonian palaeokarst, controls the reservoir quality of the Mishrif Formation.

The studied area is an oil field containing two domal salt-driven structures (Fig. 1). Mishrif reservoir oil has been produced for nearly 25 years from these structures. The full potential of the Cenomanian carbonate reservoirs in this area is, however, neither documented nor understood because, although many structural highs have been drilled, the intervening areas are virtually unexplored. Resolving the complexities of these fields and identifying the unknown stratigraphic traps require the predictive techniques of seismic/sequence stratigraphic principles.

The dataset used in this study consists of high quality three-dimensional seismic data, well logs and core descriptions from industry (Iranian Offshore Oil Company). It is one of the first datasets of this kind from the southeastern Persian Gulf to be presented in the literature. Seismic stratigraphy integrated with well data analysis gives new insights into the internal variability of the reservoir unit that are essential for estimation of reservoir volume and connectivity. The study also shows the presence of new, very low-risk exploration targets within the Khatiyah Formation, which has previously been known only as a potential source rock of the Mishrif reservoir. The results of this study may serve as a reference for time-equivalent deposits between structures in the southern Persian Gulf.

GEOLOGICAL SETTING

The evolution of the depositional basin of the northeastern margin of Arabia, including the Persian Gulf, has been a long and complex process (Murris 1980). From initiation and spreading of Neo-Tethys I in the Late Permian and its replacement by Neo-Tethys II which occurred from the Jurassic (Glennie 1995, 2000) to around Middle Cretaceous times, the northern part of the UAE, including the study area (Fig. 1), was a tectonically passive carbonate shelf (Alsharhan & Scott 2000). During the Jurassic and the Cretaceous, the Arabian platform was in an equatorial position and attached to the northern margin of Africa (Smith *et al.* 1994). In this tropical zone, a mixture of clastics, carbonates and evaporites were deposited upon a low-relief shelf both laterally and iteratively through time. The Middle to Late Cretaceous was a period of major change in the area of the modern Persian Gulf. Global sea-levels were rising steadily (Sharland *et al.* 2001) towards the Early Turonian global maximum flooding surface (Haq *et al.* 1988). In the southeastern Persian Gulf, mudstones/wackstones of the Khatiyah Formation (Fig. 2) were deposited above the regionally developed Maudud Formation (James & Wynd 1968). The strongly progradational Mishrif Formation, which is the main oil producer in the studied area and elsewhere in the Persian Gulf (IOOC unpublished reports), was formed by rudist reef development.

Sometime between the Turonian and Campanian, obduction of oceanic crust began along the modern eastern margin of the Arabian platform (Glennie 1995). Consequently, swelling of the Arabian platform, associated with salt diapirism, resulted in a considerable period of non-deposition and erosion. The Late Cenomanian to the Early Turonian was a period of generally favourable conditions world-wide for high organic productivity (Van Buchem *et al.* 1996, 2002*a*). During the Cenomanian, eustasy was the major element controlling the growth, development and location of build-ups (Sharland *et al.* 2001; Van Buchem *et al.* 2002*a*). Salt diapirism, local subsidence and tilting of the basin had minor influences on the development and subsequent submergence of the platforms.

Middle Cretaceous carbonate build-ups within the southeastern Persian Gulf show several third-order developments (0.5–3 Ma), similar to those described for the Arabian plate (Sharland *et al.* 2001; Droste &Steenwinkel 2004) and, in particular, for the Middle Cretaceous stratigraphy of the northern Oman (Van Buchem *et al.* 2002*a*). These third-order sequences are separated by discontinuities in their growth, with evidence of episodic subaerial exposure. The build-ups under study fit the paradigm documented by Sharland *et al.* (2001) and Droste & Steenwinkel (2004). They showed that the generally rising second-order sea-level, which allowed thick rudist reefs and skeletal banks to develop across the Arabian plate, was halted by the relative sea-level fall of the Turonian. The effects of meteoric water leaching and karstification were most intense beneath this regional erosional surface, which is where the best reservoir quality is commonly developed (Loucks & Sarg 1993; Montenat *et al.* 1999; Hunt *et al.* 2003).

Long-term shoaling-upward sequences of the lateral age-equivalent Natih Formation have been documented by several studies (e.g. Harris *et al.* 1984; Scott 1990; Burchette 1993; Philip *et al.* 1995; Van Buchem *et al.* 1996, 2000, 2002*a*; Granjeon & Van Buchem, 2000). The generation and importance of time-equivalent unconformities have been studied elsewhere in the UAE (Alsharhan & Kendall 1991; Pascoe *et al.* 1995). However, studies of the Cretaceous stratigraphic framework in the Iranian southeastern Persian Gulf are limited to unpublished company reports (IOOC & NIOC).

DATA

In this study a 3D seismic dataset covering 300 km^2 and wireline logs of five vertical wells were used for interpretation. The seismic data have a bin size of 12.5 × 12.5 m, 40-fold coverage, a sampling interval of 4 ms and a record length of 6 s. These pre-stack time-migrated seismic data have a broad frequency bandwidth, with a dominant frequency in the range of 37–42 Hz within the interval of interest (1.59–1.67 s).

Limited core description reports and faunal content palaeologs allowed an estimation of the time framework and spatial relationships of events.

METHODOLOGY

In this study, sub-seismic depositional cycles derived from gamma-ray (GR) log, core description and biostratigraphy are used to enhance the seismic sequence analysis to investigate the stratigraphic architecture of the carbonate sedimentary system. The method used can be summarized in four steps.

1. Seismic interpretation of the key horizons. This enables identification of reflection configurations and stratal geometries and the recognition of chronostratigraphic surfaces using a well-to-seismic tie.
2. Identification of depositional cycles using GR logs from well data followed by the determination of the relation between these cycles and the occurrence of fossils on available palaeologs and core descriptions. A one-dimensional sequence analysis is built in this step.
3. Study of spatial relationships, lateral–vertical distributions and identification of the hierarchy of depositional cycles (sequence analysis). Known geology is limited to 2D sections at well locations, hence the main constraint is the recognition of event timing in the areas between wells.
4. Create an integrated seismic stratigraphic model that allows definition of the spatial relationship of events, the direction of progradation and relative aggradation angles.

SEISMIC INTERPRETATION

The seismic responses to the top boundaries of the Maudud, Khatiyah and Laffan formations were interpreted throughout the seismic volume. A good well-to-seismic tie and the lateral continuity of these horizons allowed a confident interpretation of the visible geometric features. Horizon flattening on top of the key horizons (Fig. 3) shows that this area does not have a history of intense local tectonic activity during the deposition of the studied strata (Figs 2, 4). However, a relatively low rate of subsidence towards the northwest is recognizable within the Khatiyah Formation.

An upper zero crossing of a trough is interpreted as the top of the Maudud Formation (Fig. 5). The Maudud Formation is a well-developed Orbitolina-rich limestone (James & Wynd 1965). It has generated a continuous seismic marker throughout the studied area (Fig. 3). The Maudud Formation is a thin layer (20 m) causing a seismic 'tuning effect'. This effect is destructive and the depositional cycles of the Maudud Formation do not make a seismic signature within the dominant frequency range (37–42 Hz) of the seismic data.

An upper zero crossing of a trough represents the top of the Khatiyah Formation (Fig. 5). This formation consists of well-bedded pelagic lime mudstones (Fig. 4) with great lateral extent in the studied area. The total thickness of the Khatiyah Formation averages 200 m, reaching 300 m in the deepest portion of the basin. The interval thickness gradually increases in a SE–NW direction. This gradual thickening of the Khatiyah Formation was first considered as a simple deepening of the

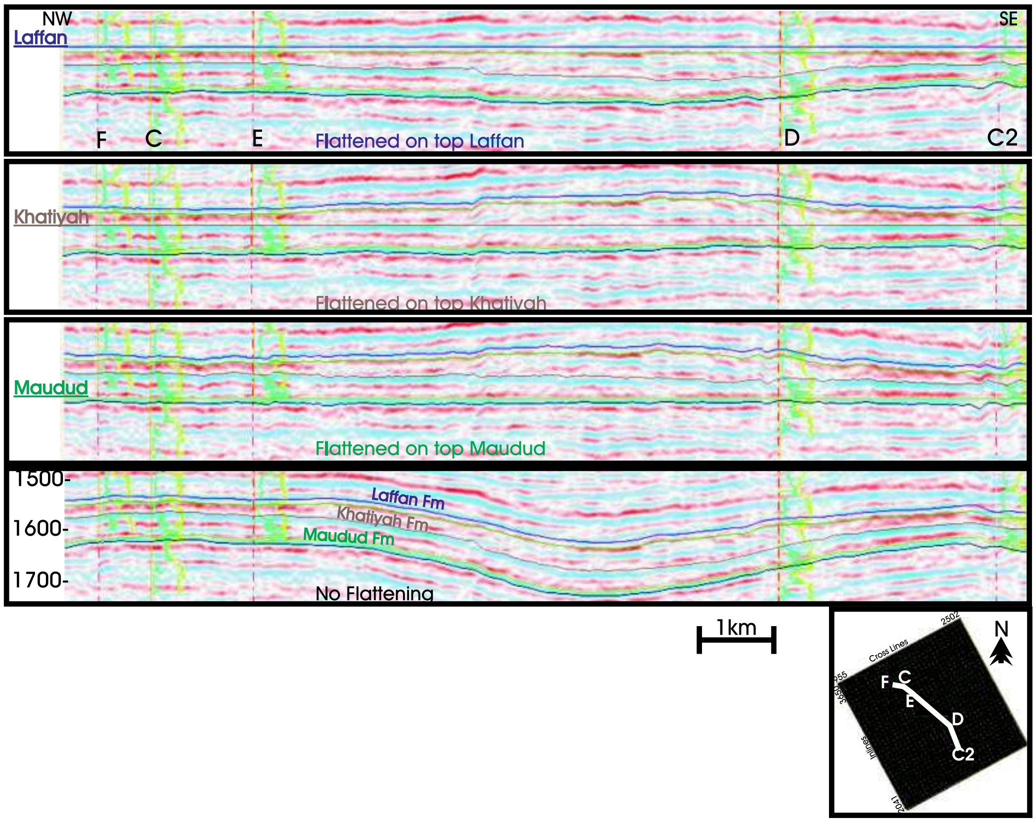

Fig. 3. A random line passing through all wells before and after flattening on the Maudud, Khatiyah and Laffan seismic markers. Horizon flattening shows no evidence of a significant structural event or salt diapirism during the deposition of the studied interval (Khatiyah–Mishrif) before the Turonian regional emergence. The seismic line flattened on top of the Laffan marker indicates that the structures began to grow after the deposition of the studied interval.

basin towards the northwest, but this study demonstrates that the basin architecture is more complex and that a carbonate platform has developed within this interval. Nevertheless, a characteristic seismic reflection is not associated with the top of the Mishrif Formation. A regional unconformity marks the upper boundary of this formation (Alsharhan & Narin 1988; Alsharhan & Kendall 1991; Pascoe *et al.* 1995; Philip *et al.* 1995; Montenat *et al.* 1999; Sharland *et al.* 2001). Turonian karsts cut into rudist-rich limestones at the top Mishrif Formation as seen in core description data (Fig. 4). The heterogeneous nature of the karstified surface that has resulted from dual control of depositional facies variability and karst distribution makes it difficult to map this surface with confidence. Seismic interpretation of the Mishrif Formation, even if undertaken on a line-by-line basis, is difficult to translate into a 3D model. Horizons become difficult to follow or geological features between horizons can be difficult to map in the horizontal dimension. The internal heterogeneity and lateral varying bed thickness is due to progradation of the platform margin, which is the main focus of this study. Where the Mishrif Formation thins to tuning thickness, peaks and troughs interfere to produce a composite reflection (Fig. 5). The amplitude of the composite event increases as the Mishrif Formation thins (amplitude error). It seems that the tuning effect is concentrated in the crestal area of the two domes; therefore, it may be suggested that thinning of the Mishrif Formation towards the top is caused by either syn-depositional salt tectonism or erosion. However, clinoform seismic architectures are recognized within both the Mishrif and the Khatiyah formations. These clinoforms are superbly imaged by the three-dimensional multi-channel seismic volume. Figure 6 illustrates two vertically stacked clinoform reflection units expanding laterally in the area between two domes. A strong negative reflection representing the Laffan Formation (Late Turonian–Early Coniacian) overlies the upper clinoform (Figs 3, 5, 6). The Laffan shale overlies the Turonian unconformity and belongs, therefore, to the overlying sequence (Fig. 2). The Laffan Formation is of great importance in the studied area because it provides a reliable seal to the underlying Mishrif reservoir.

Geometries

The studied interval in the area between the domal structures (Figs 1–3) is dominated by inclined geometries. An enlarged view of a seismic line cutting through these geometries (shown in Fig. 7) shows two vertically stacked clinoforms. These clinoforms show bidirectional progradation and delineate prograding carbonate-platform systems separated vertically by a strong continuous seismic trough. The lower clinoform (platform (Plt) 1 in Fig. 7) shows approximately 3.5 km of progradation, with about 55 m of aggradation between two continuous seismic reflection events of the Maudud and Khatiyah formations. Dips range between 14° and 16°. The seismic line (Fig. 7) runs parallel to the direction of progradation. Investigation of seismic mapping of the clinoform confirms that variations in dip are real and unrelated to different progradation directions. This relatively steep-dipping clinoform (Fig. 7, Plt1) is clearly separated from surrounding parallel seismic reflection events. These parallel reflections climb up the margin of platform 1. The seismic signatures of platform 1 and its peripheral sub-horizontal reflections are bounded at the top by a well-developed seismic marker which represents the top

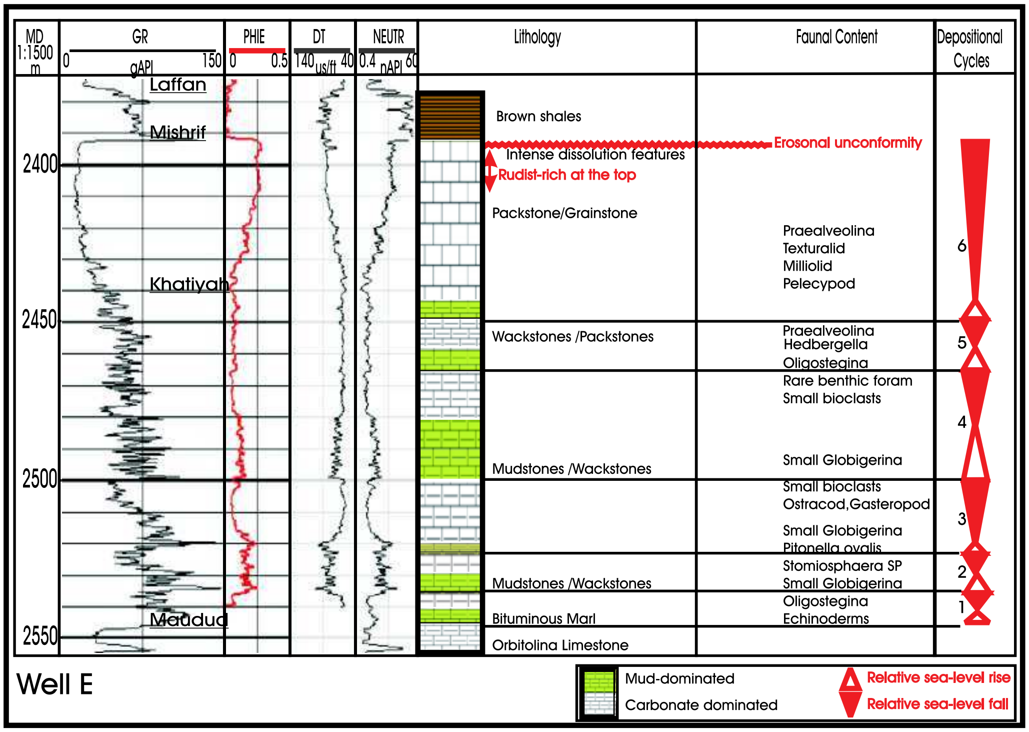

Fig. 4. Well E. Gamma ray, porosity, sonic and neutron logs are shown within the studied interval (2393–2547 m). A comparison between sonic velocity and neutron logs indicates that high GR values are generated by organic-rich mud-supported limestones. Six organic-rich mudstone/wackstone units are recognizable from log data and core description. Faunal content from core and proposed accommodation variations are shown on the right.

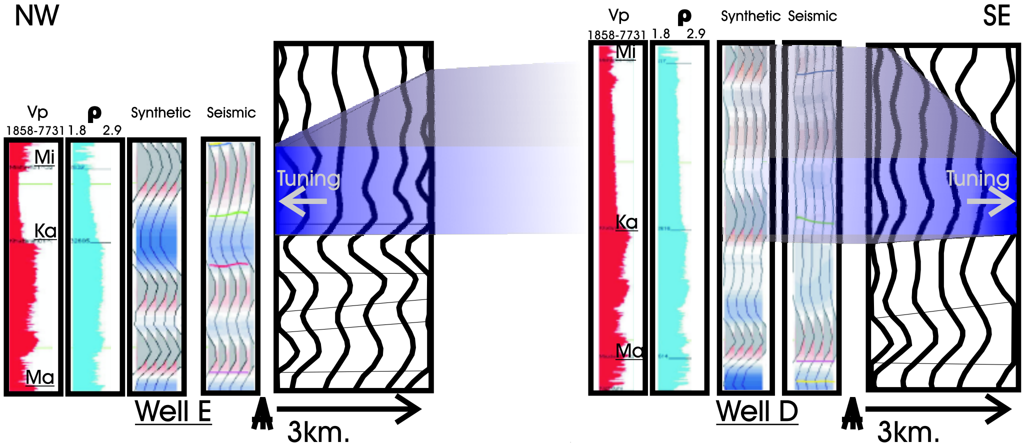

Fig. 5. Synthetic seismograms, generated for wells E and D, with a correlation coefficient of 0.96. Acoustic velocity (V_p), density log (ρ) and seismic traces at the well locations are shown. Some of the seismic traces are shown along a distance of 3 km from each well towards the southeast. The Mishrif Formation (Mi) thickens between two wells. Where the Mishrif Formation thins to tuning thickness (17.8 m), peaks and troughs interfere to produce a composite reflection with higher amplitude. The Khatiyah Formation (Ka) thickens gradually towards the northwest with a complex internal heterogeneity that is discussed in the text.

Khatiyah Formation. An upper clinoform seismic geometry (platform (Plt) 2 in Fig. 7) overlies this continuous reflection. Approximately 5.2 km of clinoform progradation is observed, with about 90 m of aggradation within the upper section of the studied interval (Fig. 7). Similar to platform 1, downlap surfaces are clearly distinguishable from peripheral sub-horizontal reflections. Reflection dips of downlaps range between 11° and 13°. Seismic observations of platform 2 (Fig. 7) indicate an upward narrowing, where a distinct build-up stands out near well 'D' on top of platform 2. The isolated build-up at platform 2 and the surrounding sub-horizontal reflections are bounded at the top by a well-developed seismic marker similar to that described for platform 1. Here the seismic marker represents the regionally developed Laffan Formation (James & Wynd 1965). Based on a purely geometrical interpretation of the seismic signature, seven packages of successive events can be differentiated. As illustrated in Figure 7, these packages are marked 'Time 1' to 'Time 7' to track event hierarchy.

WELL LOG ANALYSIS

Wireline logs provide the fine vertical detail of the wells and complement seismic data for a better understanding of the subsurface geology. The studied interval consists of alternating mud-supported (organic-rich) and clean carbonate layers. A clear differentiation can be made between these layers as the GR

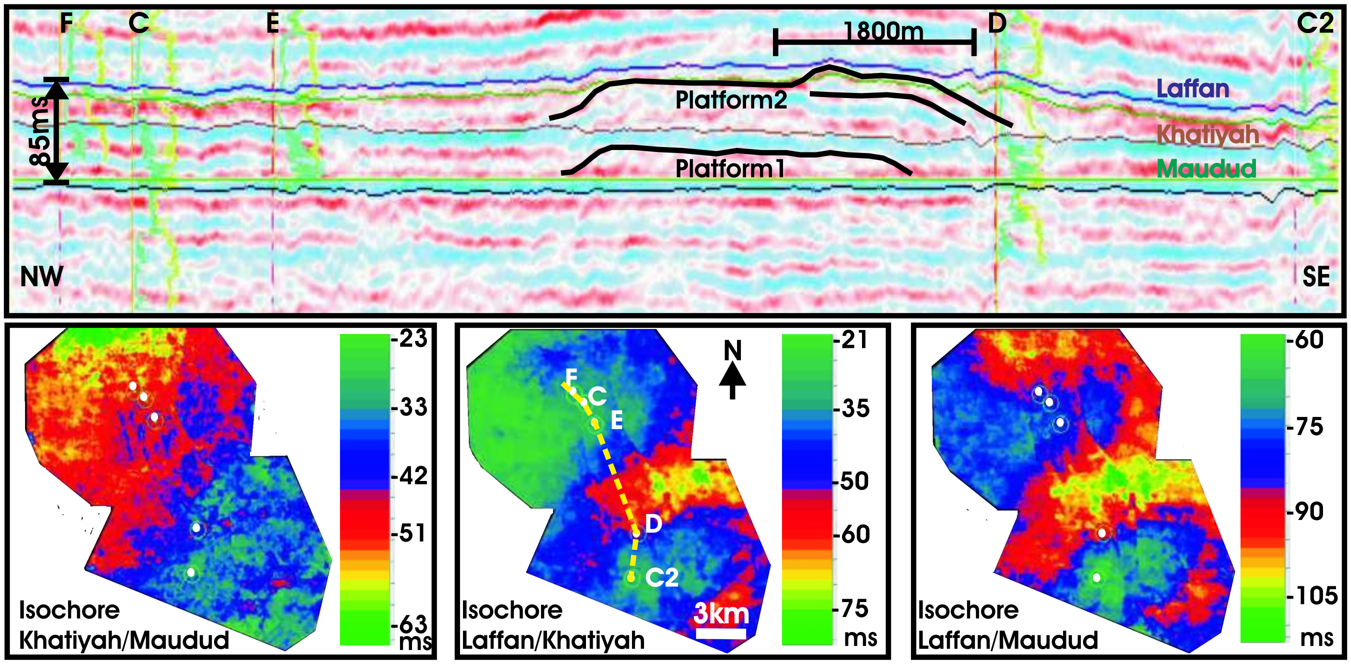

Fig. 6. A random line cutting through all wells, flattened on top of the Maudud seismic marker. In the area between wells E and D, two superimposed clinoform geometries are developed within the Khatiyah (platform 1) and Mishrif (platform 2) formations. The lower clinoform is not penetrated by wells but the margin of the upper clinoform is drilled. Isochore maps show the thickening of the two formations in the intervening area between wells and a gradual thickening of the Khatiyah Formation towards the northwest.

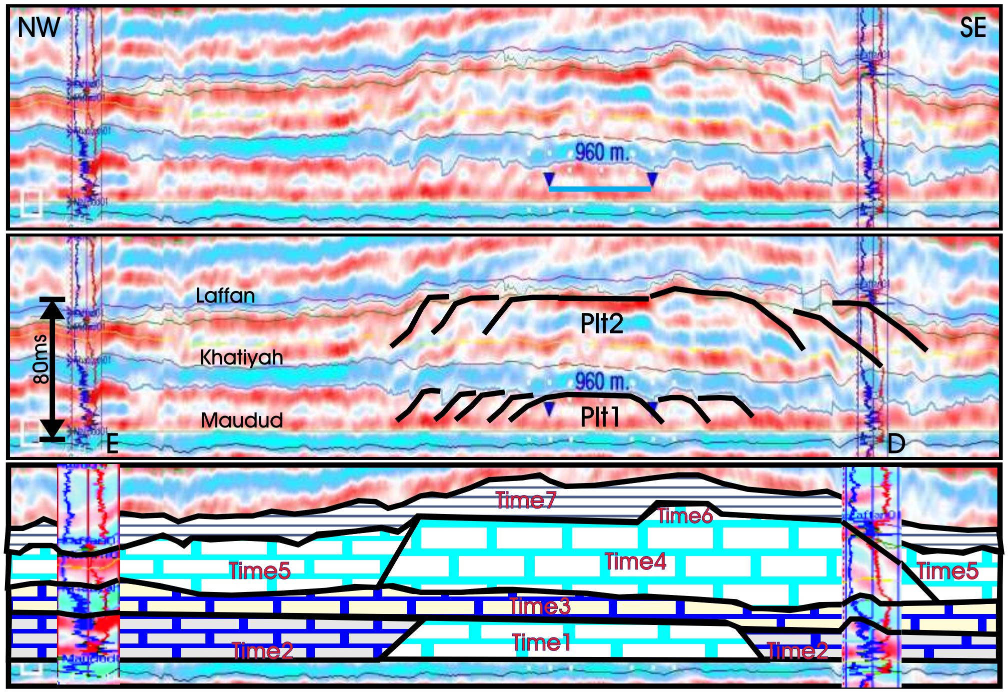

Fig. 7. Enlarged view of the random line of Figures 3 and 6 between wells E and D. Details of seismic geometries within the studied interval are observable. Timing of the seismic events is interpreted based on the seismic stratigraphic relationship between them (Time 1 to Time 7), which enables tracking of the hierarchy of these events.

values immediately drop below 50 API units in clean carbonate intervals and increase above 50 API units in muddy layers (Fig. 4). A comparison of GR, sonic and neutron logs in well E (Fig. 4) shows that the high GR values within the Khatiyah Formation are generated mainly by organic matter concentrated in mudstones and wackstones. A marked GR spike indicates the base of the succession at the top of the Maudud Formation. The lowermost part of the Khatiyah Formation consists of bituminous marls, mudstones and wackstones, as indicated by high GR, neutron and low sonic velocity values in (Fig. 4).

Small-scale variability observed in the GR, porosity, sonic and neutron profiles largely represents variations in depositional energy associated with high-frequency cyclicity. Several depositional sequences corresponding with cyclic occurrence of

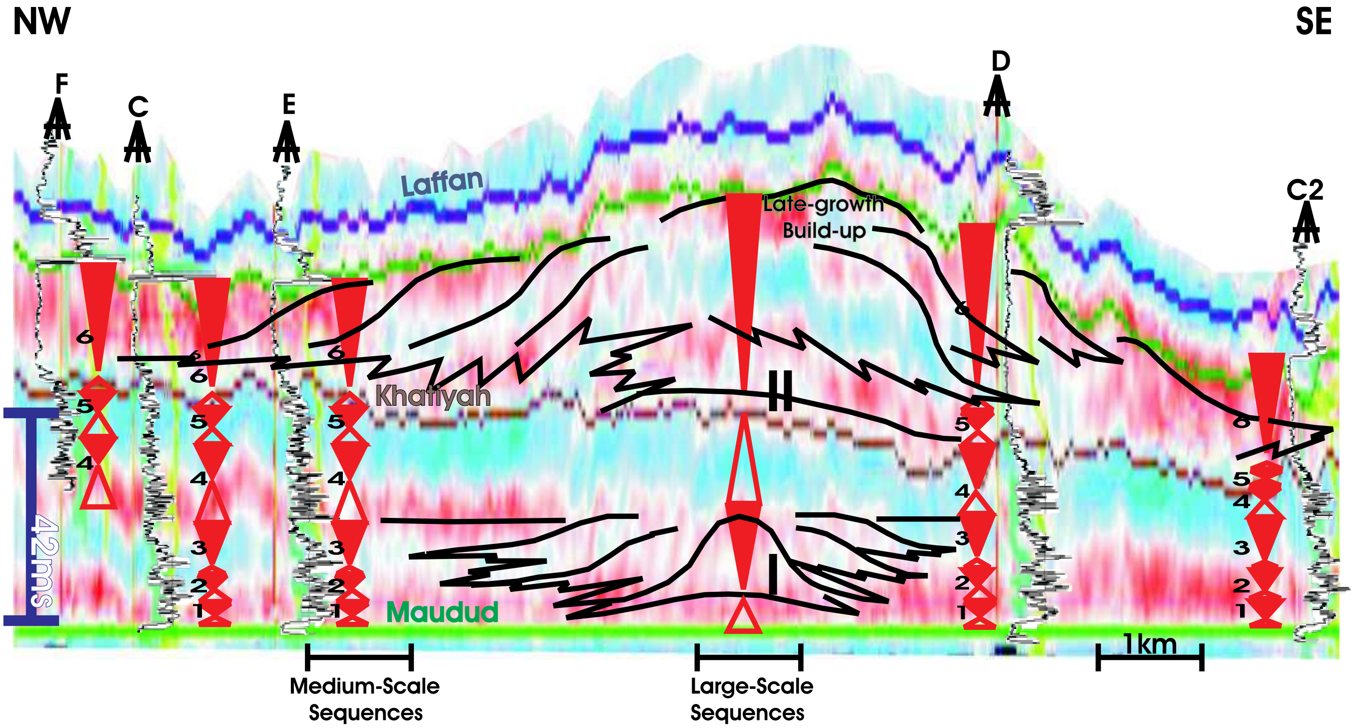

Fig. 8. A combination of the geometric control from the seismic data with the lithological and facies control from the well. Two prograding platform complexes, consisting of laterally stacked clinoform wedges, are shown in relation to accommodation cycles. Note the late-growth build-up geometry at the top of the upper platform. This geobody was generated during back-stepping of this platform due to a northwest tilting of the basin prior to the Turonian emergence.

small Globigerina-rich mudstones and small bioclastic wackestones are identified within the Khatiyah Formation and the overlying Mishrif Formation. These sequences are represented by a gradual fluctuation in GR values. A one-dimensional sequence interpretation is shown in Figure 4 (location in Fig. 1). Six GR-derived sequences are recognized within the studied interval in well E. The base of sequence 1 is taken at the top of the Maudud Formation. The first two sequences are characterized by 20 m of organic-rich marls, mudstones and wackestones, consisting of echinoderms and Oligostegina. The latter is an old name, referred to as one of the typical planktonic microfossils of the Cenomanian of southern Iran (Kent *et al.* 1951; James & Wynd 1968). Mud-dominated limestones rich in organic matter and deposited at highstand relative sea-level correspond with the lowermost part of each sequence. A change in GR response occurs at the boundary of sequences 2 and 3 where the lower GR values indicate a higher-energy depositional environment with relatively cleaner limestones. Wackstones consist of *Pitonella ovalis*, Stomiosphaera sp. and small Globigerina are dominant. The thickness of sequence 3 is about 25 m, probably indicating a slight increase in differential subsidence. The lower part of sequence 3 consists of abundant small Globigerina and the upper part is characterized by ostracods and gastropods. An important change in facies occurs in the upper part of sequence 3. A decrease in GR response corresponding with the presence of abundant small bioclasts and rare benthic foraminifera may indicate a higher rate of relative sea-level fall.

Sequence 4 (35 m) and sequence 5 (15 m), with abundant small Globigerina, *Favusella washitensis* (Hedbergella in core reports) and Oligostegina, show a continued development of an intrashelf basin at the location of well E. The GR log signatures corresponding with sequences 4 and 5 show a more varied character. The top boundary of sequence 5 is approximately 10 m below the top of the Khatiyah Formation and is marked by a decrease in GR values that continues towards the top of the succession. Sequence 6 (60 m) has a very flat GR response. The log patterns within this sequence are undifferentiated and, apart from the top and bottom of the sequence, show no markers useful for lateral correlations. Without core data control, the definition of this sequence is, therefore, ambiguous. Core data description (unpublished IOOC reports) of this interval in well E shows alternating bioclastic packstones and grainstones, with abundant rudist debris at the top. Bioclasts consist of Praealveolina, textularids, milliolid and plecypod. The top boundary of sequence 6 is chosen as the top of a rudist-rich unit capped by an erosional surface with intense dissolution features (Fig. 4). A cross-section of the Khatiyah and Mishrif formations, based on well data (shown in Fig. 8), highlights that the log-derived sequences recognized in well E (shown in Fig. 4) can be correlated throughout the study area. The total thickness of sequences 1–3 is fairly uniform (45 m) in all wells. The lithology and faunal associations are similar to those described in well E. Sequence 4, apart from thinning in wells D and C2 in the southeastern area, shows a different log signature with gradually decreasing GR values. Sequences 4 and 5 in wells F (upper part of sequence 4 is penetrated), C and E consist mostly of wackstones with abundant small Globigerina and the appearance of Praealveolina in sequence 5, whereas sequence 4 in wells D and C2 shows a gradual change to a dominant packstone and the appearance of Praealveolina in the back-stepping portion of the sequence. Sequence 5, which is similar in wells E, C and F, appears with different facies in wells D and C2. In the latter wells this sequence is characterized by lower GR values and a lithology dominated by bioclastic packstones and grainstones with rudist debris. Sequence 6 with a flat GR response is, apart from thickness variations, similar in all wells except in well D where larger fragments of rudist are more abundant. The larger thickness of this sequence in well D (Fig. 8) is interpreted as lying at the margin of platform 2.

SEQUENCE ANALYSIS

The geometries seen on seismic data and their relationship with the high frequency sequence framework derived from wells allow for sequence stratigraphic correlations along the seismic section of Figure 6. The sequence stratigraphic model shown in Figure 8 is orientated parallel to the progradation direction of the seismic clinoform geometries. As indicated by the integrated well and seismic data, two large-scale sequences, referred to as sequences I and II, and six medium-scale sequences (1–6) are distinguished. The sequence analysis presented in this study is based primarily on a subsurface dataset. High-resolution stratigraphic correlations at metre-scale are not included.

Large-scale sequences

The base of large-scale sequence I is taken as the top of the Maudud Formation, a lithological unit with continuous seismic response that can be followed throughout the studied area. The regionally continuous, shallow-water Orbitolina-rich Maudud Formation (James & Wynd 1965) passes upwards into marls and wackstones with abundant planktonic fauna of the Khatiyah Formation, indicating a continued rise in relative sea-level. During relative sea-level rise, slight relief developed in the area between wells E and D (Fig. 8). Sea-level rise was probably slow during this time, allowing the initiation and development of a carbonate platform keeping up with this rise in the interwell area.

The inclined geometry as a seismic response to this platform is shown in Figures 6, 7 and 8. This clinoform delineates a prograding carbonate platform system (platform 1) that is isolated in an intrashelf basin. This platform is not penetrated by the wells. The top boundary of large-scale sequence I is a correlatable surface in all wells, marking a relative sea-level drop to below the platform top. The progradation of this platform was halted by a major flooding event. A strong, continuous seismic marker as a trough represents this event (Figs 6, 7), which belongs to the upper large-scale sequence. Large accommodation space was created during the flooding, resulting in a predominance of wackstones and packstones with abundant planktonic fauna throughout the study area. The GR log signature corresponding with the lower portion of large-scale sequence II is rather similar in all wells (Fig. 8), showing high values with more varied character. During the transgressive part of sequence II a continued increase in subsidence rate towards the northwest is evident by the gradual thickening in this direction. The isochore map of the Khatiyah/Maudud interval in Figure 6 also indicates the gradual thickening of this interval.

The upper part of the large-scale sequence II corresponds with the initiation and development of a second platform (platform 2 in Figs 6–8). This platform is penetrated in the marginal area by all wells, showing its progradation out over larger distances throughout the study area. This interval is characterized by alternating bioclastic packstones and grainstones with rudist debris. The wireline log patterns show no markers for lateral correlation. Platform II, however, consists internally of inclined seismic geometries similar to, but at a larger scale than, the one described above for platform 1. The top boundary of large-scale sequence II is an unconformable surface corresponding to the top of the Mishrif Formation.

Medium-scale sequences

Six medium-scale sequences are superimposed on sequences I and II (sequences 1–6, Fig. 8). Sequences 1–3, with their rather uniform thicknesses, correspond with sequence I. The uniform thickness of these sequences indicates that their development is controlled by higher frequency sea-level fluctuations alone, with differential subsidence of probable less importance. Clinoform progradation, shown as platform 1 (Figs 7, 8) formed strongly inclined time-stratigraphic surfaces that allowed for different facies types to develop towards the intrashelf basin. These time-stratigraphic surfaces are shown as sequences 1–3 in four nearby wells. A limited frequency content, however, results in seismic data that tend to follow thicker lithofacies units (time-transgressive units). Therefore, a clear differentiation of medium-scale sequences, where the interval thins down to tuning thickness, is impossible. During the deposition of sequences 1–3, platform 1 aggraded and prograded gradually. Accommodation space was still created at a lower pace and an intrashelf basin accumulated mudstones to wackstones with abundant small Globigerina. Mud-dominated carbonates that correspond with the lower part of each medium-scale sequence were generated during relative sea-level rise. The base of sequence 4 is a characteristic log marker indicating a rapid rise in relative sea-level that caused drowning of platform 1. Sequence 4 consists of deeper-water, organic-rich carbonates with the top boundary at approximately the top of the Khatiyah Formation in wells D and C2. The back-stepping part of sequence 4 is greater in the northeastern wells, confirming an increase in differential subsidence in this area. An important change occurs around the boundary of sequences 4 and 5. In wells F, C and E, this boundary is transitional and the deeper-water, organic-rich carbonates of the intrashelf basin dominate and continue throughout sequence 5. In wells D and C2 the boundary between sequences 4 and 5 corresponds with the base of a platform carbonate interval. Here, sequence 5 consists of packstones and grainstones with abundant Praealveolina, plecypod, textularids, milliolid and rudist debris.

As inferred from seismic expression, a lateral facies change developed between wells D and E during sequence 5 (Fig. 8). Platform 2 was being initiated during sequence 5 in the southeastern area, while the intrashelf basin was dominant towards the northwest before prograding carbonates could fill in the intrashelf basin.

Sequence 6 is defined based on overall platform facies evolution. There was no intrashelf basin development in the studied area during this sequence. The top boundary of this sequence lies at the top of the Mishrif Formation. This surface is erosional and karstified, corresponding with the regional Turonian unconformity. The re-establishment of carbonate platform 2 is the result of a transgressive pulse that flushed cleaner water onto platform 1 during sequence 4. Gradual sea-level rise during sequence 6 combined with tilting of the basin towards the northwest prior to complete exposure of the area. The tilting caused sea-level to rise faster locally at this time. Platform carbonate sedimentation halted in the northwest because of drowning, while, in the southeast, platform growth kept pace only over shoal areas. A centrally located bank, with an elevated rim at the top of platform 2 near well D, is interpreted as a late-growth build-up development prior to the Turonian emergence.

DISCUSSION

Integration of seismic sequence stratigraphy and well log analysis with biostratigraphy and lithostratigrahy data from industry, offers a robust opportunity to understand the geological development of Middle Cretaceous carbonate platforms. Two large-scale transgressive–regressive cycles in the Cenomanian Khatiyah and Mishrif formations created two vertically stacked platform-to-intrashelf basin topographies. The transgressive part of each cycle that initiated a platform probably correlates with major regional flooding events. The earliest Cenomanian maximum flooding surface (MFS) (k120) of Sharland *et al.* (2001) of offshore Dubai (Pascoe *et al.* 1995) probably corresponds with the base of the Khatiyah Formation, which is interpreted to have been deposited during a relative sea-level rise. In Oman this MFS is recognized between surfaces 1a and 1b of Van Buchem *et al.* (1996, 2002*a*) at the base of the Natih E member where it created carbonate ramp to intrashelf basin topography.

Sequence I of this study probably correlates with large-scale sequence I of Van Buchem *et al.* (2002*a*) in Oman. However, due to an absence of good dating, correlation of its top and base is uncertain. During the progradation the intrashelf basin gradually filled in, leaving the sequence with a nearly flat platform. Thickening of sequence I towards the northwest may indicate a gradual increase in differential subsidence in this direction. The subaerial exposure surface at the top boundary of sequence I (10 m below the top of Natih E) of Oman (Van Buchem *et al.* 2002*a*) is, however, not recognizable here. In Oman, this surface is a bored, iron-stained, phosphatic hardground traceable in outcrop and into the subsurface (Scott 1990; Wagner 1990; Philip *et al.* 1995; Van Buchem *et al.* 1996, 2002*a*; Scott *et al.* 2000). Graphic correlation analysis (Scott *et al.* 2000) suggested that this disconformity was virtually synchronous in Oman, and evidence of meteoric diagenesis has been identified from carbon-isotope analysis (Wagner 1990). Absence of evidence for this Mid-Cenomanian sequence boundary (Scott *et al.* 1988, 2000; Scott 1990) in the studied well data causes an ambiguous correlation of top sequence I with Oman.

Another major flooding event over sequence I in the studied area probably correlates with MFS (k130) of Sharland *et al.* (2001) and surface 5a of Van Buchem *et al.* (1996) of Oman. This transgressive pulse initiated large-scale sequence II and the second platform that probably correlates with sequence II of Van Buchem *et al.* (1996). The base of the sequence as seen in the well data corresponds with a Praealveolina biozone. The top boundary in both areas has been chosen based on the overall facies evolution, showing a turnaround to a long-term increase in accommodation (this study and Van Buchem *et al.* 2002*a*). A remarkable difference between sequence II in the studied area and Oman is that the latter shows no intrashelf basin creation during this sequence (Van Buchem *et al.* 2002*a*), whereas intrashelf basinal deposition continued in the northeastern part of the studied area during the transgressive part of the sequence. The top boundary of sequence II can be correlated with a regional subaerial exposure in the Turonian. A few million years of emergence (Scott 1990) related to the initial phase of the collision between Eurasia and the Arabian margin (O'Conner & Patton 1986; Warburton *et al.* 1990) formed a faulted, truncated, karstified surface at the equivalent top of the Natih Formation of Oman (Montenat *et al.* 1999). Well-developed dissolution features are observed at the top of the Mishrif Formation in the studied wells. A tilting of the studied area towards the northwest formed a late-growth build-up as the platform back-stepped towards the southeast. This build-up was the last phase of drowning and back-stepping of the platforms before emersion.

The number of superimposed repetitive medium-scale cycles recognized within the studied interval (sequences 1–6) correlates with markers M1–M6 of the equivalent interval studied by Pascoe *et al.* (1995) in Dubai. Their cycles start with a thin mixed carbonate-siliciclastic that is overlain by thick carbonate. The correlation of the number of transgressive pulses supports the idea of a eustatic origin of the studied sequences suggested by Van Buchem *et al.* (2002*a*) based on detailed outcrop analysis in Oman. The equivalent Shilaif to Mishrif formations in the UAE also contain evidence of six small rises in sea-level (Alsharhan & Kendall 1991; Kendall *et al.* 1991). High-resolution outcrop analysis of the Natih Formation (Van Buchem *et al.* 1996, 2000, 2002*a*) of Oman resulted in definition of twelve fourth-order sequences. Their high-frequency sequences 1–6 are recognized within the Natih F, E and C and probably correlate with the studied interval.

Petroleum system implications

Recognition of the inclined geometries of carbonate platforms that form the diachronic character of lithological units has important implications for reservoir characterization. Lateral correlations of clinoforms, particularly in strongly progradational carbonate systems, based on well data alone are impossible. This study shows that a geological model without sequence stratigraphic correlation using high resolution seismic data will leave important aspects of reservoir behavior poorly understood.

Medium-scale depositional cycles picked up from log and core data form different reservoir properties. The vertical stacking analysis of these cycles, if integrated with cycles of progradation, aggradation and back-stepping in interwell areas, determines the direction of internal reservoir facies variations. Successive stages of depositional cycles determine the overall architecture of the carbonate platforms within the study interval. A combination of source rock (Khatiyah Formation), reservoir (Mishrif Formation) and seal facies (Laffan Formation) has been producing oil in the studied area. This study provides a field-scale geological model to predict the development of stratigraphic traps and exploration targets in the interwell area. The analysis of carbonate platforms and isolated build-up geometries from the Persian Gulf contributes a promising example and step forward towards exploration of stratigraphic traps and reservoir characterization.

CONCLUSIONS

The Middle Cretaceous Khatiyah (Ahmadi in the Zagros, Shilaif in the UAE) and Mishrif (Sarvak in the Zagros) formations in the southeastern Persian Gulf contain many potential structural and stratigraphic traps. The organic-rich marls, mudstones and wackstones of the Khatiyah Formation are regarded as a source for the Mishrif reservoir. A high concentration of organic matter in an intrashelf basin, associated with shoaling-upward successions, can create source and reservoir within the same depositional system. Carbonate platforms developed within the Khatiyah Formation as a response to a transgressive pulse of relative sea-level. It is a real challenge to predict the location of these platforms because they can be initiated on any slight topographic relief (basement highs) within the intrashelf basin. Most of the hydrocarbon accumulations are found in structural traps; stratigraphic traps have yet to be found. Carbonate growth in the Cenomanian intrashelf basin is controlled mainly by eustatic variation of relative sea-level. Recognition of transgressive–regressive cycles is therefore essential to correlate the diachronous surfaces detected by seismic data. Analysis of cyclical variations using biostratigraphy, lithostratigrahy and wireline logs, integrated with sequence stratigraphic principles, resulted in a detailed geological model. This model is of great value for understanding and predicting Mishrif reservoir heterogeneities and provides an opportunity for evaluation of the Khatiyah Formation.

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