GeoArabia, Vol. 1, No. 4, 1996
Gulf PetroLink, Bahrain

The Role of Hydrogeology in Petroleum Development Oman

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ABSTRACT

A hydrogeological study of the South Oman Salt basin in particular, and the Oman basin in general, was carried out by Petroleum Development Oman to support basin modelling. The study focused on major aquifer systems: the Tertiary Umm Er Radhuma aquifer and the Paleozoic Haima-Haushi aquifers. Temperature, water quality, radiocarbon age dating and potentiometric data was used to determine the flow, thermal and salinity regimes of the systems. The resulting models were then used to define areas where oil biodegradation due to meteoric water influx can be expected. A review of oil chemistry data confirmed that fields in these areas have the highest API gravity oil demonstrating that hydrogeological modelling can be beneficial in predicting oil quality for prospect evaluation. An additional benefit of this study was the development of a formation water resistivity model for enhancing log analysis techniques.

INTRODUCTION

The Oman hydrogeological basin is bounded to the North by the Oman Mountains (elevation 3,000 meters (m)), to the South by the Dhofar Mountains (elevation 1,800 m) and to the east by the low lying Huqf outcrops (Figures 1 and 2). Previous hydrogeological studies were restricted to depths of approximately 500 m, in Tertiary rocks from which most of the water used for the oil industry is extracted (Parker, 1985). Recognition that meteoric water flow could have an impact on oil quality and basin modelling, resulted in the extension of hydrogeological studies to encompass the deeper oil-producing Paleozoic horizons. The result is a coherent picture of the aquifer systems operating in the subsurface of the interior of Oman.

Since the advent of hydrocarbon exploration in Oman, some 700 exploration and over 2,000 production wells have been drilled. In addition some 800 water wells have been drilled mainly in the Tertiary Umm Er Radhuma Formation. Water salinities in the deeper Paleozoic aquifers were obtained either from Repeat Formation Test (RFT) chambers, in either exploration or appraisal wells, or from associated production water in development wells. Static water levels were monitored and salinity variations measured in over 500 Tertiary water wells. Spatial variations in static water levels are subtle and reflect the regional water flow pattern. Pressure data in the deeper Paleozoic aquifers are restricted to the oil fields and analysis of these data will not be discussed in this paper.

Hydrodynamic studies have significantly contributed to further our understanding of heat flow. Aquifer temperature data have been stored in PDO's well log temperature database. The database incorporates some 1,500 Bottom Hole Temperature (BHT) data from over 250 selected oil exploration and appraisal wells. From these data, the thermal structure was modelled using the Shell proprietary software programme, THERMOSTAT™. The program allows temperature slices to be created at different depth levels and the thermal structure to be studied in detail as a non-linear function of depth.

It is now possible using salinity patterns to predict oil gravities from water flow models, since biodegradation of oil results mainly from meteoric water influx. This study shows that most of the oils along the flow path close to recharge are heavily biodegraded. Understanding salinity variations has also resulted in a better appreciation of fluid resistivities associated with petrophysical logging and reduced the uncertainties in hydrocarbon detection.

Readers interested in further reading on hydraulic theory are referred to Hubbert (1953), Toth (1980, 1986) and Villegas et al. (1994).

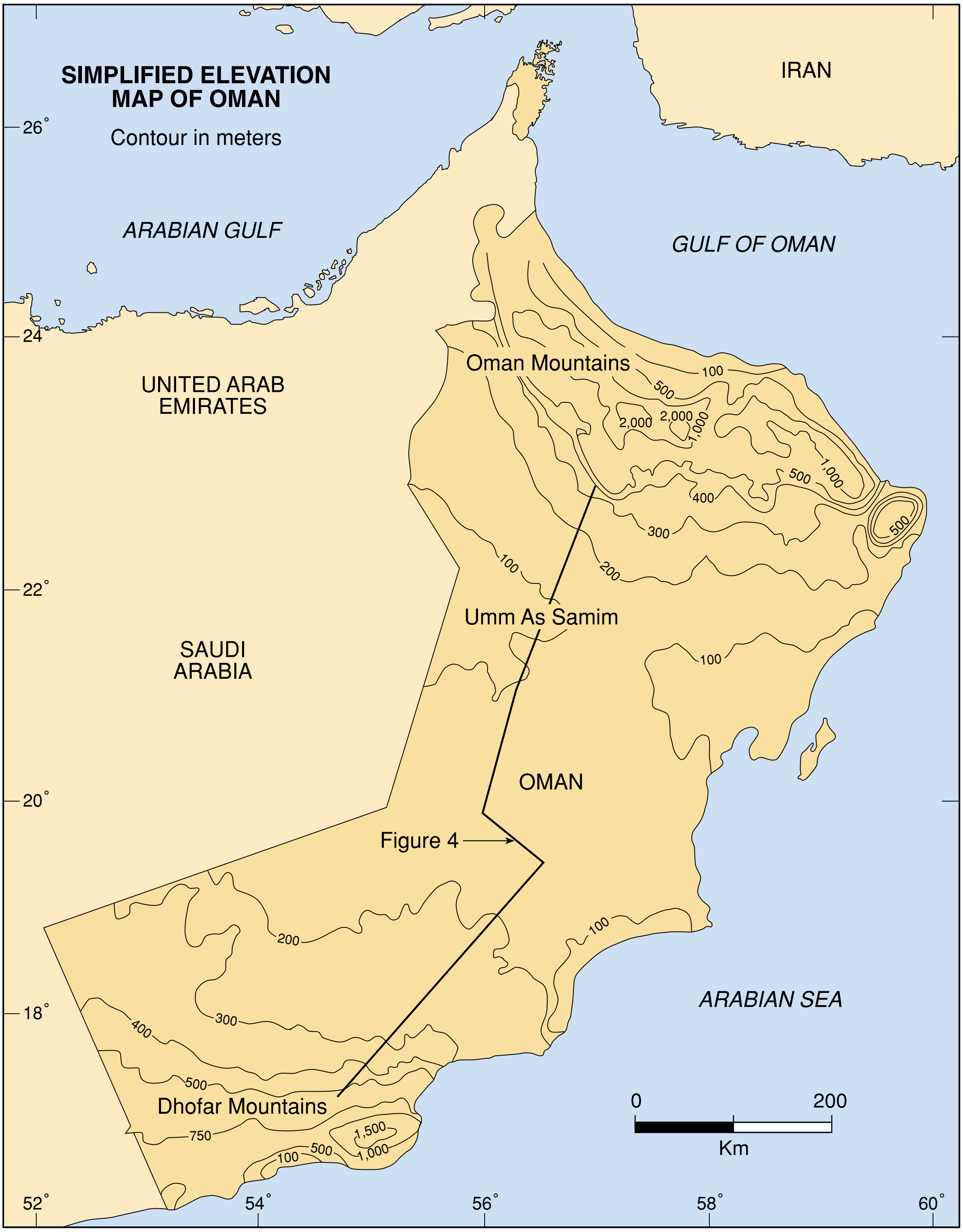

Figure 1: Elevation map of Oman. The topography of Oman is dominated by the Oman Mountains (elevation 3,000 m) to the North and the Dhofar Mountains (elevation 1,800 m) to the South.

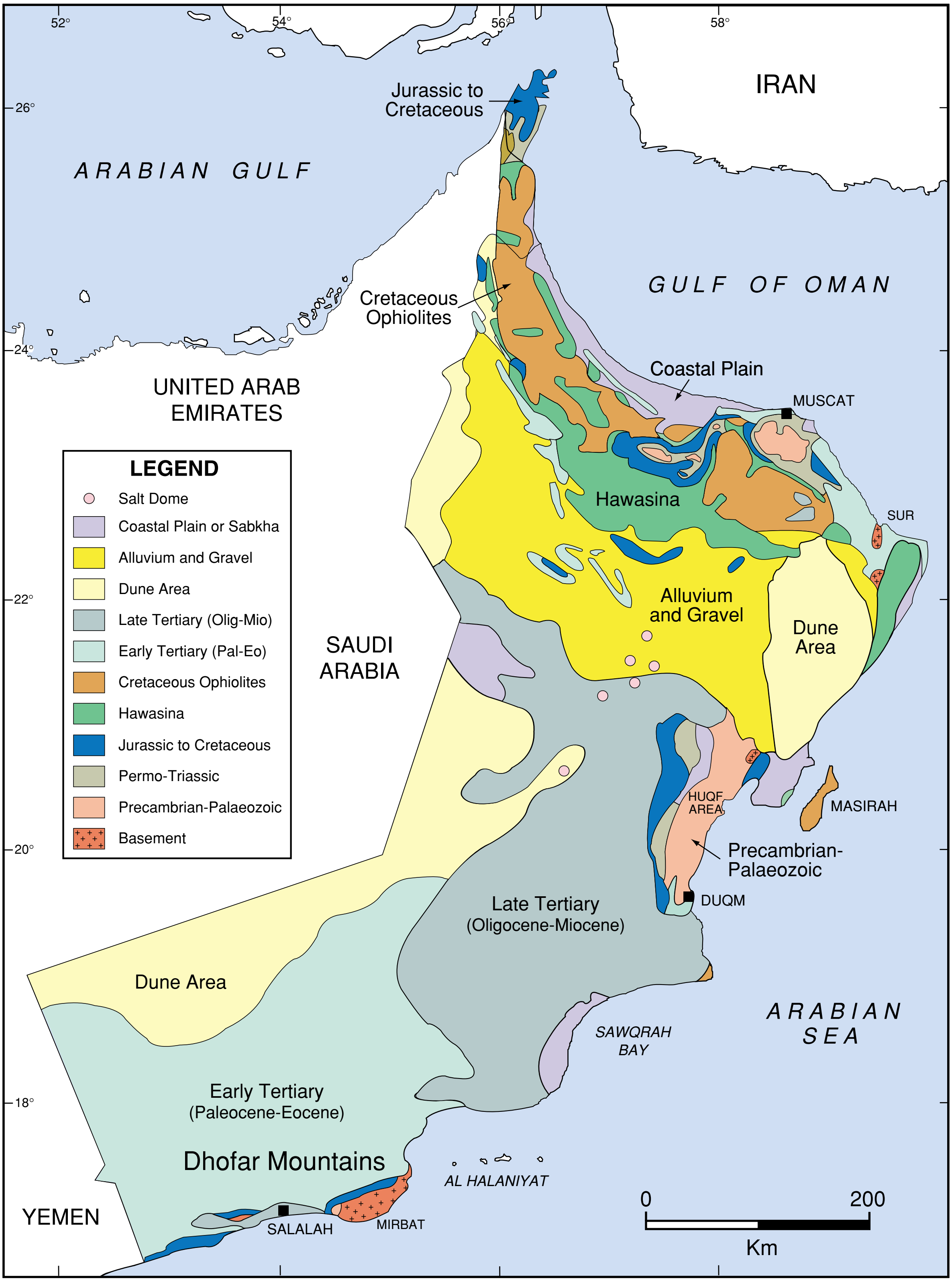

Figure 2: Geology of Oman.

BASIN SETTING OF OMAN

Oman lies along the eastern margin of the Arabian Plate which was, during its early history, part of the Gondwana continent. The gradual break-up of this huge landmass has dominated the tectonic setting and is thought to be responsible for early Paleozoic rifting and the progressive, phased uplift of the Eastern flank (Figure 2) since the late Paleozoic. The most recent expression of this ongoing process is the opening of the Gulf of Aden during mid-Tertiary times, which created an extensive basinward-dipping monocline in the Dhofar area. Since the Late Cretaceous, the closing of the Neo-Tethys caused thrusting and uplift of the Oman Mountains and foreland sedimentation (Loosveld et al., 1996).

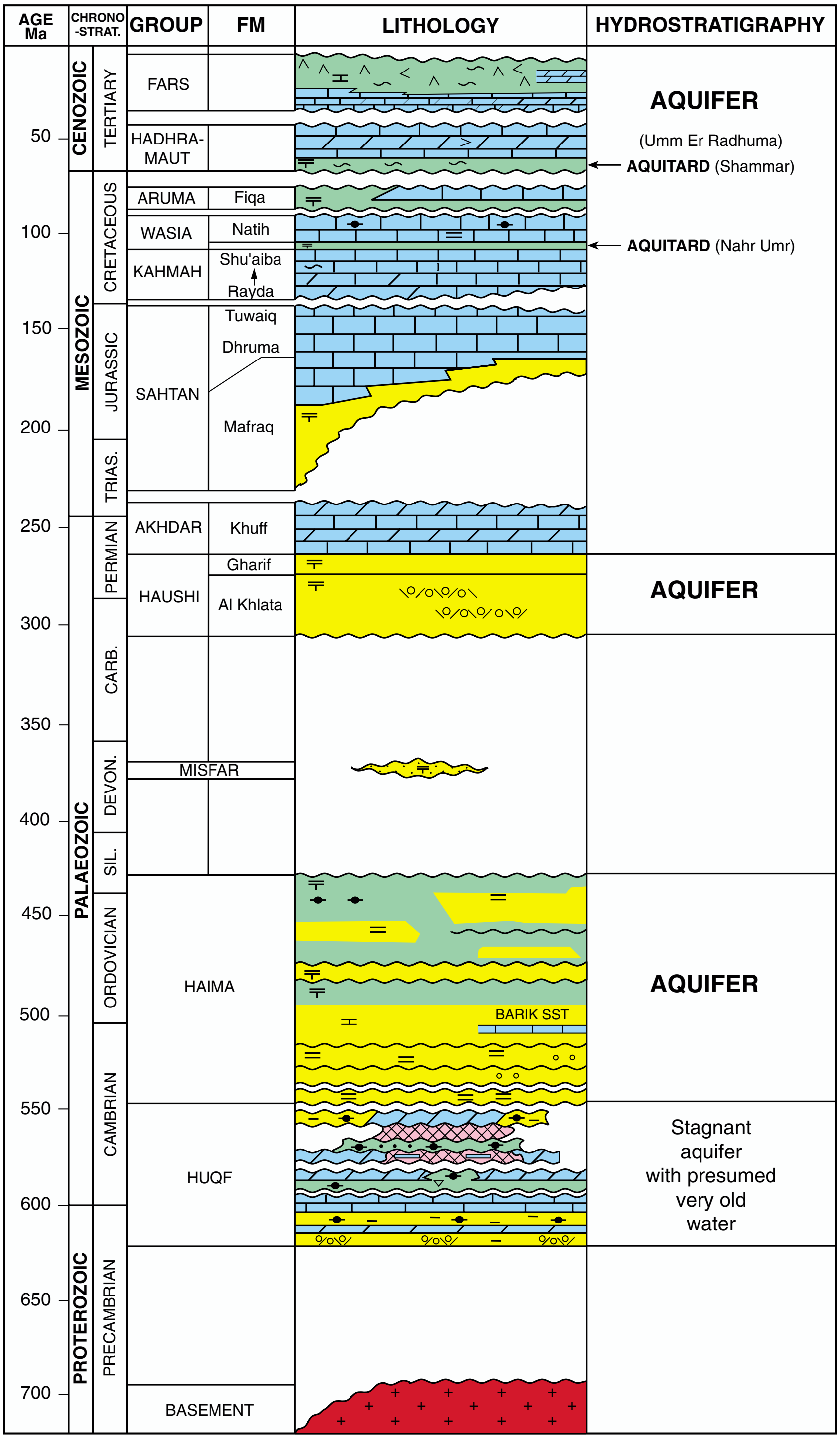

Figure 3: Stratigraphy and hydrostratigraphy of Oman. Aquitards act as regional seals to water flow.

The stratigraphic record (Figure 3) comprises strata ranging from Precambrian to Quaternary in age and is marked by many hiatuses and extreme climatic changes due to Oman's varied latitudinal position through time.

The oldest sequence consists of siliciclastics, carbonates and thick evaporites of the Precambrian to Early Cambrian Huqf Supergroup. The evaporites represent the earliest deposits in a series of rift basins and are covered by late syn-rift clastics. This rift sequence is overlain basinwide by marginal marine and continental siliciclastic sediments of the Cambrian to Early Silurian Haima Supergroup.

The Haima clastics are the deepest known aquifers. These clastic sediments represent the post-rift sagging of the basin and are unconformably overlain by glacial, continental and shallow marine, predominantly siliciclastics of the Permo-Carboniferous Haushi Group. Haushi Group sediments thin towards the north and east and have been associated with the thermal doming phase that preceded the separation of the Indian craton from the Gondwana continent. The Haushi clastics also contain an important aquifer.

Platform carbonates dominate the Mesozoic Akhdar, Sahtan, Kahmah and Wasia Groups and represent the successive drift-phase, passive margin succession that flanked the Neo-Tethys ocean. The foredeep that developed in the north in response to obduction and thrusting in the Oman Mountains was initially filled with marine Aruma shales and carbonates. Later, since Oligocene times, when deformation intensified, alluvial fan sedimentation (Fars Formation) prograded towards the south. The saucer shaped relief created by the active margin in the north and passive margin in the south currently drives the hydrodynamic activity in Oman (Figure 4). Following an unconformity at the Cretaceous-Tertiary boundary due to a global sea level fall, the thin basal Shammar shale was deposited. Early to mid-Tertiary sedimentation over a stable shallow marine platform produced a uniform sequence of shallow marine carbonates. These include the Umm Er Radhuma (main aquifer), Rus and Dammam formations together with the mainly evaporitic Fars Group.

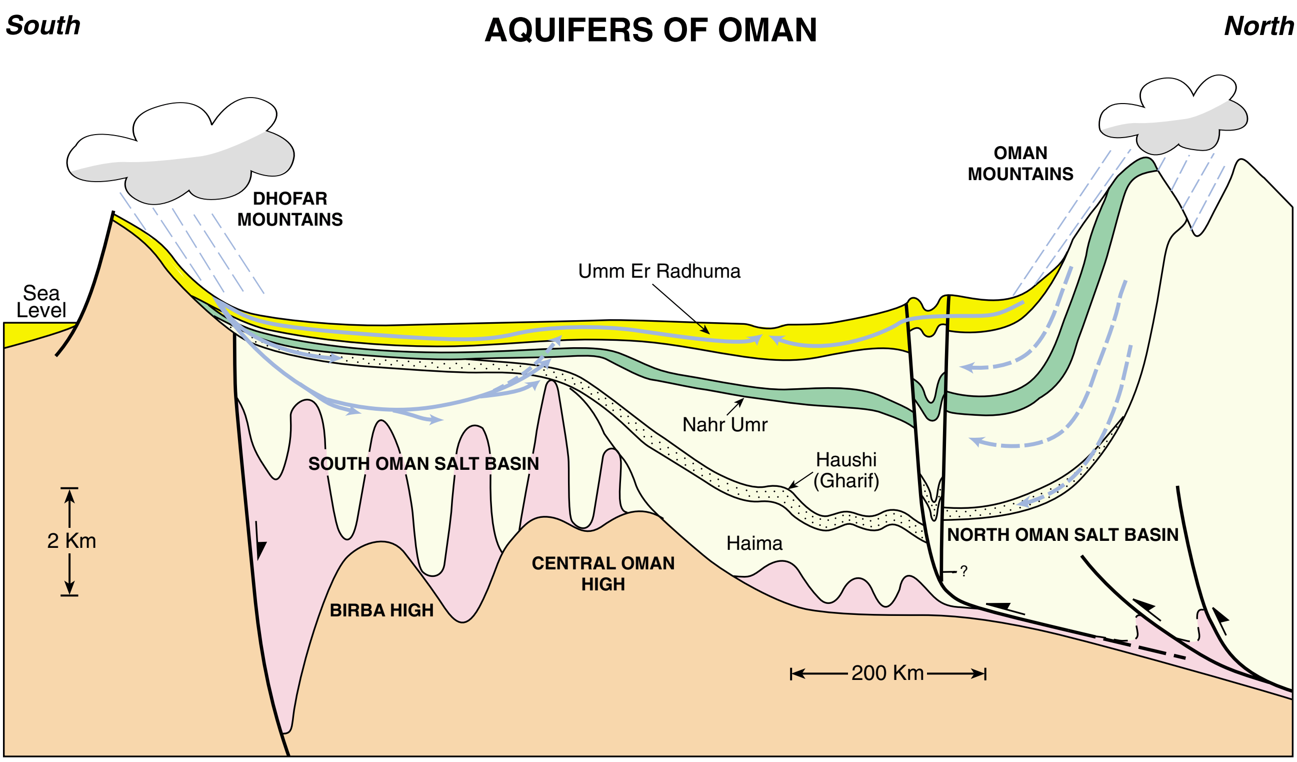

Figure 4: Hydrogeological cross-section of Oman shows water flow regime.

FLUID FLOW AND HYDROSTRATIGRAPHY

Water flow in the Oman hydrogeological basin is gravity-induced and topographically driven. The flow of meteoric water into the formations is through highland recharge, and the discharge is at relatively low relief areas. There are two mountainous areas in Oman, one in the north of the country and the other in the south (Figure1). Rechar ge takes place over the Mountains into the Tertiary rocks (Figure4). Rechar ge over the Dhofar Mountains is the most important at present, in that it is estimated that as much as 300 millimeters (mm) of misty precipitation takes place during the monsoon period (July to September). Precipitation over the Oman Mountains is estimated at 150 mm. Towards the end of last pluvial period, between 20,000 and 10,000 years before present, Oman was much wetter than it is today (Beydoun, 1980). Therefore more infiltration into the groundwater system was likely at these times. The bulk of the water volume is believed to have been recharged during this period.

The hydrostratigraphic subdivision of rocks in the Oman basin is predominantly based on salinity data. Two main groups of aquifers have been recognized:

The shallowest and currently most active aquifers are the Tertiary carbonates (approximately 500 m thick). The Tertiary interval comprises two aquifers: the Fars/Dammam and the Umm Er Radhuma. Most of the water flow, however, is believed to occur in the Umm Er Radhuma Formation, underlain by the Shammar Shale aquitard. The thickness of this aquitard rarely exceeds 30 m and its continuity is questionable. Local cross-formational flow from the Umm Er Radhuma into the underlying Natih carbonates is believed to occur in the fold and thrust belt of the Oman mountains.

The Natih Formation is underlain by the thick and extensive shales of the Nahr Umr Formation (Figure 3), an important regional seal for hydrocarbons and considered to be an effective aquitard. Only in the very south, has uplift related to the opening of the Gulf of Aden caused the erosion of this aquitard. Over the rest of Oman, the Nahr Umr aquitard separates the Tertiary aquifer from the Permo-Cretaceous platform carbonates and the Haima Group and Haushi Group clastic aquifers. The platform carbonates are absent nearer to the recharge area in South Oman and their hydrogeological attributes are poorly understood. Hydrochemical data from this carbonate platform are scarce except in North Oman oil fields where oil production is from the ShuaÕba and Natih formations. The limited data show salinity in excess of 200,000 milligram per liter (mg/L) suggesting that these fields are in a discharge area.

The second main aquifer group comprises the fluvio-glacial and essentially continental deposits belonging to the Haushi and Haima groups. The distinction between the Haushi and the underlying Haima aquifer is geological (Figure3), not hydr ogeological. Hydrostatic gradients between the two groups are mostly continuous and it is possible that the two units may be locally in hydraulic communication. There are intra-formational shales which may in places act as local aquitards but, regionally the Haushi and Haima groups aquifers are considered as a single entity.

The Precambrian basement is considered to be an aquiclude. There are few salinity data from the Precambrian - Cambrian (Huqf) sediments due to lack of well penetrations. Measured salinities below the massive salt deposits (up to 2,000 m thick in places) exceed 200,000 mg/L. This suggests that the water is likely to be very old and stagnant with no significant flushing having occurred in the recent past.

TERTIARY AQUIFER FLOW

Hydrochemistry and Fluid Flow Potential

In large sedimentary basins, water flow is associated with dissolution of salts along the flow path. Enrichment of conservative ions like chloride and sodium is quite common in basinal waters which are characterized by an increase in salinity from recharge to discharge zones. Many chemical interactions may be responsible for the solutes found in water. Concentrations of major cations including Potassium (K), Magnesium (Mg) and Sodium (Na) increase with passage of water through rocks. Similarly, anions such as chloride and sulphate increase and bicarbonate ions decrease. Loss of bicarbonate ions leads to an increase in pH and hence an increase in alkalinity. Collection of salinity data from wells drilled so far has enabled a large salinity database to be compiled.

Total dissolved solids (TDS) (Figure5a) in the Umm Er Radhuma depict a similar flow tr end as the equipotential map (Figure 5b). These salinity trends are observed in both the Umm Er Radhuma and the Paleozoic aquifers (Figure 6) and again confirm the present-day direction of movement of basinal waters.

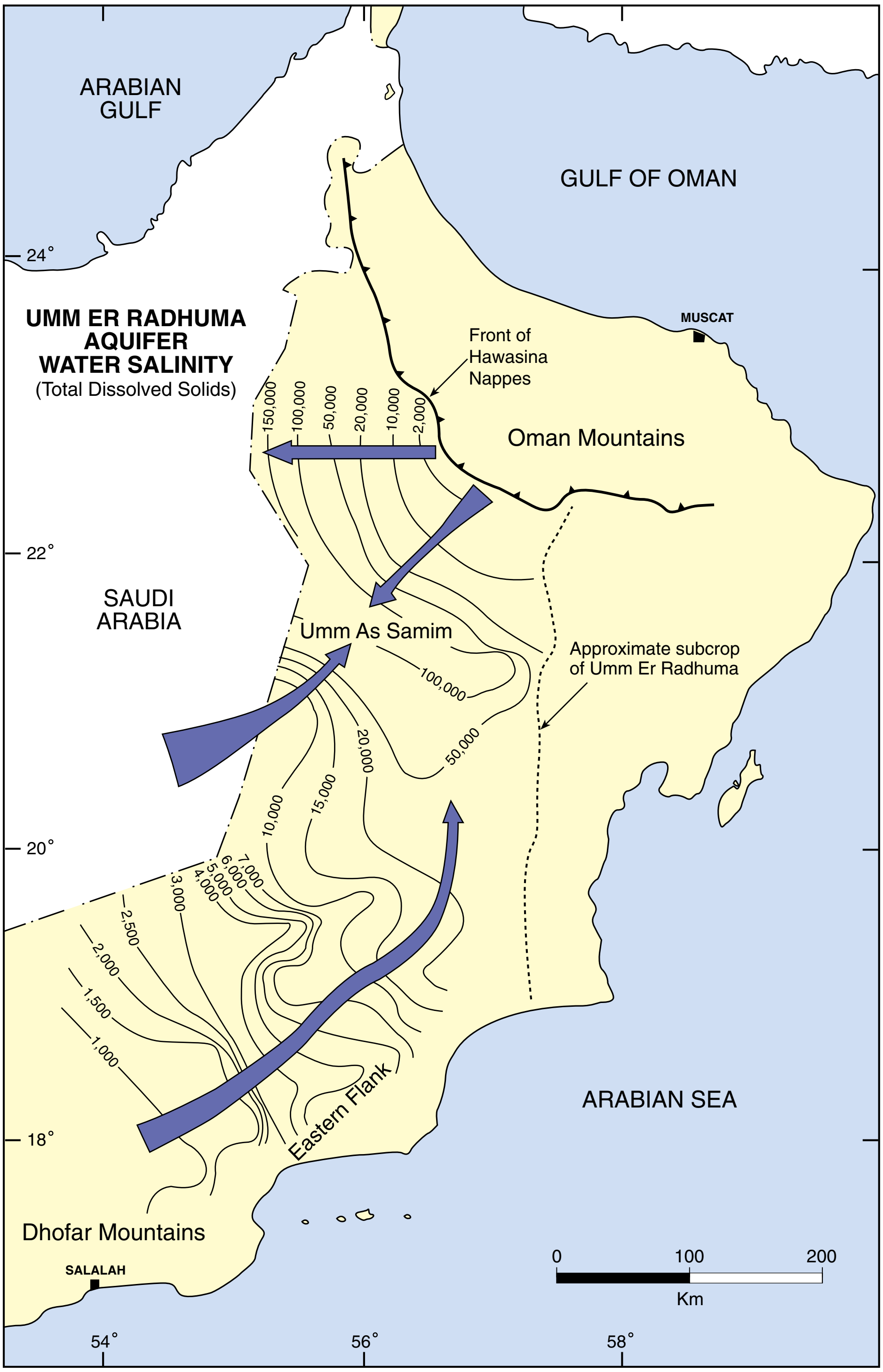

Figure 5a: Water salinity of the Umm Er Radhuma indicates flow from the Oman and Dhofar Mountains to the Umm As Samim sabkha.

Figure 5b shows the equipotential map of the Umm Er Radhuma aquifer. From the figure it is confirmed that the main recharge areas are the Dhofar mountains and the Oman mountains with some component from Saudi Arabia. The main discharge area is the inland Umm as Samim sabkha. Although it appears in Figure 5b as if discharge is also taking place in the Eastern Flank, this is misleading as elevation in this area is 150 meters above sea level (masl). This implies that the water would have to overcome a 100 m head in order to come to surface. This is the area where water stagnates and groundwater

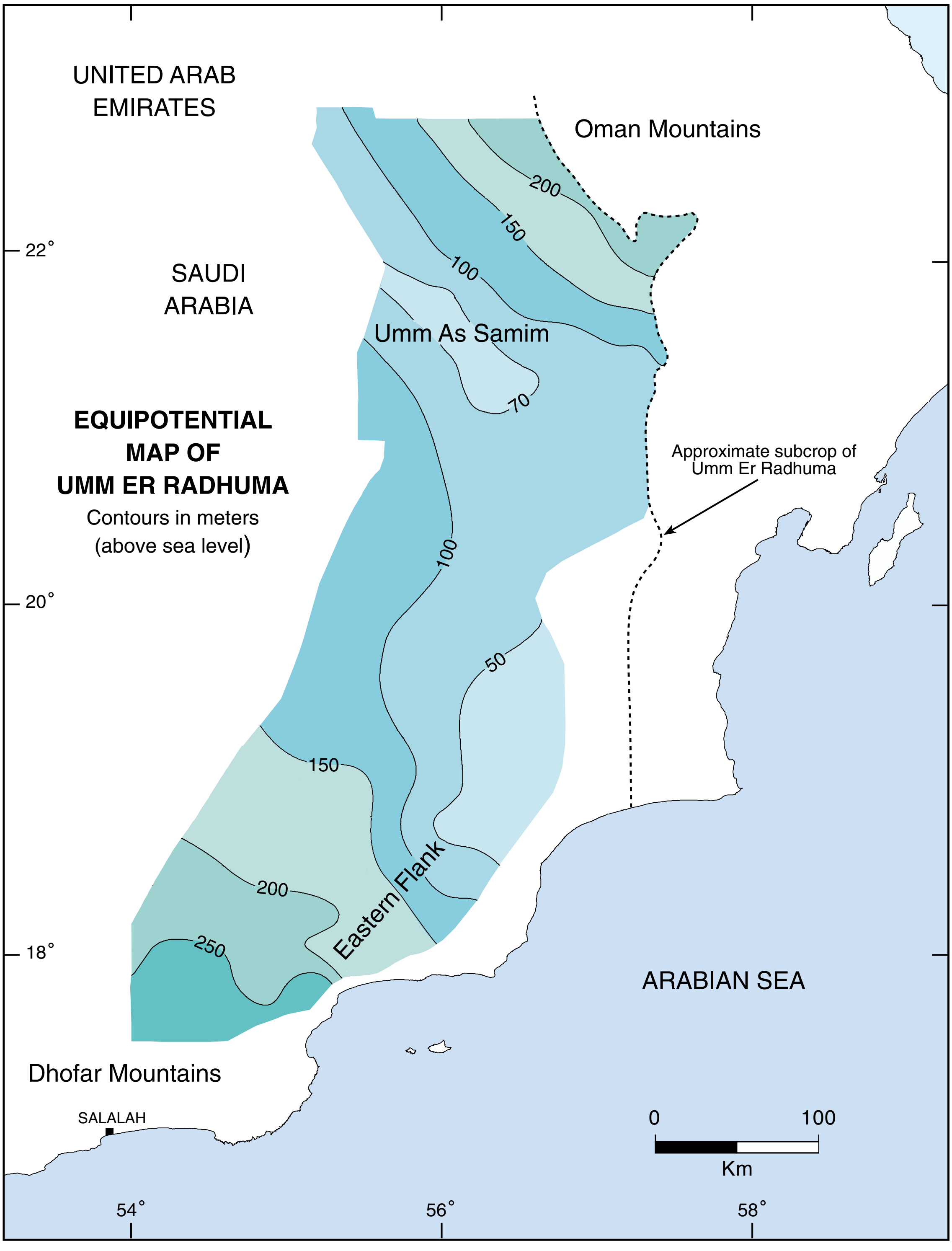

Figure 5b: Equipotential map of the Umm Er Radhuma indicates that the main recharge area is the Oman and Dhofar Mountains and the discharge area the Umm As Samim sabkha.

under such conditions is likely to have high TDS as observed in a few wells close to the Umm Er Radhuma subcrop. It is also possible the Tertiary water in this area enters the Paleozoic aquifers through Natih Formation sinkholes.

Radiocarbon Age Dating

In 1984, PDO carried out isotopic studies through the International Atomic Energy Agency (IAEA). Stable isotopes, tritium and Carbon-14 data were analyzed from various wells. Estimates of groundwater ages were made using radiocarbon age-dating methods (IAEA, 1984 client report). The results indicated that the groundwater ages of the Umm Er Radhuma waters are relatively young, 5,000 - 17,000 years (Table 1).

Table 1

Well Name	Approximate Distance to Recharge Area	Age (Years)	Error (±) Years
Sabsab WSW-3	150	10,000	3,600
Marmul WSW-4	150	9,900	2,700
Sayyala WSW-1	300	9,500	8,700
Haima WSW-11	350	1,100	3,800
Fahud WSW-4	150	5,700	4,900
Rima WSW-3	200	17,000	12,500
Birba North WSW-1	170	9,400	3,400
Birba WSW-2	160	8,400	3,400
Berbazoum WSW-1	100	9,100	2,700

Flow Rates

The distribution of ages and distances from recharge area in Table 1 indicate flow rates of around 10 m/yr. Outcrop studies on the Tertiary Umm Er Radhuma in the Dhofar Mountains revealed prominent features such as caverns, gorges and sinkholes. This development of secondary permeability is a diagnostic feature of water flow (Parker, 1985). Similar features are observed in the limited petrophysical logging of the Tertiary aquifer, especially in the Rima area. Water flow through these karstic features accounts for most of the fluid flow within the Tertiary rocks. An estimation of flow rate within the Tertiary of approximately 10 m/yr was made based on pumping test data from South Oman (Al-Lamki, 1992).

PALEOZOIC AQUIFER WATER FLOW

Water flow in the deeper Paleozoic aquifers is determined solely from salinity data. The salinity map shown in Figure 6 suggests a flow trend similar to the Tertiary aquifer. There are no indications for intervening large-scale salt dissolution nor for local recharge-discharge areas.

The salinity (TDS) of the Gharif Formation waters, is as low as 2,000 mg/L (Figure 6) close to the recharge area in South Oman, suggesting that the strata have been flushed by meteoric water. Additional evidence of recent meteoric influx is the radiocarbon age-dating of Gharif water, found to be 30,000 years in the Marmul area, 150kmfr omr echargear ea (IAEA, 1984 client report).

Hydraulic communication is known to occur across aquitards at a time scale in excess of 30,000 years. However, the younger age of the water in the Paleozoic aquifer in the Marmul area, coupled with its lower salinity, indicates that the aquitard is probably discontinuous in the recharge area. Very little drilling has been done close to the Dhofar Mountains in the south, but seismic evidence suggests that the Nahr Umr Formation aquitard thins toward the recharge area in the south and may be absent in places. This suggests that direct communication exists between the Tertiary and the Paleozoic aquifers (Figure 4).

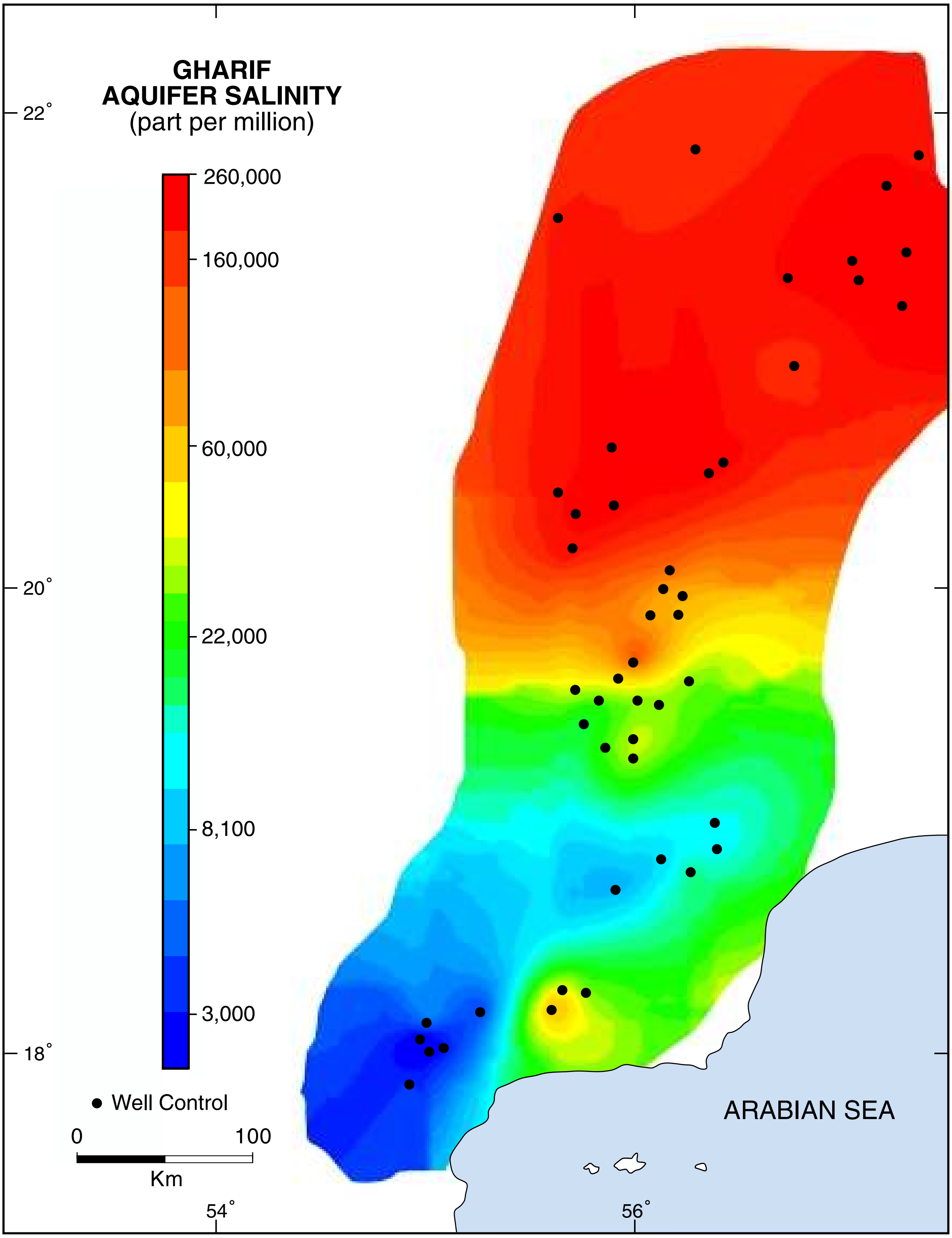

Figure 6: Aquifer salinity of the Paleozoic Gharif Formation indicates a flow of meteoric water from south to north.

EFFECTS OF WATER FLOW

Water Flow Evidenced by Temperature

Today Oman is a stable continental area characterized by moderate terrestrial heat flows. Variations in heat flow range between 40 to 60 milli Watts/sq m (Bachu and Hitchon, 1996) and can be linked to the observed fluid flow pattern derived from salinity and water pressure data.

Cold water influx lowers subsurface temperatures and this is confirmed by temperature slices made at different stratigraphic levels. A temperature slice at 500 m (Figure 7a), approximately the depth of the Tertiary Umm Er Radhuma Formation aquifer, reveals lower temperatures closer to the southern mountain recharge. Conversely, discharge areas are relatively elevated in temperature. The

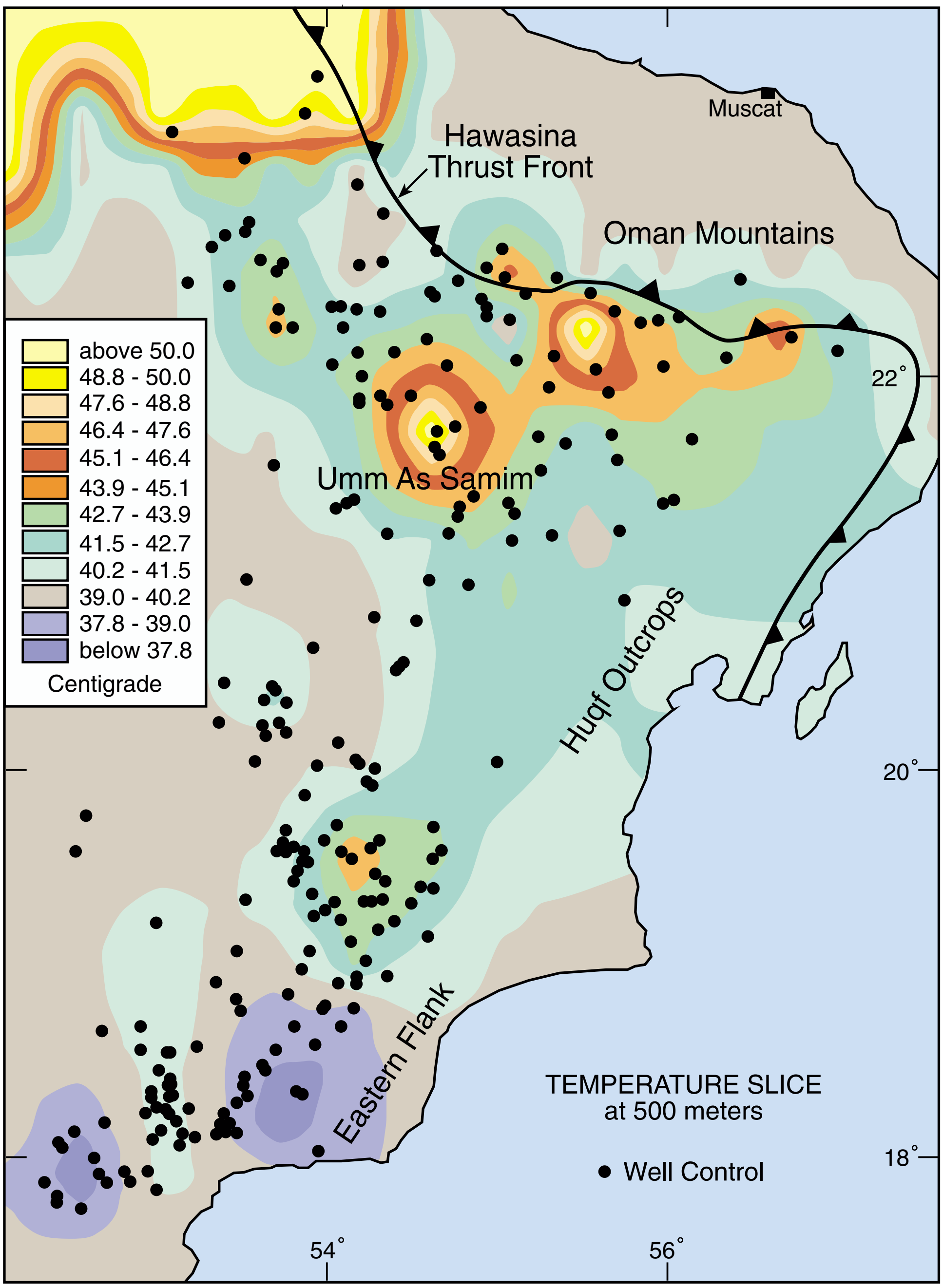

Figure 7a: Temperature slice at 500 m (approx. depth of Umm Er Radhuma) indicates lower temperature to the south where water recharge occurs along the Dhofar Mountains.

temperatures appear to gradually increase northwards towards the discharge point at Umm as Samim (Figures 7a and 7b) where discharge of warm waters occurs.

A temperature slice at 1,500 m (Figure 7b), associated with the Paleozoic aquifers, shows a similar trend of lower temperatures in the southern recharge area and progressively becoming higher northwards. Lower temperatures along the Eastern Flank and the Huqf (Precambrian outcrop) area (Figures 2 and 9) are likely to be indicative of recharge areas during recent past pluvial periods, although there is no recharge today.

Temperature slices taken at different depths in the Oman basin therefore confirm the effect of hydrodynamics on geothermal gradients and that there is a genetic link between the two. This has been noted in similar large-scale basins in Alberta (Bachu and Underschultz, 1993; Bachu, 1995) and Saudi Arabia (Hitchon, 1984).

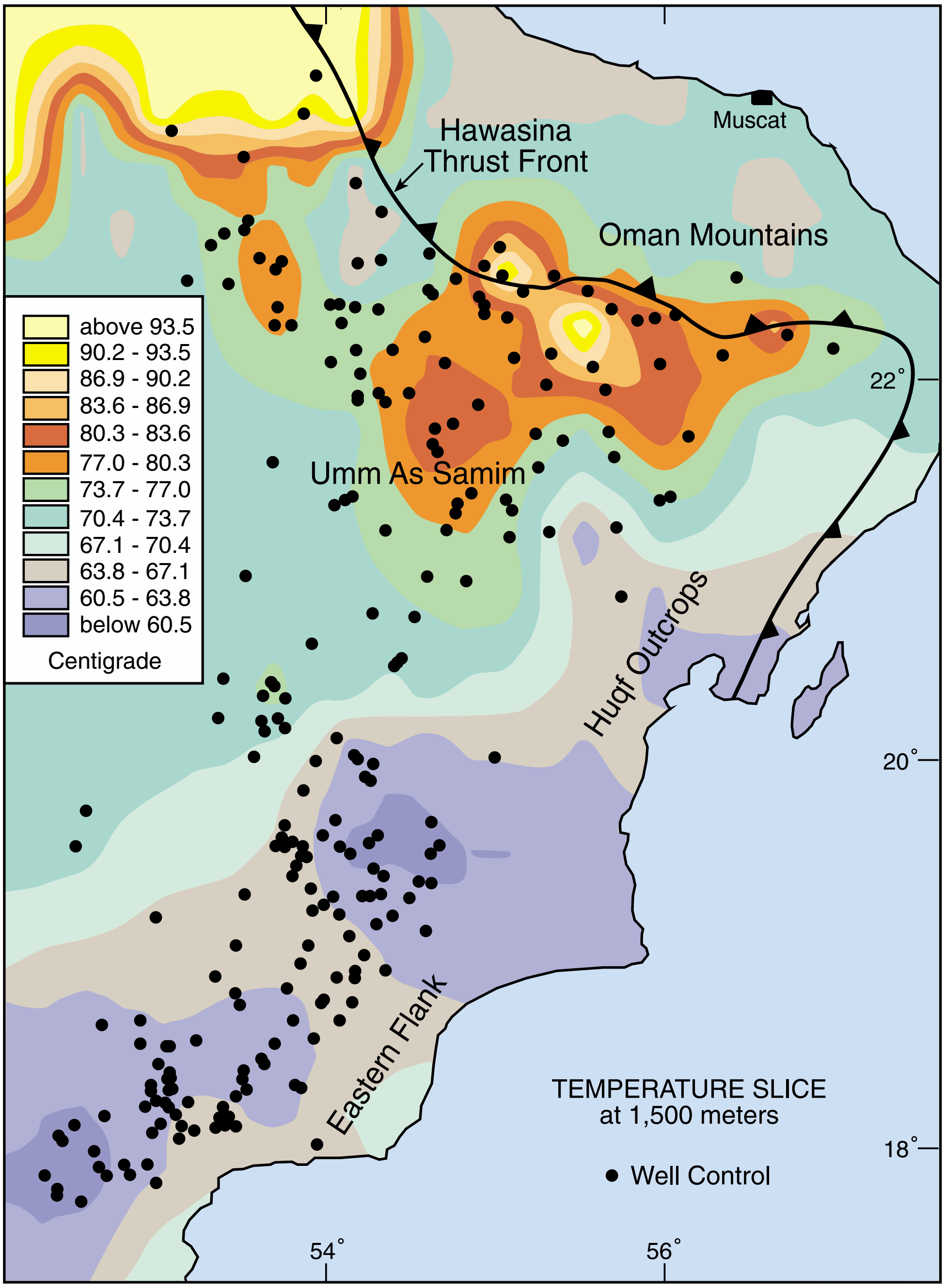

Figure 7b: Temperature slice at 1,500 m (approx. depth of Paleozoic strata) indicates lower temperature to the south where water recharge occurs along the Dhofar Mountains.

Oil Resistivities

A problem when interpreting the petrophysical logs of wells drilled in untested areas is estimating water resistivity, R_W (Smalley et al., 1995). Values of resistivity were measured directly on water samples collected for salinity determination in the laboratory. The temperature database was then used to calculate the actual resistivity by temperature-correcting the laboratory resistivity according to the depth of the formation. The resulting resistivity information and the trends of changes in R_W are an invaluable tool in areas that are not well understood (Figure 8).

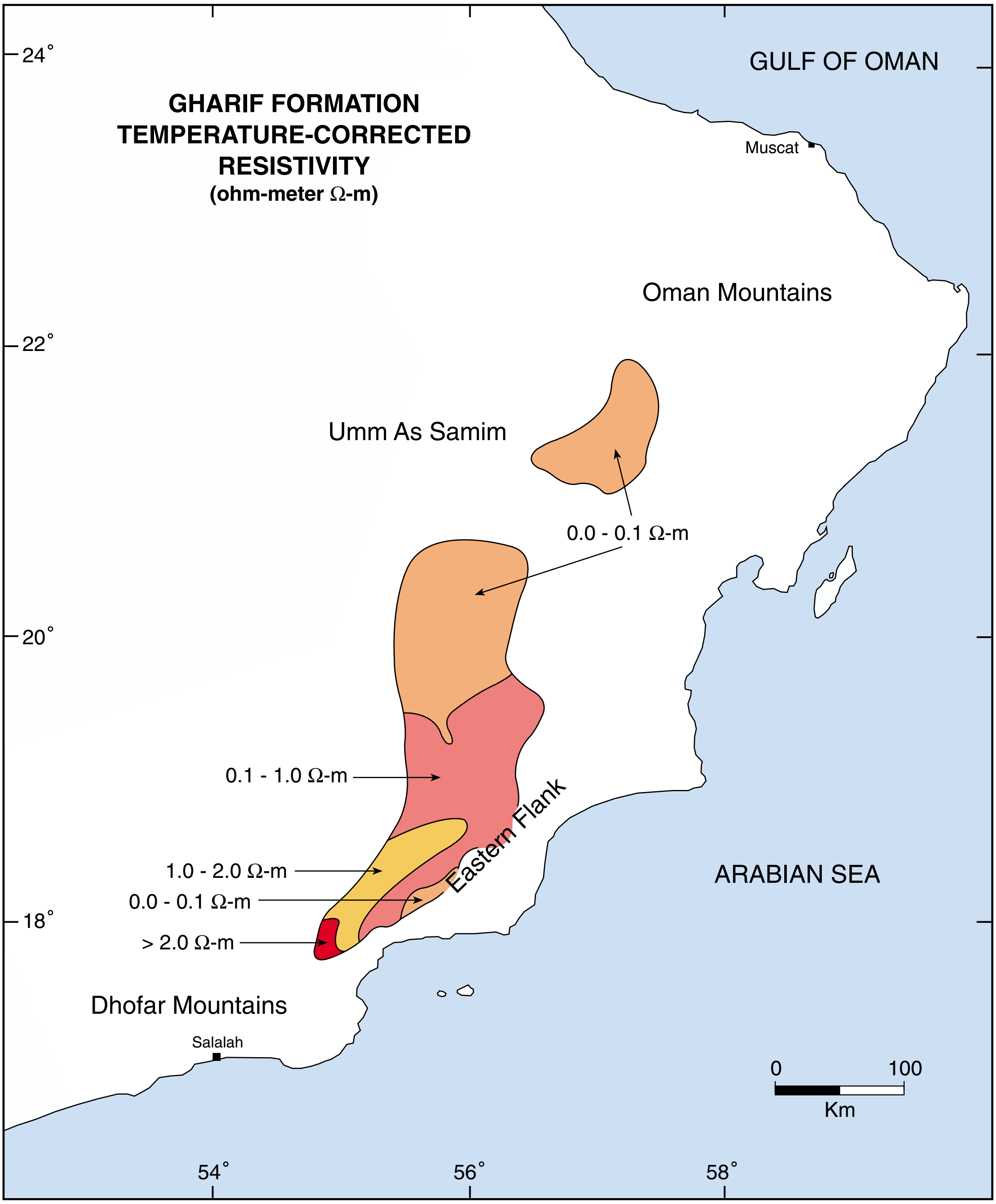

Figure 8: Temperature-corrected resistivity of the Gharif Formation.

Oil Biodegradation

Meteoric water flow in a hydrocarbon-bearing reservoir brings with it nutrients and oxygen for bacteria that degrade oil. It is therefore expected that oils in regions closer to meteoric water recharge will suffer biodegradation more frequently than regions further along the flow path where salinity and temperature are higher. Many oil consuming bacteria are aerobic and do not survive unless their nutrients as well as oxygen are replenished. In addition, such bacteria do not survive well in water temperatures exceeding 80°C (Peters and Moldowan, 1993).

Oil gravity data for the Haushi Group (Figure9), illustrate a str ong correlation between biodegradation and water salinity: along the Eastern Flank of the Oman Salt Basins gravities average around 15° API, whereas closer to center of the basins, where high salinity water is found, the gravity is higher than 30° API.

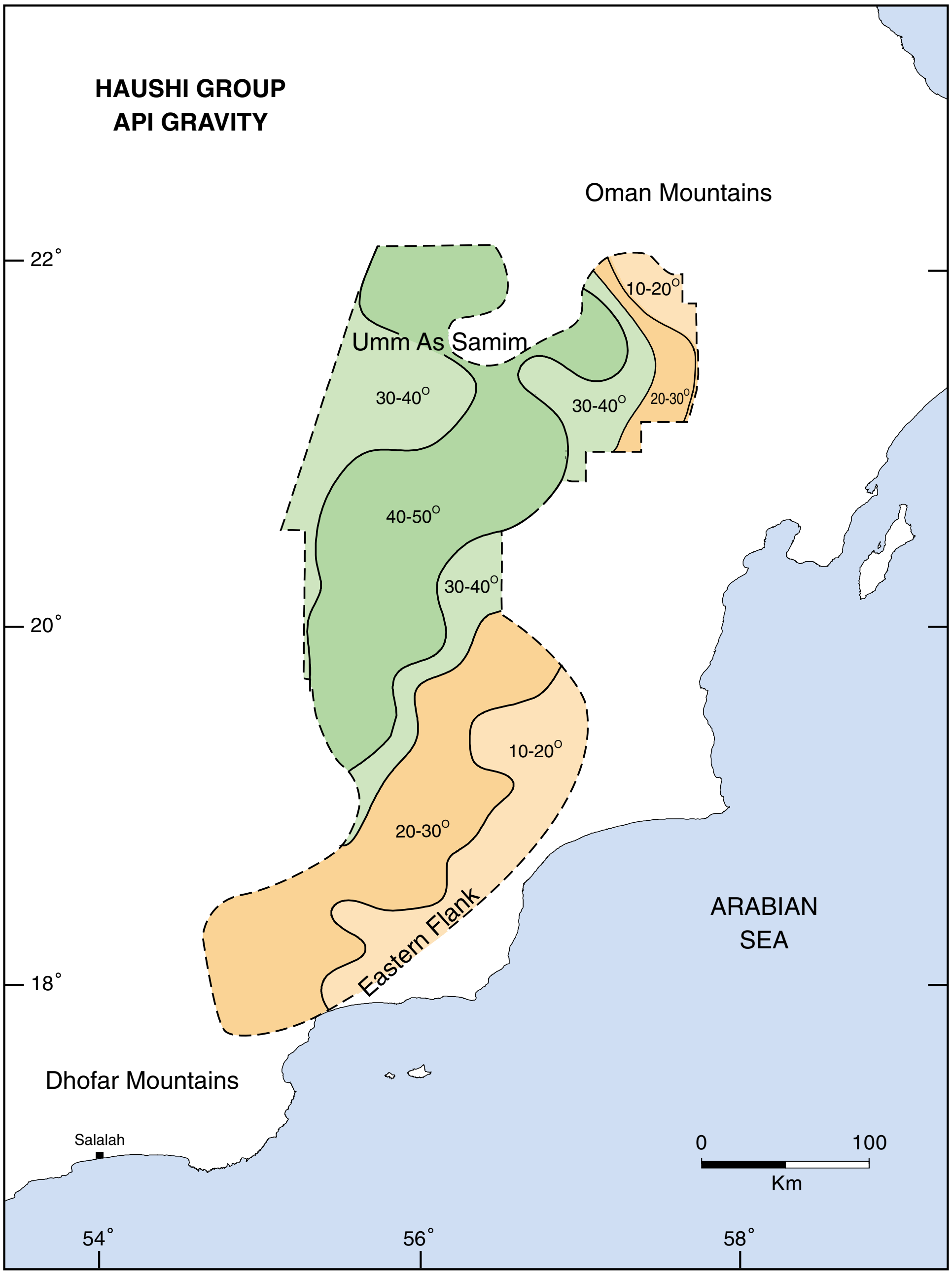

Figure 9: The API gravity of oils in the Upper Paleozoic Haushi Group correlates with the higher salinity (Figure 6).

The oil quality in Central Oman (green area in Figure 9) reflects the highly mature charge from a different source rock. The oil quality in this area is primarily determined by southward migrating Q oil (Guit et al., 1995), which is not affected by biodegradation in this region of highly saline waters (>200,000 mg/L).

The role of hydrodynamics prior to Oligocene-Miocene times, when the main recharge areas developed, is speculative. Early uplift of the Eastern Flank coincided with glacial conditions during Permo-Carboniferous time. Strong hydrodynamic activity may have taken place during the subsequent deglaciation in later Haushi (Gharif) fluvial deposition. For the most part of the subsequent geological history Oman enjoyed a submarine environment. The long lived Huqf axis to the east of the country is likely to have remained high for most of Oman's geological history. The gravity of Paleozoic oils (Figure 9) suggest that biodegradation, observed in the east and south may have initially been influenced by recharge along this Huqf axis.

CONCLUSIONS

The Oman Basin is a classic hydrogeological basin in which recharge to the basin takes place in topographically elevated areas both to the north and south of the country. Hydrodynamic flow takes place on a basinwide scale with no intervening localized recharge-discharge systems. The direction of flow is manifested by differences in fluid potential, by variations in total dissolved solids (TDS) and by differences in temperature gradients. The low salinity waters observed in the oil producing reservoirs, the Ordovician Haima Group and the Permian Haushi Group, indicate cross-formational flow of meteoric water. Radiocarbon dating of water from the Tertiary and the Permian (Haushi) aquifers confirms cross-formational flow with ages of 10,000 and 30,000 years respectively suggesting flow rates of about 10 m/y in the Tertiary aquifer and 3 m/y in the Paleozoic aquifer. Oil gravity evidence suggests, at least in part, that existence of heavy oils are close to meteoric water influx. Salinity values are easily convertible to resistivity values. The latter can be used effectively to reduce uncertainties in petrophysical evaluations.

ACKNOWLEDGEMENT

The authors wish to thank the Ministry of Petroleum and Minerals and Petroleum Development Oman for their permission to publish this paper. Thanks are also due to Dr. M. Naylor and Dr. P. Nederlof and Mr. M. Ormerod for their stimulating discussions. The manuscript improved significantly from the helpful comments and suggestions from three anonymous reviewers. The authors also thank Gulf PetroLink for their assistance in redrafting the figures.

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Paper presented at the 2nd Middle East Geosciences Conference and Exhibition, GEO'96, Bahrain, 15-17 April 1996

Manuscript Received 7 October, 1996

Revised 2 November, 1996

Accepted 5 November, 1996