Exploration for a Frontier Salt Basin in Southwest Oman

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ABSTRACT

An undrilled Infracambrian-lower Paleozoic salt basin is interpreted as being present in the Dhofar area of southwest Oman. A re-evaluation of the existing seismic and gravity data indicated that the basin is located immediately north of a major NE-orientated basement feature known as the Ghudun-Khasfah High. The basin is centered in the southern part of the Al Hashman Block 36 and the northern part of Mudayy Block 38, both operated by Phillips. Studies conducted by Phillips suggest that the basin has a similar structural history and pre-Silurian stratigraphy to the known salt basins of Oman. New stratigraphically deeper Paleozoic and Infracambrian exploration plays that are proven in the other Oman salt basins are proposed for this undrilled basin. The new plays rely on an unproven Infracambrian Huqf source. Source and reservoir degradation through widespread post-Huqf deformation is possible, but structural modeling and seismic facies analysis, together with the detection of significant micro-seepage anomalies, suggest otherwise. In addition, the identification and gravity modeling of what appear to be salt features on seismic lines support the presence of Lower Cambrian salt swells and piercement structures. The salt features are believed to be age equivalent to the Ara salt section of the upper Huqf Supergroup present in the other salt basins. Phillips has named this potential salt basin the Ghudun Salt Basin.

INTRODUCTION

A new regional tectonic model has been developed by Phillips (Webster, 2000), which allows for the development in central and southern Oman of Infracambrian salt basins that are considered to have evolved with similar structural and depositional histories. In the late 1980s and early 1990s, southwest Oman was believed to have been affected by Early Cambrian regional deformation due to the collision of two Precambrian continental blocks. The deformation resulted in what has been described as the ‘Western Deformation Front’ (see Loosveld et al., 1996) that loosely delineated the western margin of prospectivity in Oman. Recent work by Phillips suggests that the deformation was likely to be of an intra-cratonic nature and to be much more localized than previously thought. As a result of the Phillips work, the prospectivity of southwest Oman has been upgraded.

The paper focuses primarily on the two concessions (Block 36, Al Hashman; and Block 38, Mudayy) that Phillips operates in southwest Oman (Figure 1) in association with Maersk Oil and Gas and Berkley Petroleum. It attempts to demonstrate through a re-evaluation of the existing reprocessed seismic and gravity data the presence of a fourth, as yet undrilled, Infracambrian salt basin in this part of Oman. Several exploration plays are proposed for the new salt basin that are analogous to plays proven in the known salt basins of Oman.

Blocks 36 and 38 have a combined area of approximately 36,000 sq km (8.5 million acres). Immediately to the west is the Republic of Yemen, to the north the Kingdom of Saudi Arabia and the Rub’ Al Khali Basin and to the east lies the prolific South Oman Salt Basin (SOSB). Separating the SOSB from Blocks 36 and 38 is a NE-trending linear basement feature known as the Ghudun-Khasfah High. The High is represented on gravity and seismic data as a positive anomaly and is one of several such features in Oman. As a structural high, it dates from the later stages of the formation of the Arabian Plate in the late Neoproterozoic (Webster, 2000). It has had a strong influence on the depositional history of the adjacent basins.
Figure 1: Bouguer Gravity Map of Oman (after Ravaut and Warsi, 1977) showing the locations of Blocks 36 and 38.
Blocks 36 and 38 were formerly part of the Dhofar Concession that covered much of southern and southwestern Oman. This large area had previously been operated and explored by Cities Services Petroleum, BP, and Petroleum Development Oman (PDO) from the early 1950s to the early 1990s. In that time, however, only four wells were drilled in what are now Blocks 36 and 38 (see Figure 1 inset). Moreover, three of them were drilled in the late 1950s and early 1960s on either surface and/or gravity anomalies before the acquisition of modern seismic data. They provided little significant log data and did not penetrate below the upper Paleozoic, thus ignoring the Infracambrian and Cambrian–Lower Ordovician sections. The fourth and most recent well (Al Hashman-1) was drilled in 1991 by PDO to test a Permian Gharif structure. The well was unsuccessful and PDO subsequently relinquished that part of its concession in 1995.

Phillips was awarded Block 36 as part of the 1995 first Oman License Round, and acquired Block 38 in 1999 following a data-room visit to the Ministry of Oil and Gas in Muscat. It was at this stage that the potential for stratigraphically deeper Cambrian-Ordovician exploration play targets was recognized. A comprehensive work program consisting of a complete re-interpretation of the existing seismic and gravity data sets, together with additional studies, was put into place in an attempt to further understand and pursue these new and potentially rewarding plays.

**REGIONAL GRAVITY**

A combination of land-based gravity and regional airborne and satellite gravity surveys covers much of Oman (Ravaut and Warsi, 1997). This information has been compiled to produce a regional Bouguer gravity display of the country, which the Ministry of Oil and Gas has recently made available to companies operating in Oman. Figure 1 shows the Bouguer anomalies after additional filtering and redisplay by Phillips. Gravity lows (indicated by blue tones) and gravity highs (red tones) broadly correlate with the main basement features.

The most important tectonic elements in Oman are the three known Infracambrian salt basins, the outlines of which are shown on Figure 1. They are the Fahud and Ghaba basins in the north and the SOSB in the central-southern part of the country. The Ghaba Salt Basin does not appear as a significant low on the Bouguer anomaly map, despite containing large amounts of salt. This may be because of regional effects caused by proximity to the Huqf-Haushi Uplift, and/or crustal thinning due to isostatic compensation.

Immediately to the west of the SOSB is the Ghudun-Khasfah High. On the gravity map it shows as a NE-trending positive linear anomaly that separates the SOSB from a gravity low to the west. It is this western gravity low in the extreme southwest of the country that is thought to represent a fourth and undrilled Infracambrian salt basin. This new basin, called the Ghudun Salt Basin, appears to be comparable in areal extent with the Ghaba Salt Basin.

Figure 2 is a more detailed view of the gravity display for the southern part of Oman. The Ghudun Salt Basin appears to be centered in the southern part of Block 36 and the northern part of Block 38 with its eastern flank extending into adjacent Block 49. From a model of the gravity and aeromagnetic data (see ‘Gravity Modeling’), the depth to basement is estimated to be in the range of 8 to 10 km. Seismic and well data place the base of the Silurian at about 1.5 to 2 km.

An observed gravity low can be accounted for by the presence of a significant pre-Silurian section that has not yet been explored. The thickness of the pre-Silurian section is graphically illustrated (Figure 3) on a regional 2-D seismic line (880513v) that traverses almost the entire length of Block 38 for a distance of about 120 km (see Figure 1, inset, for location).
Figure 2: Bouguer gravity map of Southern Oman showing the major tectonic elements.
As no well control occurs below the Early Ordovician Base Ghudun reflector, the presence of salt can only be inferred from features observed on the existing seismic data. Possible salt features (Figure 4) are salt swells, pillows, piercement structures and turtle backs. The observations are supported by gravity modeling of the interpreted salt. The salt features are believed to be age-equivalent to the Upper Huqf Ara salt section present in the other salt basins.

**SEISMIC EVIDENCE FOR SALT**

Figure 4 shows interpreted and uninterpreted versions of part of reprocessed seismic line 890652v located in the south of Block 36 (see Figure 1, inset). The Base Ghudun marker is a generally continuous, sometimes bright peak that shows a gentle anticlinal roll-over, probably in response to deeper structuring. Below the Base Ghudun, possible salt piercements appear to be associated with adjacent mini-basins from which salt withdrawal can be inferred. A possible salt-induced ‘turtle back’ structure occurs at the Intra-Haima level. This feature may be partly responsible for some of the structuring seen at the Base Ghudun event. Reflectors that appear to be turned up or pulled up adjacent to the western of the two interpreted salt diapirs suggest upward movement of salt through the stratigraphic section. On the other hand, it could be argued that the interpreted diapirs on this seismic section merely represent wrench faulting, with or without salt intrusion.

Bright, discontinuous reflections (indicated in yellow on Figure 4a) have been tentatively interpreted within the proposed salt layer and may represent intra-salt reservoir bodies. The possibility of an intra-salt carbonate stringer play in Blocks 36 and 38 is discussed in more detail in the section on ‘Proposed Exploration Plays’.

Additional evidence to support the presence of salt in this part of Oman is provided by the Phillips regional tectonic model (Webster, 2000), and from gravity modeling of the interpreted salt.
Figure 4: (a) Interpreted and (b) uninterpreted versions of seismic line 890652v showing evidence for salt features (Block 36 South). The apparent turtle back structure may be the result of an underlying salt swell, created by adjacent salt withdrawal (see Figure 1, inset, for location).
Gravity Modeling

The author has undertaken gravity modeling on several key seismic lines in Blocks 36 and 38 in order to determine the amount and extent of the salt layer. The results have helped to confirm the likely presence of a salt layer in the southern part of Block 36 and the northern part of Block 38. Figure 5 is a 2-D model in which the whole of seismic line 890652v (see Figure 4) has been interpreted and modeled for the late Paleozoic and Mesozoic units. The 50-km high-pass filtered Bouguer gravity data, together with rock densities obtained from samples taken from the Al Hashman-1 well (Figure 1, inset), were used in the interpretation and modeling. A contaminated-salt density of 2.34 g/cm³ (assuming 80% salt at 2.20 g/cm³ and 20% anhydrite at 2.90 g/cm³) was used in the modeling. A good fit was obtained between the salt model and the observed gravity profile. If the salt unit was replaced with the surrounding rock at a density of 2.7 g/cm³, there was virtually no match between the no-salt model and the observed gravity.

The results of the gravity modeling indicate that a low-density medium such as salt is required in the deeper part of the section to achieve a reasonable match with the observed gravity profile. Alternatively, solutions such as basement contrasts, facies changes, and the like, may equally explain the effect. Nevertheless, within the available constraints on density and stratigraphy, the salt model adequately explains the effects seen on the gravity profile and the salt-like character observed on the seismic data. Finally, it should be noted that the modeling can only infer the presence of salt bodies whose dimensions exceed 5 km. Piercement features such as those identified on line 890652v (Figure 4), whose dimensions are only 1 to 2 km, will alias and give no response on the modeled gravity curve.

Figure 5: Gravity modeling of seismic line 890652v (Block 36 South) showing close match between the observed gravity and the calculated salt model.
PROPOSED EXPLORATION PLAYS

The exploration plays are based on the assumption that the Ghudun Salt Basin contains salt and has a generally similar stratigraphic succession to the known salt basins in Oman, in particular to the SOSB and the Ghaba Salt Basin. Three broad-scale exploration plays proven in the other salt basins are proposed for the Ghudun Salt Basin.

1. Cambrian-Ordovician clastic plays broadly equivalent to the Haima Supergroup.
2. Lower Cambrian Huqf intra-salt plays.
3. Infracambrian Huqf pre-salt carbonate and clastic plays.

Figure 6 shows the simplified lithostratigraphy of the Ghudun Salt Basin and the likely stratigraphic distribution of the three proposed plays. Each play has been color coded to indicate at this preliminary stage of exploration whether it is considered a primary or secondary play. Figure 6 also depicts the reservoirs, seals and source units for each play, together with important seismic markers. Again, it should be noted that there is no well control below the Base Ghudun marker (Lower Ordovician) for this part of Oman. Consequently, the proposed lithostratigraphy below that event is hypothetical and based almost entirely on the known stratigraphy in the SOSB and the Ghaba Salt Basin (Droste, 1997; Oterdoom et al, 1999). However, other seismic examples indicate possible salt swells that can be supported by independent evidence. This evidence is provided by gravity modeling, the presence of tilted fault blocks beneath the modeled salt layer, and seismic characteristics that are very similar to examples from the other salt basins in Oman. In addition, the presence of reservoirs and seals within the Haima Supergroup is supported by extrapolating paleofacies maps of Droste (1997) to cover the southeastern flank of the Rub’ Al Khali Basin (see Haima Clastic Play).

Each play is discussed below in more detail and analogies are drawn, where appropriate, with examples from the other salt basins in Oman.

Haima Clastic Play

The proposed Haima play is based on the known stratigraphy and plays in the Ghaba and South Oman salt basins (Droste, 1997). It is suggested that up to five reservoir-seal pairs might be present within the Haima Supergroup equivalent to sandstones of the Ghudun, Barik, Miqrat, Amin (and possibly Nimr). Seals are provided by intra-formational continental sabkha/lacustrine deposits in the lower Haima or by marine flooding events in the upper Haima Andam and Ghudun formations.

Droste (1997) interpreted a series of regional maximum flooding events that deposited marine shales and intervening deltaic and marginal-marine clastics through the Late Cambrian and Early Ordovician in central and north Oman. The flooding episodes define a series of transgressive-regressive cycles lasting from 3 to 5 my that punctuate the upper Haima Supergroup. It is likely that these events, which show an increasing marine influence, were widely distributed throughout the Rub’ Al Khali Basin to its southern flank which was a region of low relief. It is probable that the transgressive cycles will be represented in the Ghudun Salt Basin (H. Droste, personal commun., 2000).

Further evidence for marine incursions, and therefore for potential regional seals within the Haima, comes from the Arabian Study Group (Sharland et al., 2000). Their sequence stratigraphic interpretation places several candidate maximum flooding surfaces in this interval. These surfaces extend across the Arabian plate and correlate with Droste’s Haima Supergroup stratigraphy in northern and central Oman. Paleofacies maps of Droste (1997) for the Haima section have been extrapolated from the southeastern flank of the Rub’ Al Khali Basin into the Ghudun Salt Basin. The maps support the presence of Haima reservoirs and seals in southern Oman (Figure 6).

Using the SOSB as an analogy, the primary source to charge these reservoirs is believed to be either an equivalent of the Dhahaban Formation of the Ara Group (Terken and Frewin, 2000), or underlying restricted-basin carbonates and shales of the Huqf Supergroup. Oil in Al Hashman-1 (Block 36) has
Figure 6: Blocks 36 South and 38 North—Simplified lithostratigraphy and the distribution of proposed exploration plays for the Ghudun Salt Basin. The location of the Cambrian/Infracambrian boundary is placed near the base of the Nafun Group. This is in accordance with Oterdoom et al. (1999).
been typed as Silurian but a Silurian hydrocarbon system would not appear to operate south of this well unless long-range migration of more than 80 km from the north is invoked. The oil-mature Silurian source facies has been shown by Milner (1998) to be confined to the narrow southern margin of the Rub’ Al Khali Basin that covers only the northern third of Block 36 and adjacent areas.

Indirect evidence for the presence of a lower Haima or Huqf hydrocarbon system can be demonstrated from the presence of light-hydrocarbon surface microseepage anomalies in the area. These anomalies have been identified from the analysis of soil samples collected as part of an extensive microbial hydrocarbon seep survey that the Phillips partnership conducted in southwest Oman during the second half of 1999. It is noteworthy that the oil in Al Hashman-1 was in an insufficiently mature or migrating state to give significant surface microseepage anomalies.

Good examples of potential trapping mechanisms for hydrocarbons within the Haima reservoir section are shown on seismic line 890652v (Figures 4a and 4b). These include:

- Low-relief Base Ghudun anticlinal structures due to saltpillowing and piercements.
- Intra-Haima salt wall traps.
- Intra-Haima ‘turtle back’ structures due to adjacent salt withdrawal.

A second example of the Haima play is shown as Figures 7a and 7b that are interpreted and uninterpreted versions of reprocessed line 920420v, respectively. Structuring can be seen at the Base Ghudun reflector in two areas and possible additional stacked targets occur in the lower Haima. As previously noted, as many as five reservoir-seal pairs could be present within the Haima Supergroup, each one capable of containing hydrocarbons. A possible salt diapir has been identified on Figure 7a that could provide potential traps against the salt wall within the Haima section. The Huqf sequence contains the presumed source rock to charge these features.

Evidence for a Huqf Hydrocarbon System

During late 1999, about 7,800 soil samples from large parts of Blocks 36, 38 and the surrounding area were collected and analyzed using the Microbial Oil Sampling Technique (MOST). The underlying assumption of all near-surface geochemical exploration techniques is that hydrocarbons are generated and/or trapped at depth and leak in varying, but detectable quantities, to the surface. A defined (mappable) surface microseepage anomaly is the end-result of this process (Schumacher and Abrams, 1996).

The main objective of the 1999 survey was to determine if an active petroleum system existed in this part of southwest Oman. It was also hoped to identify key anomalous areas that could be associated with potential exploration leads and prospects and with other subsurface features such as faults and possible salt diapirs.

The results of the microbial survey indicate the presence of strong hydrocarbon microseepages in parts of the survey area. Seepage anomalies were particularly apparent in the southern part of Block 36 and northern part of Block 38 where the Ghudun Salt Basin has been inferred from gravity and regional seismic data. A total of 20 principal anomaly groups have been identified, ranging from small multi-point groupings to areally extensive anomalies that extend across several seismic lines.

Figure 8 shows the Microbial Lineplot (microbial value plotted against sample point), for seismic lines 920420v (Figure 7) and 880502v (Block 49) along which samples were collected at regular 250-m intervals. The plot of line 920420v shows regionally elevated and highly variable microbial values that are probably typical of an area where oil and gas has been generated and migrated from. As the curve is traced from west to east, the background microbial values of approximately 100 to 150 abruptly increase to almost 300 over the interpreted salt diapir in Figure 7a. Similarly, the profile shows an increase in microbial values corresponding to the anticlinal structure at the Base Ghudun level.
Figure 7: (a) Interpreted and (b) uninterpreted versions of seismic line 920420v (Block 38 North) depicting Lower Ordovician Base Ghudun and ?Middle to Upper Cambrian Haima leads, together with a possible salt piercement structure (see Figure 1, inset, for location).
It is probable that the correlation between the interpreted salt diapir and anticlinal structure and the high microbial readings is the result of trapped and/or generated hydrocarbons leaking in small but detectable amounts to the surface. It is important to note that this phenomenon is seen on several adjacent seismic lines where the combined microbial lineplots result in a definable surface microseepage anomaly. In contrast, seismic line 880502v in Block 49, some distance from the Ghudun Salt Basin, has a microbial profile (Figure 8) that shows little variation and for which the microbial readings are relatively low. This is considered typical of an area having little or no hydrocarbon generation and migration and would indicate a low exploration potential unless the geological setting suggests the presence of exceptionally good sealing mechanisms.

Intra-Salt Play

As previously discussed, seismic morphologies, gravity modeling and recent developments by Phillips in the tectono-stratigraphic understanding of the Arabian Plate, support the possible presence of intra-Cambrian Ara salt in southwest Oman. More detailed observations within the postulated salt section reveal discrete packages of bright reflectors that, by analogy with similar features in the SOSB, are interpreted as isolated Ara carbonate stringers (see Figure 4a). The depositional history and extent of these potential reservoirs, together with compartmentalization and access to charge, are currently poorly understood. As a minimum requirement, high-quality 3-D seismic data will be needed to further mature this play. Nevertheless, there are several unusual and interesting features seen within the interpreted salt section on the reprocessed 2-D seismic data that deserve further discussion.

Figures 9a and 9b are, respectively, interpreted and uninterpreted versions of reprocessed seismic line 920412v from the northern part of Block 38. The top of the salt layer is identified as the divide between the more transparent salt section containing the interpreted stringers, and the overlying, more banded, seismic package of the lower Haima Supergroup. Key reflectors can be seen to onlap the Top Salt horizon. The onlap surfaces are believed to represent the deposition of lower Haima sediments onto the salt and are a further aid in the identification of the Top Salt unit.

The salt layer contains several stacked, bright, discrete reflectors that may represent carbonate stringers encased within a more transparent halite section. The interpretation of carbonates is possible when
Figure 9: (a) Interpreted and (b) uninterpreted versions of seismic line 920412v (Block 38 North) showing possible carbonate stringers within the interpreted and gravity-modeled salt layer (see Figure 1, inset, for location).
one considers the overall morphology of the stringers presented in this example, and the knowledge that this is a proven play in the adjacent SOSB (for example, in the Birba and Ghafeer discoveries; Reinhardt, PDO, personal commun., 1999).

Figure 10, courtesy of PDO, is an arbitrary seismic section taken from the 3-D survey over the Ghafeer stringer discovery made by PDO in the southern part of the SOSB in 1999. The PDO section shows that the discovery well, Ghafeer-1H1, intersected four carbonate stringers within the Ara Salt, each one characterized by a bright ‘red’ trough on the seismic display. The stringer package was tested at a combined flow-rate of 6,500 barrels of oil per day. When the Ghafeer example is compared with what appears to be a similar feature on line 890677v (Figure 11) in the south of Block 36, several similarities can be seen. In particular, there are common features in the seismic character of the interpreted stringer events and the overall morphology of the salt and pre-salt sections. The reflector colors and vertical and horizontal scales have been reproduced on line 890677v to mimic the PDO example and help facilitate the visual comparison. One can speculate that if a hypothetical well were located at approximately shot point 650 on line 890677v, it too might intersect four possible stringers within the Ara Salt.
The third exploration play proposed for this part of Oman is a Pre-Salt Play of carbonates and clastics within the Nafun and Abu Mahara groups, respectively (see Figure 6). Seismic evidence strongly suggests that the trap type is tilted fault blocks with footwall and horst closures, having the overlying Ara Salt acting as the regional top seal. The source is again believed to be primarily marine shales within the upper Huqf, although there is some evidence for an additional source rock in the Abu Mahara in other Oman salt basins (Oterdoom et al., 1999). The main risks associated with this play are considered to be fault-imaging problems using the present seismic data set, together with the preservation of primary porosity at depths that are estimated to be greater than 4,500 m. As a result, the Pre-Salt Play is viewed by Phillips as a secondary objective relative to the stratigraphically younger Haima and Intra-Salt plays.

Figure 12 shows interpreted and uninterpreted versions of reprocessed seismic line 890673v located in the southern part of Block 36. Several tilted fault blocks and half grabens can be seen immediately below the interpreted salt layer, providing potential footwall and horst structural closures in this area. Similarly, Figure 13 (courtesy of PDO), taken from the Fahud Salt Basin in north Oman shows comparable structuring of the pre-salt Huqf section. Note the faulted bright reflector package immediately underlying the base of the Ara Salt that represents the carbonate and shale section from the Buah, Shuram and Khufai formations of the Huqf Supergroup (Figure 6). Similar reflectors can be seen on the Block 36 examples (Figure 12), suggesting that a Pre-Salt Play could be present in Blocks 36 and 38.
Figures 12: (a) Interpreted and (b) uninterpreted versions of seismic line 890673v (Block 36 South) showing potential pre-Ara Salt fault blocks of the upper Huqf. Exploration targets for this play are interpreted as footwall and horst block closures (see Figure 1, inset, for location).
CONCLUSIONS

No well data exists to support the observations and concepts presented in this paper. However, a re-evaluation of existing seismic and gravity data, together with positive results from the microbial hydrocarbon-seep survey, provide sufficient evidence to suggest that the exploration potential of southwest Oman is greater than was previously thought.

The possible existence of the Ghudun frontier salt basin has been demonstrated on both regional Bouguer gravity and reprocessed seismic data sets. Features such as salt piercement structures, salt swells, and associated salt withdrawal structures have been identified, and gravity modeling supports the presence of such a low-density medium. Accordingly, newly recognized exploration plays are proposed for the area that are analogous to known plays in the other Oman salt basins. These include a Haima clastics play, an Intra-Salt carbonate stringer play and a Pre-Salt clastics and carbonates play. Seismic examples from the proposed Ghudun salt basin are analogous with those from the other salt basins of Oman. The presence of a viable Huqf and/or lower Haima source is also supported by encouraging results obtained from the microbial seep survey.

On the assumption that these plays are present and contain trapped hydrocarbons, the possibility exists for discovering and developing a new hydrocarbon province in southwest Oman that might extend into adjacent areas.

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Figure 13: Fahud Salt Basin—Seismic line (courtesy of PDO) showing tilted fault blocks beneath the salt layer and thought to be analogous to the Pre-Salt Play identified in Blocks 36 and 38.
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