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Source Rock Distribution and Thermal Maturity in the Southern Arabian Peninsula

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ABSTRACT

Recent work by Phillips Petroleum in the Southern Arabian Peninsula has elucidated the source potential of the Palaeozoic strata. A group of newly drilled and older wells, together with exclusive and non-exclusive reports, have been used in order to develop improved maturation and migration models for emerging plays, and to gain a better understanding of the subsidence and maturation history of this large and diverse area. It has been possible to conduct comprehensive burial history modelling for a number of wells from Oman, Saudi Arabia and the United Arab Emirates. This, together with the modelling of hypothetical wells derived from depth structure maps, has improved our understanding of oil- and gas-prone source rocks in the Cretaceous, Jurassic and Palaeozoic strata. The resultant maturity distribution has been developed with the aid of a more detailed structural model for the Southern Arabian Peninsula.

In tandem with this study, available cores and cuttings were analysed to measure source rock total organic carbon, maturity and richness parameters and summarised using proprietary techniques. It is concluded that the Jurassic Hanifa Formation is less mature and not source facies to the south and west of the Rub' Al-Khali. The oil and gas mature source facies is present in the north and east of the Rub' Al-Khali and in the Western Emirates. In addition, it is concluded that the oil mature Silurian source facies is confined to the narrow southern and western margins of the Rub' Al-Khali. Outside this area the over-mature area is in the core of the Rub' Al-Khali extending northeast to the United Arab Emirates. The remaining area is modelled as gas mature in western Saudi Arabia and Qatar.

INTRODUCTION

Oil and gas maturity mapping of key Middle East source rocks is often simplified and confined to the Mesozoic. This paper describes a study conducted on 68 locations in Southern Saudi Arabia, Western Oman, Abu Dhabi, Dubai, Sharjah and Yemen, and applied to several established source intervals of both Mesozoic and Palaeozoic age. Recognized source formations in the area are the Infra-Cambrian Huqf and so-called 'Q' source (Grantham et al., 1987), the Silurian Qusaiba Member (Mahmoud et al., 1992), the Permian Unayzah-Khuff Transition Zone (Abu-Ali et al., 1991), the Jurassic Hanifa Formation (Ayres et al., 1982; Wilson, 1984), the Lower Cretaceous Sulaiy Formation (Ayres et al., 1982; Taher, 1997), the Middle Cretaceous Shilaif Formation (Ayres et al., 1982; Wilson, 1984) and the Pabdeh Shale (Ala et al., 1980; Beydoun, 1993). The study was conducted to establish the distribution of source rocks and their maturity in the region of newly acquired acreage by Phillips on the southern flank of the Rub' Al-Khali Basin (Figure 1). A suite of burial history models was generated for wells from concessions previously licensed by Phillips Petroleum in Abu Dhabi and Saudi Arabia.

The first objective of this paper is to establish those areas of the Southern Arabian Peninsula which are mature for the presence of oil and gas. To accomplish this, it is necessary to map both source presence and maturity distribution. Through the integration of regional depth, isopach and facies maps, source rock presence and maturity distributions have been established for the Hanifa and Safiq formations. Mapping of Tertiary and Cretaceous source rocks is in progress. In addition, this paper intends to provide some insight into the Silurian source rock, a potential key to future exploration in the Middle East.

Source rock samples were analysed for both richness and maturity. Statistical evaluation using Phillips Petroleum Company proprietary software 'Source Rock Advisor' (SRA) has provided a simple output useful for demonstrating source rock quality and maturity information for selected wells in the area.

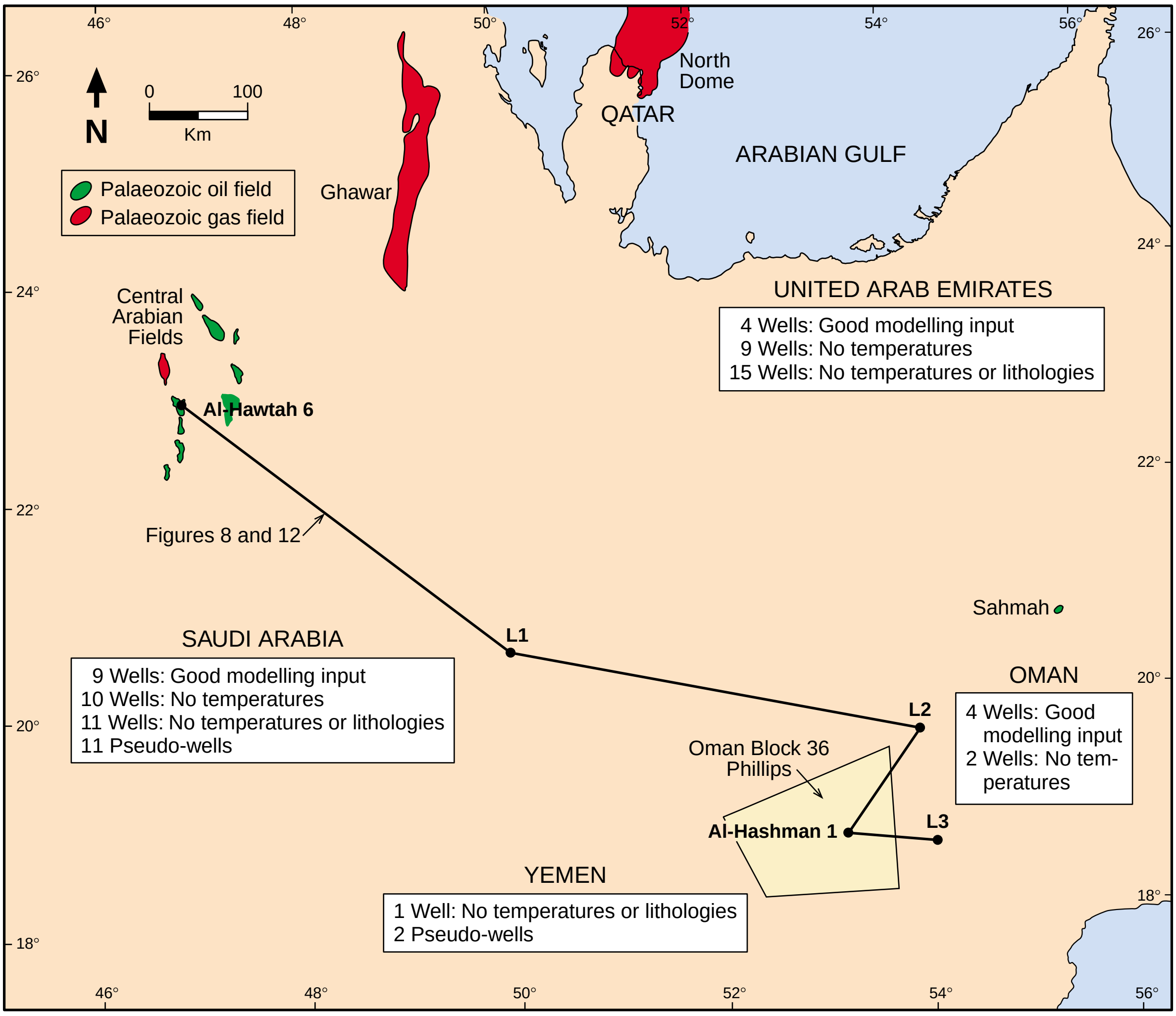

Figure 1: Base map showing the area of study and modelling database for each country. No temperatures indicates lack of bottom hole temperature data. 'Pseudo-wells' are synthetic locations sited on key basins or highs. Major Palaeozoic fields are outlined.

METHOD

Structural Framework

The structural framework for the study area was constructed using Middle East in-house literature, references, published reports and a historical database of seismic structure maps, supplemented by in-house interpretations of gravity, magnetics and satellite image data for the Arabian Plate (Figure 2). The Rub' Al-Khali, a large basinal area, is composed of a number of sub-basins separated by northwest- and northeast-trending faults, attributed to the ancient Infra-Cambrian structural Najd and Dibba (informal) Trends, respectively (Husseini, 1989). This framework map provides the structural setting, for example, basin or high, for the burial history models. Knowledge of the tectonic evolution of certain structural elements was used to indicate the timing and amount of uplift in the models. In addition, an explanation for the presence of thin units in certain wells could be made using the accompanying tectonic history. These issues are key to the development of realistic burial history models.

Chronostratigraphic Framework

By subdividing each country into major structural segments, for example Southwest Oman, then further subdividing these areas into more detailed elements, such as the Rub' Al-Khali and the Ghudun

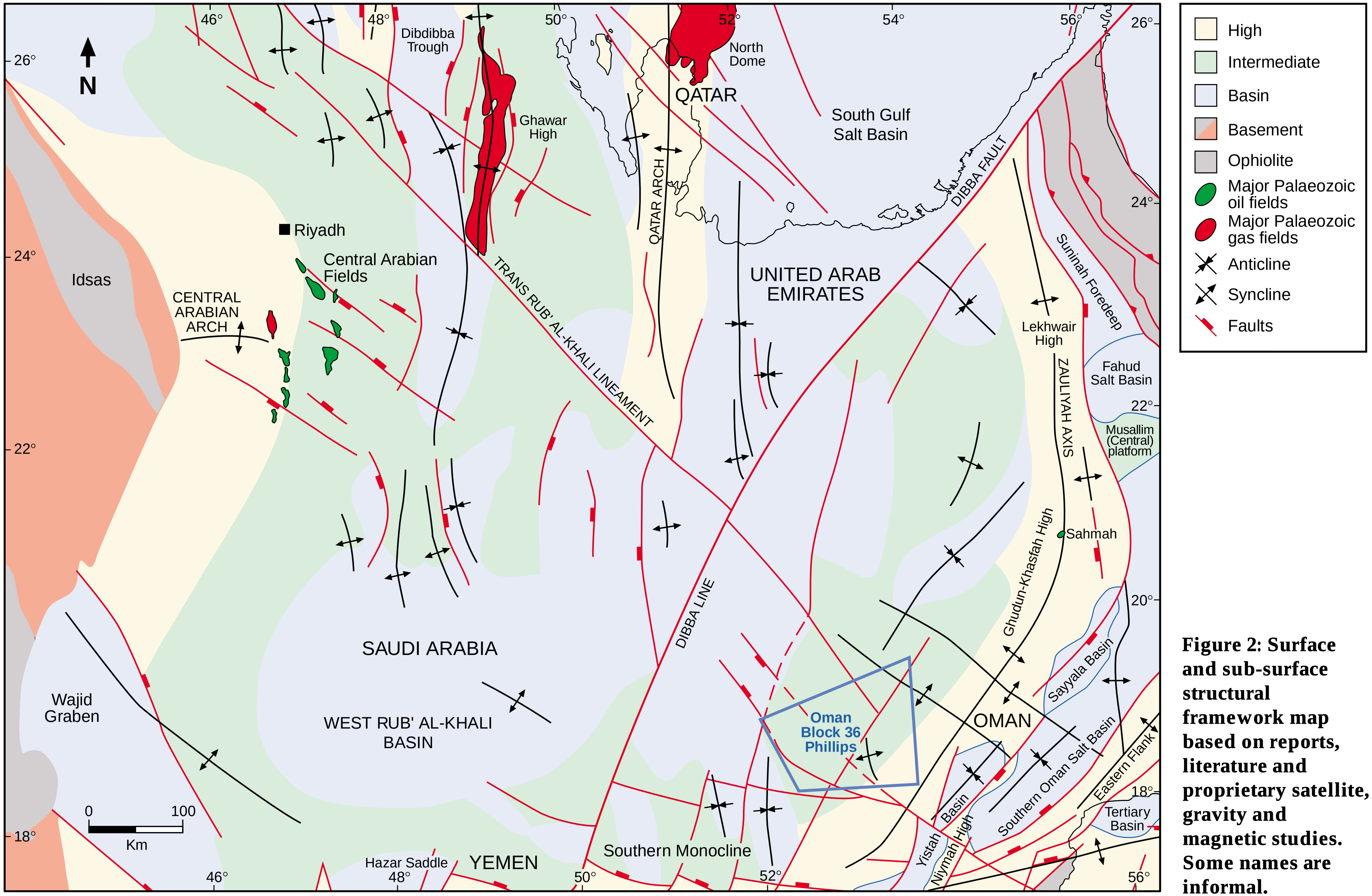

Figure 2: Surface and sub-surface structural framework map based on reports, literature and proprietary satellite, gravity and magnetic studies. Some names are informal.

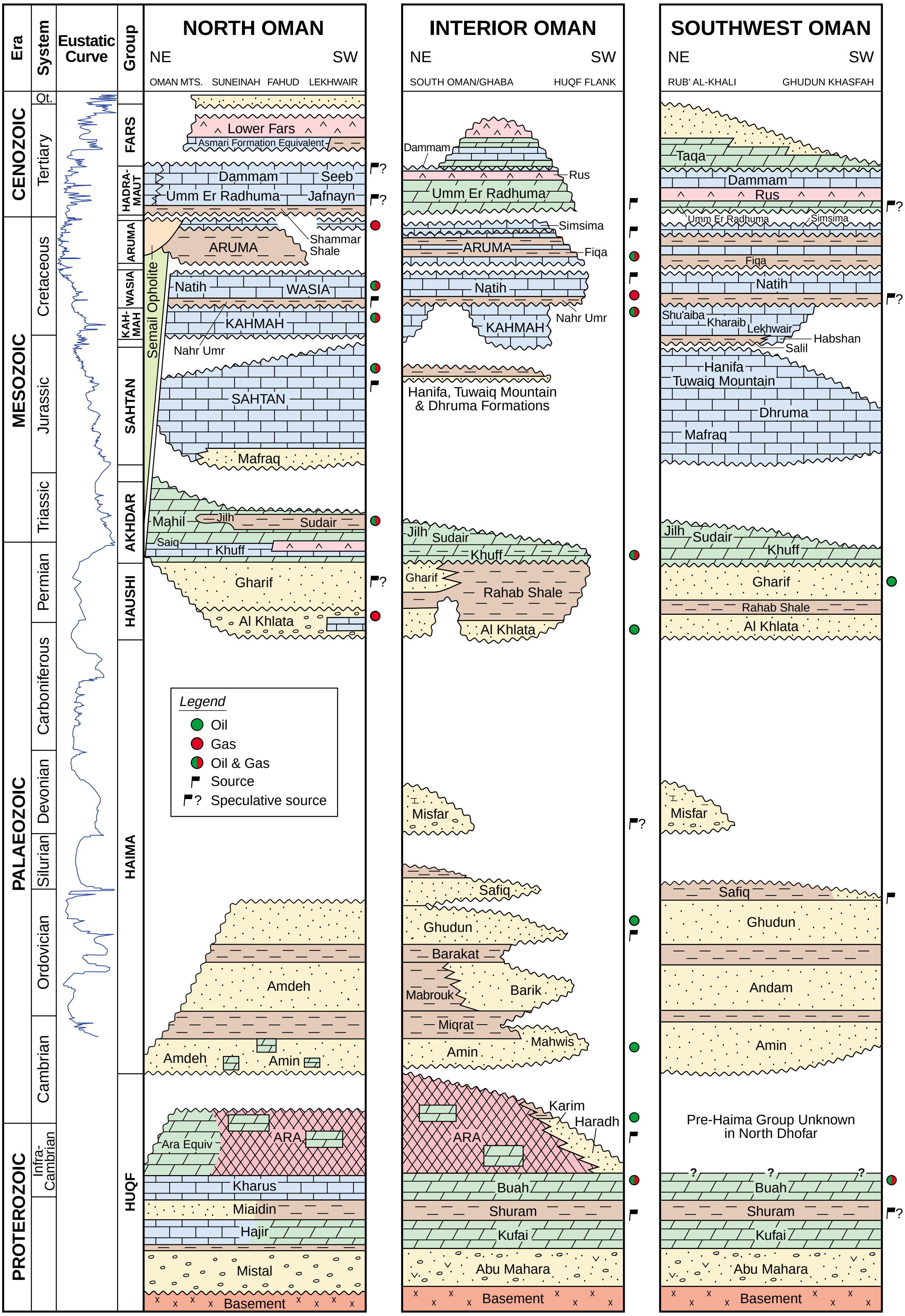

Figure 3: Oman chronostratigraphic summary for different regions and sub-regions.

Khasfah High, a series of chronostratigraphic summaries were made. An example for Oman is shown in Figure 3. These summaries detail where each formation is present and its age, and allow a relatively simple comparison of the differing stratigraphic nomenclature from different countries.

One key input related to the burial history modelling is the identification of major unconformities. These may be long-lived, for example the Hercynian Orogeny of Devonian to Carboniferous times (McGillivray and Husseini, 1992), or may be shorter events such as the Cretaceous pre-Aruma Unconformity which resulted from the uplift of the Oman Mountains (Figure 3).

Burial History Modelling

A series of burial history models was generated for 65 wells in the area with available log, lithology, and temperature data. Of these, logs, comprehensive lithology information and bottom hole temperatures were available for 17 wells (Category 1: “good modelling input” in Figure 1). An additional 21 wells had logs and lithologies but no temperatures (Category 2: “no temperatures”) and 27 wells had only formation tops (Category 3: “no temperatures or lithologies”). Bottom hole temperature data were taken from the log headers and corrected for cooling effects of drilling, where possible, which then allow the computation of present-day heat flows for each well. A surface temperature of 80°F was considered reasonable, based on the extrapolation of bottom hole temperatures to surface. This agrees with surface temperatures derived from extrapolation of published bottom hole temperatures from Abu Dhabi (Clarke, 1975). By assigning appropriate lithology to each well, an approximation can be made for thermal conductivity through the rocks. This, together with the temperatures, resulted in a map of present-day heat flow (Figure 4) that takes into account variations in thermal conductivity and temperature gradient.

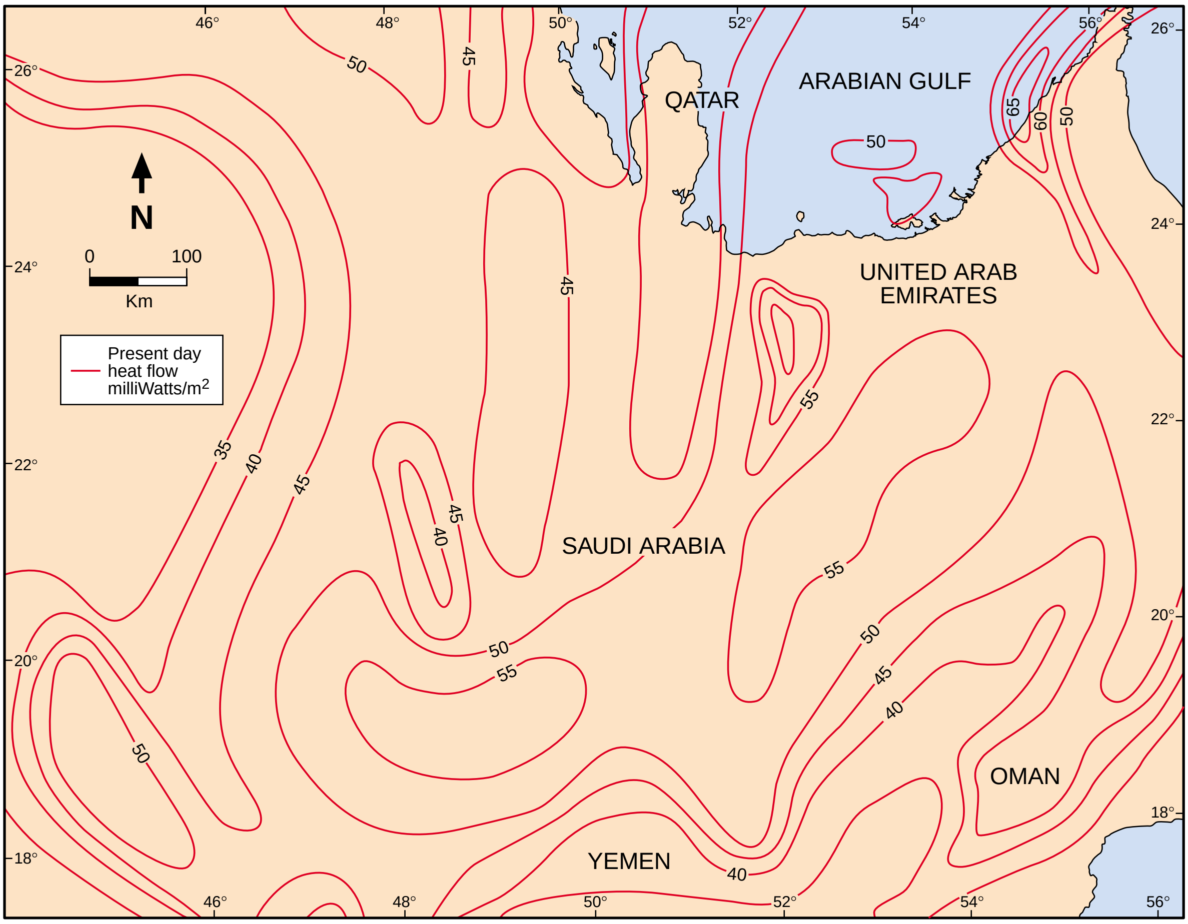

Figure 4: Present-day heat flow based on modelling wells with borehole temperatures and mapped using the structural framework for trends.

Heat Flow Distribution

Heat flows for Category 1 wells (Figure 4) were mapped using the structural framework and depth maps. The depth maps were produced using a well-tops database and a number of regional reports. The heat flow values were derived from modelling locations with the best data, for example, comprehensive lithology information and bottom hole temperatures. It was found that high heat flows of 50 to 55 milliWatts per square meter (mW / sq m) occur in the basins, whereas on structural highs, the heat flows were approximately 40 mW / sq m. These heat values are within the generally accepted range of 41 mW / sq m to 61 mW / sq m for continents (Sass, 1971). The variation in modelled heat flows can be explained with respect to crustal thickness. On the Ghudun Khasfah High, for example, there is evidence of crustal shortening (thickening) due to thrust faulting. Thicker crust results in a greater depth to the mantle heat source compared with thinner crust in basinal areas and consequently lower heat flows.

Heat flow for Category 2 and 3 wells and the hypothetical wells was estimated from the heat flow map (Figure 4). Lithologies were taken from nearby wells or from wells in a similar structural setting by building a table of lithologies for each unit from composite and lithology logs. Then, for example, a well with no lithologies on the Qatar Arch would draw upon information from a well with lithologies. If no such well was available on the Qatar Arch, lithologies from wells located on the nearby Ghawar Arch would be considered.

Burial History Modelling Examples

Each well location was modelled using Platte River's Basin Mod 1-D modelling software, the Falvey and Middleton compaction curve, the Kozeny-Carman permeability function and the Lawrence Livermore National Laboratories (LLNL) maturity calculation (Basin Mod 1-D manual). A typical model, for location L2, is shown in Figure 5. This well is on the southern flank of the Rub' Al-Khali, north of the Phillips Oman Block 36 concession. The model shows a subsidence history influenced predominantly by deposition in the subsiding Rub' Al-Khali. Considerable thicknesses of the Middle Cretaceous Wasia Group (1,590 feet (ft)) and the Upper Cretaceous Aruma Group (848 ft), compared with Northern Oman, indicate that the compression, which resulted in the formation of the Oman Mountains at the end of the Middle Cretaceous (Murris, 1980), had little effect on the L2 area. Therefore, the pre-Aruma Unconformity is not represented on the burial history plot (Figure 5). The presence of only 180 ft of Triassic at this location, together with documentation of uplift at the margins of the Arabian Plate (Murris, 1980), are indicative of an erosional event at approximately 200 million years (Figure 5). Lastly, this well did not penetrate pre-Permian section and therefore the Devonian to Carboniferous Hercynian Orogeny need not be represented.

The L2 model may be compared with the Al-Hashman 1 burial history model (Figure 6) situated closer to the Ghudun-Khasfah High on Oman Block 36. This well is located near an old and periodically active fault-related high as demonstrated by the disrupted subsidence history curve. There was uplift in the Late Carboniferous attributed to the Hercynian Orogeny (labelled 'M' for Mississippian and 'P' for Pennsylvanian on Figure 6). In addition, there was uplift in the Late Jurassic due to movement of the Indian Plate away from the African-Arabian Craton, and in the Early Cretaceous following rifting in nearby Yemen also associated with Gulf of Aden rifting. The formation of the distant Oman Mountains is represented by hiatuses rather than by uplift.

Both models illustrate the relatively immature nature of potential source rocks on the southern flank of the Rub' Al-Khali thereby demonstrating the need to identify more mature areas close to Oman Block 36. In the case of the L2 location (Figure 5), the Jurassic section is early mature for oil generation (0.5 to 0.7% Ro equivalent). However, expulsion is more likely to occur in the main oil mature window (0.7 to 1.0% Ro equivalent).

Model Calibration

Due to the historical nature of the database and the lack of reliable published data with measured maturity values, only limited calibration has been possible. Available core and cuttings have been

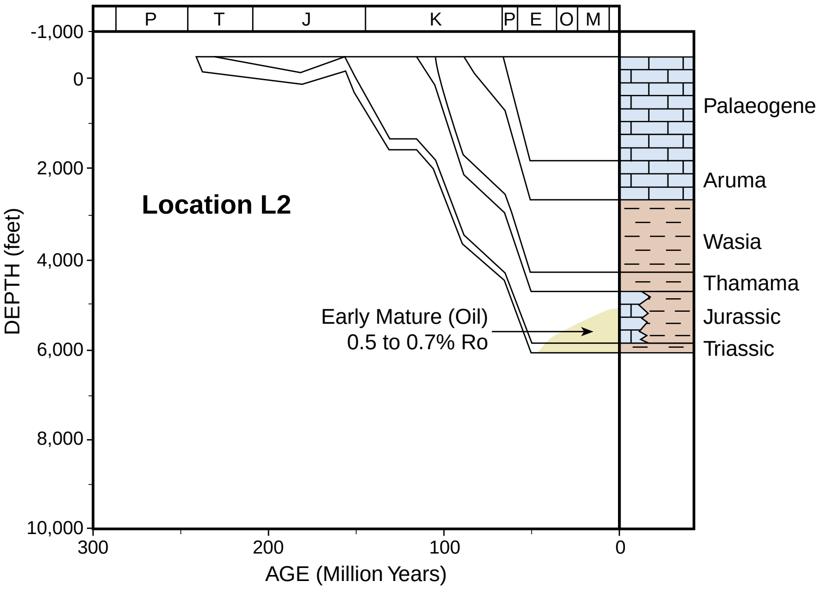

Figure 5: Burial history for a well, known as L2, located on the southern margin of the Rub' Al-Khali.

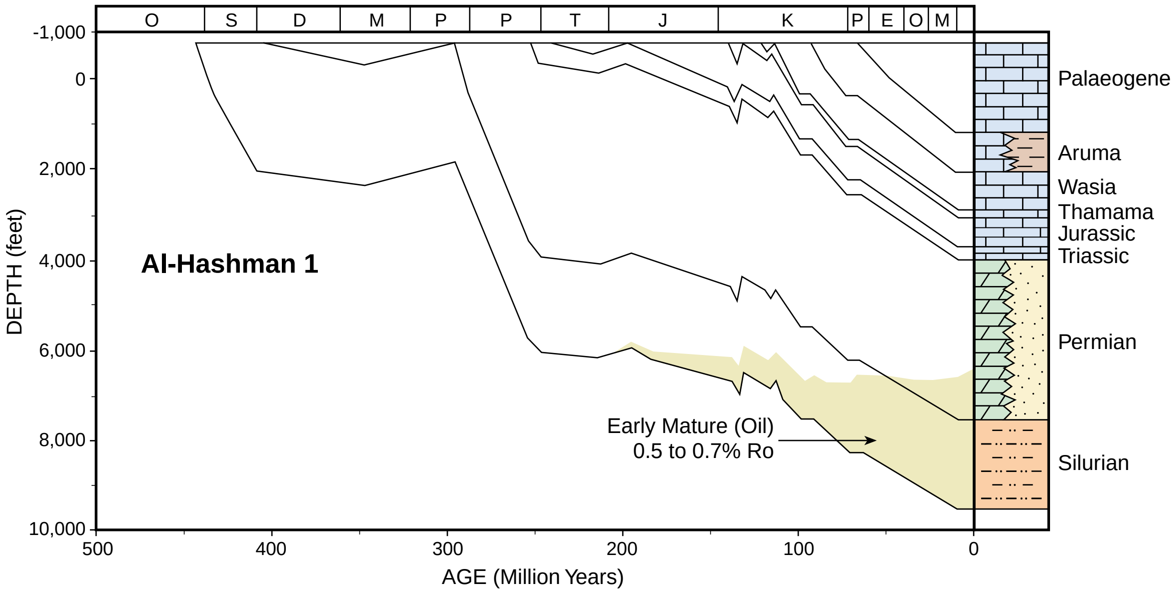

Figure 6: Burial history for the Al-Hashman 1 well located on the flank of the Ghudun-Khasfah High.

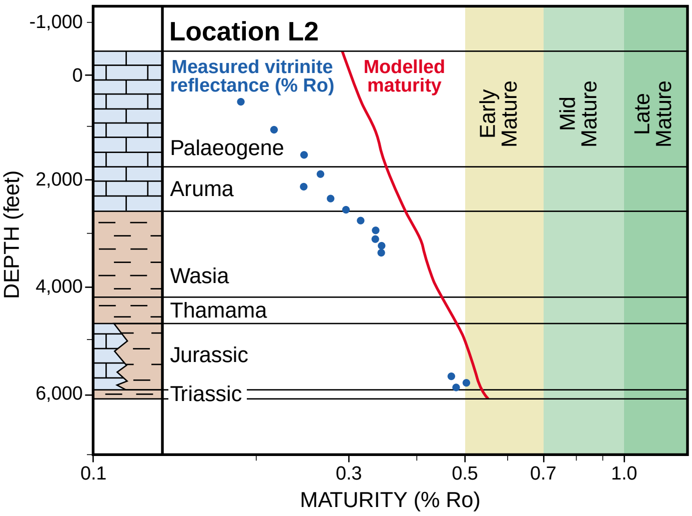

Figure 7: Maturity-depth graph for a well, known as L2, located on the southern margin of the Rub' Al-Khali.

analysed in the laboratory for quality and maturity. The results of vitrinite reflectance (Ro) measurement at the L2 location, however, did suggest a decrease in the mapped heat flow value from 50 to 40 mW / sq m to enable modelled and measured maturity to agree within 0.1% Ro (Figure 7). It should be noted that only reflectance values from samples with more than 12 measurements were used to ensure that a statistically reliable result was obtained. Modelled maturity most closely matches Ro% in the Jurassic section close to the total depth of the well (Figure 7), but trends diverge at shallower depths. An explanation for the better correlation at depth is the more accurate modelling of maturity values above the 0.45% Ro range when using the Arrhenius Reaction in the modelling algorithms (Basin Mod 1-D manual).

RESULTS

Mesozoic Results

Modelled data from the 38 higher-confidence first and second category locations from Oman, Saudi Arabia and the United Arab Emirates were used to estimate the average depths at which the key maturity windows were entered (Table 1). The average depth to the top of the mid-mature oil window is 8,500 ft. There will obviously be a range of depths, depending on structural position and heat flow. The standard deviation from 8,500 ft has been calculated as 1,250 ft. The average depth is illustrated on a northwest-southeast cross-section across the West Rub' Al-Khali from the central fields of Saudi Arabia to the Phillips Oman concession, Block 36 (Figure 8).

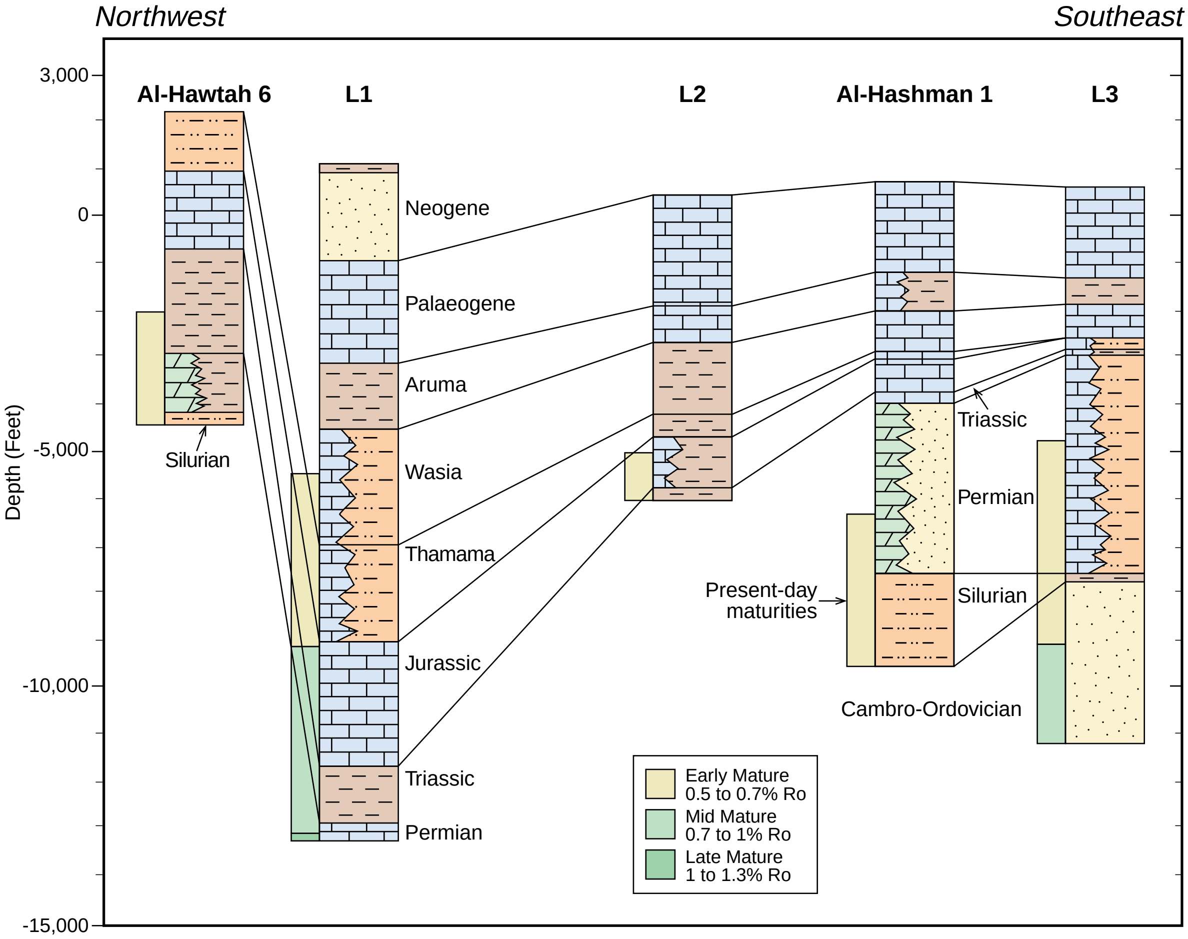

Figure 8: Cross-section showing present-day maturity with depth for wells across the Southern Rub' Al-Khali. (For line of cross-section refer to Figure 1). Note: Al-Hawtah 6 and Permian Silurian tops after Senalp and Al-Duaiji, 1995.

Table 1

Average depths at which maturity windows are entered.

Window	Vitrinite reflectance equivalent (%Ro)	Depth (feet)
Early mature	0.5 to 0.7	<8,500
Mid mature (main oil generation)	0.7 to 0.1	8,500 to 12,000
Late mature (oil), early mature (gas)	1.0 to 1.3	12,000 to 14,000
Mature post oil (main gas generation)	1.3 to 2.6	14,000 to 20,500
Over-mature	>2.6	>20,500

Limited tops and lithology information have been published for the Al-Hawtah 6 well (Senalp and Al-Duaiji, 1995). However, the remaining stratigraphy is provided from offset wells. This cross-section shows that, in the centre of the basin at the L1 location, the Jurassic is in the main oil mature window, whilst on the northwest and southeast flanks of the basin, Jurassic source rocks are probably too immature to have expelled hydrocarbons. The Al-Hawtah 6 model predicts that the Silurian Qusaiba Shale, a thin section shown in orange on Figure 8, is close to the mid mature oil window whereas, at Al-Hashman 1, the equivalent Safiq is early mature.

By using the average depth at which each maturity window is entered, based on higher confidence Category 1 and 2 wells, and depth structure maps, it is possible to produce source maturity maps for each of the key source intervals. The likely facies distribution of the intra-shelf basin can be added to summarize source rock distribution as well as maturity. An example of this mapping, for the Upper Jurassic Hanifa source rock, is shown in Figure 9.

Verification of Modelling

Whilst limited calibration is possible and little temperature correction data are available, some verification of these models is possible. Figure 9 shows the present-day maturity distribution for the Top Hanifa Formation. By comparing this distribution with the known occurrences of petroleums derived from this source in a number of Middle East fields (Figure 10), few discrepancies are observed. Only two fields are situated away from their corresponding mature source intervals. In the case of the Khurais group of fields in central Saudi Arabia, maturities are modelled to be in the region of 0.68% Ro. However the source rock has a high average Total Organic Carbon (TOC) content of 4% and can be up to 13% (non-exclusive report by Wilson, 1997). Consequently, expulsion from such a saturated source will occur early at lower maturities. The modelled maturity of 0.68% will be sufficient to expel hydrocarbons from such a good source rock.

In the second case, the Kidan field produces gas believed to be sourced from the Hanifa Formation (non-exclusive report by Geomark Research Inc., 1995). However, maturity modelling indicates the Hanifa Formation is only mature for oil generation with a 0.73% Ro despite a heat flow of 55.7 mW/sq m. Thus either lateral migration from the gas kitchen 40 kilometers (km) to the west must be invoked, or heat flows are anomalous. In view of the close proximity of the Kidan area to the gravity-defined Dibba Fault Zone (Figure 2), which may provide conduits for mantle heat to rise, anomalously high heat flow is a possibility, but this is not supported by the temperature data.

It may be concluded from the distribution of mature Hanifa basinal facies that the largest mature kitchen area is in the eastern Rub' Al-Khali where the medium and dark green and pink mature belts and the blue intra-shelf basin overlap (Figure 9). On the southern flank, however, both maturity and the likelihood of Hanifa source rock presence are low.

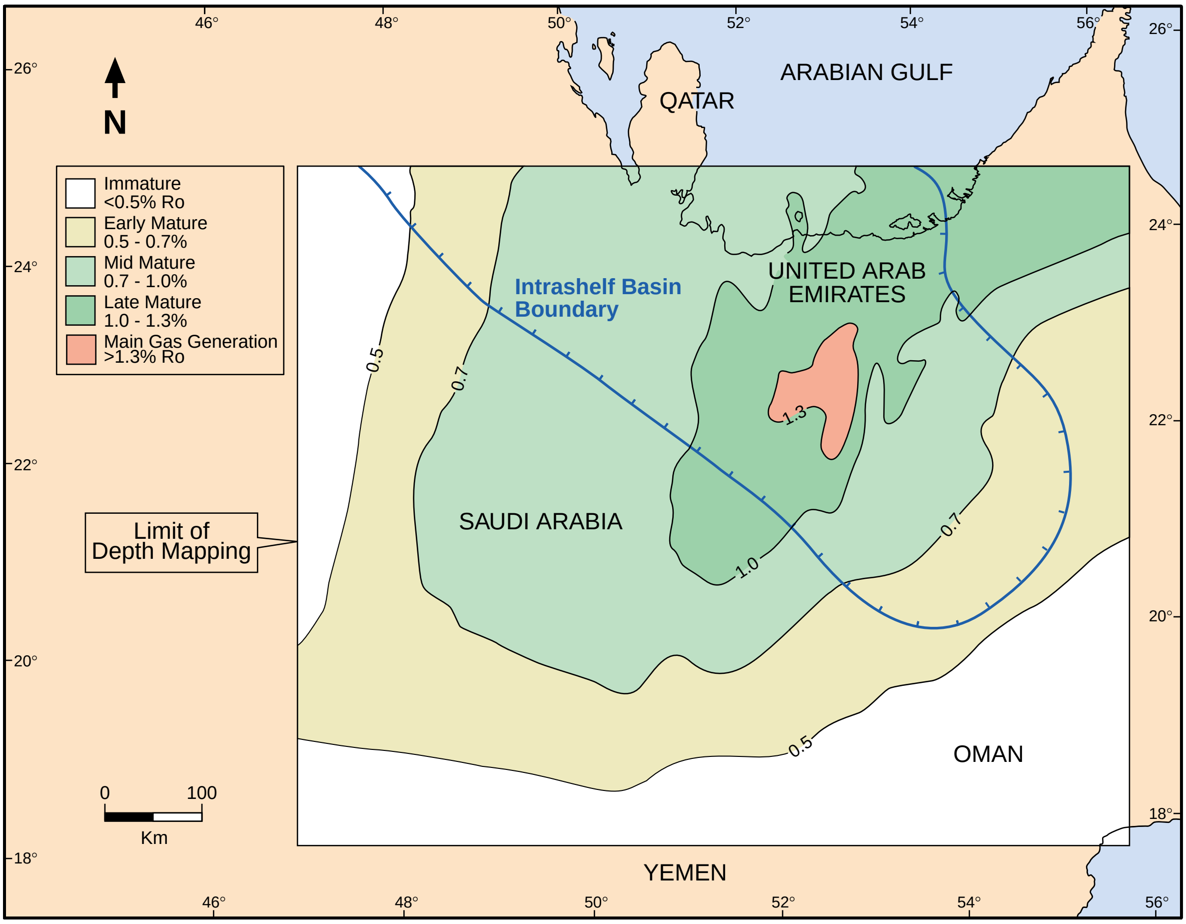

Figure 9: Southern Rub' Al-Khali Jurassic Hanifa source summary map showing present-day maturity windows and extent of source facies.

Table 2

Source Rock Advisor results summarising geochemical analysis for samples from a South Oman Salt Basin well.

Sample code	Upper Depth	Lower Depth	Nativity	Quantity	Quality	Maturity
EP97AHR	6,972	6,979		sufficient	acceptable	immature

Sample code	Grade	Final call	CF%	Ro	S2	HI	BO/AF
EP97AHR	very good	possible oil where more mature	99	0.42	15.37	538	38.2

Notes:

Nativity : If blank, nativity fits normal limits.
If*, non-native extract present.
If **, extract nativity can't be determined for this sample.
Ro : Ro maturity, measured or estimated.
S2 - Estimated original potential at thermal immaturity of Ro = .4%.
HI - Estimated original HI at thermal immaturity of Ro = .4%.
BO / AF : Estimated original potential oil yield in barrels of oil per acre foot. Derived by (S2*) X (2.485).
The 'estimated original' S2, HI, and BO / AF have not been calibrated for coals.

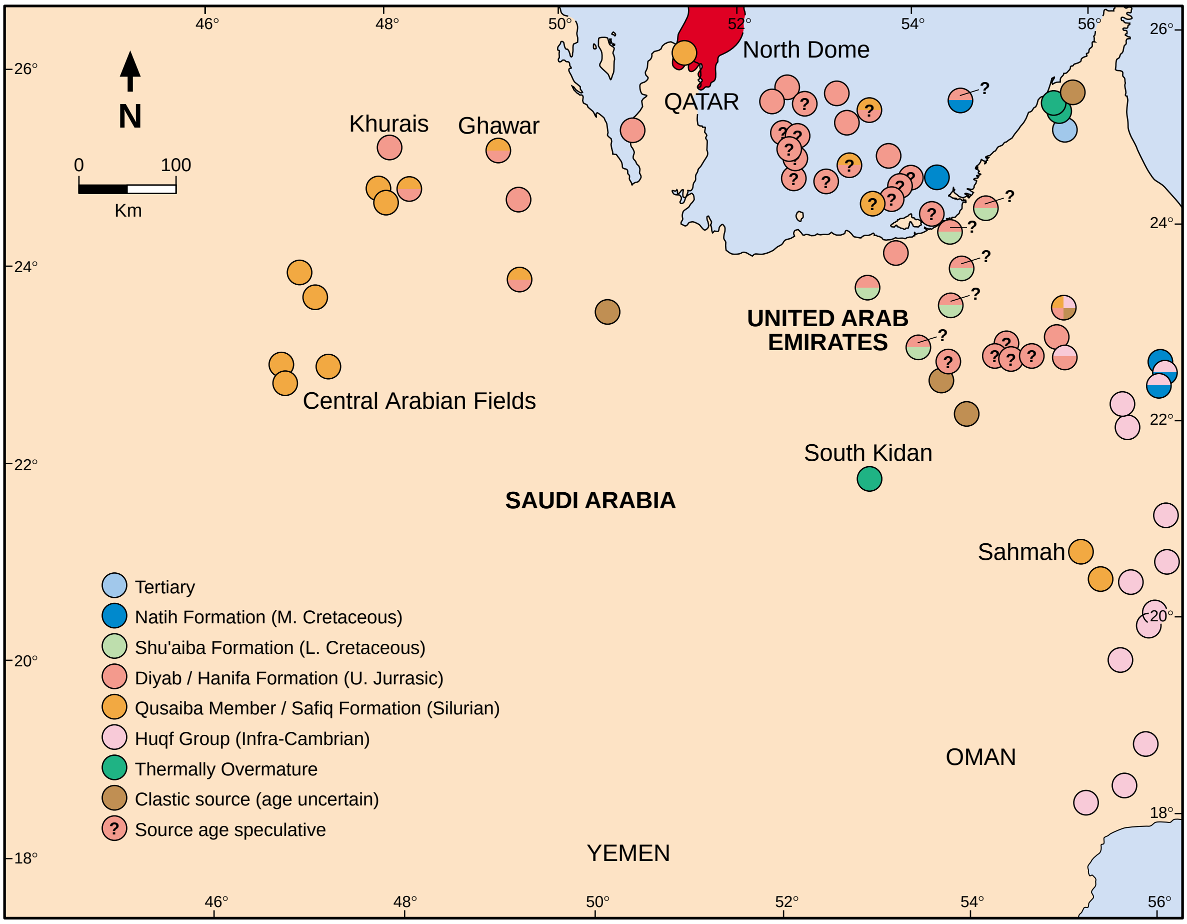

Figure 10: Age of petroleum for reservoirs in the study area from oil-typing and firm literature sources (colour-filled circles) and from speculative scout sources (queried colour-filled circles).

Source Rock Advisor

All available samples were analysed to measure total organic carbon, maturity and richness parameters and summarised using Phillips' proprietary Source Rock Adviser (SRA). Both pyrolysis and Ro measurements were obtained. After listing sample code name and depths from which the sample was taken, some indication of whether the hydrocarbons are likely to be *in situ* or whether they have migrated from elsewhere is given. By comparing the low temperature peak from pyrolysis (S1) with maturity measurements the 'nativity' indicates whether the sample is native by leaving the column blank. If part of the extract is thought to have migrated in from elsewhere it is 'non-native' and labelled with an asterix (*). If the 'nativity' of the extract is ambiguous, a double asterix (**) is used. The samples are screened for 'sufficient' TOC of more than 0.5% in quantity for analysis to proceed. 'Acceptable' quality source rock must have a Hydrogen Index (HI) of more than 300 for low Ro percentage maturities of less than 0.4. Maturity definitions are the same as those used for maturity modelling.

The 'grade' of the sample is another measure of its quality according to the high temperature peak from pyrolysis (S2) versus vitrinite reflectance (Ro) graph. Anything above poor, i.e. greater than 3.5 mg^{HC}/g rock (milligram of hydrocarbons per gram of rock), is a reasonable grade source rock but, obviously, fair, good and very good ratings of above 4 mg^{HC}/g rock, above 7 mg^{HC}/g rock and above $10mg^{HC}/g$ rock S2 values respectively are more reasonable. The final call is a description of the capacity of the rock to be a good source rock based on quantity, quality and maturity. The CF% value denotes the confidence in this call based on a number of parameters such as number of vitrinite reflectance points in a sample, whether maturity is measured from spore colour or vitrinite measurement, and the standard deviation of Ro. Lastly BO / AF denotes the potential yield of the source rock in barrels of oil per acre foot. A value over 7 BO / AF is considered good.

The SRA results for wells on the flanks of the Rub' Al-Khali revealed no candidate source rocks. The samples are Mesozoic in age and therefore the results do not contradict the previously discussed Hanifa facies and maturity mapping (Figure 9) i.e. immature non-source Hanifa Formation, to the southwest.

To the south, however, in the South Oman Salt Basin at the L4 well, a potential source rock is indicated by a final call of 'possible oil where more mature'. A typical result from this analysis have been included to demonstrate the software (Table 2). The extract is an *in situ* measurement as indicated by the blank nativity column. The sufficient quantity is derived from a TOC of 2.86%. The acceptable quality is caused by an S2 value of 15.37 mg^{HC}/g rock and an HI of 538, and the grade is therefore deemed very good. The potential yield is excellent at 38.2 BO/AF. However, the sample is immature because Ro reaches only 0.42%. The results are given a high confidence level of 99%.

Due to lack of tops information, the stratigraphic interval from which this sample is taken is unknown. From offset wells on the same field, and considering the variations in thickness owing to salt movement, it is suggested that this sample is Lower Palaeozoic in age.

Palaeozoic Modelling

Pseudo-wells and Deepening Existing Wells

In order to establish the distribution of mature source rock in the Palaeozoic, an additional section was added to the base of existing models and new hypothetical well models were built, sited on key basins and highs. The depth structure maps from published reports and from the Phillips database of 300 well tops were used to add best estimates of the Triassic to Silurian thicknesses to the existing models and to new pseudo-wells.

Owing to the substantial reduction in number of well data points below the Jurassic, there is some uncertainty in the accuracy of thicknesses. However, by integrating the lineaments from the structural framework map and trends from shallower interval isopachs with well isopach values, it is possible to produce a satisfactory suite of maps down to the Base Carboniferous. Below this, a limited database, together with a number of publications were used to construct isopach maps of the Devonian and Silurian intervals.

Devonian Isopach

The Devonian is not omnipresent across the Southern Arabian Peninsula owing to its uplift and removal by the Hercynian Orogeny at the end of the Devonian and during the Carboniferous (Al-Laboun and Walthall, 1988; McGillivray and Husseini, 1992; Stump et al., 1995). The results of these studies, together with limited Devonian isopach data and a number of wells which confirm whether the Devonian is present, have been used to produce a Devonian isopach map (not shown). Whilst the uncertainty in the accuracy of this map is recognized, it represents a best estimate. The accuracy of the isopach is estimated at ±1,000 ft. From the map, areas uplifted and eroded during the Hercynian Orogeny are highlighted. Where the Devonian is absent, a standard 500 ft of section was deemed originally present and subsequently eroded in all models. This was made consistent between all wells and hypothetical wells with no Devonian section, to avoid introducing variations to the models which could not be supported, since there is no documentation of how much Devonian was deposited and subsequently removed.

Sensitivity to Devonian Changes

The amount of Devonian uplift and erosion representing the Hercynian Orogeny was varied for the L2 model from 500 ft to 2,000 ft every 500 ft to test the effect on the depth of the maturity windows. The depth of the main oil mature window was the same in all cases because the uplift event is earlier than the main deposition and depth of burial.

Secondly the Devonian isopach, where present, was varied to test the effect on Base Silurian maturity. The isopach was halved for the twenty-six wells and locations with Devonian present. This resulted in a decrease in maturity of between 0.01 and 0.21% Ro, depending on the well. In the case of one well, the Base Silurian moved from one maturity window to another (i.e. from overmature to main gas generation).

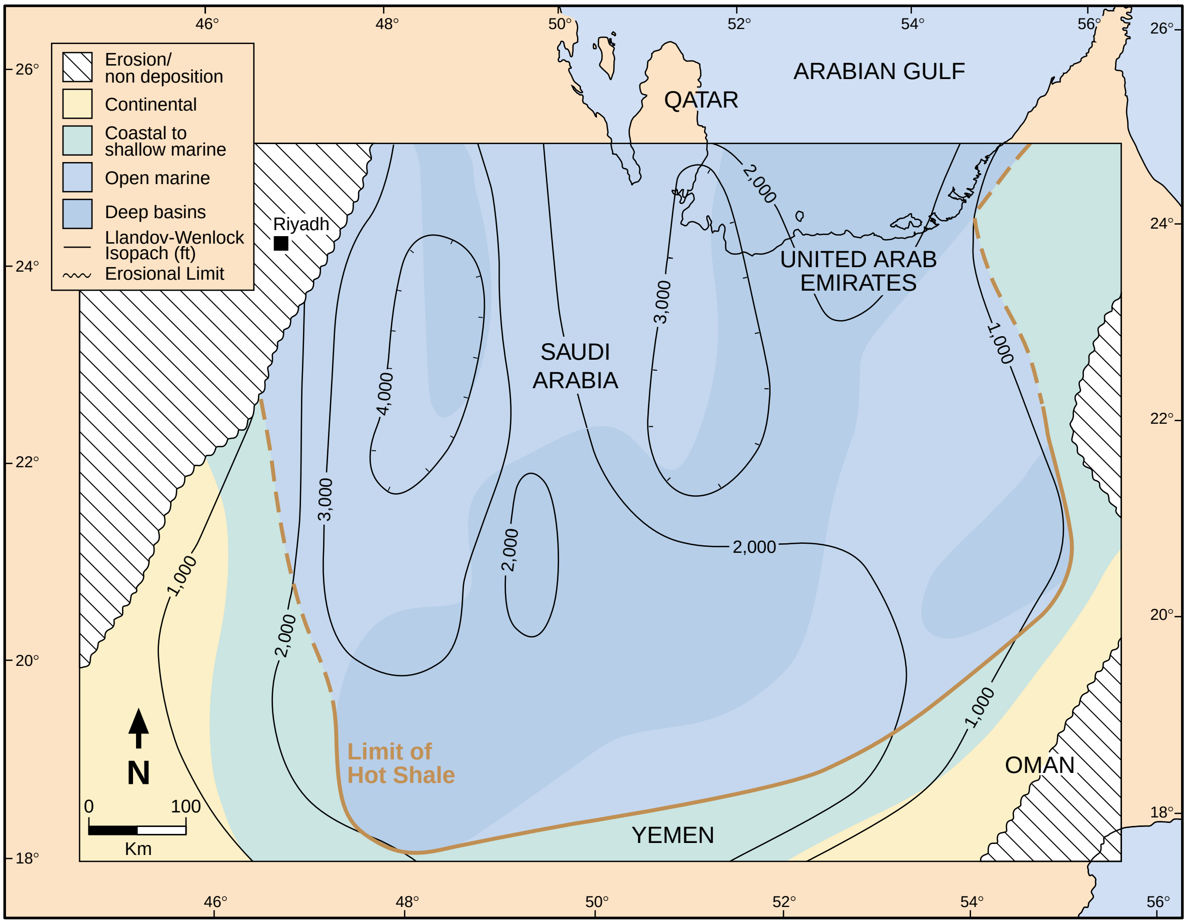

Figure 11: Silurian (Safiq equivalent) paleogeography and lithofacies based on limited well isopach and facies information and published sources (see text).

The isopach was also doubled for the twenty-six models. This increased Base Silurian maturity by 0.03 to 0.43% Ro. Again, only one model had a Base Silurian maturity change which resulted in a window move (i.e. from late oil-early gas generation to main gas generation).

These sensitivities demonstrate that, for the majority of models, varying the amount of Devonian section and the amount uplifted and eroded has a relatively small effect on the maturity of the Safiq / Qusaiba Shale across the area of study.

Silurian Isopach and Facies

Despite the availability of more Silurian than Devonian penetrations, estimation of the maturity of the Silurian Safiq Formation (Qusaiba Member in Saudi Arabia) is more problematic because the good source interval is at the base of this formation (Mahmoud et al., 1992) and this is often not reached. Again a distribution of where the Safiq / Qusaiba is present was produced and an isopach of the Qalibah Formation, which includes the Safiq / Qusaiba, was made with the help of the structural framework map (Figure 11). The Qalibah Formation in Saudi Arabia is described as Llandoverian to Wenlockian in age (Mahmoud et al., 1992; McGillivray and Husseini, 1992) and the Qusaiba Member (Safiq Formation in Oman) is ascribed to the lowermost part of the Qalibah.

By using the limited facies information available from eight wells, the isopach trends and the structural framework map, a facies distribution for the Safiq has been produced (Mahmoud et al., 1992; Senalp and Al-Duaiji, 1995; Stump et al., 1995). This map (Figure 11) shows continental and coastal to shallow marine deposits fringing the Rub' Al-Khali. Transgression resulted in widespread, open marine deposition following the Ordovician deglaciation (Murris, 1980). Southeast of Riyadh, in the area of the central fields, hot shales are overlain directly by coastal deposits of the Sharawra Member (Mahmoud et al., 1992) and their extent is represented by a dashed brown facies boundary on the map (Figure 11).

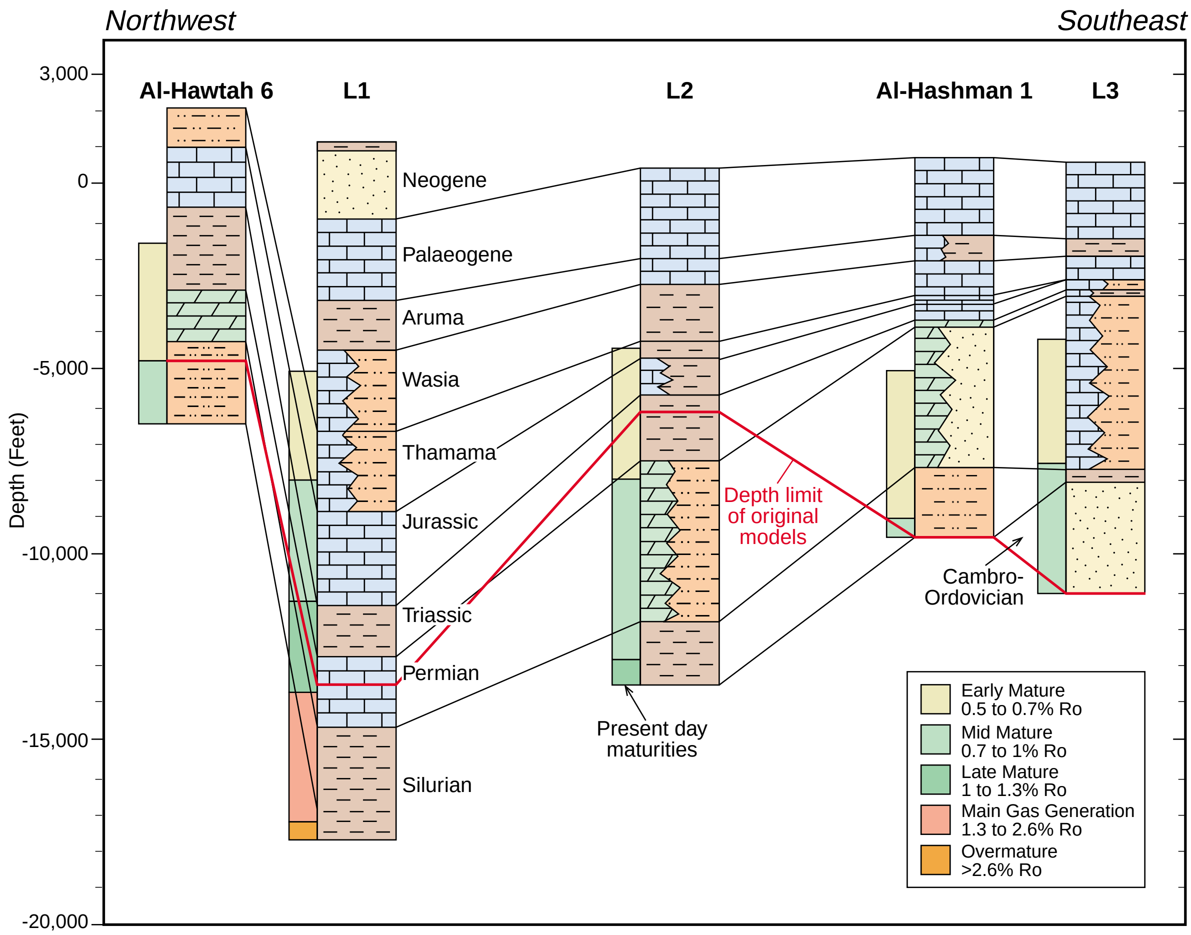

Figure 12: Southern Rub' Al-Khali deepened maturity cross-section showing present-day maturity with depth for wells across the southern Rub' Al-Khali. (For line of cross-section refer to Figure 1).

Within the area of open marine deposition, several zones have been defined as potentially deep sub-basins, which may be prone to source rock development. These are recognized from the structural framework map in the Rub' Al-Khali, east of Riyadh, and the basin on the Oman / Saudi Arabia border (west of Samah field). The basin east of Riyadh is from the Silurian thickness maps of Mahmoud et al. (1992). It is suggested that these areas were sediment starved and lacked circulation, providing ideal conditions for source rock deposition. The Sahmah field immediately east of the Oman / Saudi border, in Oman, is known to be sourced by the Safiq Formation (non-exclusive report by Geomark Research Inc., 1995), and supports the existence of good source rocks in the Oman / Saudi Arabia basin.

Modelling Results

Isopach maps for the Devonian and Silurian, together with shallower intervals, were used to extend the stratigraphy for selected models produced from first and second category wells and to construct the stratigraphy at pseudo-locations. Appropriate uplift, erosion, and hiatuses were implied where thin intervals were observed from offset well control and from structural knowledge. An example of the deepened stratigraphy is shown in Figure 12. This cross-section is identical to Figure 8 but with early Mesozoic and Palaeozoic section added. However, it has a different vertical scale. As a result of adding representative thicknesses below the total depth at these locations, the Silurian section is now in the oil window at the margins of the Rub' Al-Khali. In the center of the basin, the Silurian is gas mature.

By using the same depths for maturity windows summarised in Table 1, a Base Silurian Maturity map can be produced (Figure 13). Although the majority of the area is in the gas window or overmature at the present-day, an oil mature belt fringes the Rub' Al-Khali. This belt is broader on the southern flank owing to lower structural dips than in the central fields area, where steeper dips are due to proximity to the Arabian Shield.

Verification of Palaeozoic Maturity

The plausibility of the modelling results is increased by the following:

1. The Qatar North field, a Permian gas reservoir, lies in the mapped gas mature window (Figure 10) although no Qatar locations were modelled.

2. Devonian discoveries in the Ghawar field are gas (Wender et al., 1998) and Ghawar is mapped as gas mature at this level.

3. The Sahmah field of Oman is a Silurian-sourced oil reservoir (non-exclusive report by Geomark Research Inc., 1995). It is located just within the late oil mature window as mapped.

4. The central fields of Saudi Arabia, which produce Silurian-sourced super-light sweet crude oil, lie 60 km from the late oil mature window, which may be the kitchen area for the high gravity oil of 47°API (Abu-Ali et al., 1991), assuming that long distance lateral migration is operating.

In view of the uncertainty in the Devonian isopach, these petroleum occurrences add credibility to the Base Silurian maturity map.

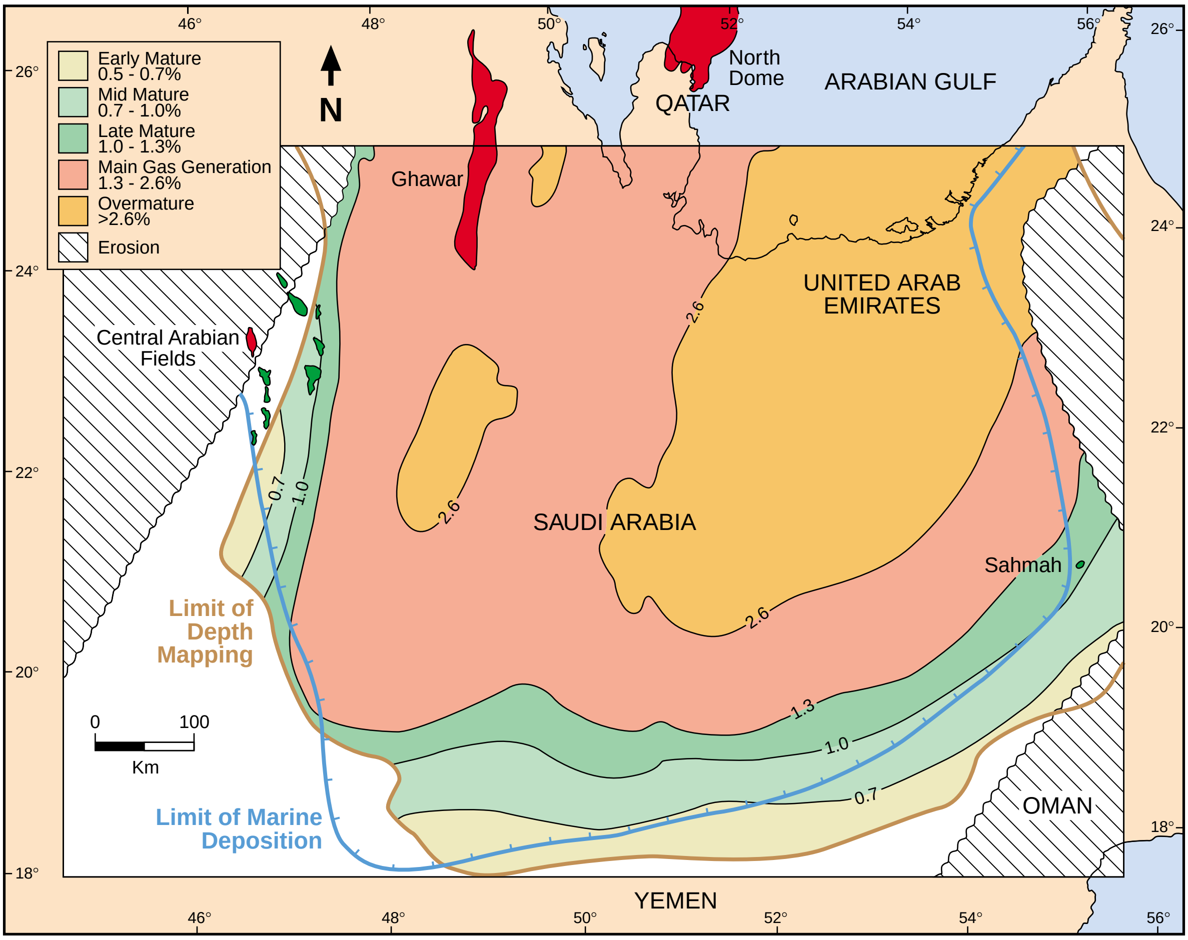

Figure 13: Southern Rub' Al-Khali Silurian Safiq source summary map showing present-day maturity windows and extent of source facies.

The Safiq source summary map (Figure 13) also shows the area where open marine source rock deposition, marked in blue, is coincident with maturity. This is relatively restricted on the southern flank of the Rub' Al-Khali in Oman but improves north and west into Saudi Arabia.

Integration of Source Rock Maturity and Facies

A map summarizing source rocks currently in the main oil window is shown in Figure 14. Facies work is still in progress for the Lower Cretaceous and Tertiary. The Tertiary Pabdeh Shale (Umm Er Radhuma equivalent in Figure 3) is dominantly mature in a narrow zone in the foredeep adjacent to the Oman Mountain Front. The Lower Cretaceous Shu'aiba Basinal Facies identified by Ayres et al (1982) and Taher (1997) follows the trend of the Rub' Al-Khali basin axis. The Upper Jurassic Hanifa Formation, like the Shu'aiba, is immature on the flanks of the basin, but is mature for oil deeper in the basin. A gas mature Hanifa zone, not shown, is coincident with the area of Shu'aiba oil maturity. The Silurian Safiq (Qusaiba) oil mature source rocks are confined to the basin margins and source rock facies may be intermittent. Lastly, the Middle Cretaceous Mishrif mature source rock is not included because source facies belt and oil mature areas do not overlap in the Rub' Al-Khali. This is consistent with the small number of Middle Cretaceous-sourced fields in this area (Figure 10).

CONCLUSIONS

Comprehensive burial history modelling has been conducted using integrated tectonic history, lithology and temperature information. A more detailed structural and chronostratigraphic framework has

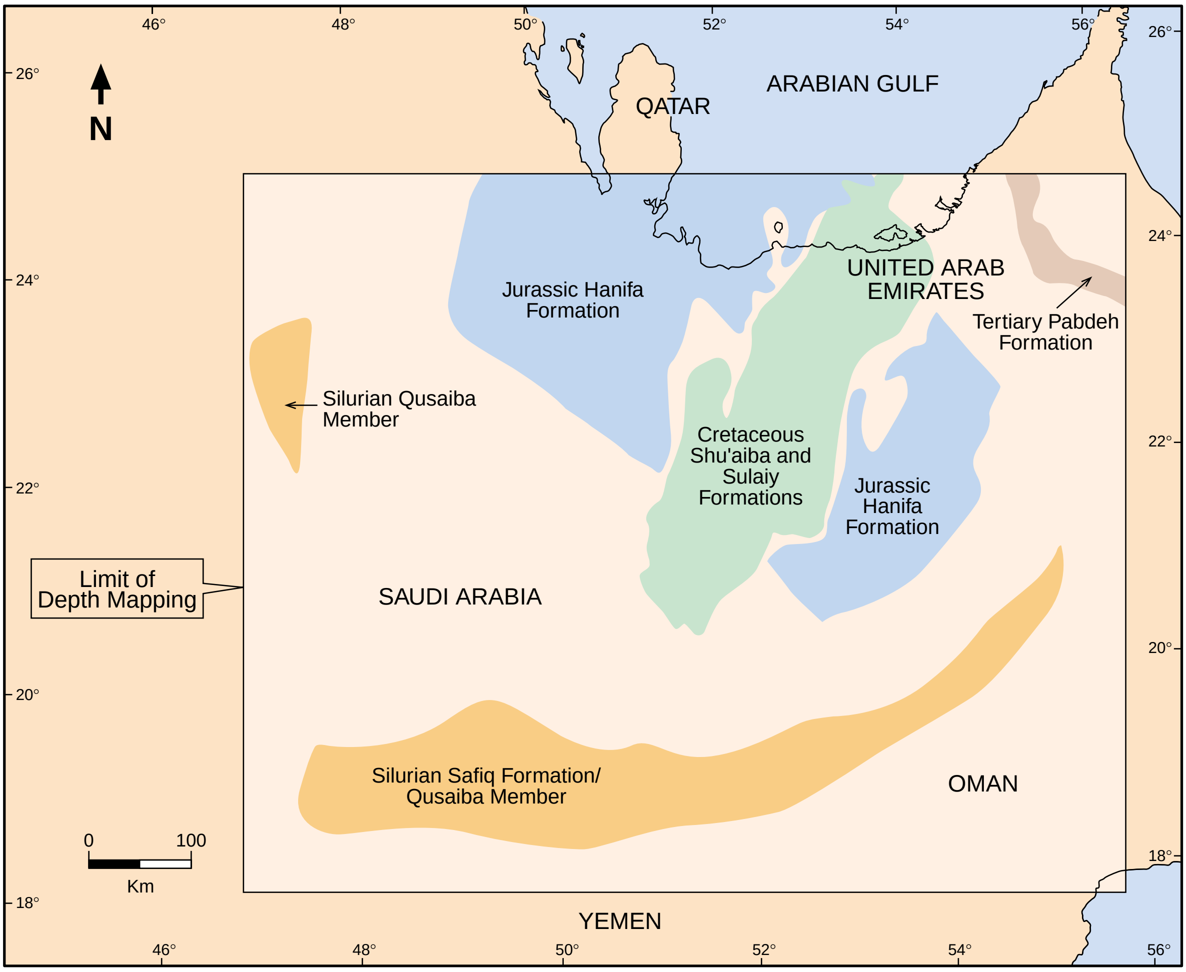

Figure 14: Summary of present-day main oil mature (0.7-1.0% Ro) source facies areas.

enabled the deepening of these models and the creation of pseudo-wells in key areas. Facies mapping based on well control and published maps has resulted in a distribution of source rock facies and maturity for each of the recognized Middle East source rocks. A new distribution of heat flow has been produced using the structural framework and the Phillips bottom hole temperature database. This heat flow distribution has been used to produce maturity models for 68 locations.

The Hanifa Formation maturity distribution has been used as an example to confirm that the resultant maturity values agree with the oil and gas maturities observed in known Hanifa-sourced reservoirs. Acceptable reasons for the outliers to the mapped maturity trends have been given. A new screening of source rock analysis and maturity has helped to confirm that the Hanifa is immature on the southern flank of the Rub' Al-Khali. The oil and gas mature Hanifa source facies is present in the northern and eastern half of the study area. The Hanifa formation is less mature and unlikely to be source facies to the south and west.

Using the available Devonian and Silurian well data and references has resulted in a Base Silurian maturity and facies distribution, which again fits those fields known to be sourced by the Safiq. The main oil and late oil-early gas mature windows are on the flanks of the Rub' Al-Khali. Maturities on the southern flank of the Rub' Al-Khali, in the vicinity of Block 36, are acceptable and source rock deposition is possible. Generally, however, the Silurian source formation in the Rub' Al-Khali is gas-mature in the west in Saudi Arabia and Qatar, and is overmature for gas in the eastern Rub' Al-Khali and the United Arab Emirates.

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