Salt tectonics in the Thumrait area, in the southern part of the South Oman Salt Basin: Implications for mini-basin evolution

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ABSTRACT

The Upper Proterozoic - Lower Cambrian South Oman Salt Basin contains exploration targets consisting principally of slabs of carbonate encased within the infra-Cambrian Ara Salt. The southern part of the South Oman Salt Basin was reviewed by using a 40 by 50 km 3-D seismic survey, 30 2-D regional seismic lines and 15 wells. The study focused on the evolution of the Ara Salt in relation to the overlying lower Paleozoic Nimr, Mahatta Humaid and Ghudun groups. Deformation of the thick sequence of Ara Salt dominated the history of mini-basins or “Haima pods” that developed above the salt. The syn-kinematic, predominantly clastic units of the Nimr and overlying Mahatta Humaid groups were deposited in the mini-basins above the Ara Salt. These sequences vary greatly in thickness due to salt movement. In seismic cross-sections, the Ara Salt is opaque, and obscured by seismic multiples generated by sub-horizontal reflectors higher in the section. Where internal geometries are imaged, however, complex internal structures are commonly observed. The Ara Salt structures evolved through several stages of deformation that were driven mainly by phases of sediment progradation from the west and northwest. Four main evolutionary phases for the mini-basins have been identified. Pre-existing topography and regional faults also played a role in triggering and delineating the regional salt trends. The basin has retained much the same shape from the Devonian Period until today. In contrast, in northern Oman, six salt domes have pierced the surface due to the reactivation of major basement faults during the late Palaeozoic.

INTRODUCTION

A large proportion of the world’s discovered hydrocarbon reserves are associated with structures formed as a consequence of the movement of rock salt within the subsurface. In areas as diverse as the Gulf of Mexico, offshore Angola, offshore Brazil, Europe’s North Sea and the Middle East, billions of barrels of oil and gas are trapped within salt-related structures. For example, 60% of the 600 billion barrels of oil reserves in the Middle East are related to salt structures (Edgell, 1996). The prevalence of salt structures and their implication for hydrocarbon prospecting has ensured that salt tectonics has been an active field of research for over 70 years.

In Oman three infra-Cambrian Ara Salt basins have been recognised: Fahud, Ghaba and the South Oman Salt Basin (Figure 1; Loosveld et al., 1996). Lees (1928) was among the first geologists to link the Ara Salt of Oman to the Hormuz Salt of the Arabian Gulf and Iran. Although many hydrocarbon fields have been discovered in the Oman salt basins (Al-Marjeby and Nash, 1986; Heward, 1990; Loosveld et al., 1996), few studies have been published linking these to mini-basins developed by halokinesis above the salt. More recently, additional significant Proterozoic-Cambrian oil discoveries in the stringers incised in the Ara Salt of the South Oman Salt Basin have been made (Peters et al., 2003; Amthor et al., 2005; Al-Siyabi, 2005). These discoveries, together with the growing exploration and continuing maturity of the salt basin provinces in Oman have increased interest in the stringers.

A number of models have been proposed for the complex geometry of salt structures found within the region, ranging from down-building, differential loading, thin-skinned extension, compressional diaprim and salt dissolution (Heward, 1990; Boserio et al., 1994; Loosveld et al., 1996; Al-Siyabi, 2005). Nevertheless, it is clear that previous studies on salt tectonics in the South Oman Salt Basin have not fully explained the observed salt structures and their relationships to mini-basins above the salt in a regional context (Al-Barwani, 2003). The principal aim of this paper is to develop an integrated model of salt tectonics in the South Oman Salt Basin. The paper uses 2-D and 3-D seismic data to show the 3-D geometries of the salt structures. It seeks to characterise their tectonic evolution while taking into account the influence and effects of variable 3-D sedimentation patterns.
Figure 1: Regional tectonic map of Oman showing the major structural features and distribution of the salt basins (modified from Al-Siyabi, 2005; Loosveld et al., 1996; Droste, 1997).
REGIONAL GEOLOGIC SETTING

The South Oman Salt Basin is a NE-trending, asymmetric basin (Figure 1), approximately 400 by 150 km in extent. It is bound to the west by a structurally complex zone, known as the Western Deformation Front, which was interpreted as a transpressional feature that became inactive in the Early Cambrian as manifested by the Angudan unconformity (Immerz et al., 2000). It is bounded to the east by onlap and thinning of basin strata onto a structurally high crystalline basement. The basement of Oman and the Arabian Plate is believed to be a series of basement terranes that coalesced to form the western shield of the Arabian Plate during the Neopetrozoic (Husseini, 1989; Husseini and Husseini, 1990; Stern, 1994; Al-Husseini, 2000; Sharland et al., 2001; Blasband et al., 2001).

The basin fill of the South Oman Salt Basin is comprised of up to 7 km of sediments ranging in age from the Proterozoic to the Recent (Figure 2). The lower part comprises the Huqf Supergroup, which is divided into six lithostratigraphic units including the mobile Ara Group (Figure 2, Gorin et al., 1982; Sharland et al., 2001). The hydrocarbon-bearing Ara carbonate stringers represent isolated carbonate platforms that consist of six third-order cycles of carbonates and evaporites (Peters et al., 2003; Amthor et al., 2005; Al-Siyabi, 2005). The evaporites of the Ara Group are the key structural elements controlling the geometry of the overlying strata, and provide a mechanical detachment horizon between the mechanically brittle pre-Ara and post-Ara layers.

Overlying the Ara Group, the clastics of the Lower Cambrian Nimr and Cambrian-Ordovician Mahatta Humaid groups were deposited in mini-basins associated with salt withdrawal. Devonian-Lower Carboniferous sediments of the Misfar Group (Figure 2) are sometimes preserved in dissolution lows on top of the salt ridges separating the mini-basins. At a regional scale, the Haima Supergroup is overlain by a thick, blanketing Carboniferous-Recent succession consisting of a mixture of clastic and carbonate platform deposits (Figure 2, Droste, 1997).

The Oman sedimentary succession was affected by a series of Proterozoic to Recent regional tectonic phases. Five main tectonic phases have been identified (Stern, 1994; Loosveld et al., 1996; Droste, 1997; Johnson, 2000; Sharland et al., 2001):

1. A Proterozoic compressional phase (c. 715 to 610 Ma) of terrane accretion which led to the assembly of the Arabian Plate.
2. A Late Proterozoic to Early Carboniferous extensional phase (c. 610 to 325 Ma) during which the Huqf and Haima supergroups and Misfar Group were deposited in Oman.
3. A Mid-Carboniferous to Mid-Permian phase (from 325 to 255 Ma), laterally equivalent to the Hercynian Orogeny in Europe; the creation of the Neo-Tethyan Ocean and a new passive margin along the northeastern Arabian Plate margin.
4. A largely Mesozoic (Mid-Permian to mid-Cretaceous) extensional phase (from 255 to 92 Ma). This phase was dominated by the deposition of carbonate and evaporites followed by mixed open-marine clastics and carbonates.
5. A late Mesozoic to Recent phase (from 92 Ma to present-day), which first commenced with the Semail Ophiolite obduction in the northeast and Masirah Ophiolite in the southeast, followed by the closure of the Neo-Tethys Ocean, uplift of the Oman Mountains and Zagros fold belt, and rifting and spreading of the Gulf of Aden and the Red Sea.

SEISMIC STRATIGRAPHY

Several key horizons were interpreted throughout the Thumrait area: base Ara Salt (top Nafun Group), top Ara Salt, several intra-Ara Salt reflectors, top Mahwis, top Ghudun and top Natih-E. Figure 3 shows the seismic stratigraphy of the area using a representative seismic line segment. The seismic section is divided into four units based on salt-related deformation:

1. Pre-kinematic section refers to the section below the Ara Salt;
2. Mobile Ara Salt group;
3. Syn-kinematic section includes the Nimr and Mahatta Humaid groups;
4. Post-kinematic section includes the Ghudun, Haushi and younger groups, which blanket the entire basin.
Figure 2: Chronostratigraphic chart of the South Oman Salt Basin showing the sedimentary record and megasequences associated with the different tectonic events (modified from Droste, 1997; Sharland et al., 2001).
Figure 3: Seismic stratigraphy column of the Thumrait area showing the seismic character of the horizons interpreted and the relative ages.

The lower part of the seismic section features low-amplitude chaotic reflectors, representing the Nafun and Abu Mahara groups (below 3.5 sec, not shown in Figure 3). Due to poor seismic resolution and poor lateral continuity, only one horizon was interpreted within this unit (base Ara Salt or top Nafun).

The isochron of the Ara Salt across the study area varies from as little as 10 msec two-way time (TWT) (c. 20 m) in areas of complete salt withdrawal, to 500 msec TWT (c. 1,100 m) in areas of salt ridges. Within the Ara Salt, layers of high-amplitude, high frequency, discontinuous reflectors represent alternating layers of carbonates and evaporites.

The 600-msec-isochron interval (c. 1 km) between the top Ara Salt and the top Mahwis horizon represents the syn-kinematic sequence of the Nimr Group and lower part of the Haima Supergroup (Figure 3). The lowermost part of the Haima Supergroup is divided into the Amin and Mahwis formations, which were deposited in areas of salt withdrawal known as Haima pods or mini-basins. Onlapping surfaces, growth packages and unconformities have been interpreted in the fill of the Haima mini-basins. Correlation of horizons between pods is difficult due to significant changes in seismic character across each mini-basin and the occurrence of seismic multiples. These changes are caused by the nature of sedimentary deposits, which varies from mini-basin to mini-basin. The absence of well data also renders cross-basin correlations inconclusive.

Approximately 800 msec (c. 1.3 km) above the Mahwis Formation, the post-kinematic Ghudun Group has very poor internal seismic reflectivity, poor lateral continuity and consists of discontinuous reflectors. Only a few reflections can be confidently chosen and correlated over the entire survey. Unlike the underlying units, this sequence shows only minor variations in thicknesses. Over most of Oman, the pre-Haushi unconformity represents a gap of 100 million years (non-deposition and erosion) in the middle Palaeozoic (Droste, 1997).

Between 0.6 and 0.3 sec TWT, the Permian to Cretaceous carbonate units are characterised by high-amplitude, high frequency reflectors, with no significant variations in thickness. Extensional faults occur in this sequence above some salt highs. Above 0.3 sec TWT, low-amplitude, continuous reflectors are correlated with Tertiary and Recent deposits.
SALT-RELATED DEFORMATION

The geometry and evolution of the structures within the Thumrait area are described using five main seismic horizons: base Ara Salt, top Ara Salt, top Amin, top Mahwis and top Natih-E. Figure 4a shows a 3-D visualisation map of top Ara Salt in which thirteen salt-withdrawal mini-basins have been identified; these are chronologically numbered from west to east. Figure 4b shows the TWT isochron of the Ara Salt. Highs represent salt ridges and pillows, lows are salt withdrawal mini-basins; both are clearly seen in the maps. Different Haima mini-basin morphologies are found in the Thumrait area. Haima mini-basins or pods are defined by isopach maxima, with lateral dimensions of 1–12 km, and are surrounded by salt ridges or pillows. These mini-basins are encircled with salt ridges, which are elongated and narrow (1–4 km wide), with maximum depth-of-burial of up to c. 5 km (3.2 sec) (Figure 4a and Table 1). The mini-basins vary in shape and size from 2 km (e.g. part of XII) to approximately 12 km in width (e.g. II). They are both circular and oval in shape, with the main mini-basin axis being oriented to the northeast or north.

The term “mini-basin” refers to the creation of accommodation space controlled by salt withdrawal (Smith et al., 1993). These structures are commonly observed in salt basins worldwide, although their mode of formation may vary from one area to another. Examples of these structures are found in the Gulf of Mexico (Worrall and Snelson, 1989; Diegel et al., 1995; Rowan et al., 2000), central North Sea (Hodgson et al., 1992; Smith et al., 1993; Stewart and Clark et al., 1999), and in the Red Sea (Heaton et al., 1995).

Different styles of salt ridges have been observed in the study area (Figures 5 to 8). The Ara Salt ridges and pillows are typically spaced from 5 to 10 km apart. Their classification is based on lateral dimension, depth-of-burial and type of halokinesis:

- **Elongated salt ridges** (Figures 4 to 8). These salt structures are long, with an irregular top surface. In some places they are completely surrounded by salt welds (i.e. no salt), whereas in other areas the salt has not been completely evacuated underneath the mini-basin. The maximum width of the salt ridge ranges from 1.0–2.5 km. The depth-of-burial of these salt ridges also varies from approximately 2.0–2.5 km (1.3 to 1.7 sec TWT). Ten elongated salt ridges have been found in the area. They are usually inter-connected (Figure 4), asymmetric and associated with growth faults that sole-out on top of the Ara Salt (Figures 5 to 8).

| Mini-basin | Orientation of the Main Axis | Size (km) | Maximum Mini-basin Height (Msec TWT) | Maximum Time (Msec TWT) | Weld | Notes |
|------------|-----------------------------|-----------|-------------------------------------|-------------------------|------|-------|
| I          | N-S                         | 3 x 6     | 1,130                               | 3,120                   | Yes  |       |
| II         | E-W                         |           | 1,250                               | 3,120                   |      |       |
| III        | Circular                    | 15 x 14   | 1,080                               | 2,860                   | Yes  |       |
| IV         | N-S                         | 6 x 3     | 710                                 | 2,890                   |      |       |
| V          | NE-SW                       | 7 x 4     | 600                                 | 2,800                   |      |       |
| VI         | E-W                         | 7 x 4     | 700                                 | 3,000                   |      | Partially covered |
| VII        | Circular                    |           |                                     |                         |      |       |
| VIII       | E-W                         | 8 x 6     | 1,090                               | 2,890                   | Partially covered |
| IX         | N-S                         | 3 x 3     | 1,030                               | 2,760                   |      |       |
| X          | NE-SW                       | 10 x 7    | 1,050                               | 2,550                   |      |       |
| XI         | NE-SW                       | 13 x 6    | 700                                 | 2,320                   | Yes  | Partially covered |
| XII        | E-W                         | 11 x 5    | 490                                 | 2,210                   |      | 3 small mini-basins |
| XIII       | Circular                    | 13 x 10   | 100                                 | 1,840                   | No   |       |

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• **Elongated salt pillows** (Figures 5, 7 and 8). Three examples of this type of salt wall were found in the study area. They differ from the elongated salt ridges in terms of size, shape and depth-of-burial. They are NE-oriented, pyramidal, with a maximum thickness of c. 1,100 m (500 msec TWT) and an average width of 2.5 km at the centre of the pillow. The burial depth of both these structures is approximately 3.7 km (2.5 sec TWT).

• **Salt walls** (Figure 6). Two salt walls (c. 7 km thick) were formed within the 3-D seismic survey. One is located at the southeast end of the survey area and the other was found in the central southern section. They have a minimum depth-of-burial of c. 2,250 m (1.5 sec TWT).

• **Salt-dissolution features** (Figure 8). Three salt dissolution features were formed on top of some salt ridges. They are small (2 km wide) circular features separated by small salt ridges.

From the analysis of the TWT thickness map of the Ara Salt (Figure 4b), a series of salt welds were formed and there was complete or near complete salt evacuation from underneath some of the mini-basins (i.e. mini-basins II, III, VIII, X, and XI).

**DETAILED ANALYSIS OF MINI-BASIN FORMATION**

A number of significant observations that provide clues to the evolution and nature of the salt mini-basins have been made from the analysis and interpretations of various seismic cross-sections. In general, the sedimentary fills in the mini-basins exhibit the following features (Figures 5 to 9):

(a) onlap of tilted/folded reflector packages;
(b) top-lap of tilted reflector packages;
(c) divergent packages of reflectors;
(d) folding of Haima units over salt ridges;
(e) fault terminations of intra-Nimr and intra-Haima reflectors on salt ridges;
(f) erosional truncation at the top Mahwis unconformity.

The mini-basins in the Thumrait area have a sub-circular shape with a dominant northeast orientation. Their sedimentary fill is complex, and because of considerable thickness variations and the lack of impedance contrast, cross-correlating seismic data from one mini-basin to the next across salt ridges is difficult. Only the identification of major units is possible. Local unconformities, relevant only to one single mini-basin, can be occasionally observed on seismic data. It is most likely that most of these mini-basins had distinct infill histories controlled by salt withdrawal, erosion and volume of sediment deposited.

**Classification of Mini-basins**

The mini-basins found in the study area are subdivided into four main groups (Figure 4b). This classification is descriptive because there are no correlations possible between the mini-basins to tie certain markers in the Haima. The subdivisions are based on time of growth, size and seismic characteristics.

**First-Generation Mini-basins**

The first-generation mini-basins formed at the early stages of halokinesis as a result of the deposition by the Nimr Group, which is the youngest group of the Huqf Supergroup (Figures 4b and 10). Six mini-basins have been identified. These are NE-oriented and located to the west of the survey area. They are asymmetric, encircled with salt ridges and associated with complete salt evacuation. Some of the salt ridges associated with these mini-basins are controlled by pre-existing faults.

**Second-Generation Mini-basins**

The second-generation mini-basins formed as a result of the second phase of sediment deposition by either the upper part of the Nimr Group or the Amin Formation (Figures 4b and 11). This group is comprised of six mini-basins, which are located adjacent (mainly to the east) to the first-generation mini-basins.
Figure 4a: Seismic structural map (two-way time) of top Ara Salt in Thumrait area, South Oman Salt Basin (see Figures 1 and 2 for location).
Figure 4b: Seismic isochron map (two-way time) showing orientation of basins relative to surroundings salt ridges. White and yellow coloured areas indicate complete to near-complete salt withdrawal and are referred to as "welds". Mini-basin types are: (1) first generation; (2) second generation; (3) third generation; and (4) fourth generation, associated with salt dissolution (see Figures 1 and 2 for location).
Figure 5a: E-W seismic Line B, Thumrait 3-D survey (see insert for location of line B, and Figures 1 and 2 for location of Thumrait 3-D survey).
Figure 5b: Interpretation of seismic Line B showing the geometries of salt-related withdrawal mini-basin II, III and XIII.
Figure 6a: E-W seismic Line C, Thumrait 3-D survey (see insert for location of line B, and Figures 1 and 2 for location of Thumrait 3-D survey).
Figure 6b: Interpretation of seismic Line C showing the geometries of salt-related withdrawal mini-basin. Mini-basin IV is an example of a third-generation mini-basin caused as a result of salt withdrawal from the flank of the salt ridge.
Figure 7a: NE-SW seismic traverse A, Thumrait 3-D survey (see insert for location of line A, and Figures 1 and 2 for location of Thumrait 3-D survey).
Figure 7b: Interpretation of seismic Line A showing the geometries of salt-related withdrawal mini-basins.
Figure 8a: E-W seismic Line D, Thumrait 3-D survey (see insert for location of line D, and Figures 1 and 2 for location of Thumrait 3-D survey).
Figure 8b: Interpretation of seismic Line D showing the geometries of salt-related withdrawal mini-basin.
During the deposition of the Amin Formation at approximately 520–490 Ma (Hughes-Clark, 1988; Droste, 1997), there was a change in the environment of deposition from proximal alluvial fans to a more distal fluvial-dominated environment with an aeolian influence and playa lakes (Hughes-Clark, 1988; Droste, 1997). The Amin Formation consists of massive clastics that blanketed the entire basin. A series of mini-basins and salt ridges were already developed at that time. These salt ridges acted as barriers for Lower Amin sediments by controlling deposition pathways. Initially, sediments were deposited in the areas of the earlier mini-basins until the formation of salt welds. As a result, no more accommodation space could be created. Therefore, sedimentary deposition shifted to adjacent areas controlled by salt ridges (Figure 11). Evidence of this shift is observed in Mini-basins II, III, X and XI. The Nimr Group in Mini-basins II and X is thicker with evidence of earlier stages of salt withdrawal and mini-basin formation. In contrast, in Mini-basins III and XI the Nimr Group is much thinner or absent, and variations in thicknesses are found in the overlying Amin and Mahwis formations (Figure 12). Intense sedimentation during the Amin and Mahwis formations triggered further salt withdrawal in the flanks of some of salt ridges.

**Third-Generation Mini-basins**

Third-generation mini-basins (Figures 4b and 13) are associated with salt withdrawal on the flanks of salt ridges. In contrast, in the first- and second-generation mini-basins salt withdrawal occurred beneath the mini-basins. The third-generation mini-basins were formed at later stages during the deposition of the Mahwis Formation. During that time, a series of listric growth faults that were detached or were absorbed near the top of the ductile Ara Salt were formed. Formations adjacent to these faults show considerable variations in thicknesses, with thicker sections on the hanging-wall indicating syn-sedimentary growth of the faults. These faults are interpreted to have formed as a result of the shift of accommodation space from older to younger mini-basins and withdrawal on the flanks of existing salt ridges.
Figure 10: (a) Interpretation of Line E (Figure 9) showing the geometries of salt withdrawal in Mini-basin I. (b to d) Schematic model illustrating the growth of a first-generation mini-basin based on Line E. Salt withdrawal has a dominant easterly withdrawal direction away from the applied load.
Fourth-Generation Mini-basins

Fourth-generation mini-basins occur on the crests of salt ridges (Figures 4b and 14). They are interpreted to have formed as a result of salt dissolution during the deposition of the Mahwis and the lower formations of the Ghudun Group. They are smaller (c. 1–2 km wide) compared to other mini-basins (5–15 km wide) with no major variation in layer thicknesses. Evidence of salt dissolution can only be observed in some areas at the crest of the salt ridge.

Structures at the Base of Ara Salt

The TWT seismic map of the base Ara Salt is smooth, dipping gently towards the northwest with an average dip of 3° to 5° (Figure 15). Despite the strong seismic amplitude response at the base of the Ara Salt, its interpretation was hindered by velocity pull-ups underneath the salt ridges and the presence of intra-salt reflectors. This made the task of identifying faults, correlating across faults and the interpretation of the basal Ara Salt reflector difficult over large parts of the 3-D seismic survey.

A series of NE- and NNE-trending extensional/transtensional faults were identified at the base of the Ara Salt sequence (Figure 15). It remains unclear if these faults were active during the deposition of the Ara Salt sequence (Ara syn-depositional), or were activated after the deposition of the salt and caused (at least in part) by the highly faulted and deformed carbonate stringers within the ductile Ara Salt. Other extensional/transtensional faults with smaller displacements and different orientations are discontinuous and segmented, with poor lateral continuity. In seismic sections these extensional faults are mostly planar (Figures 5, 7 and 8).
SALT TECTONICS

Several salt tectonic mechanisms have been discussed in the literature. Their applicability to the South Oman Salt Basin is considered in this section.

(a) Thin-skinned extension of the cover, with the salt diapirs piercing the overburden (e.g. Vendeville and Jackson, 1992a).
(b) Thick-skinned extension, including pre-existing basement high, or reactivated basement fault (e.g. The Central Graben, North Sea, Stewart and Coward, 1995; Steward and Clark et al., 1999).
(c) Contractional salt tectonics, folding the overlying unit and forcing the rise of the diapir (e.g. the Zagros fold belt, Talbot and Alavi, 1996).
(d) Differential loading, caused by prograding sediment systems into the basin (e.g. Ge et al., 1998).
(e) Gravity instability, caused by the basement dip, initiating salt movement either up or and down slope within the basin (e.g. Gulf of Mexico, Rowan et al., 1995).
(f) Salt dissolution, either internal or external dissolution (e.g. West Central Shelf, Central North Sea, Clark et al., 1998).
Differential loading is the most probable principal mechanism for initiating and driving halokinesis as well as forming the mini-basins in the South Oman Salt Basin. This is interpreted to have occurred at the early stages during the deposition of the Nimr Group and lower part of the Haima Supergroup. Sediment progradation from the west and southwest, as indicated by the orientation of clinoforms and/or sedimentary wedges, is interpreted to be a main factor in driving the salt movement. Extensional/transtensional faults, mapped in the pre-salt sequence and possibly shaping the Ara topography, appear to play a major role in determining the direction of salt migration; e.g. the strike of the first-generation mini-basins. These mini-basins are parallel to the main NW-trending structural grain observed in the western margin of the South Oman Salt Basin.

Basal Ara faults, which might be located above deeper basement faults, appear to play a role in the location and orientation of the salt ridges in the South Oman Salt Basin. Extensional/transtensional faults mapped in the Basal Ara occur in the Thumrait area underneath or adjacent to some of the salt ridges (Figure 15). Reactivation of deep basement faults could have provided the triggering mechanism for the initiation of halokinesis.

Thin-skinned extension as the main trigger mechanism for halokinesis in the South Oman Salt Basin (Vendeville and Jackson, 1992) is ruled out. In some areas (e.g. Figures 5 and 6), the occurrence of listric-shaped growth faults that sole-out onto the flank of the top of the Ara Salt are interpreted as a product of salt/ridge rise and the generation of accommodation space at different times within the adjacent mini-basins, rather than having been generated by extension of the supra-salt cover section.
A regional compressional event in the early stages of halokinesis (often referred to as the “Angudan event”) is widely discussed within Oman’s geosciences community. However no publication exists that describes this compressional event or substantiates it with data. The area west of the South Oman Salt Basin, which is named the Western Deformation Front, may represent a transpressional/compressional inversion phase that followed salt deposition (Figures 16 and 17). It became the focus for inversion and associated structures (anticlines, reverse faults, and thrusts). The end of this transpressional/compressional phase is manifested by the Angudan unconformity. The structural nature of the Western Deformation Front, poor 2-D seismic resolution and definitive infra Cambrian plate reconstructions have resulted difficulty in reconstructing its structural nature. Thicker salt sections, imaged to the east, form salt ridges and mini-basins (Figures 17 and 18). The Western Deformation Front and the associated uplift to the west are interpreted as a source of most of the sediment that drove halokinesis of the mini-basins by differential loading.
Figure 15: (a) Regional seismic line showing the South Oman Salt Basin, Western Deformation Front and Rub' Al-Khali Basin.

See facing page (insert) and Figure 1 for location.

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Figure 15: (b) Interpretation of seismic Line in Figure 15a.
Figure 16: 2-D regional line showing structural complexity in the Western Deformation Front. See Figure 1 for location.
Salt Dissolution

Regional-scale salt dissolution has been documented in many basins (e.g. the West Central Shelf, Central North Sea, Clark et al., 1999) and the Forth Approaches Basin, UK North Sea (Cartwright et al., 2001). Dissolution salt tectonics has been documented in some parts of the South Oman Salt Basin, especially at its eastern margin (Al-Marjeby and Nash, 1986; Heward, 1989, 1990; Loosveld et al., 1996). Heward (1990) regarded salt dissolution as the main factor driving halokinesis in the eastern flank of the basin. However, there are environmental and tectonic differences between the eastern segment of the South Oman Salt Basin, where salt dissolution has previously been documented and the study area in the western segment of the basin. In the eastern part of the basin, the basement and the Ara Salt are at shallower depths compared to the central and western parts. Therefore, the Ara Salt was subjected to suprajacent dissolution caused by the overlying aquifer of the Haushi, Cretaceous and Tertiary strata in the eastern part of the basin but not in the central and western parts. (Al Lamki and Terken, 1996).

Mini-basin Growth and Tectonic Evolution

The first-generation mini-basins were formed as a result of sediment progradation sourced from the uplifted basement high in the Western Deformation Front and the Ghudun High to the west and northwest of the South Oman Salt Basin (Figures 1, 16 and 17). These mini-basins formed...
as a result of syn-sedimentary movement of salt following sediment-loading (Figure 18). Pre-existing structures in the pre-salt basement played a role in the orientation and location of the mini-basins above the salt and associated salt ridges.

It is likely that when the base of the clastic sediments reached the pre-salt in the deepest part of a mini-basin grounding the mini-basins onto the pre-salt strata, that the mini-basins became inactive. This would have caused a shift of depocentre to another location resulting in second-generation mini-basins (Figure 18). Intense sedimentation during the Amin and Mahwis formations triggered further salt withdrawal in the flanks of some of the salt ridges.

Massive sedimentation in the Ordovician (Hughes-Clark, 1988; Droste, 1997), during the deposition of the lower formations of the Ghudun Group (thickness up to 1,500 m), prevented continued growth of the salt ridges (Figure 18). Although minor variations in thicknesses exist in the lower part of the group, these are attributed to the creation of accommodation space in some of the mini-basins by secondary salt withdrawal adjacent to the flanks and are associated with listric faults on the margin of salt ridges.
The duration of the halokinesis in the study area was approximately 60 million years. This is the approximate duration of deposition for the Nimr and Mahatta Humaid groups (Droste, 1997). The main phase of halokinesis in the South Oman Salt Basin was terminated by the deposition of the Ghudun Group. Initially, the rising salt ridges kept pace with sedimentation during the deposition of the Mahatta Humaid Group as evidenced by the formation of third-generation mini-basins and listric growth faults. This was followed by a complete halt when rising salt ridges could not keep pace with the massive deposits of the Ghudun Group. Some of these ridges were reactivated as point-source diapirs triggered by reactivated basement faults in the Carboniferous. They continued to grow by down-building followed by compressional salt diapirism during the Cretaceous.

**Comparison to Other Salt Tectonic Basins**

A review of the published literature suggests there are only a few documented analogues for the salt-tectonic style of the South Oman Salt Basin. The salt structures of the Gulf of Mexico are often allochthonous in nature and more closely resemble salt sheets extruded onto multiple stratigraphic levels (Worrall and Snelson, 1989; Rowan, 1995). The evolution of these structures was strongly influenced by a regional slope and a progradational differential load, and many of the structures have principally evolved over the last 10 million years. Other passive margins, such as in Angola and Brazil, are characterised by brittle faulting (Vendeville and Jackson, 1992), rift-raft processes and salt-wall rise/fall.

The Pre-Caspian Basin is a close analogue to the style of salt tectonics observed in the South Oman Salt Basin. It too is dominated by mini-basins and associated salt ridges, mainly driven by sediment progradation eroded from the uplifted margin (Figure 18; after Barde et al., 2002). The Pre-Caspian Basin is 600 km wide (from east to west) and underlain by the Lower Permian (Kungurian) salt (260 Ma, up to 4.5 km thick in the centre of the basin) at the northern end of the Caspian Sea (Barde et al., 2002; Volozh et al., 2003). The sub-salt sequence has a complex deformation history dominated by carbonate reefs and clastic fans. The post-salt sequence consists of terrigenous Upper Permian through Neogene strata. Deformation of Permian salt controlled the main structures observed in this basin (Barde et al., 2002; Volozh et al., 2003). Salt structures evolved through several stages that were driven by basin-ward sediment progradation eroded from the Ural Mountains. Clastic sediments, which eroded from the east, prograded into the basin and provided the main driving mechanism for halokinesis. This resulted in a series of salt ridges/walls and associated basins by the end of the Permian (Figure 18).

**CONCLUSIONS**

The evolution of the Thumrait area in the southern part of the South Oman Salt Basin has been described in terms of salt tectonics. The interior of the basin is dominated by a series of salt ridges and basins. The infra-Cambrian Ara Salt controls the depositional architecture observed in the overlying Nimr Group and Haima Supergroup. The Thumrait area shows interconnected NE-, NS- and NW-trending salt ridges, and 13 salt withdrawal mini-basins that vary in size from 1-15 km. The mini-basins are encircled with salt ridges. These salt ridges have been classified into (i) elongated salt ridges, (ii) pillow structures and (iii) salt walls. Four types of mini-basins occur. The first-generation mini-basins formed as a result of the first phase of halokinesis caused by differential loading during the deposition of the Nimr Group. The second-generation withdrawal mini-basins are linked with the first-generation withdrawal mini-basins but formed as a result of a shift in the Haima sediment depocentres during the deposition of the Amin Formation. The third phase withdrawal mini-basins formed in areas adjacent to salt ridges during the deposition of the Mahwis Formation. Fourth-generation mini-basins formed as a result of salt dissolution on top of salt ridges during the deposition of the Ghudun Group. Most of the deformation associated with halokinesis occurred at an early stage during the deposition of the Nimr Group and the Amin Formation (lowermost Haima Supergroup) in the Thumrait area. The grounding of mini-basins onto the pre-salt strata was the main factor that terminated the growth of the salt ridges at the early stages of halokinesis. Subsequent thick blanketing sedimentation of the Ghudun Group appears to have prevented further halokinesis.
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