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Generation and Retention of Hydrocarbon in the Haushi Play, North Oman

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ABSTRACT

In North Oman, 20 fields, with a combined oil-in-place of 500 million cubic meters (3,145 million barrels), have reserves booked in the Permian-Carboniferous Haushi (Gharif and Al-Khlata formations) reservoirs. In addition, some 150 prospects are recognized with a combined ultimate recoverable reserves expectation of 39 million cubic meters (245 million barrels). Following a successful exploration campaign, the success ratio decreased progressively. An integrated charge and retention study was therefore carried out to revitalize the play. The aim of this study was to establish a framework for predicting fluid content (gas, oil, and water). Components of this framework were a charge study to explain the hydrocarbon distribution on a basin scale and a retention study addressing top and fault seal quality.

The oil in the Haushi has been generated by three different source rocks: 'Q', Huqf Group (Shuram Formation) and Haima Group (Safiq Formation). However, oil-typing shows that over 90% of the oil-in-place is derived from the 'Q' source rock. This seems to indicate a charge problem for prospects outside the 'Q' migration fairways. The 'Q' kitchen was defined with the help of chemical odometers (nitrogen compounds whose relative concentrations provide a measure of migration distance). Measurements on 18 'Q' oils suggest a source area on the western margin of the Ghaba Salt Basin, immediately to the east of Ramlat Rawl and Saih Rawl. Seismic lines across this area show salt-filled rim synclines, which possibly contain the 'Q' source beds.

The two main sealing lithologies are carbonate (Khuff and Haushi limestone) and shale (intra-Haushi shales), which can act as both top seal and/or fault seal. Based on log response, seal lithologies for gas-only, gas-and-oil and oil-only could not be discriminated. Recent mud logs over the Khuff Formation (top seal of the Gharif reservoirs) showed no evidence for a gas fraction, suggesting that the Khuff is an efficient gas seal. However, it has been observed that gas fields tend to have a thicker Khuff seal and smaller fault throw than the oil fields. This trend is related to the regional westward tilting of the basin during Khuff deposition. Fault seal has been analyzed on across-fault juxtaposition diagrams.

Highly-faulted prospects, above salt domes, are water-bearing. However, apart from these extreme cases, seal breaching is not seen as a general problem. Sand-sand juxtaposition areas along faults were calculated in several Gharif accumulations. Although cross-fault juxtaposition was identified as the critical factor determining the hydrocarbon contacts in some moderately faulted fields (e.g. Burhaan), there seems to be no general relation between hydrocarbon fill and Khuff thickness. An opportunity map was generated for North Oman. A strategy for exploring for stratigraphic traps in the 'Q' migration fairways is believed to have the greatest chance of success.

INTRODUCTION

In North Oman, 20 fields, with a combined stock tank oil initially in place (STOIIP) of 500 millions cubic meters (m^3) (3,145 million barrels (mn brls)), have reserves booked in the Permian-Carboniferous Haushi (Gharif and Al Khlata formations) reservoirs (Figure 1). In addition, some 40 prospects were recognized, at the beginning of the study, with a combined ultimate recoverable reserves (UR) expectation of 39 millions m^3 (245 mn brls). Following a successful exploration campaign from 1970 to

1985, the success ratio has since then decreased progressively. Since 1985, only 6 of 40 wells have booked reserves (Figure2).

A hydrocarbon habitat study was therefore carried out to revitalize the play by establishing a framework for predicting fluid type (gas, oil and water). A critical issue was to determine whether charge or retention was controlling the type of hydrocarbons trapped in the fields.

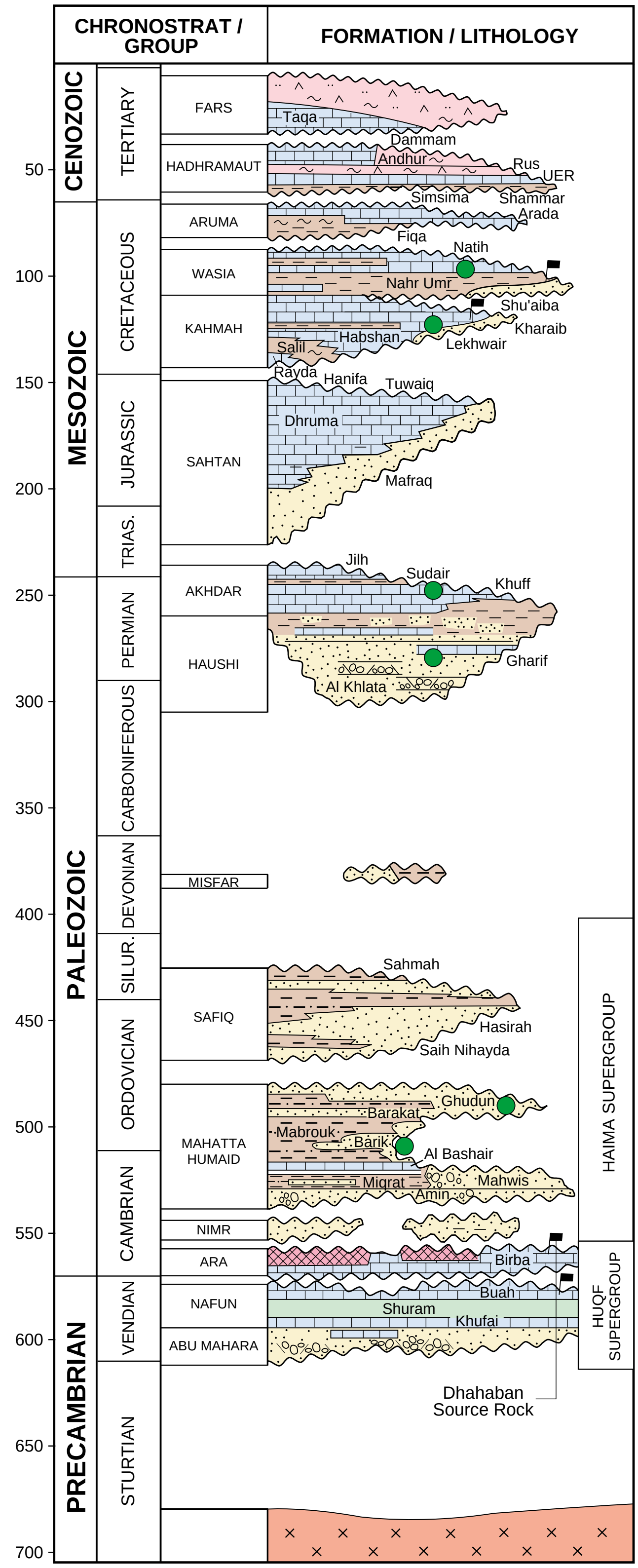


Figure 1: Oman stratigraphy and petroleum geology, showing the top-salt Dhahaban source rock (modified after Droste, 1997). Oil reservoirs are indicated (●) and source rocks as flags (▶).

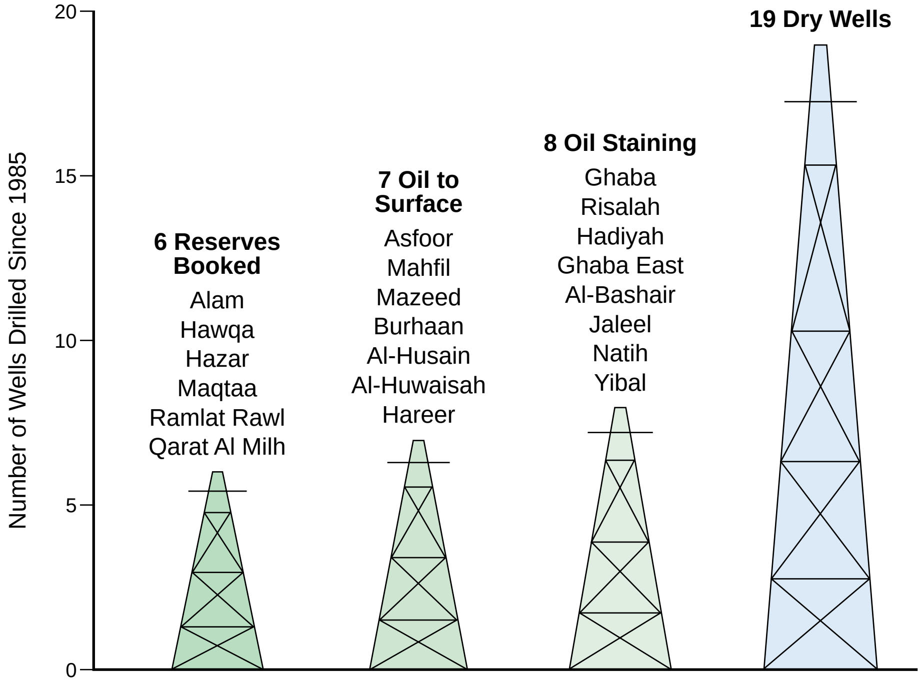


Figure 2: The success ratio since 1985 has decreased progressively following an initially successful exploration program between 1975 and 1985. As the figure indicates since 1985, only 6 of 40 wells have booked reserves.

Components of this investigation were a charge (geochemistry and basin modeling) study to explain the hydrocarbon distribution on a basin scale, and a retention (structural geology) study addressing hydrocarbon distribution at a prospect scale. The geochemistry focused on the oil-typing in the Haushi accumulations and the determination of oil migration distances. A basin model was developed to determine the source rock location and reconstruct the oil migration fairway. The structural geology primarily focused on top and fault seal quality.

GEOCHEMISTRY

Oil-typing

Oil-typing was achieved by using gas chromatography / mass spectrometry and organic carbon isotope techniques (Figure 3). The results show that the oils in the Haushi reservoirs were generated by at least two source rocks resulting in clearly different chemical signatures (Grantham et al., 1987). The two types of oil may be distinguished as ‘Q’ and Huqf families (Figure 3).

The ‘Q’ oil type is characterized by high concentrations of C_{27} steranes, carbon isotope ratios around -31‰ (parts per thousand) and increased abundance of tricyclic hopanes. The ‘Q’ oil is also distinguished by an unknown peak (‘A’) which is apparent in the sterane mass chromatogram (Figure 3).

The Huqf oils have a high abundance of C_{29} steranes and carbon isotopes lighter than -33‰. Both of these families are characterized by the presence of so-called ‘X’ compounds: methyl and dimethyl alkanes apparently characteristic of Precambrian-sourced oils (Imbus and McKirdy, 1993).

In addition to these two distinct families, a third class of hydrocarbons (the so-called ‘B’ family) is apparent. The characteristic ‘B’ signature has only been found in gas condensates and reservoir bitumen extracts. No low maturity ‘B’ oil has yet been identified or produced. The biomarker distribution of the ‘B’ is characterized by the presence of C_{27} diasteranes with carbon isotope ratios in the range of ‘Q’ oils (-30‰).

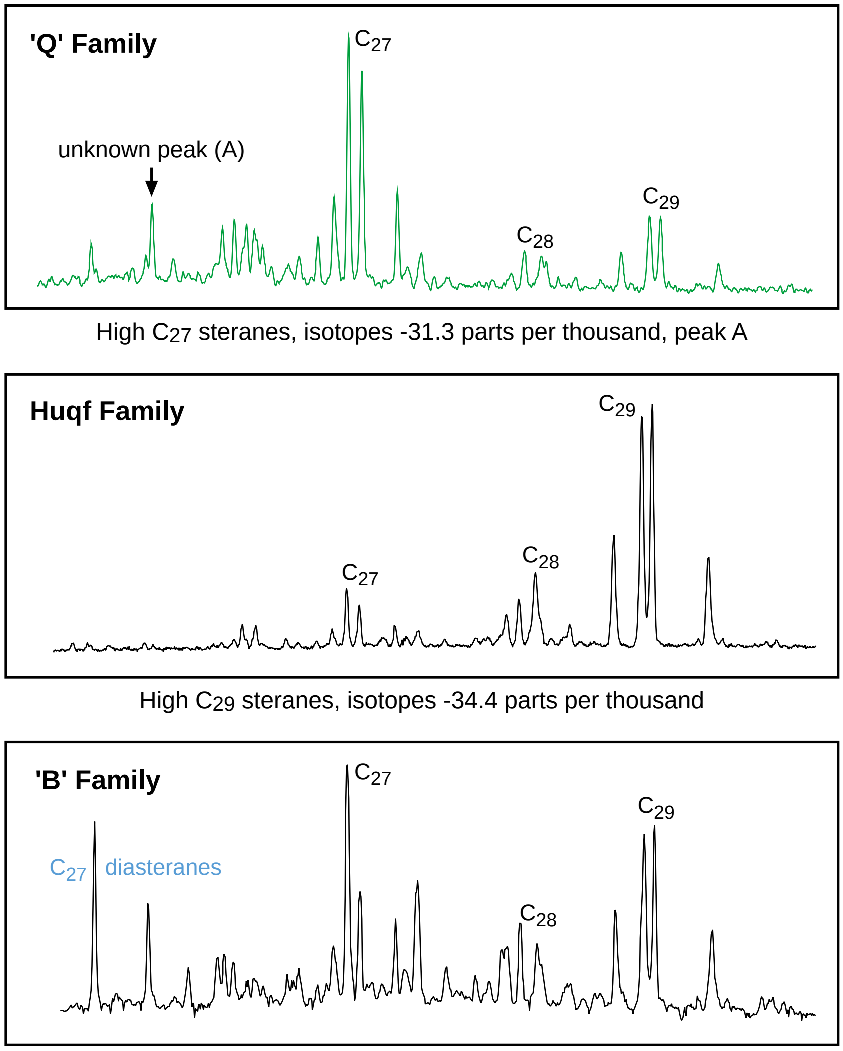


Figure 3: Oil-typing in the Haushi Group. Oil-typing was achieved by using gas chromatography/ mass spectrometry and organic carbon isotope techniques.

The Huqf oils have been definitively typed against Precambrian-Cambrian Huqf intra-salt rocks in South Oman, including the enigmatic Athel silicilyte (Alixant et al., in press). The ‘Q’ and ‘B’ families remain uncorrelated against source rocks due to limited penetration of varying facies in the north of Oman. In particular, the typing of the ‘B’ family is difficult due to the residual occurrence of this hydrocarbon family and the possibility of analytical artefacts. It is still not clear as to whether the ‘B’ family is derived from a third unknown source rock or from the thermal cracking of oil-in-place. Over 90% of the oil-in-place is derived from the ‘Q’ source rock.

A total of 16 fields (STOIIP 465 millions m^3 (2,925 mn brls.), Figure 4) produce either pure ‘Q’ oil, or mixtures with a high ‘Q’ component. Only three accumulations produced non-’Q’ oil. Two of these are marginal and not in production (Tawf Dahm and Barakat), and the third (Sahmah) has a declining production. The exploration results between 1985 and 1995 thus reflect the oil-typing of the producing fields; namely, all economic accumulations and discoveries contain ‘Q’ oil. Oil staining was reported in 25 “dry” wells including ‘B’ type hydrocarbons in 11 wells.

Oil Migration Distances

The observed hydrocarbon distribution seems to indicate a potential charge problem for prospects outside the ‘Q’ migration fairways. With the source area(s) of the ‘Q’ oil still undefined, it was decided to constrain the areal extent of the ‘Q’ kitchen with the help of chemical “odometers” (Larter et al., 1996). Crude oils

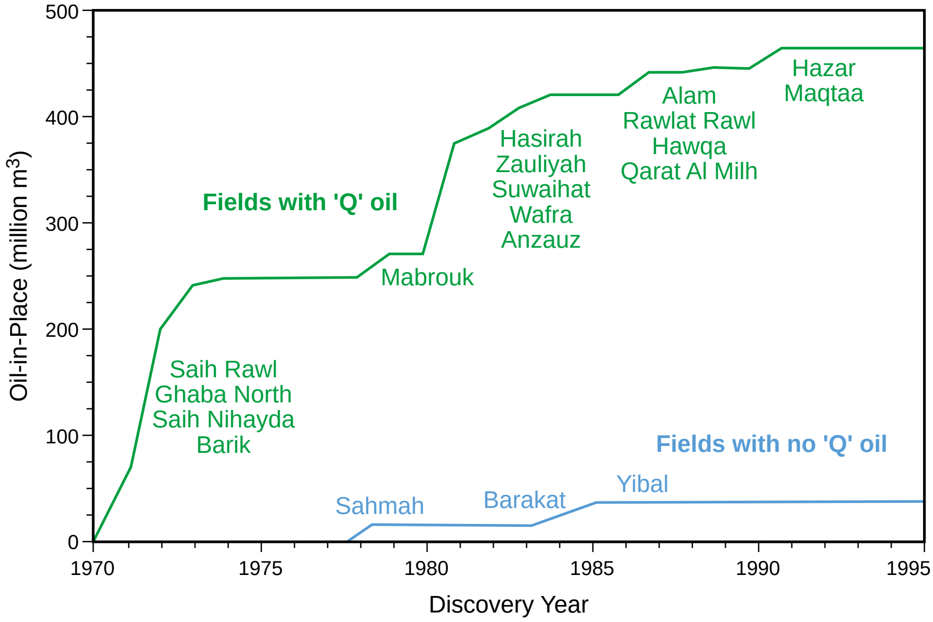
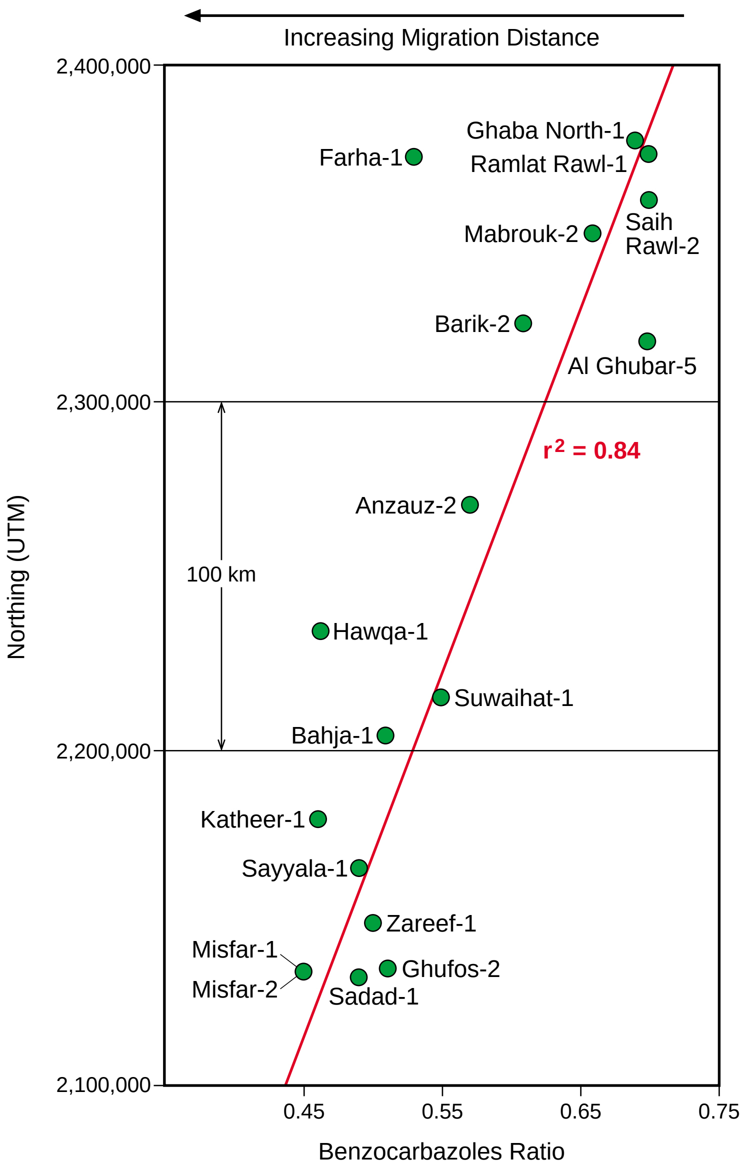
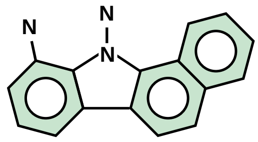
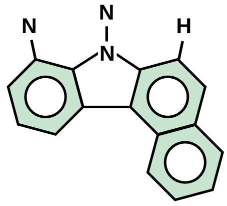


Figure 4: Creaming curve - North Oman Haushi fields. A total of 16 fields, with a total STOIIP of 465 million m^3 produce either pure 'Q' oil, or mixtures with a high 'Q' component.





Benzo(a)carbazole



Benzo(b)carbazole

Figure 5: 'Q' oil migration paths in North Oman based on geochemical odometer. Ratios of benzocarbazoles are used as molecular indicators of oil migration distance (Larter et al., 1996). Benzocarbazoles are polar compounds which partition between oil, water and mineral surfaces during oil migration. The correlation coefficient r^2 is 0.84.

contain between 0.1 and 2.0% weight nitrogen, primarily in the form of pyrrolic compounds. Among these are the benzocarbazoles (benzo[a]carbazole and benzo[b]carbazole), which are polar compounds and partition between oil, water and mineral surfaces during oil migration. Their ratio can thus be used to estimate oil migration distances. These odometers were measured in 18 'Q' oils and indicated migration distances in excess of 250 kilometers (km) (Figure 5). These results were then integrated with basin modeling to determine the 'Q' source area.

BASIN MODELING

'Q' Source Rock Location

The estimated relative oil migration distances and modeling of the migration path suggest the 'Q' oils are derived from two different kitchens (Figure 6):

(1) a source along the western margin of the Ghaba Salt Basin, to the east of Ramlat Rawl and Saih Rawl; and

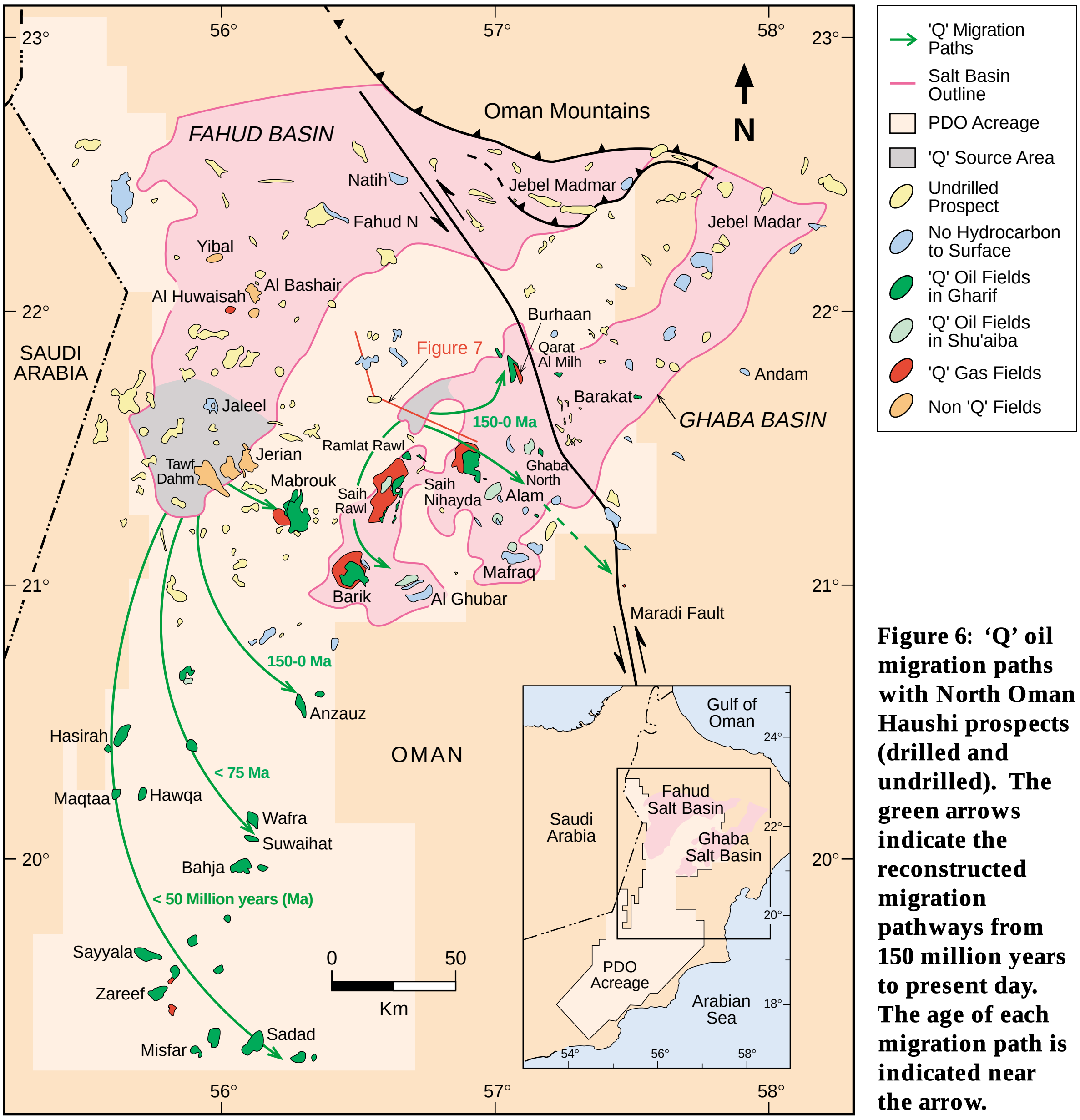


Figure 6: 'Q' oil migration paths with North Oman Haushi prospects (drilled and undrilled). The green arrows indicate the reconstructed migration pathways from 150 million years to present day. The age of each migration path is indicated near the arrow.

(2) a source in the southern part of the Fahud Salt Basin.

The potential geographic locations of the source rock areas were determined by integrating the migration distances of the different oil accumulations. Then, the source rock areas were identified by a systematic screening of the seismic data.

The first source is related from seismic data to a small synclinal rim basin with a high seismic amplitude infill adjacent to the Ghaba Salt Basin (Figure 7) which is interpreted to contain mainly source rock. The second, in the Fahud Salt Basin, is marked on seismic by a high amplitude reflector at the top of the Ara salt (Huqf salt). Both source areas are considered to have been restricted areas during Ara deposition and ideal sites for source rock preservation.

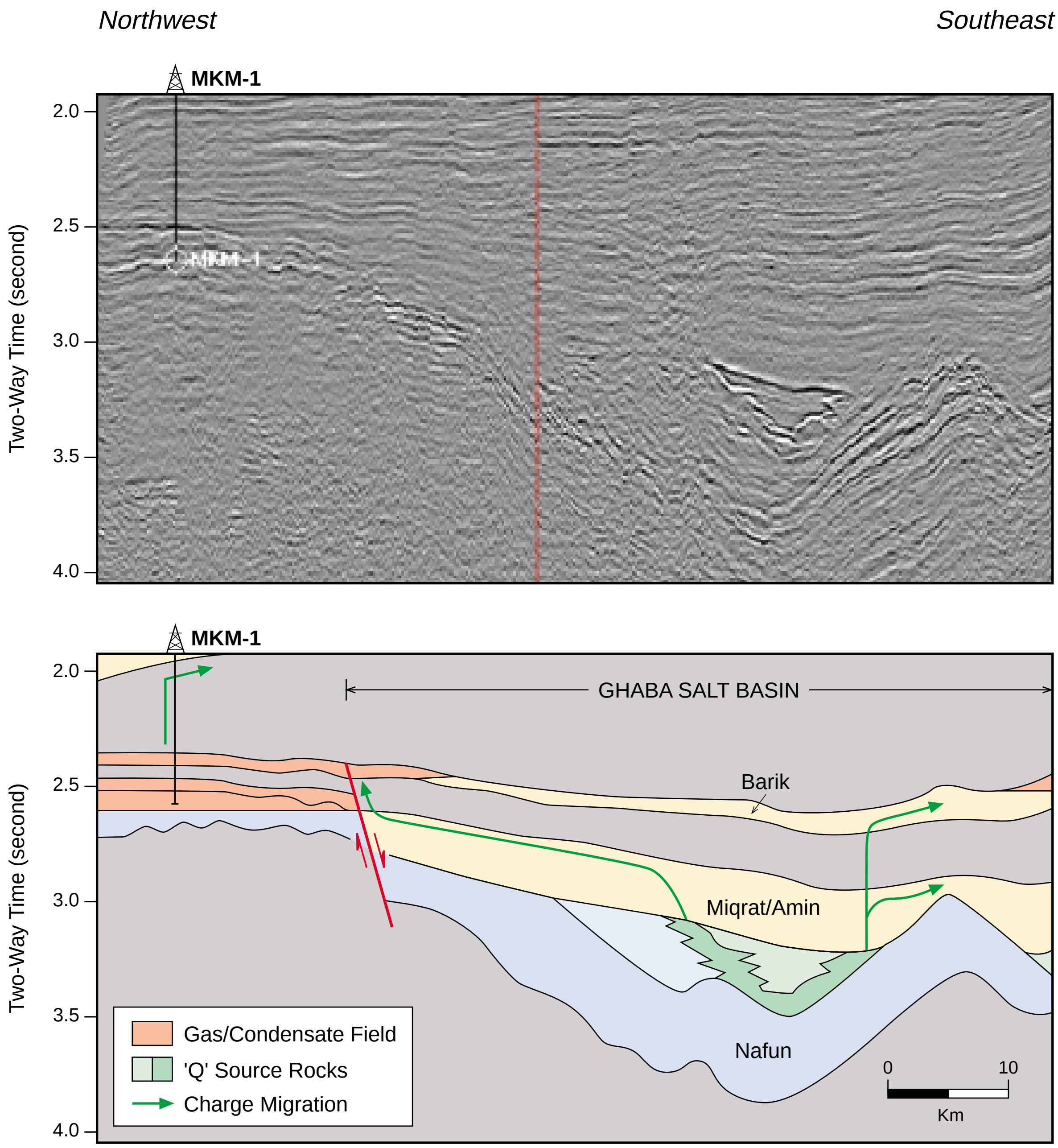


Figure 7: (Top) Possible 'Q' Kitchen Area (see Figure 6 for location). One 'Q' source has been related on seismic data to a small synclinal rim basin with a high amplitude infill adjacent to the Ghaba Salt Basin. (Lower) A schematic geological section of the 'Q' kitchen area.

Generation and Migration History

Burial and thermal history (Abdullah et al., 1997; Giles et al., in press) were derived from 12 distinct horizons based on seismic and well data. Burial and thermal modeling suggest that, due to the early charge timing in pre-salt or intra-salt source rock, only the shallower, top-salt Dhahaban source rock interval can be regarded as the origin for the remaining liquid hydrocarbons in North Oman.

Generation modeling of the top-salt Dhahaban (Figure 1) source rock interval indicates that the rim basin 'Q' oil was generated in the Paleozoic and Mesozoic and peaked in Middle Paleozoic and Triassic times (Figure 8). On the west flank, in the shallower Fahud Salt Basin (Figure 8), generation occurred from the Jurassic until Early Tertiary and also peaked twice during Early and Late Cretaceous, when new burial maxima were reached. Currently, only the west-flank has remaining charge potential, and is expected to generate dry gas.

Regional paleo-structure maps were used to reconstruct the 'Q' migration fairway. The modeling shows that the oil expelled from the rim basin migrated to the southeast across the deformed core of the Ghaba Salt Basin towards the tilted East Flank (Figure 6). This migration direction changed little over time. Migration from the Fahud Salt Basin was initially also towards the southeast (Figure 6), but shifted gradually southward during the Late Cretaceous and Tertiary with ongoing foreland basin development (Loosveld et al., 1995).

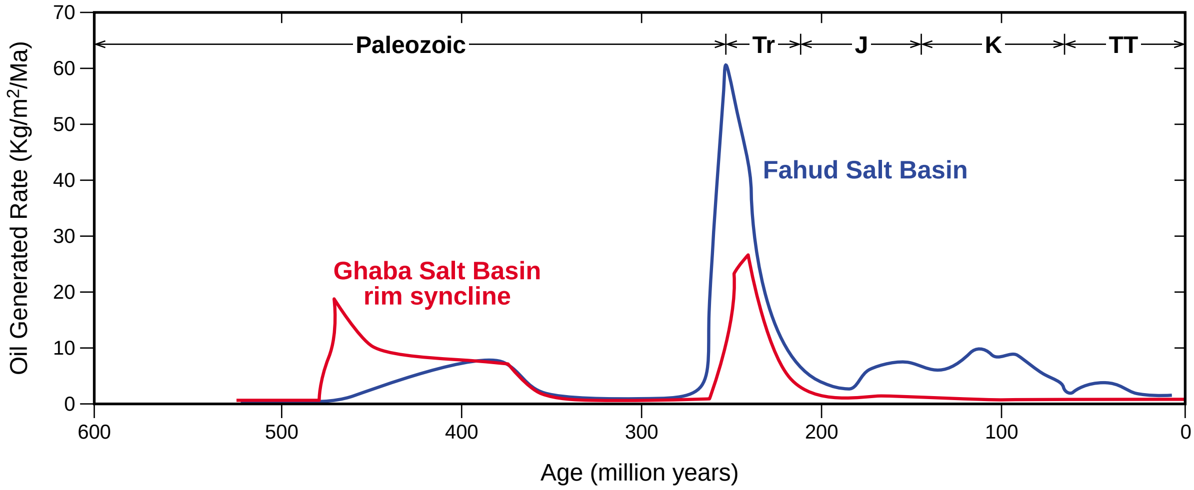


Figure 8: Oil generation modeling history of the top-salt Dhahaban source rock interval (Figure 1).

STRUCTURAL GEOLOGY

To identify the factors which may have determined the retention capacity in the Haushi reservoirs, systematic data gathering was carried out in a selection of fields varying from gentle, salt-induced anticlines to highly complicated structures related to strike-slip movement. Faulting (e.g., orientation, magnitude, timing), structural style (e.g., salt-induced, strike-slip related) and sealing configuration (e.g., top seal, fault seal, seal type, seal thickness) were analyzed. Of these, only the top and fault seal analysis highlighted a possible relationship with fluid content.

Fault Seal Analysis

Highly-faulted structures (fault throw larger than top seal thickness) above salt domes, are water-bearing at Haushi level (Qarat Kibrit, Qarn Alam, Al Ghubar, Mafraq and Ghaba). However, apart from these extreme cases, seal breaching is not a general problem.

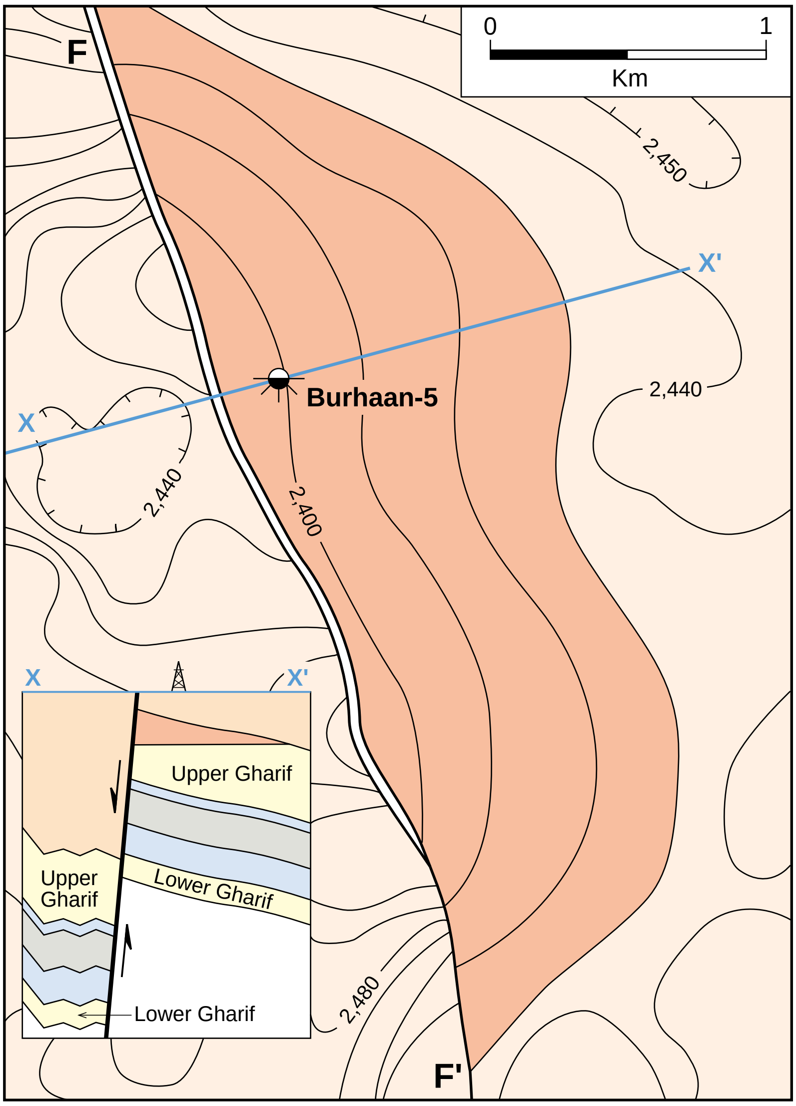


Figure 9: Burhaan gas field map view and cross-section (X-X'). Burhaan is located in the Ghaba Basin, west of the Maradi Fault. A cross-fault juxtaposition diagram of the main fault (F-F') is displayed in Figure 10.

Fault seal has been analyzed on a number of across-fault juxtaposition diagrams. A dedicated software (X-FAULT) was developed for this study to quickly display and calculate sand-sand juxtaposition windows along fault planes. For example, X-FAULT was used to analyze two stacked gas accumulations in Haushi sandstone reservoirs of the Burhaan field. The trap is a faulted, dip closure (Figure 9) and the accumulations are located in the footwall of a normal fault (insert in Figure 9).

A simplified juxtaposition diagram (Figure 10) provides a geometrical analysis; however its use is mainly familiar to structural geologists. An alternative display is the size of sand-sand windows plotted against depth (Figure 11, the horizontal scale represents the areal extent of the sand-sand windows). From this, it is clear that the gas / water contacts (GWC) of both the Upper Gharif (UG) and Lower Gharif (LG) reservoir correspond to the top of the UG and LG sand-sand windows respectively. This indicates that juxtaposition controls the position of the GWC's and the leak points of the accumulation.

Similarly, sand-sand juxtaposition areas along faults were calculated in all major, moderately-faulted Gharif accumulations. Overall, fault planes were not found to be active seals (Ingram and Naylor, in press) and therefore, cross-fault juxtaposition was identified as the critical factor determining the hydrocarbon contacts in many cases.

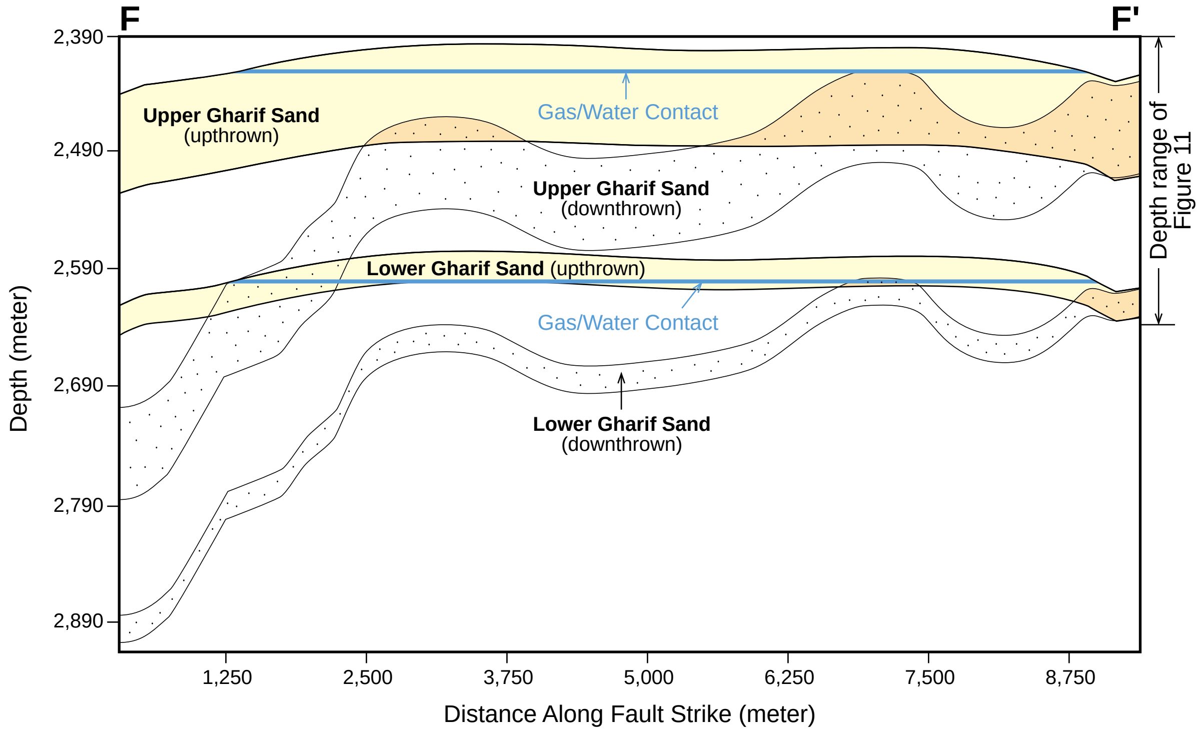


Figure 10: Burhaan field simplified fault juxtaposition diagram without extra layers. F-F' corresponds to the fault shown in Figure 9. The sand-sand juxtaposition is shown as a darker yellow. 'Seal' layers for Upper Gharif and Lower Gharif are present but not shown.

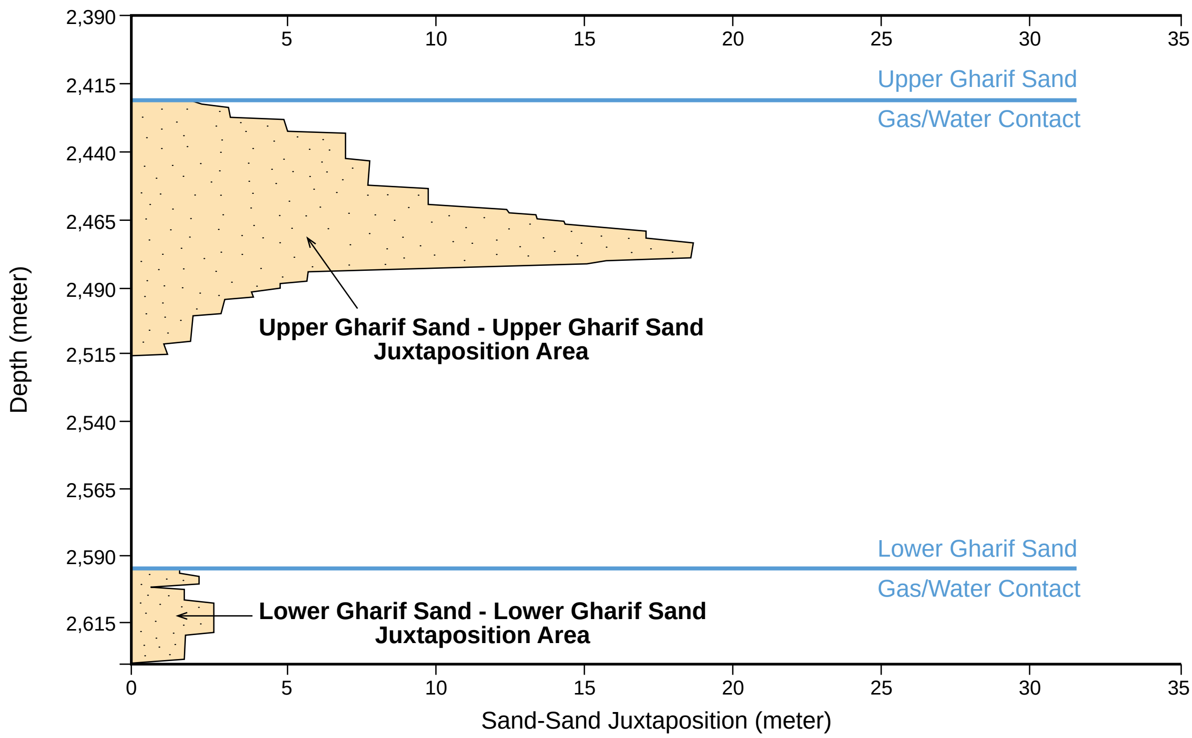


Figure 11: Burhaan field sand-sand juxtaposition versus depth. The vertical extent of the different sand-sand juxtaposition window is plotted against the depth (with a one-meter depth increment). The Upper Gharif (UG) and Lower Gharif (LG) gas/water contacts correspond to the top of the UG and the LG sand-sand windows respectively. This correspondence indicates that juxtaposition controls the position of the gas/water contacts and the leak points of the accumulation.

Top Seal Analysis

The two main sealing lithologies are carbonate (Khuff Formation (Akhdar Group, Figure 1) and Haushi Limestone) and shale (intra-Haushi shales), which can both act as top seal and / or fault juxtaposition seal. Fields containing gas-only, gas-and-oil and oil-only could not be discriminated based on the lithological interpretation of log response of the top seals.

A detailed analysis of recent mud logs of the Khuff Formation (top seal of the Gharif reservoir) was carried out to determine whether or not the Khuff was an efficient seal for gas. If gas had been leaking through the Khuff at a geological scale, a gradient of gas fraction should be observed (decreasing heavier gas fractions from base to top). Mud logs were analyzed in fields containing gas-only, oil-only, and mixed gas-and-oil. The analysis showed no evidence that the Khuff is an inefficient gas seal. Qarat Al Milh-2 was the only well that showed some heavy gas fraction in the Khuff. This might be due to the high fracture density in this top seal, related to deformation along the Maradi Fault zone.

The gas fields also tend to have thicker Khuff seals and smaller fault throw than the oil fields. This trend can be highlighted by plotting the total thickness of Khuff against the total Khuff thickness minus the maximum fault throw observed in an accumulation (Figure12). This r elationship could have two explanations. Firstly, it might reflect (sub-seismic) faults breaching the top seal. Faults with larger throw are associated with greater density of sub-seismic faults, which leads to a greater probability of breaching a layered top seal (Ingram and Naylor, in press). However, a second more likely explanation is that the relation between Khuff thickness and fluid content simply reflects the charge history. The Khuff thickens to the west due to the regional westward tilting of the basin during its deposition. This tilting causes the kitchen area to deepen westward, such that gas being currently generated forces the oil to remigrate up-dip, to the east and to the south.

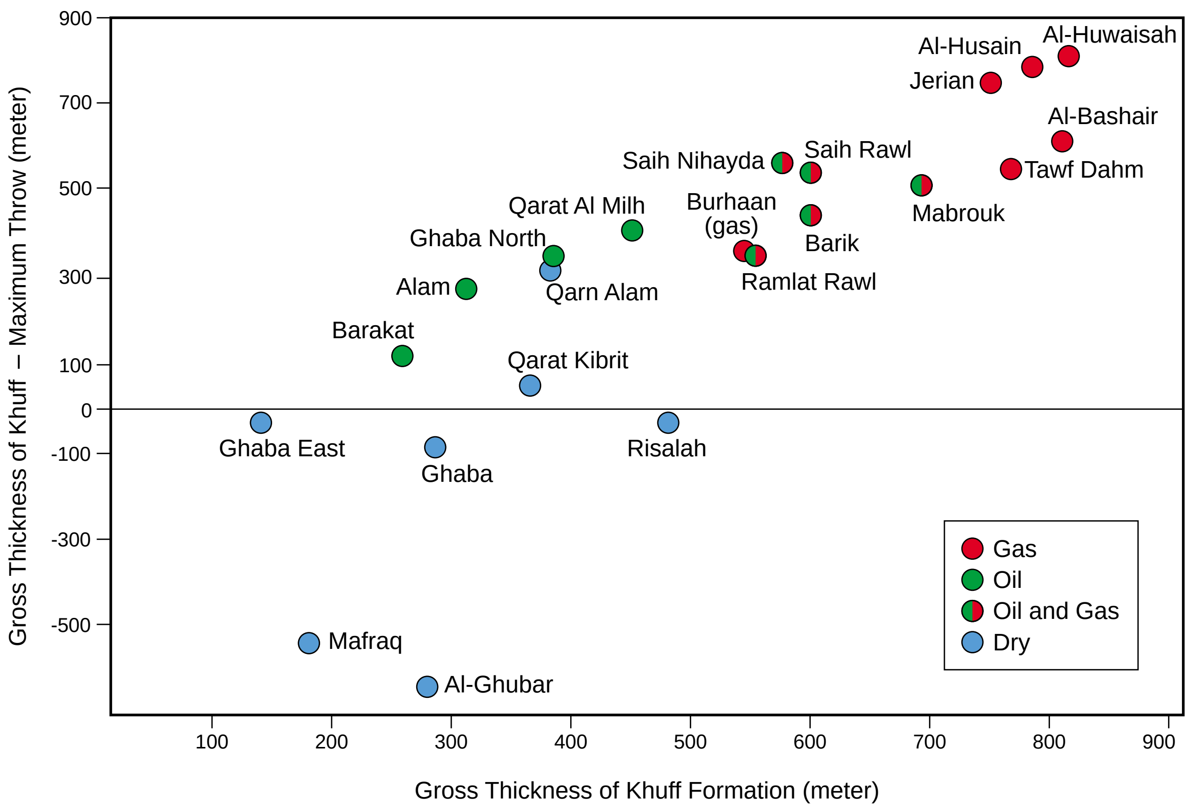


Figure 12: Pore-fill - Top seal thickness/faulting relationship. Gas fields tend to have thicker Khuff seals and smaller fault throw than the oil fields.

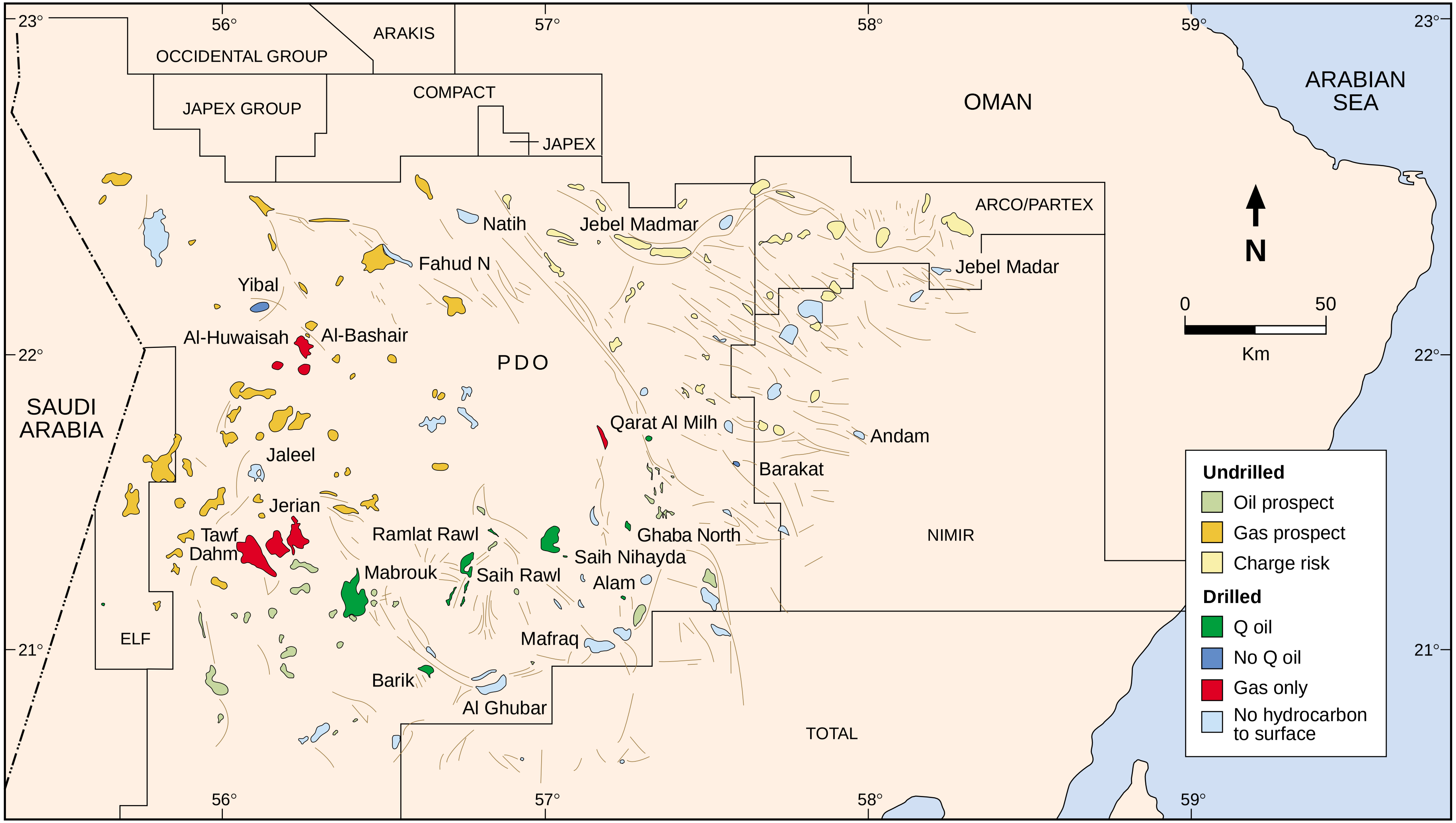


Figure 13: Haushi hydrocarbon opportunity map. Exploration in the Haushi should focus on stratigraphic traps in the 'Q' migration fairway for oil, and on deep prospects westwards of the Ghaba Salt Basin for gas.

CONCLUSIONS

All economic oil accumulations discovered, to date, in the Haushi are charged with the 'Q' oil. Thus the presence of 'Q' oil is a key success factor for oil exploration in the Haushi Formation. Putative 'Q' source areas have been located on the western margin of the Ghaba and Fahud Salt basins, as suggested by chemical odometers. Charge, and not sealing capacity, is the main factor controlling the Haushi reservoir fill in North Oman.

Based on the charge and seal control, and the 'Q' fairways, we have defined an opportunity map for North Oman (Figure 13). We propose that oil exploration in the Haushi should focus on stratigraphic traps in the 'Q' migration fairway, while exploration for gas should focus on deep prospects westwards of the Ghaba Salt Basin. The integration of these results with the outcome of an ongoing intensive re-mapping and the development of a stratigraphic and facies framework will lead to economically drillable prospects in 1999.

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REFERENCES

Alixant, J.L., N. Frewin, P. Nederlof and N. Al-Ruwehy (in press). *Characterization of the Athel Silicilyte Source Rock/Reservoir: Petrophysics Meets Geochemistry*. Transactions of 39th Annual Logging Symposium, Salt Lake City, May 26th-29th 1998. SPWLA 1998.

Abdullah, F.H.A., P.J.R. Nederlof, M.P. Ormerod and R.F. Kinghorn 1997. *Thermal History of the Lower and Middle Cretaceous Source Rocks in Kuwait*. GeoArabia, v. 2, n. 2, p. 151-164.

Droste, H.H., 1997. *Stratigraphy of the Lower Paleozoic Haima Supergroup of Oman*. GeoArabia, v. 2, n. 4, p. 421.

Giles, M.R., S.L. Indrelid, N.J. Kusznir, A. Loopik, J.A. Meijerink, J. McNutt, P. Dijkstra, W. Heidug, J. Toth, M. Willis, K. Rutten, B. Elsinga, P. Huysse, P. Riviera and H. Burgisser (in press). *Charge and Overpressure Modelling in the North Sea: Multi-Dimensional Modelling and Uncertainty Analysis*. To be published in the "Geology of NW Europe", 5th Proceedings, London, 1997.

Grantham, P.J., G.W.M. Lijmbach, J. Posthuma, M.W. Hughes Clarke and R.J. Willink 1987. *Origin of Crude Oils in Oman*. Journal of Petroleum Geology, v. 11, n. 1, p. 61-80.

Imbus, S.W. and D.M. McKirdy, 1993. *Organic Geochemistry of Precambrian Sedimentary Rocks*. In M.H. Engel and S.A. Macko, Plenum Press, New York, 1993.

Ingram, G.M. and M.A. Naylor (in press). *Sealing Processes and Top Seal Assessment*. In P. Pedersen, (Ed.), Proceedings of the Norwegian Petroleum Society Conference on "Hydrocarbon Seals – Importance for Exploration and Production", Trondheim, Norway, January 27th-29th 1996.

Larter, S.R., B.F.J. Bowler, M. Li, D. Chen, B. Brincat, Bennett, K. Noke, P. Donohoe, D.J. Simmons, M. Kohnen, J. Allan, N. Telnaes and I. Horstad 1996. *Molecular Indicators of Secondary Oil Migration Distances*. Nature, v. 383, p. 593-597.

Loosveld, R., A. Bell and J. Terken 1995. *The Tectonic Evolution of Interior Oman*. GeoArabia, v. 1, n. 1, p. 28-51.

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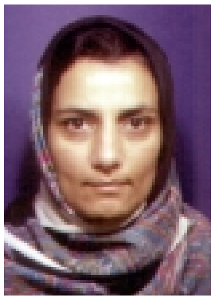

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