Geological Evolution of the Central Marib-Shabwa Basin, Yemen

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ABSTRACT

The Marib-Shabwa Basin is part of an extensive west-northwest oriented, petroliferous rift system straddling Southern Arabia and the Horn of Africa. The history of the basin has been unravelled using well and seismic data gathered by Nimir Petroleum Company between 1992 and 1995. Four megasequences have been defined using seismic data and these have been further subdivided using integrated well and seismic information. A fifth megasequence is identified from regional information but has been eroded within Nimir’s Block 4. Pre-Rift Megasequence sedimentation began in the Middle Jurassic when transgression from the southeast resulted in the deposition of paralic clastic rocks and shallow-marine carbonates of the Kohlan and Shuqra formations. Rapid deepening in the Oxfordian resulted in the deposition of anoxic shales in the basin immediately prior to rifting. The Syn-Rift Megasequence is of Kimmeridgian-Tithonian age. Adjacent to basin margins and elevated intra-basinal highs, thick turbidites of the Lam Formation accumulated. However, over much of Block 4, rift geometries produced sediment-starved areas where Madbi Formation carbonates accumulated. As rift topography was infilled, fine-grained clastics of the upper Lam Formation spread throughout the basin. Following minor fault reactivation, rifting stopped in the mid-Tithonian. Carbonate deposition (Ayad Formation) in early post-rift times was rapidly followed by isolation of the basin from the open ocean to the southeast. As a result an extensive salt basin (Sabatayn Formation) developed throughout the Marib-Shabwa system. However the salt basin was short-lived and marine carbonate deposition was re-established by late Tithonian times. Initially these carbonates were very clean (Lower Naifa Formation) but the clastic component gradually increased (Upper Naifa Formation) before sedimentation abruptly stopped in the Berriasian.

The Ayad, Sabatayn, Lower Naifa and Upper Naifa formations comprise Post-Rift Megasequence 1. Sedimentation resumed in the Barremian (Post-Rift Megasequence 2) with the deposition of mixed marine clastics and carbonates of the Qishn Formation. Sediment loading at this time mobilised the salt which flowed updip and formed a series of elongate ridges overlying the footwall crests of major fault blocks. As a result, Qishn clastics were deposited in a series of discrete, elongate salt withdrawal basins. Paralic clastics prograded eastwards into the accommodation space left by retreating salt. The most distal basins were initially starved and contain condensed limestones. These basins were infilled by Tawilah Group fluvial sandstones which constitute the upper part of Post-Rift Megasequence 2. Following resubmergence in the Early Tertiary the widespread Hadramaut Group carbonates and evaporites (Post-Rift Megasequence 3) were deposited but uplift and erosion in the Late Tertiary has removed them from large parts of the Shabwa Basin, including Block 4.

INTRODUCTION

The Marib-Shabwa Basin (Redfern and Jones, 1995) is a west northwest-east southeast trending Late Jurassic rift system which lies in southwestern Yemen (Figure 1). It is part of an extensive system of basins which trend across southern Arabia and the Horn of Africa, from Sana’a in the northwest to the east coast of Somalia in the south. To the east, the system extends almost to the island of Socotra, which, prior to Tertiary sea-floor spreading lay just south of Salalah in southwestern Oman (Figure 1; Beydoun, 1970; Richardson et al., 1995).
Figure 1: Tectonic framework Marib-Shabwa Basin.
The Marib-Shabwa Basin can be subdivided into several linked grabens and half-grabens (Figure 1). The gross tectono-stratigraphic development of this basin system has recently been summarised by Redfern and Jones (1995) and Ellis et al. (1996). This paper focuses on a small area in the central part of the basin centred on Nimir Petroleum Company Ayad Ltd.’s (NPC) Block 4 (Figure 1). By concentrating on this small area we provide detail that has not been possible to review in regional studies. We also provide key subsurface seismic and well data which previous authors have been unable to publish. These data will allow the reader to critically evaluate the various models proposed for the development of the Marib-Shabwa Basin. The data also allow new geological insights which may be applicable to the rift system as a whole. The interpretation is based on over 5,000 kilometres (km) of seismic data, 12 exploration wells and 73 development or appraisal wells (Figure 2).

DATABASE AND PREVIOUS WORK

Modern geological investigation of the area began in the late 1940s when Wetzel and Morton (1948-50) undertook surface mapping of the Shabwa salt domes (Figure 1). These were revisited by teams led by Ziad Beydoun in the 1950s (Beydoun, 1964; Beydoun and Greenwood, 1968). However, detailed understanding of the basin awaited subsurface investigations which did not begin until the late 1970s. Gravity surveys undertaken at that time, suggested the possibility of a thick sedimentary section underlying the Marib-Jawf area. On the basis of the gravity data, oil companies became interested in the area, the first licences were issued and seismic surveying began.

At this time Yemen was divided into two separate states, the Yemen Arab Republic (YAR) in the northwest and the People’s Democratic Republic of Yemen (PDRY) in the southeast. Exploration in the YAR was carried out by western companies, led by Hunt Oil whilst Soviet companies explored the Shabwa region of the PDRY. Seismic data confirmed the presence of thick sedimentary basins and their prospectivity was spectacularly confirmed when Hunt discovered the giant Alif field with their first well in 1984. Progress in the PDRY was not so dramatic but by 1988 three small accumulations had been found in the area which is now Block 4 (Schlumberger, 1992). This early phase of drilling confirmed the presence of a deep, extensive Late Jurassic basin system (Paul, 1990).

Following unification in 1990, the Shabwa area of the former PDRY was opened to western oil companies and an accelerated exploration drive began. Although this exploration phase, which lasted from 1991 to 1995, did not identify hydrocarbon accumulations on the scale of the Alif field, it did provide a wealth of information which helped to unravel the history of the basin and the region as a whole.

The primary data set for this study consists of 1,500 km of 80-fold vibroseis seismic acquired by Nimir in 1991 and 1992, plus three wells drilled in 1992-93 (Sawaqi-1, Sulahfah-1 and North Amal-1; Figure 2). Also available were 3,500 km of Soviet seismic data and 85 exploration and development wells. The Soviet seismic data is significantly inferior to 1990s vintage western data and cannot be used for detailed sequence stratigraphic mapping. Reformatted Soviet logs (equivalent to 1950s vintage western logs; Harrison, 1995) are of considerable value, although they are inferior to recent western data. In addition to the block specific data, traded data from adjacent blocks were used to establish the regional setting.

Detailed biostratigraphic and palaeoenvironmental data were obtained from the three Nimir wells and interpretative data were available from Soviet reports for many of the old exploration wells. 1,890 metres (m) of core inherited from the Soviet period were logged and described. 1,149 core plugs from 47 wells were analysed for porosity, permeability, stratigraphy and rock texture information. 630 petrographic thin sections were prepared and described for texture, mineralogy and poroperm characteristics. These data provided the basis for the stratigraphic and sedimentological description of the basin. These also provided the constraints on the well log and seismic facies interpretations.

METHODOLOGY

The gross tectonic and sequence-stratigraphic framework was based on the interpretation of 1,500 km of post-1990 seismic data using GeoQuest software. Additional Soviet paper data were used to supplement the workstation-based interpretation in key areas. Regional composite seismic lines were used to set the block in its basin-wide context.
Figure 2: Well and seismic database map. Nimir wells are indicated in red text.
Figure 3: Well to seismic correlation. The Base Salt pick is not, strictly speaking, a megasequence boundary but it does lie a few tens of metres above the base of the Post-Rift.
Seven seismic reflectors were mapped block-wide (Figure 3). This allowed the gross evolution of the basin to be described using seven seismic packages spanning the interval Lower Jurassic-Upper Cretaceous. Over limited areas additional reflectors could be mapped, allowing the interpretation of basin development to be refined. Four of the block-wide reflectors correspond to megasequence boundaries (Hubbard et al., 1985, 1985a; strictly speaking the Syn-/Post-Rift boundary is not imaged but the Base Salt pick lies within a few tens of metres of it) and these have been used to provide a first-order subdivision of the basin (Figure 3). The top of the Tawilah Group, which lies close to the ground surface beneath a thin veneer of Quaternary drift, is a fifth megasequence boundary. A key composite dip-line is shown in Figure 4.

Two-way-time structure maps were constructed and converted into depth using well control. All seven seismic horizons were tied to wells. For the three wells drilled by Nimir, detailed biostratigraphy provided a first-order constraint on age ranges and stratigraphic gaps. Limited biostratigraphic control was available for Soviet wells and wireline logs therefore provided the key correlation tool. Wherever possible, the wireline log interpretations were constrained by cores and cuttings data.

GEOLOGICAL EVOLUTION

Structural Framework

The structural framework of the Marib-Shabwa Basin was established in Kimmeridgian-Tithonian times when the major period of rifting occurred. The rift system is oriented generally west northwest-east southeast (Figure 1). This orientation corresponds to the Late Proterozoic ‘Najd Trend’ (Greenwood et al., 1980; Husseini, 1989) which probably exerted some control on the orientation of the Jurassic rift. The rift widens considerably in the Shabwa area, and important north-south (‘Hadramaut Trend’, Beydoun, 1991) lineaments, such as the Shabwa Arch (Figure 1) and the Ayadim Fault (Figure 5) are present. This trend may be inherited from an underlying Proterozoic arc terrane suture (Beydoun, 1991; Seabourne, 1996).

In the area around Block 4 both sides of the basin are defined by large faults, and the symmetric half-grabens are separated by the Central High. This is illustrated by a regional cross-section from the Mahfid Uplift, through the Central High to the Asakir High (Figure 4). The major depocentres lie in the adjacent hanging walls of the basin margin faults and are parallel to the margins. Smaller depocentres occur on either flank of the Central Ayad High. A structural consequence of this symmetric half-graben pattern is that some central parts of the rift were completely isolated from provenance areas during early rift times. The Ayad-Amal Basin in Block 4 (Figure 5) is such an area.

To the northwest of Shabwa, in the Marib-Jawf area, the rift geometry is different, consisting of a series of en echelon half-grabens of the same polarity (Figure 1; Mitchell and Galbiati, 1995). The rift is also narrower perhaps reflecting the absence of a ‘Hadramaut’ basement grain in this area.

Megasequence Definition

Four megasequences have been identified and mapped throughout the study area. Their seismic expression is illustrated in Figure 3. The detailed chronostratigraphy is shown in Figure 6. A fifth megasequence overlies the uppermost sediments of Block 4 in adjacent acreage but has been eroded from the study area. Definition of the megasequence boundaries is not straightforward because rifting was not a single instantaneous event. Thus, minor faulting can be discerned prior to the main rifting phase and minor reactivation can be seen in the ‘Post-Rift’. Conversely, the ‘Syn-Rift’ contains sediments that were clearly deposited during periods of tectonic quiescence. This explains why the Syn-Rift sediments have been defined slightly differently by virtually all previous authors (compare Redfern and Jones 1995; Ellis et al., 1996; Seabourne, 1996). The simple definition employed here is that the ‘Syn-Rift’ incorporates those sediments deposited during the period in which major, basin-wide, faulting was intermittently occurring.

The Pre-Rift Megasequence includes Lower to Middle Jurassic carbonates and clastics overlying the Precambrian Basement. The Syn-Rift Megasequence includes Oxfordian to Tithonian carbonates,
Figure 4: Composite regional seismic line across the widest part of the Marib-Shabwa Basin. Note the change in style and timing of salt tectonics north of the Central Ayad High compared to that documented in this paper for the Block 4 area.
clastics and minor evaporites. Clastics dominate against basin margins whilst carbonates are better developed remote from major faults. Three Post-Rift megasequences have been identified. The Post-Rift can be subdivided at the megasequence level due to regional uplift and erosion in the Early Cretaceous, followed by salt mobilisation in the Barremian/Aptian which caused profound changes to basin geometry, architecture and depositional environments. Furthermore, the development of younger basins to the east of Shabwa may provide the fundamental, tectonic control on 'Post-Rift' events within Shabwa.

Post-Rift Megasequence 1 comprises evaporites and carbonates of Tithonian to Berriasian age. It was deposited during a period of tectonic quiescence during the early part of which the connection to the open ocean was restricted. Post-Rift Megasequence 2 is of Middle to Late Cretaceous age and comprises clastics and carbonates. It was deposited during a period of major salt movement. In the lower part of this megasequence there is a striking contrast between clastic sedimentation in the west and carbonates in the east. Outside the block boundaries, this unit is overlain by the Post-Rift Megasequence 3 which is comprised of Early Tertiary carbonates. Within the block itself, this unit has been removed by Late Tertiary erosion.
Figure 6: Chronostratigraphy.
Pre-Rift Megasequence

The base of the Pre-Rift Megasequence unit, corresponding to the contact with Precambrian Basement, is not always well resolved on seismic data, but it can be picked over most of the basin as the deepest mappable reflector (Figures 3 and 4). Well data confirm that it corresponds to the boundary between Precambrian plutonic igneous rocks (predominantly granites) or metasediments, and a Lower to Middle Jurassic package of thin, basal clastics overlain by carbonates. The upper boundary is a low-angle onlap surface and, over restricted areas, an erosional unconformity (Figures 3 and 4). Onlap is a result of rotation of the Pre-Rift strata during Middle to Late Jurassic extensional faulting. The Pre-Rift Megasequence is characterised on seismic data by 3-4 cycles (trough-peak) of moderate-high amplitude, low-moderate frequency, moderately continuous, parallel-bedded reflectors.

The Pre-Rift Megasequence occurs throughout Yemen and is present everywhere in the block, except over the east of the Central Ayad High where it appears to have been removed by erosion. Within the block the seismic isopach shows a gradual thickening from southeast to northwest, from about 300 m to over 700 m (Figure 7). There is also a slight thickening towards the Central Basin High as evidenced on wireline log data (Figure 8). This suggests the presence of a Pre-Rift sag but there was little faulting associated with it.

Figure 7: Pre-Rift isopach. The gradual northwesterly thickening reflects the existence of a pre-rift sag rather than active fault control.
Figure 8: Wireline log correlation.
Well data indicates that the Pre-Rift Megasequence corresponds to the Kohlan Formation, the Shuqra Formation and a thin mudstone informally termed the Shuqra Shale Marker, so called due to the ease with which it can be identified on wireline logs (Figure 8).

The Kohlan Formation is a variable clastic unit dominated by sandstones, siltstones and conglomerates. The sediments are immature, poorly-sorted with metamorphic rock fragments and an argillaceous matrix. Minor amounts of mudstone and anhydrite also occur. The formation is present throughout the block and ranges from 3 to 30 m in thickness in wells; it is below seismic resolution. A tentative Bathonian age is attributed to the formation in well North Amal-1. The unit is generally barren elsewhere but an age range of Callovian to Oxfordian has been assumed based on limited fossil data and stratigraphic position. The lithological diversity of the formation suggests a range of paralic environments and an arid climate. Oil and gas occur in this interval in Block 4, for example in East Ayad, but no commercial accumulation has yet been proven. This is due to the rapid lateral variation in reservoir quality in this thin zone (gross thickness less than 10 m). Porosity reaches a maximum of 14% and flow rates of over 200 barrels of oil per day (bopd) were achieved in East Ayad-1.

The Shuqra Formation conformably overlies the Kohlan Formation. Evidence from outcrop sections suggests that the boundary is transitional. It ranges up to 518 m in thickness in Ayadim-1 (Figure 8). In contrast it is only 73 m thick at Samad-1 and is absent from the eastern part of the Central Ayad High. The formation is mainly limestone with some muddy and minor anhydritic horizons. The limestones are variable and include relatively pure packstones and wackestones with occasional grainstones. Oolitic horizons occur in the middle part of the formation. Argillaceous and silty intervals occur occasionally especially in the upper part. Core data over the upper part shows an alternation of burrowed and laminated strata and occasional carbonate turbidites.

There are many highly-fossiliferous horizons within the Shuqra Formation, indicating an age range of Oxfordian to Kimmeridgian. Various fossil associations suggest a variety of marine depositional environments. Near the base of the formation oysters, bivalves, gastropods, forams and dasyclade algae suggest a shallow-marine environment, whilst mudcracks and anhydrite indicate periods of emergence. Higher in the succession, intervals containing ammonites, pteroid bivalves and radiolarians suggest relatively deep-marine conditions. This is supported by the presence of turbidite beds noted above. The Shuqra Formation is a producing reservoir in the West Ayad field, and hydrocarbons have been encountered at this level in several other wells. Porosity is restricted to thin zones of packstones and grainstones with the wackestones and mudstones being invariably tight. Permeability is low even when porosity is good. There is little fracturing so production depends on matrix permeability alone. Net-to-gross is 9% and average porosity is 8%.

The Shuqra Shale is an informal in-house term for a thin, widespread organic-rich mudstone unit of Oxfordian/Kimmeridgian age. It varies in thickness from a few metres at Samad-1 to 66 m in Ayadim-1 and contains a fauna of ammonites, belemnites and deep-water bivalves. Together with the widespread occurrence of pyrite and the characteristic high gamma ray log signature (Figure 8), this suggests deposition in a deep anoxic basin.

The top of the Pre-Rift Megasequence in the Marib-Shabwa Basin has generally been placed at the boundary between the Shuqra and Madbi/Lam formations (e.g. Ellis et al., 1996). The presence of the Shuqra Shale Marker in Block 4 allows greater precision: the unit occurs throughout the basin, except on the eastern part of the Central Ayad High and averages only 30 m in thickness. Even in West Ayad-13 (Figure 8), in the hanging wall of the Central Ayad High, no thickening occurs implying that the fault was inactive at this time. Therefore there can have been little relative relief in the basin during shale marker deposition. In fact the interval seems to record a rapid flooding event which immediately preceded the major phase of rifting. Preservation of this unit beneath the Syn-Rift unconformity suggests that the whole basin was submerged at the onset of rifting. The Shuqra Shale is a typical ‘hot-shale’ with a characteristic high gamma ray log signature (Figure 8). It is a rich, oil-prone, source rock and is probably the main source of hydrocarbons in the block. Samples lying in the main oil window have residual Total Organic Carbon (TOC) values of up to 12%, source rock potential measured by Rock-Eval pyrolysis (S₂) values up to 36 kilogram per ton (kg/ton) and Hydrogen Index (HI) of over 300.
The Pre-Rift Megasequence represents the first marine incursion into Shabwa. Transgression outpaced deposition through Kohlan and early Shuqra times. Carbonate deposition then caught up with sea-level rise and a series of shoaling-upward cycles developed. Further rapid transgression and drowning then resulted in deep-marine carbonate deposition succeeded by organic-rich shales. A ‘snapshot’ of pre-rift depositional environments is shown in Figure 9. The stratigraphic positions of the palaeogeographic time slices are shown in Figure 6.

**Syn-Rift Megasequence**

The Syn-Rift Megasequence includes all sediments deposited during the main period of rifting. Rifting was episodic and sediment packages showing active fault control are sandwiched by others deposited during intervals of tectonic quiescence. Within the rift basins up to 4 km or more of turbiditic sediments were deposited but outside the rift basins only a thin interval of muddy limestones and shales occurs.

The base of the Syn-Rift Megasequence is marked by onlap onto pre-rift sediments. The top is marked by onlap and /or downlap of Post-Rift Megasequence 1 onto parallel/conformable to mildly rotated and occasionally eroded strata (Figure 4). Seismic geometry and facies are laterally variable. The characteristic wedge geometries of discontinuous, low-medium amplitude and frequency are developed in depocentres adjacent to major faults, allowing growth packages to be discerned (Figure 4). However,
opaque facies are also observed, particularly in the southern hanging wall of the Central High. Here the overall geometry is a high-relief wedge (Figures 3 and 4) but internal reflection character and seismic facies are very poorly imaged. This is probably due to a lack of acoustic impedance contrast within the wedge, resulting from its locally derived, chaotic, unsorted lithological composition (see below). In the central and deepest part of the basin in Block 4, moderate-high amplitude, medium frequency, parallel to sub-parallel seismic reflectors are more characteristic. The influence of faulting on depositional patterns is shown on the Syn-Rift isopach map (Figure 10).

The Syn-Rift Megasequence contains a wide variety of both clastic and carbonate lithofacies. For nomenclatural simplicity only two formation names are utilised; the thick, clastic-rich, generally turbiditic units are referred to the Lam Formation and the deep-marine carbonates to the Madbi Formation (Ellis et al., 1996).

The Madbi Formation comprises fine-grained limestones and chalks with occasional argillaceous and pyritic horizons and thin bituminous mudstones. There is an occasional rich, but low diversity nannofossil/dinocyst assemblage (SSI, 1993) which in combination with the lithologic data suggests a relatively deep, partly restricted depositional environment. The formation was restricted to areas remote from the emergent fault blocks which supplied coarse clastics to the basin. Nevertheless, even in these sediment-starved areas up to 300 m of carbonate accumulated.
Hydrocarbons occur in fractured limestones of the Madbi Formation in the Amal accumulation. However productivity is very low due to the low matrix porosity and the limited fracture system. Numerous thin, oil-prone source horizons also occur in this interval. Though not as rich as the Shuqra Shale, TOC values of 2-5% are common with S₂ yields reaching 25 kg/ton and HIs of 580.

The Lam Formation is the product of erosion of the emergent footwall areas created by rifting. Close to the major faults, conglomerates, sandstones and siltstones typify the formation. Thus, in the southern hanging wall of the Central Basin High, 900 m of coarse clastics were penetrated in well West Ayad-13. Seismic data suggests that over 1,400 m of Lam Formation could be present in the undrilled eastern end of the wedge. In more distal areas mudstones and calcareous shales become increasingly common and thickness is reduced to 200-500 m (Figure 10). A gradual northwest thickening (also seen in the Pre-Rift) is also apparent. The fauna includes ammonites, belemnites and deep-water bivalves demonstrating the prevalence of deep-marine conditions over most of the block, even in the major clastic depocentres. Sediments appear to have been shed from footwall highs directly into adjacent fault-controlled deep-marine troughs. This is illustrated in a palaeogeographic map of syn-rift times (Figure 11).

Well and seismic correlation within the West Ayad field indicates that most of the ‘wedge’ is the lateral equivalent of the Madbi Formation (Figure 8). The Lam Formation gradually prograded into distal

Figure 11: Syn-Rift palaeogeography.
‘Madbi’ areas as deposition infilled basin relief, so eliminating sediment-starved areas where carbonates could accumulate. Within the wedge a fining-upward trend can be distinguished. This is clearly illustrated by wireline log data through West Ayad-13 (Figure 8). It probably reflects the gradual reduction of rift topography as margins were eroded and the rift infilled. Numerous wells in the basin have encountered hydrocarbon shows in the Lam Formation but porosity is often occluded as a result of carbonate cementation or breakdown of feldspars.

The depositional history described above records the infill of rifted topography. The main rift event created a number of deep grabens and half-grabens. Over most of Block 4 this rift topography lay below sea-level. The only large emergent area was the Central Ayad High (Figures 5 and 11). Sediments eroded off this high were trapped in the axis of the Ayad fault block, adjacent to the high.

To the south the nearest clastic source was the Mahfid Uplift, outside the basin (Figure 1). Sediments derived from there were similarly trapped in the hanging wall axis of the southern half-graben and could not prograde into Block 4. This southern half-graben differs from the Central High area in several ways. Firstly, it is controlled by a larger fault and is much deeper (Figure 4). Additionally, seismic facies suggest lateral continuity of sediments in the southern graben, in contrast to the chaotic facies adjacent to the Central High. This could reflect different depositional patterns: the southern graben plunges steeply southeastward from a tip in the northwest where the fault dies out. Most

Figure 12: Lower Post-Rift 1 palaeogeography. Erosion of the Alm area is probably due to minor late-stage fault reactivation.
sediments may have entered the basin at this point and then spread south-eastwards parallel to the half-graben axis. In contrast, the Central High area lacks an obvious plunge, and sediment seems to have been eroded straight off the footwall and deposited in the adjacent trough. No significant longitudinal reworking appears to have occurred.

As a result of the basin geometry, clastic deposition was initially restricted to the two narrow fairways on either flank of the basin, whilst the rest of the block continued to accumulate carbonates. As clastics continued to be shed into the basin, rift topography was gradually subdued, with carbonate deposition persisting longest in the most distal areas.

**Post-Rift Megasequence 1**

Post-Rift Megasequence 1 comprises three distinct seismic sequences (Figure 4). Well data shows that the basal sequence begins with thin carbonates of the Ayad Formation (Figure 12) but is salt-dominated. Movement of the salt in the mid-Cretaceous has resulted in a discontinuous distribution. The base of the salt is characterised by rotated downlaps as a result of salt withdrawal triggered by sediment loading. In certain areas, complete withdrawal has produced salt welds. The salt now forms a series of linear ridges overlying the footwalls of the major west northwest-east southeast extensional faults. These ridges form the west-east highs on the top salt depth map (Figure 13) and their seismic expression is shown in Figure 14. The former positions of the salt can be identified by the turtle structures and salt withdrawal basins developed in the overlying sediments.

![Top Salt depth map](http://pubs.geoscienceworld.org/geoarabia/article-pdf/4/1/9/5439060/brannan.pdf)
Figure 14: Seismic Line AR92-435. For location see Figure 2; for key to seismic horizons see Figure 4. The orange horizons between Top Naifa and Top Qishn are intra-Qishn reflectors which can only be mapped locally in salt-withdrawal depocentres.
The salt is conformably overlain by a thin (generally less than 100 m) isopachous unit of high amplitude, medium-high frequency, parallel and continuous seismic facies. The uppermost sequence is another isopachous unit, typically less than 200 m in thickness, which is typified by high amplitude and high frequency, laterally continuous, 3-4 trough-peak cycles on seismic data. Well penetrations of these two sequences encountered carbonates of the Lower and Upper Naifa formations, respectively, but in restricted areas adjacent to the Central Ayad High, proximal clastics (Lam Formation) probably occur.

The basal Post-Rift is dominated by carbonates which are here termed the Ayad Formation. Laterally equivalent clastics continued to accumulate adjacent to the Central Ayad High (Figures 8 and 12). Within the carbonate province a wide range of depositional environments are represented. On the western part of the Ayad Terrace, laminated and bioturbated micrites, peloidal and intraclast packstones, oolitic, oncoidic and anhydritic dolomites, dolomite breccias and conglomerates occur interbedded with evaporite facies including nodular and laminated dolo-anhydrites, argillaceous anhydrites and salt-cemented limestone breccias. Similar facies occur in the southeast of the block in the Magraf well. On the eastern end of the terrace, limestones are more common, mainly packstones and grainstones, with ooids, oncoids and peloids. The fauna includes bivalves, gastropods, forams and stromatolites.

In the west and southwest of the block the Ayad Formation carbonates are thicker and have a greater clastic component. Lithofacies include lime mudstones (some organic-rich) which are often very argillaceous, silty or sandy. These are interbedded with shales, siltstones and carbonate-cemented arkosic sandstones. There is a wide range of fossils including ostracods, echinoderms, various bivalves including pteroid, ammonites and calcispheres which indicate a Tithonian age.

Whereas the underlying Lam/Madbi depositional environments in Block 4 are similar to those of the whole Marib-Shabwa System, the Ayad Formation is more areally restricted and has not been previously identified in the literature. In fact, it appears to be the lateral equivalent of the Alif Formation sandstones which overlie the Lam Formation in the Marib and Jawf sub-basins. This correlation is supported by the stratigraphic position between the Lam Formation and the Sabatayn salt, and the fact that both formations indicate a sea-level drop at the end of Lam times. Because the Block 4 area formed a structurally controlled intra-basinal high, isolated from the major clastic provenance areas outside the graben boundaries, its only source of clastics was the Central High. If this local supply was cut off, the area would revert to a carbonate province. This is what appears to have happened in Ayad times.

The Ayad Formation is currently the most important reservoir in Block 4 and is the major producing reservoir in the West Ayad field. Hydrocarbons have also been recovered from this interval in the Central Ayad, East Ayad and Magraf and Amal structures. In West Ayad (35° API oil with gas-oil ratio 500-900 standard cubic feet of gas per barrel) the reservoir is restricted to thin (1-5 m) dolomite zones separated by anhydrite. Net-to-gross is around 16% and porosity 10%. Matrix permeability ranges from 0.1 to 100 millidarcy (md) and pore throats are small. Despite the poor reservoir quality the field has performed quite well, with communication across the field being surprisingly good, suggesting the presence of an effective fracture network. This is confirmed by fractures encountered in wells, pressure data and well test analysis.

Wireline log data indicates that the Sabatayn Formation is represented mainly by salt over most of Block 4 (Figure 8). However, it also includes laterally equivalent anhydrites and dolomites, particularly in the southeast and over the western part of the Central Ayad High (Figure 15; see also Ellis et al., 1996). Seismic data from southeast of Block 4 confirms that the salt basin rapidly pinches out in that direction. Within the Block 4 ‘salt basin’ itself other lithologies are developed. Nodular anhydrite and anhydrite breccia are particularly important. Log data indicates that a number of interbedded shales occur within the unit and Rock-Eval pyrolysis indicates that some horizons are extremely rich source rocks. TOCs in the range of 5-15% are common with S2 yields reaching nearly 100 kg/ton and HIs over 600. Some of these intervals reach 20 m in thickness but, as good geochemical data is restricted to one well, their regional significance is unclear.
The Lower Naifa Formation comprises clean, fine-grained limestones with a deep-marine fauna, including ostracods, calcispheres and tintinids. The general palaeogeography is shown in Figure 16. The overlying Upper Naifa Formation contains a mixture of thin limestones and shales. Laminated and strongly bioturbated horizons are interbedded suggesting variation in oxygenation of bottom waters. Rare convoluted grainstones, packstones and wackestones indicate episodes of turbidite flow. The thickness of the Naifa sequences are remarkably constant throughout Block 4, as is Post-Rift Megasequence 1 as a whole (Figure 17). The overall northwesterly plunge of the basin is shown by the gradual thickening in that direction. With respect to salt movement the Naifa sequences form a classic pre-kinematic layer, although there may have been some salt movement close to basin margins where a narrow fan delta was probably still present. There has been some minor production from fractured Naifa reservoirs in the West Ayad field (up to 3.1 million standard cubic feet of gas per day (mmscfd) and 585 bopd) but poroperm is generally negligible. More importantly, for post-salt reservoirs, high quality, oil-prone source rocks have been found in some wells. TOCs of up to 4.5%, S, of 25 kg/ton and HIs up to 580 have been recorded, although the volume of high quality source rock appears to be quite limited.

The evolution of the basin during Post-Rift Megasequence 1 times records the restriction and re-establishment of the connection to the open ocean. The barrier to oceanic circulation must have arisen...
quickly as salt directly overlies deep-marine carbonates over large parts of the block. Evidence for fault reactivation and footwall uplift and erosion during late syn-rift times can be seen in some areas of the basin (for example in the Ayad-Amal Basin in Figure 4) and could have contributed to basin isolation.

Volume restoration suggests that the original salt thickness was in the 100 to 300 m range (Seabourne, 1996). This implies that the basin must have been periodically recharged from the ocean to the southeast. The barrier then seems to have disappeared as rapidly as it arose since salt is directly overlain by deep-marine carbonates of the Lower Naifa Formation with no transitional facies. The resumption of clastic input during Upper Naifa times probably indicates a drop in sea-level and associated rejuvenation of the Central Ayad High. The sharp boundary between the Lower and Upper Naifa combined with the evidence for drop in sea-level suggests that this is probably a sequence boundary, but no direct evidence for this boundary can be seen on the seismic data.

**Post-Rift Megasequence 2**

The base of this unit is defined by onlap or downlap onto the isopachous, conformable, parallel-bedded Upper Naifa Sequence. These relationships reflect the disturbance of the Naifa sequences caused by mobilisation of the salt which strongly influenced deposition and distribution of Post-Rift
Megasequence 2. Over most of the block all the sediments above the Upper Naifa Sequence, with the exception of Recent drift, belong to Megasequence 2. To the south and east of the block, a Lower Tertiary Post-Rift megasequence occurs but it is absent over most of Block 4 itself (see Post-Rift Megasequence 3 on page 32). Well data shows that Post-Rift Megasequence 2 comprises deposits of the Qishn Formation and Tawilah Group, and spans the age range Barremian to Late Cretaceous. The top of the megasequence has been removed by erosion over most of the block.

The Qishn Formation shows dramatic west-east thickness and facies variation within Block 4 (Figure 18). In the west a series of elongate depocentres contain up to 1,000 m of sandstones with minor siltstones and mudstones. Palaeoenvironmental data indicate that these are dominantly marine sediments though there is a strong terrestrial component, and deltaic and estuarine influences are recognised. The sandstones have immature textures suggesting short transport distances. To the east the interval is generally less than 200 m thick and contains limestones and calcareous mudstones with a marine fauna. The sandstones of the Qishn Formation are of excellent reservoir quality, and the presence of intra-formational shales make this a potential target horizon. Thus far, though, no discoveries have been made at this level in the block.

The Tawilah Group comprises mainly sandstones with minor mudstones. The sandstones contain plant roots and exhibit cross-bedding and ripple marks. Some beds contain a marginal marine fauna but most of the unit was deposited in fluvial or aeolian conditions.
Two major episodes of salt movement occurred during the deposition of these units. This is illustrated by the palaeogeography and isopachs of the Qishn and Tawilah formations (Figures 18 and 19). Figure 18 shows that during Qishn Formation times the major prograding depocentres lay in the west of the block. Well data shows that these depocentres contain sandstone-dominated successions with minor fine-grained clastics. The thinner intervals in the east contain fine-grained carbonates and shales. The upper Tawilah Group isopach (Figure 19) shows that the major depocentres have prograded eastwards. Well data indicates that carbonate deposition had ceased and the rocks are dominantly sandstones everywhere. The non-marine nature of most of the Tawilah Group sandstones, which directly overlie marine carbonates over a large area, suggests that the two formations are separated by a sequence boundary.

The geometry of the basin, plus the progradation of the Qishn sediment pile from the west resulted in a general retreat of salt eastward, combined with migration towards the crests of tilted fault blocks. Continued progradation of Qishn clastics created a self-sustaining ‘feedback loop’ in which sediments created their own accommodation space by forcing salt retreat ahead of them (Figure 4). This led to the development of turtle and half-turtle structures in the ‘active’ basins. In some salt withdrawal basins sediment supply was limited and starved basins resulted (compare, for example the thick Qishn section in the Nakaah Basin in Figure 4 with the very thin section in the adjacent Ayad-Amal Basin).
These starved basins were infilled during Tawilah times (Figures 4 and 18). The Tawilah sediments have suffered little post-depositional disturbance as they post-date the main period of salt withdrawal. However Figure 19 shows that the linear salt walls have continued to grow and in some places may have breached the surface through Tawilah times. Indeed, salt outcrops at the present day in a number of domes in the Shabwa-Marib Graben (Figure 1).

Because of the symmetric half-graben nature of the basin and the dip of the base salt surface towards the main basin bounding faults, there has been little migration of salt up basin margin faults. The depositional control exerted by salt movement is remarkable, as is the underlying structural control on the location of salt walls.

Post-Rift Megasequence 3

This megasequence is largely absent from the block but occurs extensively in outcrop to the south and east. It comprises the Umm Er Radhuma, Jeza, Rus and Habshiya formations of the Lower Tertiary Hadramaut Group. These dominantly marine sediments indicate transgression over the Marib-Shabwa area. Following deposition of this unit, the area underwent major uplift and erosion associated with the Late Tertiary rifting and opening of the Gulf of Aden. The scale of the uplift is apparent in outcrops outside the block where the base of the Umm Er Radhuma Formation lies at an altitude of about 1,000 m above sea-level.
CONCLUSIONS

The Central Marib-Shabwa Basin is a Late Jurassic rift in which basin geometry exercised a profound control on sedimentation both during syn-rift and post-rift times. During syn-rift times the deep half-grabens on the basin margin and adjacent to the Central High trapped clastics in their axes and starved the central basinal areas. During post-rift times the block-faulted topography controlled the direction of salt migration, with salt forming linear ridges overlying footwall highs. As a result, post-rift sedimentation was concentrated in a series of linear, salt-withdrawal basins overlying syn-rift lows. As in syn-rift times, basin architecture resulted in some areas being initially sediment starved. Linear depositional belts and rapid lateral facies variation therefore typified the post-rift as well as the syn-rift deposits.

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