The Rimthan Arch, basin architecture, and stratigraphic trap potential in Saudi Arabia

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Abstract

The Rimthan Arch, situated between the Arabian carbonate platform and the Gotnia intrashelf basin, represents a world class hydrocarbon province in Saudi Arabia. Middle to Upper Jurassic shallow-water depositional sequences are associated with productive hydrocarbon fields in which challenges exist in defining exploration targets, mainly stratigraphic trap plays. An attempt is made to investigate the basin depositional architecture on the flank of the Arch and also to model the stratigraphic trap potential of the youngest Arab third-order sequence. The basin architecture, stratal geometries, and impact of tectonics are explored using 3D seismic and well data. Seismic chronostratigraphy, seismic stratigraphy, seismic attribute, and log-based reservoir heterogeneity techniques are applied as an integrated approach to interpret the sequences from basin to reservoir scale. The study identifies two second-order sequences, SEQ 1 and SEQ 2, to frame a 3D geologic model and to examine basin development through time. Results derived from the integrated study indicate that although initial basin subsidence began later in SEQ 1 north of the Arch, it increased appreciably during SEQ 2. The Dhruma J20 maximum flooding surface, Lower Fadhili, and Hanifa provide clues in tracking major basin changes. Seismic stratigraphy applications highlight reflection terminations and prograding stratal geometries throughout the stratigraphic section to demonstrate tectonoeustatic influences. Tectonics impact SEQ 2 more intensely than SEQ 1 and may influence the migration of hydrocarbons across juxtaposed lithologies. A complex association between shallow marine tidal and ramp carbonates, and deeper basin halite beds, is linked to the subsiding Gotnia Basin. Log-facies analysis of the Arab third-order sequence demonstrates reservoir and seal trends, including the stratigraphic entrapment potential along a carbonate ramp profile. Seismic attributes support reservoir-depositional trends and salt-bed geometries. The integrated approach provides a targeted workflow to investigate the complex depositional systems and their stratigraphic trapping potential on the Arch.

Study area

The study area is located in the north of the supergiant Ghawar oil field and in the north of Saudi Arabia near the Kuwaiti border in the Middle East (Figure 1a and 1b). The initial size is approximately 9000 km^2, but this was subsequently reduced in aerial and vertical extent to conduct a focused evaluation of the basin architecture within the specific area of interest. The Rimthan Arch trends in a roughly northwest to southeast direction and represents a paleostructural high located between the Gotnia Basin to the north and the Arabian platform to the south. Several oil fields exist on the flanks of the Arch, including Rimthan, Dibdibah, Berri, Qatif (Husseini, 1997), and they show the potential for further exploration of stratigraphic plays. The width of the Rimthan Arch is estimated to be approximately 100 km wide in some areas (Ziegler, 2001). The purpose of this study is to examine the basin-depositional architecture of Middle to Upper Jurassic sequences on the north flank of the Rimthan Arch and to provide focus on an Upper Jurassic Arab sequence for stratigraphic play assessment.

Introduction

The Middle to Upper Jurassic in the Middle East, AP7 tectonostratigraphic megasequence dated between 182 and 149 Ma (Sharland et al., 2001), represents productive hydrocarbon-bearing carbonate reservoirs associated with world-class hydrocarbon reservoir, source, and seals in Saudi Arabia (Figure 2a). Their development started in the Early Jurassic marked by the Toarcian unconformity at the base of AP7 when accommodation space was created on the Arabian platform (Sharland et al., 2001). The top of the AP7 is marked by an early Tithonian unconformity, which overlies the Gotnia and Hith Formations in Kuwait and Saudi Arabia, respectively. Two second-order transgressive-regressive cycles (Sharland et al., 2001) developed during the AP7 with maximum flooding events such as the Dhruma J20 asso-

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ciated with deep source rock basins. Differential subsidence followed on the Arabian platform from the Callovian to the Oxfordian stages with the deposition of deeper marine carbonates in intrashelf basins (Ziegler, 2001), such as the Gotnia Basin, previously called the Lurestan Basin (Murris, 1980).

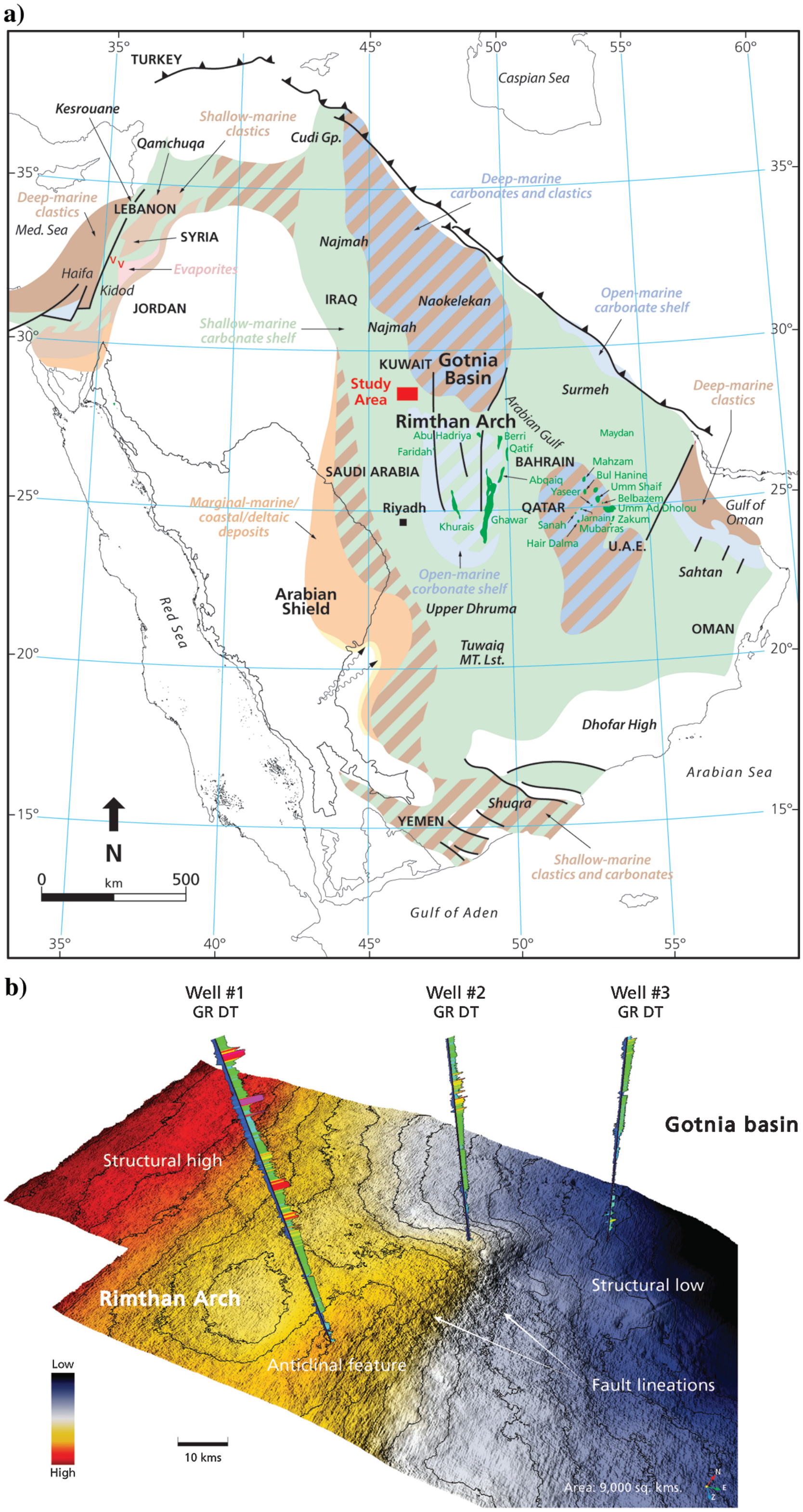


Figure 1. (a) Location of the Rimthan Arch superimposed on the Upper Jurassic paleogeography map of Saudi Arabia (modified after Ziegler, 2001). (b) Study area showing the extent of the 3D seismic survey area and the location of key wells.

Intrashelf basin margins in the Middle East are known to host stacked, cyclic world-class hydrocarbon reservoirs, but the assessment of basin architecture near these margins often requires new approaches to improve the definition of stratigraphic targets in exploration. Previous work using innovative integrated approaches improved the understanding of the complexities of the Jurassic depositional systems at the Gotnia intrashelf basin margin (Wharton et al., 2012), where they were impacted by eustacy, tectonics, and possible climatic changes (Wharton, 2015a, 2015b, 2016). These studies used seismic chronostratigraphy techniques to evaluate the depositional history of the Upper to Middle Jurassic sequences on the Rimthan Arch and adjacent areas on the Gotnia intrashelf basin margin. The main focus was to assess the distribution of the reservoir, source, and seals (Wharton, 2015a, 2015b, 2016). Isopach thickness attributes from the Dhruma (Bajorcian) to the Lower Fadhili (LFDR) (Bathonian/Callovian) stratigraphic section and also from the LFDR to top Jurassic (Kimmeridgian/Tithonian) were used to investigate the timing and stages of basin development, in particular, basin subsidence. The Gotnia intrashelf basin was interpreted to have formed during the Callovian/Oxfordian period, and the isopachs were a key data set to support initiation and development of its south flank (Wharton, 2016). The evaluation clearly demonstrated the benefits of the innovative use of 3D seismic and well data to assess the Jurassic depositional history.

Integrated workflows targeted at intrashelf basin margins have been applied elsewhere in the Cretaceous to assess basin architecture. Wharton (2015c) presents an integrated workflow incorporating seismic chronostratigraphy and seismic attribute techniques to assess basin development. In that study, it was observed that decoupling the sequences within intrashelf basins requires unique approaches owing to local variations in basin depositional history. Third-order sequences were found to show variable shelf margin positions in prograding systems with opportunities for prograding shelf margin wedges and stratigraphic trap plays derived from a 3D seismic chronostratigraphy model. Previous work on Upper Jurassic reservoirs on the Rimthan Arch at Berri field (Figure 1a) provided an insightful approach toward identifying stratigraphic trap opportunities for hydrocarbon exploration using sequence stratigraphy (McGuire et al., 1993). In their study, the application of sequence stratigraphy principles identified previously undefined reservoir opportunities and their inclusion in geological models for simulation. Well logs and cores, with no seismic data, were combined to generate sequence stratigraphic models that support a carbonate ramp to basin depositional profile showing reservoir facies degrading toward the basin.

Three Upper Jurassic salt beds were first evaluated at the Gotnia intrashelf basin margin in Saudi Arabia using well-log correlation and frequency-decomposition geobody extractions to define the morphology of the salt bodies (Wharton et al., 2012; Wharton, 2015a, 2016). The age-equivalent Upper Jurassic Arab reservoirs on the Rimthan Arch to the south were reported to show a lithologic continuity with these Gotnia salts (Sharland et al., 2001). Ziegler (2001) reports that for the age-equivalent Upper Jurassic sequences, four halite cycles are recognized offshore Saudi Arabia and Kuwait with the lowest salt in the westerly trend appearing to model pre-Jurassic grabens. Yousif and Nouman (1997) also provide details of the distribution of the cyclic interbedded anhydrites and salt beds in the nearby Kuwaiti fields and report four well-defined salt beds in well logs in a Minagish-1 well. These cyclic anhydrite and halite beds have been compared with the halite beds in the current study, and it was revealed that only three of these salt beds exist (Wharton et al., 2012; Wharton 2015a, 2016). The Upper Jurassic Arab sequences on the platform appear to be linked by a facies change across the Gotnia margin to shale-sulphate-halite rhythmites, and the base of the evaporite/halite sequence in the Gotnia intrashelf basin may be dated as post-Hanifa (Ziegler, 2001). It appears therefore that basin subsidence may have been more pronounced during the post-Hanifa period and prior to deposition of thick cyclic salt beds. Wyton et al. (2015) suggest that the thick salt beds may have been deposited during the low stand. The complexity of the current study area with limited well control, and 3D seismic data with a low fold, initially contributed to a mixed understanding of stratal geometries and related reservoir continuity of the sequences.

Regionally, areas to the north of Saudi Arabia and Kuwait share similar superimposed tectonic styles and at least five different structural trends comprised of regenerated pre-Jurassic and basement structures exist in nearby Kuwait (Carman, 1996). Toland (2010) observes that in outcrop investigations in different parts of the Arabian platform, there is evidence for syn-sedimentary tectonism associated with the reactivation of Jurassic mid-platform paleohighs, such as the Rimthan Arch. Evidence of tec-

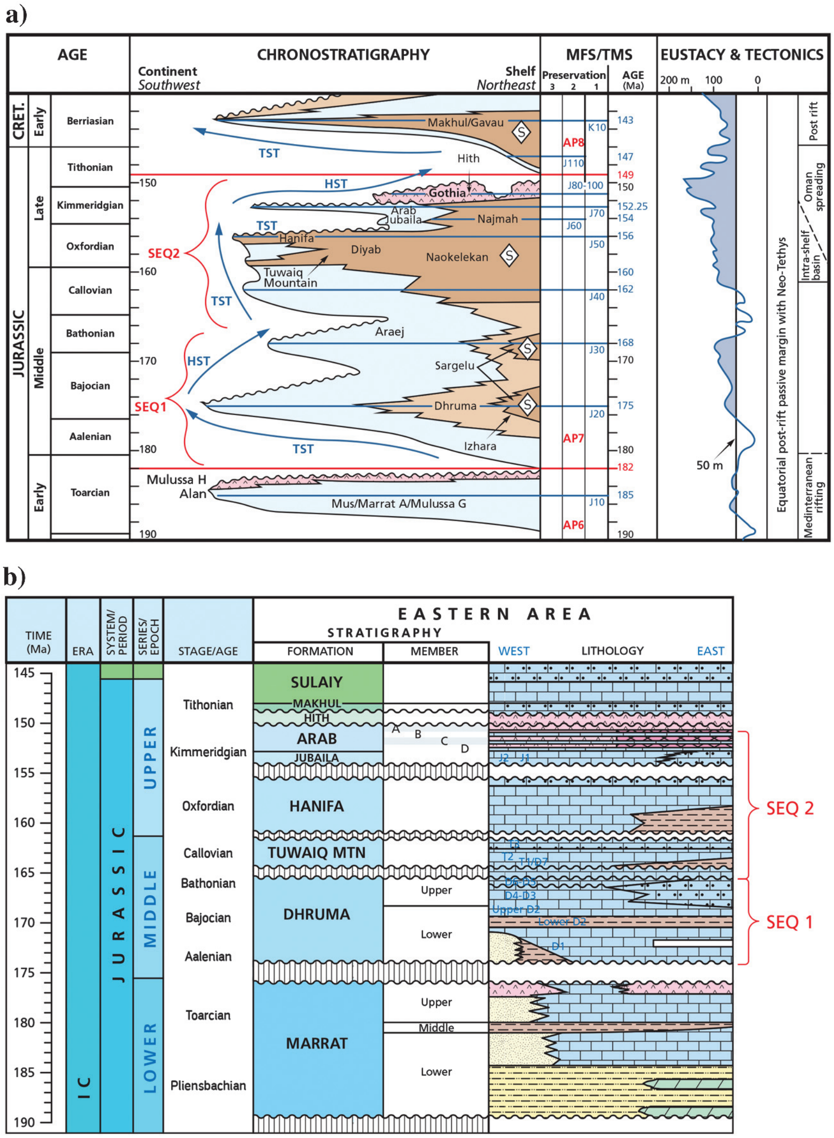


Figure 2. (a) Arabian plate Jurassic chronostratigraphy chart shows two main second-order transgressive-regressive cycles (in the sense of Vail et al., 1977) for AP7 and regional extent from Saudi Arabia to Iraq (modified after Sharland et al., 2001). Reproduced by permission of GulfPetroLink. The S in the diamond demarcates source rocks, whereas the brown and blue colors represent extent of the carbonates and shales, respectively. (b) Chronostratigraphy and lithostratigraphy chart of eastern Saudi Arabia showing Middle to Upper Jurassic Formations and their corresponding lithologies and their corresponding lithologiees. Age dates by Gradstein et al. (2004). The blue lithology is limestone, pink is salt and anhydrite, and brown is basal deposits.

tonic influences on deposition in the current study area will therefore be investigated. The basin depositional architecture is assessed using seismic chronostratigraphy and seismic stratigraphy techniques to identify the stages of basin deposition, whereas seismic attributes are used to define potential reservoir distribution within selected stratigraphic intervals at reservoir scale.

Stratigraphic chart

The stratigraphic section was subdivided into two of the potentially three second-order sequences, hereby designated as SEQ 1 and SEQ 2, to focus on the stages of basin development (Figure 2a). SEQ 1 and SEQ 2 correspond to the combined highstand systems tracts (HST) and transgressive systems tracts (TST) of the second-order sequences defined in the Arabian platform chronostratigraphy (Figure 2a). SEQ 1 and SEQ 2 are subdivided by the upper Bathonian/lower Callovian unconformity and represented by an LFDR chronostratigraphic pick hereby denoted LFDR in this paper. The Dhruma J20 maximum flooding surface (DRMS), within the first second-order sequence, SEQ 1, is one of the most significant regional events on the Arabian platform and is used as a key reference in the study. This surface was mapped in the seismic volume, and the seismic data subsequently flattened to evaluate basin architecture within the overlying HST and TST sequences (Figure 2a). The stratigraphy for eastern Saudi Arabia is used as a reference, and the dating is based on Gradstein et al. (2004) (Figure 2b).

Hughes (2009) describes the Jurassic succession in Saudi Arabia as the Shaqra, which hosts 12 hydrocarbon reservoirs of economic importance. Using biofacies analyses, Hughes (2009) reports that improved chronostratigraphic constraints of the depositional sequences reveal elevated subsidence rates for the Dhruma, Tuwaiq Mountain, and Hanifa Formations in Saudi Arabia. These rates may have been impacted by tectonoeustatic and possibly glacioeustatic controls on depositional cyclicity.

Carbonate depositional model

The depositional model used for the Middle to Upper Jurassic sequences is based on a carbonate ramp model associated with an intrashelf basin margin, where sequences are stacked and are impacted by eustacy, tectonics, and other influences. Burchette and Wright (1992) report that carbonate ramps may be developed where subsidence is flexural and gradients are slight. On the Arabian plate, such conditions exist during the Middle to Late Jurassic on the fairly stable carbonate platform. Burchette and Wright (1992) also note that owing to the featureless depositional profiles of such ramps, the sequence geometries may be observed in seismic lines. Hence, a seismic chronostratigraphy approach is adopted in the current study. At the reservoir scale, the depositional model for the Upper Arab sequence is based on a tidal to shoal to deeper water depositional environment corresponding to an inner ramp, ramp crest, and outer ramp depositional setting as presented for the Ghawar Arab D field model (Lindsay et al., 2006). Low-stand deposits may be found toward the deeper part of this ramp to basin depositional profile.

Methodology

The following techniques were applied in the study:

- A seismic chronostratigraphy technique using a poststack migrated 3D seismic volume to generate, semiautomatically, a series of stacked horizons for the definition of seismic sequences.
- A horizon-based 3D seismic facies unsupervised classification technique using neural networks for noise reduction and seismic facies map generation.
- A log-based facies classification technique using well-log elastic and petrophysical properties for reservoir heterogeneity investigation.
- A seismic attribute frequency-decomposition technique including geobody analysis on the 3D volume and selected seismic horizons to identify salt beds.

Seismic chronostratigraphy is an approach used to semiautomatically generate 3D seismic horizons from a 3D seismic cube and use of horizons to build a geologically significant depositional model tied to the chronostratigraphy well picks derived from well logs. The seismic chronostratigraphy model represents the main tool to study the 3D geologic framework over a large area where seismic horizons are manipulated in space and for sequential stacking in relative geologic time (RGT) (Wharton, 2015c). The assumption is derived from the assertion that stratal horizons mapped from the seismic reflections may approximate chronostratigraphic paleodepositional surfaces, and these can be correlated to achieve stratigraphic interpretations of coeval sedimentary units (Vail et al., 1977). Similar assumptions to this approach were previously applied in a Cretaceous study, wherein seismic horizons constrained within a seismic cube were deemed to demonstrate chronostratigraphic significance within a large seismic 3D data set (Wharton, 2015c).

However, consideration is also based on work by Zeng and Kerans (2003), Biddle et al. (1992), and Tipper (1993), who offer caution against assumptions that seismic reflections may have chonostratigraphic significance. Given the large size of the 3D seismic volume in the study, iterative assessments of several seismic chronostratigraphy models are conducted by first decimating the original data, including dip-steered volumes, in the inline, crossline, and time directions, while applying appropriate technical limits to improve the horizon tracking process and for preserving stratigraphic features. The purpose is to enhance stratigraphic features within depositional sequences and ultimately to create a reasonable geologically significant model. Key regional seismic horizons were associated with chronostratigraphy picks constrained by biostratigraphic age dating in the wells. The seismic chronostratigraphy workflow was conducted iteratively to examine details of the stratal geometries sequentially at the basin margin and to better assess reservoir potential.

The seismic chronostratigraphy technique involves the building of a 3D seismic volume comprised of stacked horizons that are generated semiautomatically. The process involves the creation of noise-filtered dip-steered seismic volumes, which guide the horizon tracking process using the dip and azimuth of each sample in the seismic trace. Seismic horizons were initially generated using manually mapped bounding horizons within the Middle to Upper Jurassic stratigraphic section. The result was a series of seismic horizons within the 3D seismic volume, which were tied to well biostratigraphy and chronostratigraphy picks and used to iteratively create 3D chronostratigraphy models. These models are checked for robustness, technical limits, and best representation of the 3D geologic framework. Each seismic horizon was considered to be stacked sequentially in RGT and time stamped with a unique number.

A manually generated seismic horizon was subjected to unsupervised seismic facies analyses to map depositional trends of the youngest Arab third-order sequence. The unsupervised technique involves use of multiattribute, multivolume seismic attribute analyses from nine 3D seismic complex attribute volumes. The volumes were subjected to a principal component analysis (PCA) to reduce noise and data redundancy. An unsupervised seismic facies map based on neural network assessment produced 12 predefined seismic facies classes.

Rock-physics charts are applied as part of a neural network-based log-based facies classification and prediction technique known as heterogeneous rock analysis (HRA). HRA is used to define rock classes based on their fundamental attributes of texture and composition (Suarez-Rivera et al., 2012). HRA is a log facies clustering workflow that involves PCA and neural network k-means clustering to characterize lithologies based on elastic and petrophysical properties crossplots of the log data linked to core data. The technique was first applied to the Arab A carbonate reservoir in the Rimthan field, Saudi Arabia, to characterize the grainstone, packstone, wackestone, and anhydrite log-facies units in the Arab reservoir (Soepriatna et al., 2016). The elastic (P- and S-waves), and petrophysical (acoustic impedance) log curves were subjected to crossplot analysis and assessed for facies clusters using input core descriptions. In that study, well logs were selected along a carbonate ramp to basin profile on the Rimthan Arch to assess reservoir heterogeneity variations. Initial assessment of the data in the $V_P V_S$-AI space is based on parameters used in the regression curves for V_P-Rho relationships and $V_P V_S$ relationships based on work by Castagna et al. (1993).

Application of frequency-decomposition seismic attributes in the workflow represents a useful technique for carbonate lithology definition and the interpretation of intrashelf basin margin depositional settings from the seismic data (Wharton et al., 2012; Wharton, 2015a, 2016). In the current study, the 3D seismic data were subjected to denoising routines and spectral enhancement techniques to improve the signal-to-noise ratio and to emphasize stratigraphic features of interest. Frequency volumes were selected to assess and highlight lithology and its distribution. Selected frequencies were blended using red, green, and blue (RGB blending) for geobody analysis. Frequency decomposition was conducted using a uniform constant Q-decomposition technique between the 10 and 60 Hz frequencies with 10 bins to construct the frequency spectrum.

Results

Seismic chronostratigraphy

The 3D chronostratigraphy models from the seismic volume were developed in stages to investigate changes in the depositional architecture within the stratigraphic sections. Using well biostratigraphic picks, at least eight wells were used in the analysis to constrain the chronostratigraphy model. Wells 1–3 are selected as representative wells located along depositional dip from the Rimthan Arch to the Gotnia Basin (Figure 1a). Seismic reflectors from the Middle to Upper Jurassic section were found to downlap onto maximum flooding surfaces, the DRMS and the LFDR. These reflectors reveal prograding clinoform geometries that were possibly formed in response to a combination of eustacy, tectonics, and other influences on the Rimthan Arch. Prograding stratal geometries have been demonstrated along selected seismic lines of section or LOS (Figure 3).

Defining the regional maximum flooding surfaces in wells and the concurrent interpretation in the seismic

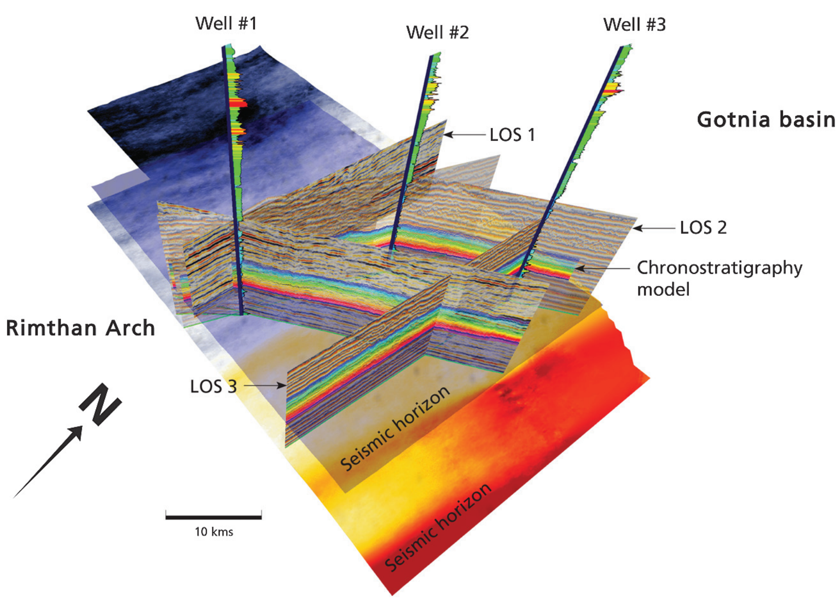


Figure 3. A seismic chronostratigraphy model derived from the 3D seismic volume for the Middle to Upper Jurassic is shown displayed on key seismic LOS. Key wells are strategically selected to traverse from the Rimthan Arch to the Gotnia Basin.

data was an integral part of the study. The DRMS flooding event is selected to represent the base of SEQ 1 seismic sequence, whereas the LFDR was identified as the top of SEQ 1 in the seismic data. The downlap surface on the LFDR demarcates the separation between the two second-order sequences (Figure 4a and 4b). Above the LFDR pick, the Tuwaiq Mountain and Hanifa Formations of SEQ 2 seismic sequence downlap onto this surface. Initial assessment of the chronostratigraphy model (Figures 3, 4a, and 4b) suggests that the thin beds associated with clinoform geometries in this stratigraphic section may not be reliably tracked and imaged on the Rimthan Arch using a semiautomatic horizon tracking approach. The approach for SEQ 2 posed a challenge due to the fault zone and the ability of the horizon to be appreciably tracked by the software algorithm across multiple small faults and graben structures. To mitigate against misinterpretations, the basin depositional history was investigated sequentially in the chronostratigraphy model in RGT from the top Marrat to the upper Bathonian LFDR seismic pick, or SEQ 1, and from the LFDR to the top of the Arab Formation, or SEQ 2 (Figure 4a and 4b). For the SEQ 2 seismic sequence, the focus was on the progradation of the Tuwaiq Mountain, Hanifa, and Arab Formations in the direction of the Gotnia Basin in the north, and the lateral lithologic changes to anhydrite and salt beds. To overcome the limitations in the horizon tracking process in SEQ 2, selected seismic hori-

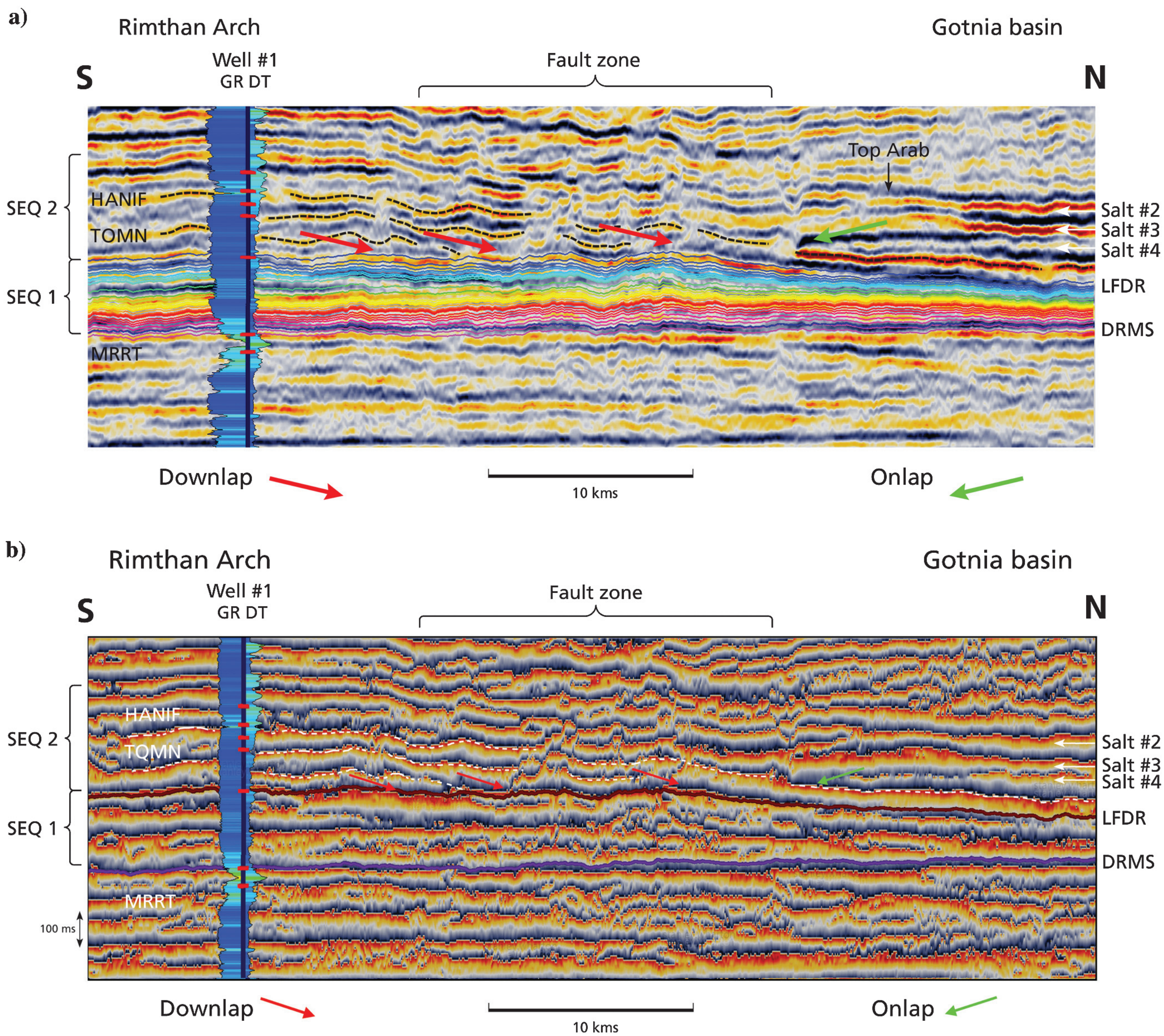


Figure 4. (a) The seismic chronostratigraphy model displayed on LOS 1 shows detailed semiautomatically generated seismic horizons arranged between the top Toarcian Marrat and the LFDR stratigraphic pick, which defines SEQ 1. Stratal geometries within the Tuwaiq Mountain and Hanifa show a downlap relationship onto the interpreted LFDR flooding surface. (b) Phase seismic attributes accentuate the stratal geometries in SEQ 2 and the ramp to basin-depositional profile between the Rimthan Arch and the Gotnia Basin margin.

zons were manually mapped using key seismic events while honoring the dip panels in the fault zone. The Hanifa interpreted surface was deemed as a key event within SEQ 2 and used to further investigate basin architecture and its development on the Rimthan Arch.

The 3D chronostratigraphy model was judged to be reasonably robust for the Marrat to the LFDR stratigraphic section (SEQ 1) because the semiautomatically generated seismic horizons tracked the stratal geometries including low-angle clinoforms features favorably (Figure 4a). Stratal geometries represented by gentle dipping clinoforms within the model suggest the existence of a fairly stable carbonate platform with gentle subsidence beginning nearer the LFDR in the Callovian, mainly in the north at the Gotnia Basin margin (Figure 4a). Low-angle clinoform geometries show progradation toward the north. Within the LFDR to top Arab (SEQ 2) stratigraphic section however, the 3D chronostratigraphy model clearly reveals changes in stratal geometries consisting of lateral changes in downlap and onlap reflection terminations. This stratigraphic section was subjected to intense faulting within a well-defined fault zone (Figure 4a and 4b). SEQ 2 contains the Tuwaiq Mountain, Hanifa, Jubaila, and Arab third-order sequences and represents the most profound basin changes, including tectonic influences and challenges in interpreting the geologic model between the Rimthan Arch and Gotnia Basin. The changes include a period of initiation and development of the Gotnia Basin, progradation of the Tuwaiq Mountain and Hanifa, an increase in accommodation space, deposition of thick salt beds in the Gotnia Basin, the transition of platform carbonates to salt basins, and the generation or regeneration of faults. The 3D chronostratigraphy model thus required a focused in-depth evaluation including the application of horizon-based seismic attributes and log-based facies analyses to investigate stratigraphic trapping potential in the area.

Seismic sequences

SEQ 1 and SEQ 2 are the two seismic sequences that correspond to the two second-order sequences and are used to sequentially investigate basin development and basin architecture from the Dhruma to the top of the Arab sequences (Figure 2a). SEQ 1 comprises members of the Dhruma Formation with the DRMS seismic pick at the base and the LFDR as the interpreted top of SEQ 1 (Figure 4b). These sequences are shown as mainly a HST above the DRMS (Figure 2a) and are associated with deepening of the basin in the north with development of world-class source rock (Figure 2b). These events were capped by a maximum flooding "surface" above the LFDR. SEQ 2 spans from the LFDR, or equivalent, to the top Arab third-order sequence (Figure 2a). In SEQ 2, the Gotnia Basin started subsiding after the late Callovian to Oxfordian Hanifa period. Complexities in interpretation of SEQ 2 relate to faulting and the ability to identify the ramp margins for the successive sequences (Figures 4a, 4b, and 5).

The prograding clinoforms within each sequence were investigated using chronostratigraphic picks from the wells to model the stratal geometries. In SEQ 1, well 1 penetrated a much thicker SEQ 1 seismic section than well 2 (Figure 4a and 4b), in which both wells straddle the flanks of the Rimthan Arch and Gotnia Basin. Basin isopach thickness attributes for SEQ 1 and SEQ 2 in previous studies (Wharton, 2016) support the variable basin thicknesses, which were developed during the Callovian (LFDR) and the Oxfordian (Hanifa) time. Based on the patterns of clinoform geometries, and evidence from the biostratigraphic picks in wells and core data in SEQ 1

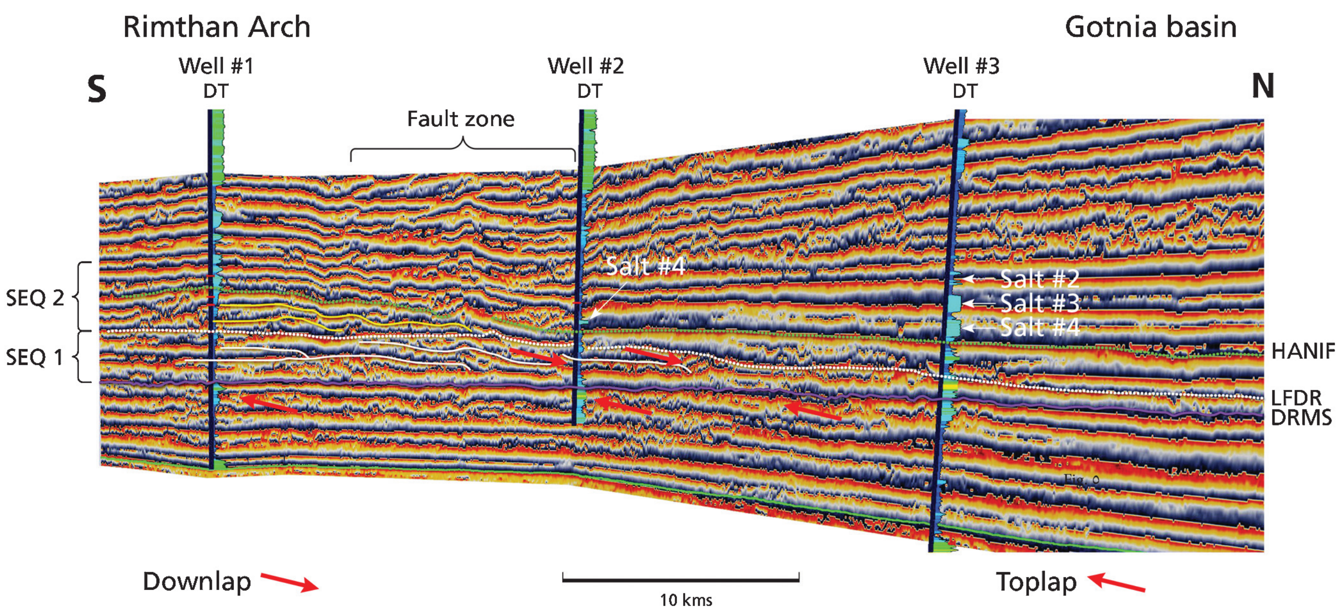


Figure 5. Seismic section along LOS 2 from the Rimthan Arch in the south to the Gotnia Basin in the north shows well-defined progradational stratal geometries. The Dhruma seismic pick is highlighted in purple and shows downlap and toplap events associated with the flooding surface. DT sonic well logs highlight the occurrence and extent of salt beds in wells 2 and 3.

and SEQ 2, there is a clear definition of the depositional systems prograding from the Rimthan Arch toward a deeper water basin in the direction of wells 2 and 3 (Figures 4a, 4b, and 5). These areas are considered to be attractive targets for undiscovered stratigraphic plays. Productive hydrocarbon reservoirs have been discovered in SEQ 1 and SEQ 2 in the area from high-quality grainstone reservoirs associated with prograding clinoforms on the Rimthan Arch. The Hanifa ramp margin in SEQ 1 has been clearly identified in other parts of the study area to the northwest, where seismic geometries can be correlated with well-core data. These relationships provide a useful analog for identifying similar stratigraphic plays.

Top Marrat to Top LFDR — SEQ 1

Along LOS 2 and leading into the Gotnia Basin, stratal geometries reveal different patterns ranging from fairly steep angle to low-angle clinoform geometries (Figure 5). The DRMS is a significant maximum flooding surface because downlap of younger sequences and toplap relationships can be readily identified within the section. Below the DRMS seismic pick, the progradation direction appears to be toward the north and northeast with a distal change over to basinal facies represented by subparallel seismic reflectors beyond well 2 (Figure 5). Prograding sequences show well-defined clinoform features between wells 1 and 2 (Figure 5). Sequences transition into basinal equivalents distal to the well 2 position in the north. Willan and Grabowski (2005) show by illustration, the Dhruma Formation transitioning to basinal deposits of the Sargelu toward the north in the Gotnia Basin in Kuwait.

The top of SEQ 1 is marked by a maximum flooding surface, in which a downlap bedding relationship exists (Figures 2 and 5). SEQ 1 shows progradation toward basinal equivalents in the direction of the Gotnia Basin in the north and alternatively reveals a distinct thinning toward the Gotnia Basin and into distal basinal equivalents (Figure 5). In this part of the basin nearer well 3, well correlation of the Tuwaiq Mountain and Hanifa Formation from the Rimthan Arch to the Gotnia Basin becomes challenging owing to poor biostratigraphic control for well penetrations in condensed sections. The linkage of shallow-water carbonates in the thickened section of SEQ 1 with basinal equivalents consisting of high source rock potential in the distal section of the intrashelf basin contribute to the world class petroleum systems in these sequences (Figures 2a and 5). Sediment bypass appears to have been active during the Oxfordian Hanifa period (late SEQ 1 deposition) because carbonate grain flows have been reported in the Oxfordian Najmah in the Gotnia Basin of nearby Kuwait (Arusu et al., 2013). Wyton et al. (2015) present the notion of productive low-stand carbonate deposits within the Jurassic intrashelf basins based on proven reservoirs in the Bajorcian/Bathonian Sargelu and Oxfordian Najmah in nearby Kuwait also.

Top LFDR to top Arab — SEQ 2

Stratal geometries above SEQ 1 infer drastic changes in depositional environments between wells 2 and 3 (Figure 5). Three salt beds interbedded with anhydrites exist toward the north and northeast within the Gotnia Basin, whereas shallow marine carbonate ramp and shoal deposits exist toward the south on the Rimthan Arch. Well correlation reveals alternating salt and anhydrite beds in wells 2 and 3 (Figure 6). These alternating beds can be correlated with wells in the nearby Minagish field in Kuwait located approximately 75 km away to the northeast. Salt bed 4 appears to extend furthest south toward the Rimthan Arch with salts 3 and 2 displaying a regressive pattern toward the Gotnia Basin. Frequency-decomposition attributes and geobody extraction using spectral enhanced seismic data support an onlapping relationship of salt 4 onto the Rimthan Arch and will be discussed later.

The alternating steep-dipping anhydrite and salt beds on the Gotnia side of the Rimthan Arch appears to show an onlap relationship unto SEQ 1 (Figures 4b and 5). The transition into a deeper salt basin, however, represents the drastic lateral lithologic changes that occurred within the carbonate depositional system

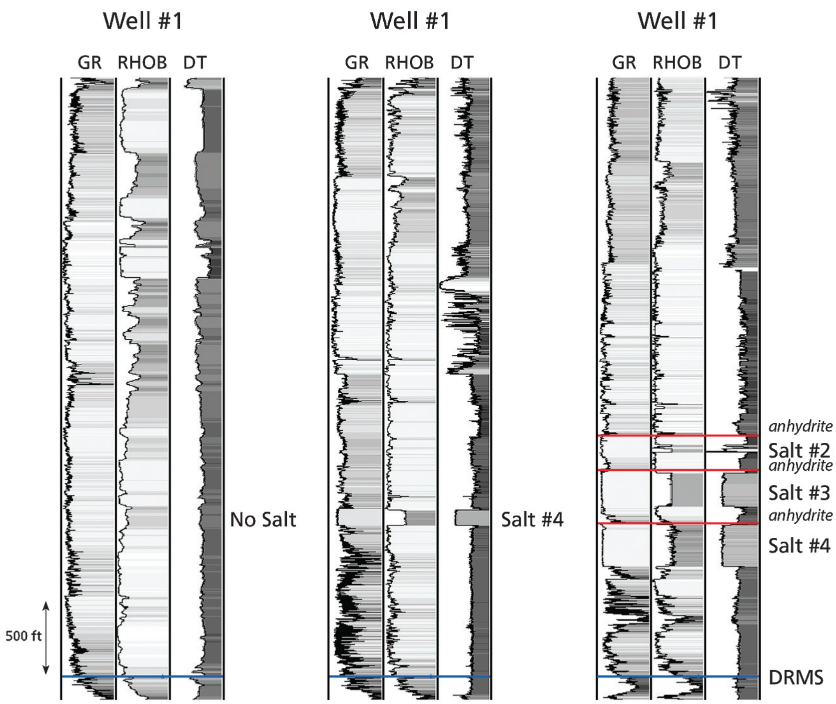


Figure 6. Well-log correlation of the three key study wells highlights the thicknesses and extent of salts 4, 3, and 2 leading from the Rimthan Arch to the Gotnia Basin.

and the opportunity for lateral seals for stratigraphic trap plays. Climatic changes possibly contributed to the existence of alternating anhydrite and salt beds during the time period when the accommodation space became reduced (Murris, 1980). These salt beds are also considered to have been initially formed in a deeper water basin, which became progressively shallower over time with a change to humid conditions in the Cretaceous (Sharland et al., 2001).

Structural styles

The impact of tectonics on deposition of SEQ 1 and SEQ 2 was investigated to gain insights into the depositional styles and to confirm the influence on the stratal geometries. To accomplish this task, seismic horizons were flattened at the key interpreted horizons DRMS to assess the impact of tectonism on deposition (Figure 7a and 7b). A profound tectonic change appears to have occurred after the DRMS as subsidence rate increased in the Gotnia Basin (Figure 5). A key challenge is to assess the nature of the interface between the Gotnia salt beds and the Rimthan Arch, where a well-defined fault zone exists. High angle faults show increasing density from SEQ 1 up into SEQ 2 and appear to be mainly post-DRMS in origin (Figure 8a and 8b).

Using selected seismic horizons from the 3D chronostratigraphy model along with manual horizons (Figure 4a), the changing structural styles were investigated from the Dhruma to the top Jurassic. Figure 7a shows a northwest to southeast complex fault system in the upper Arab sequences of SEQ 2, which may be related to possible strike-slip faulting in the area. Figure 7b reveals the existence of superimposed north–south faults dominated by a northwest–southeast fault system. The impact of faulting on sedimentation is not immediately clear because these north–south faults appear to be deeper seated and may have been reactivated over time. A north–south seismic section defines the thickening and thinning trends on the north flank of the Rimthan Arch from the carbonate platform to the Gotnia intrashelf basin (Figure 8a).

A series of dense high-angle faults appears to characterize the structural model for the area. The comparatively thinner stratigraphic section of SEQ 2 on the Rimthan Arch may represent the presence of a local paleo-topographic high during deposition and also a “hinge” zone during subsidence of the Gotnia Basin to the north. The flank of the Rimthan Arch was subjected to penecontemperaneous faulting with deposition as subsidence continued in the Gotnia Basin. Faults appear to be either through-going from SEQ 1 to SEQ 2 during a tectonic episode, or they may have been confined to SEQ 2 with later regeneration in the younger Cretaceous. Structural styles are dominated by north–south faults superimposed by a northwest to southeast fault system. In Kuwait, Ali (1995) notes that a regional unconformity below the Gotnia Formation marks a period of tectonism that occurred prior to the major basin subsidence.

Implications of the Rimthan Arch on depositional patterns in the Arab sequences in SEQ 2

Understanding the basin-depositional history is a crucial step toward deciphering the stratigraphic trapping mechanisms in the study area. Clues of the depositional setting were derived from study of the interpreted clinoform patterns and also the stratal geometries between the Arab sequences (SEQ 2) on the Arabian platform and age-equivalent Gotnia beds to the north. The formation of a local structural high appears to have impacted carbonate sediment deposition of the Arab sequences. This is revealed by a local thinning of the Arab sequences on the Arch synchronously with thickening of the Gotnia anhydrite and salt beds to the north (Figure 9). The basal Gotnia salt and anhydrite beds onlap the Arabian platform due to the deposition on preexisting structural highs. In-depth analysis of the inter-

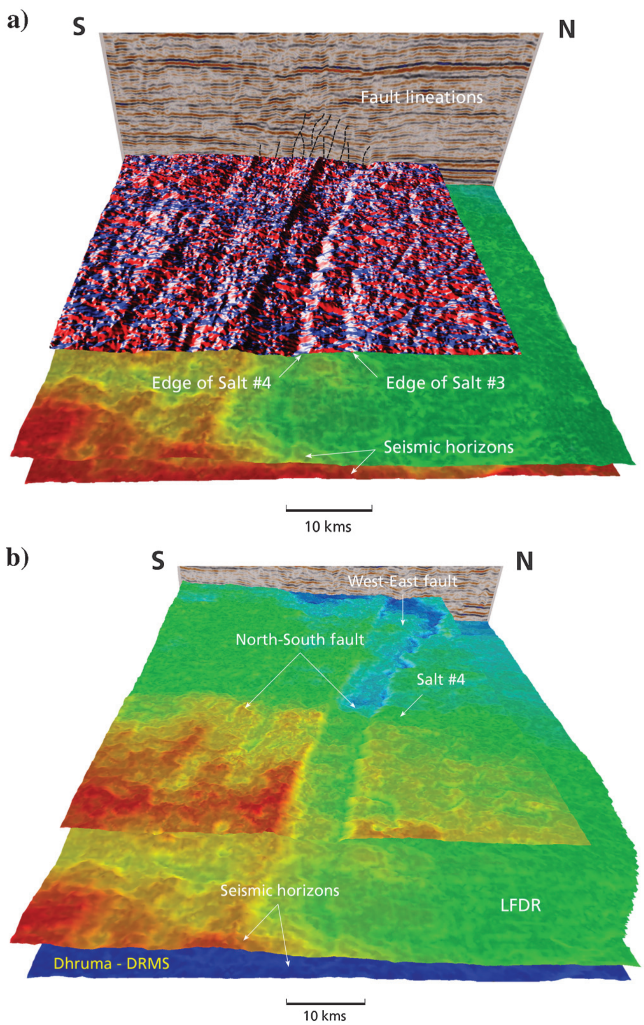


Figure 7. (a) Phase seismic attribute extracted from horizons in the seismic chronostratigraphy model reveals the potential impact of tectonics on the Rimthan Arch. Superimposed east–west faults on north–south basement-related faults highlight the intensity of faulting in the shallower horizons. (b) Subsidence of the Gotnia Basin began after the DRMS (blue horizon) and became pronounced after LFDR deposition.

preted clinoform patterns reveals a lithologic change from the Arab sequences with thinning of the sequences toward deeper water equivalents toward the Gotnia Basin salt beds (Figure 9). Salt beds from well 3 extend toward the Arabian platform, and only salt 3 is interpreted to exist in well 2 (Figure 5), which may confirm the influence of the structure on deposition. In neighboring Kuwait, salt beds thin over the crest of Jurassic structures and suggest deposition of the salt beds in basins showing differential subsidence rates (Ali, 1995). The onlap relationship of the salt beds and their extent will be discussed in a later section.

The Arab reservoir, integration of seismic facies, well logs, and core information

Seismic facies analysis was applied to an Upper Jurassic Arab horizon using nine complex attribute seismic volumes (instantaneous phase, cosine of instantaneous phase, integrated absolute amplitude, relative acoustic impedance, instantaneous frequency, signal envelope, dominant frequency, thin-bed indicator, and dominant frequency) to image significant stratigraphic features in prograding clinoforms. The combined complex seismic attribute volume was subjected to PCA, which involves application of a series of noise-reduction and data-redundancy techniques to the data. The process was followed by a hybrid classification technique using neural networks and *k*-means clustering to generate an unsupervised seismic facies map based on 12 seismic facies classes from a 30 ms horizon window. The resulting seismic facies horizon attribute map was interpreted to reveal a prograding depositional system between wells 1 and 2, in which clinoform beds transition to deeper water equivalents toward the Gotnia Basin (Figure 10).

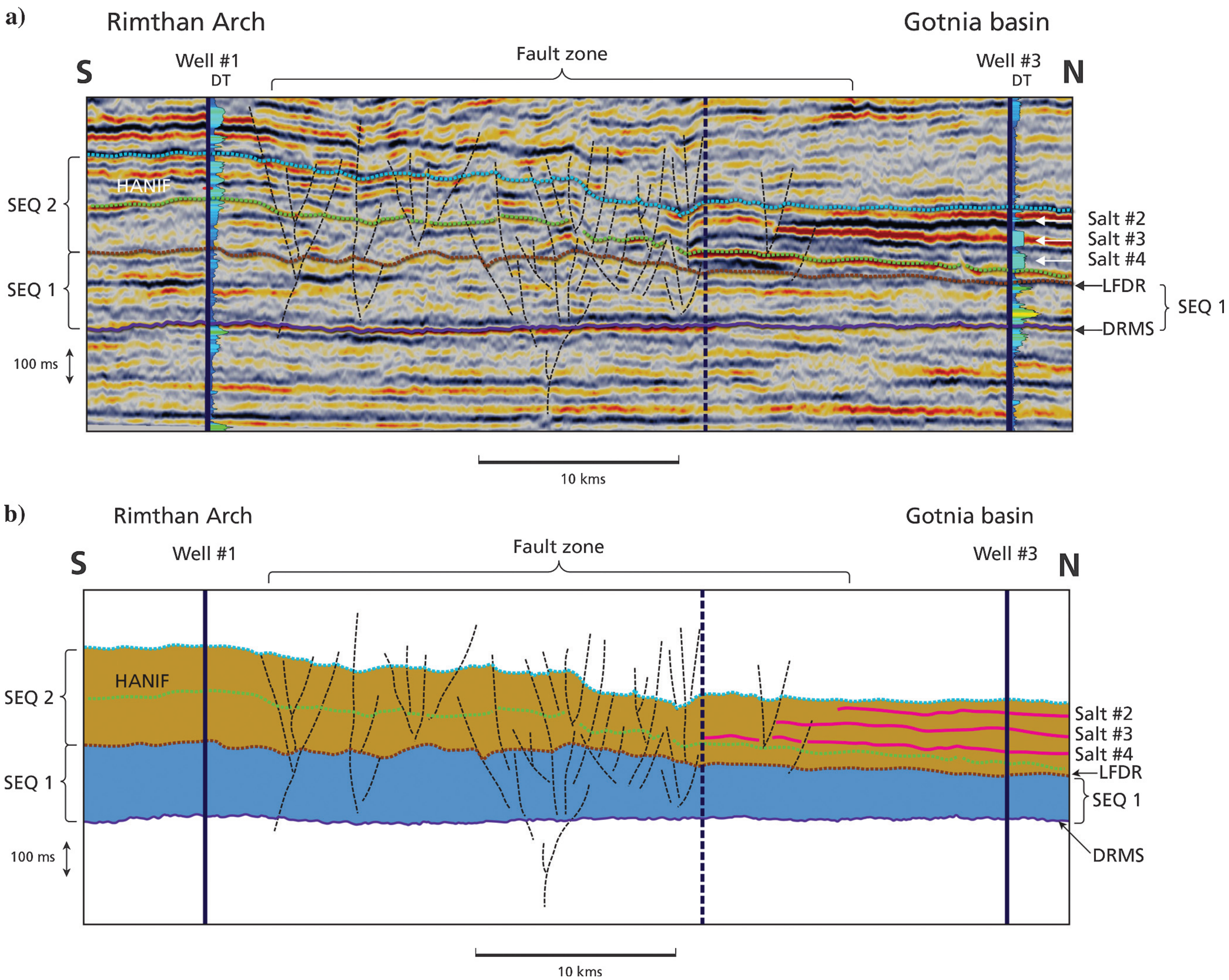


Figure 8. (a) The intensity of faulting within the fault zone may be manually mapped on the north–south seismic line through wells 1 and 3. High angle faults appear to bound graben-like structures between the Rimthan Arch and Gotnia Basin margin. The blue stippled horizon represents the top Arab sequence, whereas the green stippled horizon represents the top Hanifa. (b) Schematic diagram between the Rimthan Arch and the Gotnia Basin shows the thickening-thinning trends of SEQ 1 and SEQ 2 along with the extent of the salt beds (shown in red) along LOS 3. Subsidence of the Gotnia started after the LFDR but became more pronounced after the HANIF (Hanifa).

The Upper Jurassic top Arab sequence demonstrates a lithologic link between the Rimthan Arch platform carbonates and the Gotnia intrashelf basin sequences. The log-based rock classification known as the HRA technique was introduced to evaluate the reservoir heterogeneity of the youngest Jurassic Arab sequence. Because the wells selected for study were situated along a proximal to distal depositional transect, the approach was considered ideal to assess opportunities for stratigraphic traps on the flanks of the Rimthan Arch. The HRA log-based technique is a rock type and lithofacies prediction methodology used to assess the reservoir quality and reservoir thickness distribution of selected carbonate lithologies using well-log data calibrated to core data. The application sought to define the Arab reservoir heterogeneity and to identify stratigraphic trapping potential via juxtaposed flow units as bed units from a tidal to ramp crest to deeper water depositional system transition from the Rimthan Arch to the Gotnia Basin. Soepriatna et al. (2016) present details of the technique applied to carbonate reservoirs using well-log elastic properties and log properties to generate $V_P V_S$ versus AI crossplots and other parameters to classify well-log facies.

It was essential to focus on the Upper Jurassic Arab sequences as the cyclic Arab A, B, C, and D are considered to show a lithologic relationship with the salt beds, salts 4, 3, and 2. Previous studies have not clearly demonstrated the detailed lithologic linkages between the age-equivalent beds on the Rimthan Arch and those in the Gotnia Basin. Using rock-physics charts for

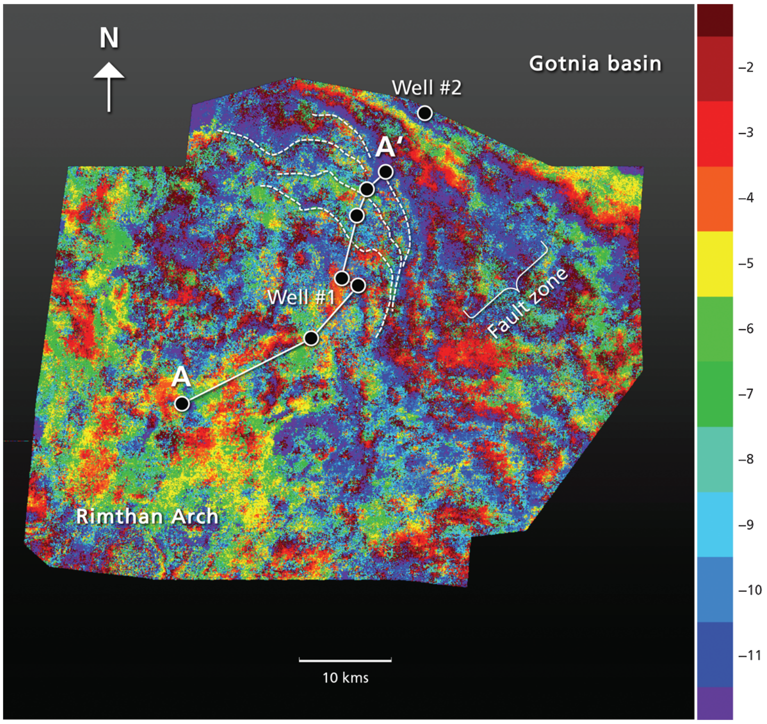


Figure 10. Unsupervised seismic facies attribute based on 12 facies classes for the upper Arab sequence reveals a general progradational direction toward the Gotnia Basin. Wells along depositional profile A-A′ penetrate reservoirs along a tidal to ramp to basin depositional profile. A local structural high is inferred for the geometry of the upper Arab ramp margin leading to the Gotnia salt beds in the north. Refer to Figure 11b for the log facies well-correlation section.

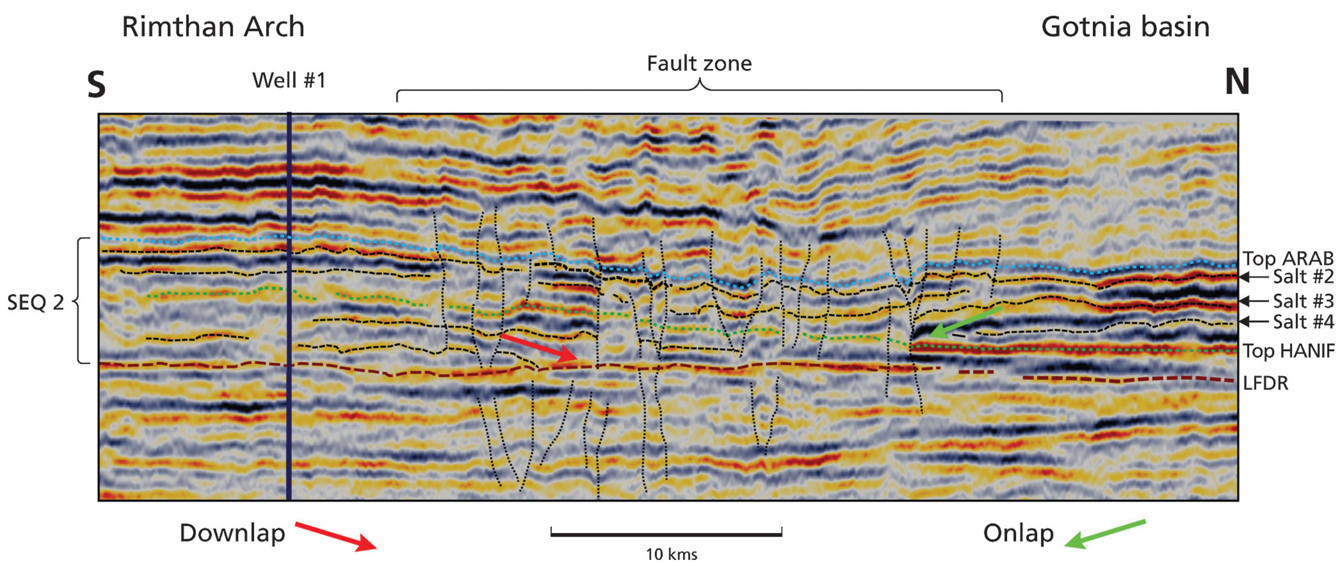
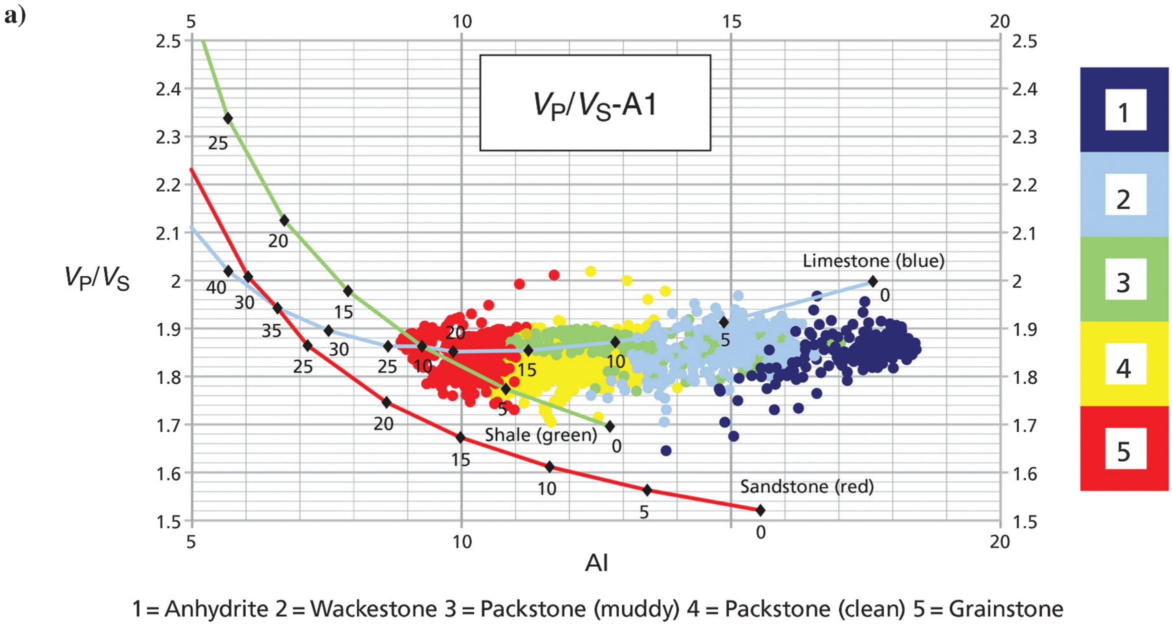


Figure 9. North–south seismic line through well 1 reveals the thinning phenomenon observed between the Rimthan Arch and the Gotnia Basin and the impact of faulting across a 20 km zone. SEQ 2 thins within the fault zone, whereas the Hanifa and underlying Tuwaiq Mountain stratal geometries (stippled black) downlap onto the LFDR. Salt beds onlap onto the Hanifa and equivalent younger stratigraphy. Note the graben-like structures located within the fault zone.

the well log's elastic and petrophysical properties, $V_P V_S$ versus AI crossplots were modeled to group the different carbonate lithologies into five different carbonate log-facies classes (Figure 11a). The approach is based on a methodology adopted by Soepriatna et al. (2016) to classify grainstone, clean packstone, muddy packstone, wackestone, and anhydrite lithologies using the HRA technique. Using the results from this analysis, log-facies correlation plots clearly illustrate the linear distribution of grainstone beds including poorer quality reservoirs comprised of packstone and wackestone beds (Figure 11b). The results show that, vertically, the reservoir quality is unevenly distributed within the wells due to the changing depositional environments interpreted to be tidal deposits in the proximal well line of the section, with a transition to a ramp crest setting, in which the reservoir quality is high and is more evenly distributed within the reservoir section. The prograding clinoforms associated with a carbonate ramp transition toward a distal ramp setting and laterally present scenarios for stratigraphic trapping of hydrocarbons. Each well is top sealed by thick anhydrite beds, which is the regional seal for the area (Figure 11b). The well-log reservoir quality distribution strongly reveals the transitions of depositional systems from a tidal to a ramp to a distal basin setting across the



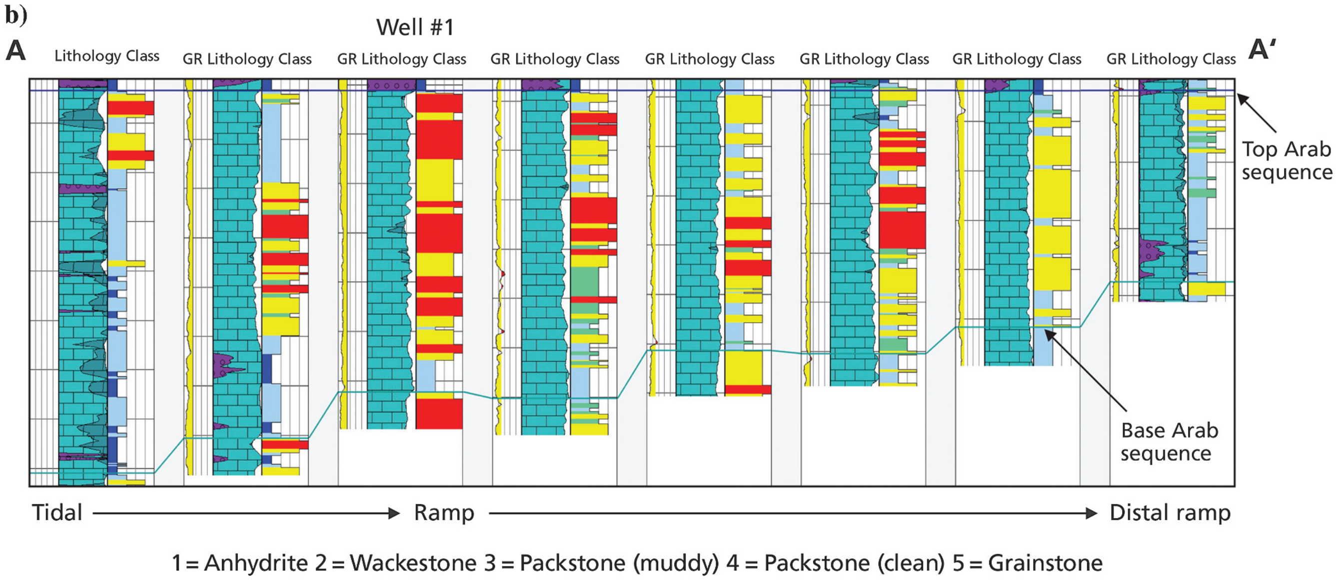


Figure 11. (a) Rock-physics chart shows $V_P V_S$ ratio versus AI scale filtered for five lithology classes in a HRA workflow (see Soepriatna et al., 2016). Modeled curve trends for limestone, shale, and sandstone show the dominance of carbonates discriminated and filtered for five classes on the crossplot. The graph shows regression curves and sensitivities for different lithologies. (b) Well-log facies plots based on the HRA results reveal the reservoir heterogeneity distribution, and thinning trends, for the upper Arab sequence. Note the reduction of grainstone reservoirs and the reservoir heterogeneity distribution along the section.

flanks of the Rimthan Arch and into the Gotnia Basin (Figure 11b). The stratigraphic trapping potential is enhanced by the presence of lateral and top seals within the sequence.

Well-log correlation from log-facies heterogeneity analysis was compared with the seismic facies data to map depositional trends based on the distribution of known grainstone and packstone reservoirs in wells. The seismic facies interpretation shows that deposition was probably controlled by a north–south-trending local preexisting topographic high, resulting in curvilinear depositional margins between wells 1 and 2 (Figure 10). Above SEQ 1, the Arab sequences transition from tidal deposits to carbonate ramps with grainstone facies, before transitioning into the deeper water Gotnia Basin in the form of anhydrite and salt beds. Lindsay et al. (2006) present a carbonate ramp depositional model for the Arab-D, Ghawar field, which shows a similarity to this area because the ramp to basin depositional profile bears applicability to the upper Arab sequences deposited on the Rimthan Arch. The relationship between the Gotnia salts and the Arab sequences is defined by some degree of onlap of the anhydrite and salt beds onto sequences of SEQ 1 as the Gotnia Basin subsided in the north (Figures 8a, 8b, and 9).

Relationship between the Gotnia salt beds and Arab sequences

The Arab sequences transition into the Gotnia Basin across the flank of the Rimthan Arch based on evidence shown in the seismic stratigraphy assessment and supported by the well-log reservoir heterogeneity assessment. In the seismic section, cyclic deposition of the anhydrite and salt sequences in the Gotnia Basin is evident within the successive beds linked to the Rimthan Arch (Figure 5). In well-log section, salt beds vary in thicknesses with salt 4 showing a thickness of 64 m (213 ft). In well 2, the salt 4 thickness measures 93 m (306 ft), whereas salt 3 measures approximately 74 m (245 ft) (Figure 6). Each successive salt sequence is shown to retreat toward the Gotnia Basin, as illustrated in the seismic section and in the well-log correlation panel (Figures 6, 12a, 12b, and 12c). Significantly, during deposition of the salt, the accommodation space was drastically increased during the formation of the Gotnia intrashelf basin.

Results from a frequency-decomposition seismic attribute analysis support the dynamics in the development of the salt beds during basin development because the salt beds appear to onlap the Rimthan Arch at fairly steep dip angles at some localities (Figures 6, 12b, and 12c). The southern edge of salt 4 and its relationship to the fault deformation zone may be imaged on a seismic horizon extracted from the seismic chronostratigraphy model (Figure 12a–12c). Salt 3 appears to recede toward the north and in the Gotnia Basin. The fault deformation zone, proximal to the salt-depositional margin, appears to be significantly positioned and localized within a hinge area between the subsiding Gotnia salt basin and the

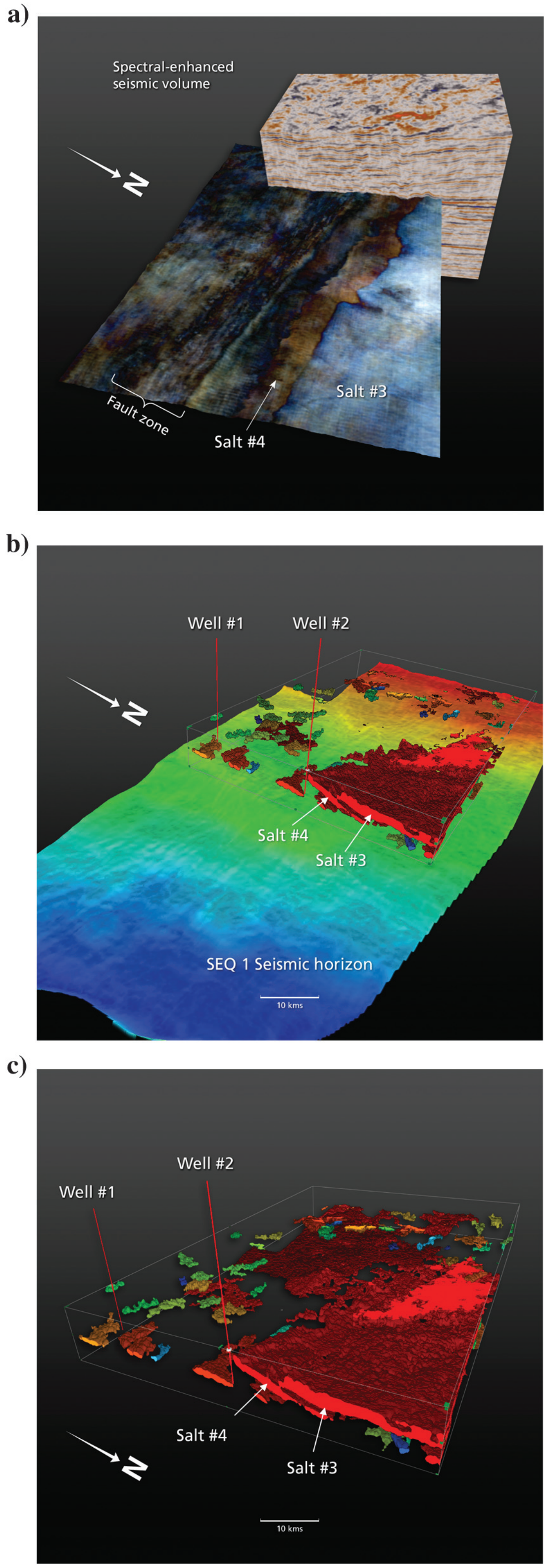


Figure 12. (a) Horizon-based frequency-decomposition attribute generated from selected horizons in the seismic chronostratigraphy model highlights the morphology of salts 4 and 3 beds at the margin of the Gotnia Basin. (b) Geobody rendering of Gotnia salts 4 and 3 shows the geometry of the salt beds onlapping onto the structure. Underlying beds of SEQ 1 dip at a lower angle. (c) The lowermost salt bed, salt 4, is penetrated by well 2 at its most distal southerly position at the Gotnia Basin margin.

flank of the Rimthan Arch. Synsedimentary tectonism and its impact on lithologic variations and rock properties in the zone may have contributed in part to the deposition of SEQ 2 as demonstrated in the seismic section (Figures 8a, 8b, and 9).

Challenges and pitfalls

The 3D seismic data presented early challenges for the project because the data did not initially allow detailed interpretations of the clinoform geometries. The size of the area studied was taken into consideration while attempting to generate a reliable interpretation of the basin's stratigraphy because in some areas, resolution was of paramount importance. Seismic data resolution may impact the seismic chronostratigraphy model because the initial project aim was to generate a robust 3D geologic interpretation to assess the basin architecture targeting depositional sequences on the Rimthan Arch. It was found that the seismic chronostratigraphy model required intense scrutiny to elucidate the detailed stratigraphy especially in SEQ 2, and a balance had to be achieved with the interpretation. Initially, the interpretation of the model for SEQ 1 was considered to be more robust than that for SEQ 2 owing to better tracking of the seismic reflectors within a less intensely faulted interval. In contrast, SEQ 2 showed a greater influence by tectonism in the form of an extended fault zone and with evidence of changing dynamics in basin subsidence displayed within the stratigraphic section.

Poor biostratigraphy control for the sequences penetrated by wells 2 and 3, in particular, contributed to the challenges in interpreting the stratigraphy in the areas nearer the Gotnia Basin. Hence, the changes in depositional setting from platform carbonates in the Arab Formation to the alternating anhydrite and salt beds located north toward the Gotnia intrashelf basin engendered a more focused evaluation using different integrated techniques.

From a petroleum exploration standpoint geared toward the identification of stratigraphic plays, the defining of the ramp to basin depositional profiles in the Dhruma, Hanifa, and Tuwaiq Mountain depositional sequences is important to target the highly productive grainstone reservoirs. The sequence stratigraphy study, using well logs and cores in the Berri field provides a useful field analog to validate the depositional systems in the Upper Jurassic Hadriya and Hanifa Formations (McGuire et al., 1993). Already successful wells have penetrated favorable grainstone reservoirs on the Rimthan Arch within the Bathonian Fadhili reservoirs, Oxfordian Hanifa, Kimmeridgian, and Tithonian reservoirs, and these provide a reference for successful exploration of stratigraphic traps. Challenges remain in defining reservoir depositional systems and stratigraphic trap opportunities because lateral seals and the impact of tectonics show variations in the tidal inner ramp and distal ramp depositional settings.

Conclusion

The Rimthan Arch demarcates a relatively under-explored area of high exploration potential and particularly for delineating additional stratigraphic trap plays. The study area presents a unique opportunity for exploration activity on the flanks of the much wider Rimthan Arch and as it transitions to the Gotnia intrashelf basin. An integrated approach based on assessment of seismic chronostratigraphy, seismic stratigraphy, and well-log-based reservoir assessment on a basin to reservoir scale appears beneficial. On the north flank of the Arch, depositional systems interpreted for SEQ 1 and SEQ 2 show the effects of tectonic and eustatic sea-level changes because the area was impacted by regional plate tectonics. SEQ 1 was developed within a relatively stable platform setting with gentle progradation occurring toward the north and northeast. The basin depositional history was evaluated using a seismic chronostratigraphy technique, and this provided a dynamic approach to interpret SEQ 1 and SEQ 2 and the key maximum flooding events. These events, when linked to the well data, provide an opportunity to selectively interpret, in chronostratigraphic order, the Dhruma, Tuwaiq Mountain, Hanifa, and Arab sequences. Superimposed tectonic events evidenced by north-trending and west–east-trending fault and fracture systems may probably impact reservoir and fluid continuity.

Based on the assessment of the seismic chronostratigraphy model, subsidence of the platform appears to have been initiated later in SEQ 1 with pronounced effects at the Gotnia Basin margin. An area of localized strike slip and extensional faulting appears to be syndepositional in origin for SEQ 2, and there is potential evidence for an increase in fault throw toward the top of the Arab sequence. Through-going faults from SEQ 1 appear to displace the clinoform geometries within the sequence and may influence hydrocarbon migration. The seismic facies classification model for the upper Arab sequence provides a spatial assessment of depositional trends and the potential effects of a paleo-high affecting reservoir distribution. The depositional setting changes from tidal to grainstone dominated ramps to deeper water basinal deposits within the Arab sequence. Alternating thick salt deposits with anhydrite beds associated with deeper salt basins in the subsiding Gotnia Basin thus provide clues to the impact of tectonics and subsidence.

Geobody analysis of the salt bodies corroborated with the stratal geometries shown along the seismic LOS to reveal the onlap relationship between alternating anhydrite and salt beds on a possible paleo-topographic high in the study area. Log-based HRA log facies results, posted on well-correlation panels, and flattened on the upper sealing anhydrites, may suggest deposition of the upper Arab sequence on a possible structural high because the stratigraphic section thins toward the Gotnia Basin and transitions to salt beds across a potential faulted hinge zone. A 3D assessment of the area is necessary to better understand the complex interaction between tectonics and eustatic sea-level changes on the wider Rimthan Arch. The tectonic and eustatic sea-level changes impact sedimentation and depositional styles on the Rimthan Arch and requires consideration when assessing the petroleum and stratigraphic potential of the area.

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