AN INITIAL ASSESSMENT OF THE HYDROCARBON POTENTIAL OF THE KHARAN BASIN, WESTERN BALOCHISTAN, PAKISTAN

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ABSTRACT

The Kharan Basin is located in a remote western part of the Balochistan Province of Pakistan and is entirely obscured by superficial deposits of the Kharan Desert. The arealy extensive basin is bounded to the north by volcanic arc complexes of Late Cretaceous-Recent age whilst to the south a series of hills are the most northerly surface expression of a Tertiary flysch belt that forms part of the large Makran Accretionary Prism. The subsurface nature of the Kharan Basin is entirely unproven but it is generally regarded as a Tertiary forearc basin within a trench-arc system that developed as the Neo-Tethys Ocean was subducted northwards beneath the continental Afghan Block.

During 1998-99 Murphy Pakistan Oil Company (MPOC) undertook reconnaissance work to assess the hydrocarbon potential of the Kharan Basin. Plate reconstructions, remote-sensing imagery, published geological maps and reports together with fieldwork provided regional context. A new airborne magnetic and gravity survey was acquired over the southern half of the basin. Integration of these data suggests that the Kharan Basin contains up to 7km of highly deformed Tertiary flysch that is partly underlain by oceanic crust.

The area surrounding the basin is thermally overmature and no hydrocarbon seepages or potential source rocks have been identified. The widespread multi-storey clastic turbidites of the Miocene Panjgur Formation appear encouraging for reservoir development, but at outcrop they are tightly folded, cleaved lithic arenites with negligible porosity and permeability. Eocene turbiditic limestones are of limited areal extent and would rely on fracture porosity to be effective reservoirs. It seems reasonable to anticipate that the interbedded shales in the Panjgur Formation would form effective seals to a variety of compressional structural traps but only seismic data and drilling will confirm whether these play elements combine to form a productive hydrocarbon system.

INTRODUCTION

The Kharan Basin covers approximately 30,000 km^2 and is entirely obscured by superficial deposits of the Kharan Desert, a regional depression approximately 500m above mean sea level located 450km northwest of Karachi and 400km southwest of Quetta (Fig. 1).

The desert, characterised by shifting sand dunes and ephemeral playa-lakes, forms part of the Mashkel Depression. Elevations rise to the north towards the Ras Koh Range where the highest peak is 3,000m above mean sea level and to the south towards the east-west trending Siahan Range where elevations exceed 2,000m. The climate is extreme with average

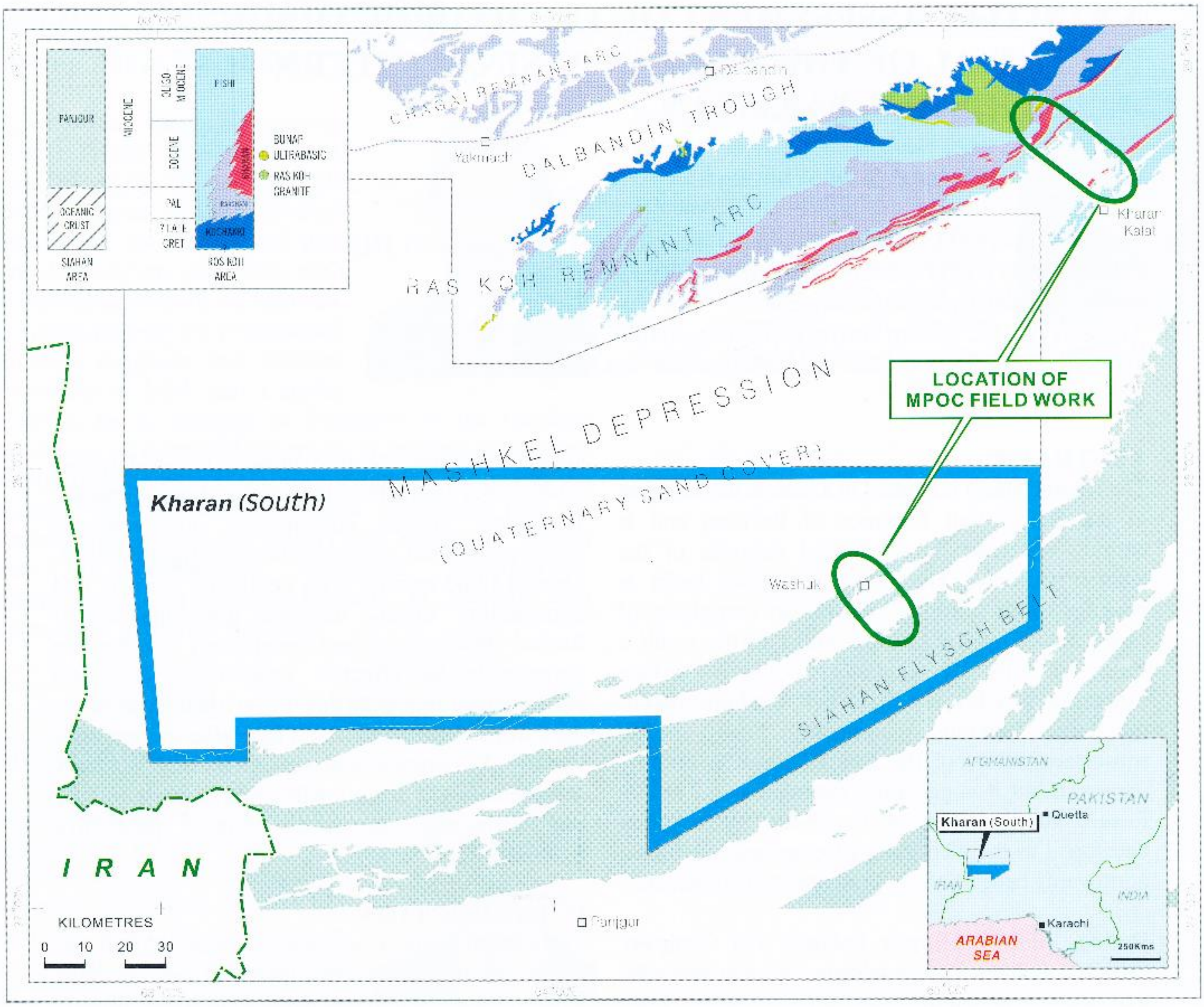

Fig 1 - Kharan Basin Geological Setting

summer temperatures of 45°C, falling to as low as -4°C in winter. Rainfall is generally less than 150mm per year and most falls in brief storms with flash flooding down the few watercourses.

The main objectives of this paper are to describe the results of the exploration reconnaissance programme carried out by MPOC during 1998/99 and to comment on the hydrocarbon potential of the Kharan Basin.

EXPLORATION HISTORY

Prior to October 1998, only very limited exploration activity directed solely towards the search for hydrocarbons had been performed within the Kharan Basin.

An early pioneering geological reconnaissance of the Balochistan Desert was made by the Geological Survey of India in 1900 (Vrendenburgh, 1901). However, the lithostratigraphy of the area was not established until 1960, when field surveys were carried out by Hunting Survey Corporation under the Colombo Plan in a joint project with the Canadian and Pakistan Governments. During the 1960's further revisions were undertaken mainly in the well exposed Chagai and Ras Koh areas by the Geological Survey of Pakistan (GSP). In 1963, the USSR sponsored a reconnaissance survey to provide information on the geology and petroleum prospects of the Kharan Desert and surrounding regions.

A geological field survey was undertaken by MPOC during March 1999. The field party operated from two base camps in Kharan Kalat and Washuk (Fig. 1) and undertook detailed stratigraphic and structural studies on sequences that plunge beneath the Quaternary cover of the Kharan Basin.

Prior to 1999 the only available potential fields data to have been acquired within the Kharan area were two aeromagnetic surveys sponsored by the USSR in 1962-63 and by Canada in 1976-77. The latter survey totalled approximately 125,000 line km of data over NW Balochistan, as far south as 28°N. In 1981 Alan Spector & Associates were awarded the contract to interpret these data and their maps have been reviewed by MPOC. The GSP has also compiled a Bouguer gravity map over the area to the northeast of the Kharan Basin and this was used by the Oil and Gas Development Corporation Ltd. (OGDCL) in evaluating the hydrocarbon potential of the area.

In 1999 the US contractor Carson Services Inc. completed an airborne potential fields survey over the Kharan Basin south of 28°N on behalf of MPOC (Fig 1.) Approximately 7,359 line km of airborne gravity and 8,771 line km of airborne magnetic data were acquired. Due to the variation in topographic relief between the desert area in the north and Siahan hills in the south, the survey was flown at two different altitudes. Both gravity and magnetic data were collected at a 1.0 second sample rate in a 6x6km grid.

Satellite imagery cover is available, including both Landsat MSS and TM data. A proprietary structural interpretation based on Landsat MSS was commissioned by MPOC and undertaken by Nigel Press Associates (NPA) in 1991. This study was enhanced in 1998 when NPA acquired Landsat TM coverage and produced a revised structural interpretation report. These data together with six Advanced Very High Resolution Radiometer scenes were used to produce a Thermal Basin Screening interpretation for the Kharan area.

DATABASE

Up until 1999 the available database was rudimentary and comprised surface geological maps at a scale of 1:253,440 (4 miles to 1 inch), published in 1958 and a 1:2,000,000 scale geological map published in 1964 under the joint auspices of the GSP and the US Agency for International Development. More recently several geological maps at a scale of 1:50,000 have been produced by the GSP and these were available for inspection at their office in Quetta. The Hunting Survey report of 1960 included a number of references to the Kharan area. In addition, various published papers, regional reports and the potential fields and remote sensing data, as noted above, were available.

GEOLOGICAL SETTING AND BASIN EVOLUTION

The western Balochistan region of southwestern Pakistan is a tectono-stratigraphically separate area from the rest of the country. It is bounded by the Ornach-Nal and Chaman faults in the east and the Afghan Block in the north. All available geological evidence suggests that the Makran is a trench-arc subduction system that has been active from the late Cretaceous, with oceanic crust currently being subducted beneath the Makran Accretionary Prism (Fig. 2). The suture zone between the Afghan Block and the Makran Accretionary Prism is believed to lie beneath the Kharan Desert. The region can thus be divided into two separate tectonic sub-provinces, namely the magmatic arc/continental margin in the north and the Makran Accretionary Prism in the south.

Northern Magmatic Arc/Continental Margin

This region comprises a series of present day and remnant volcanic arcs and inter-arc basins to the north of the Kharan forearc basin. The Chagai and Ras Koh arcs formed as a result of the onset of subduction of the Tethyan Ocean beneath the Eurasian continental plate during the late Cretaceous. These two geanticlines are separated by the Dalbandin Trough that is believed to be infilled with several thousand metres of continental and marine sediments together with volcanics. This trough has been interpreted as a forearc basin by Arthurton *et al.*, 1982. However, it is possible that the main forearc basin developed south of the Ras Koh volcanic arc and is currently obscured by the Kharan Desert.

Immediately to the north of the Kharan Desert lies the Ras Koh Flysch Belt that comprises a cleaved, highly folded and thrusted succession of probable Maastrichtian-Paleocene flysch. The flysch contains several ultrabasic intrusions in bedding-parallel lenses up to 15m wide and 1-5km long of sheared rocks that commonly contain chromite. Flysch deformation and obduction, together with tectonic emplacement of the ultrabasics, was aided by compression from the SE as the Indian Plate collided with Eurasia. A similar deformed flysch facies forms much of the Mirjawa Range to the west of the study area but no ultrabasics are present at this location.

The nature of the crust beneath the Kharan Desert remains enigmatic. In the Arthurton *et al.*, (1982) model, the area is underlain partly by the magmatic arc/continental margin and associated deeper, probably intermediate, crust together with the subducting oceanic lithosphere of the Arabian Sea, as it bends beneath the arc. Alternatively, rising magma derived from early melting of the subducting oceanic lithosphere produced sea-floor spreading above the subduction zone, as demonstrated by the supra-subduction model (Pearce *et al.*, 1984). A characteristic of supra-subduction spreading is chromium enrichment in the associated ophiolites; the presence of chromites in the Ras Koh Arc supports this model.

Further to the west in Iran, a belt of chromite-rich ophiolites crop out between the Jaz Murian Depression and the Makran Accretionary Prism to the south, suggesting that this depression is also likely to be underlain by oceanic, and possibly supra-subduction crust.

Whichever model is adopted there is scope to develop a substantial forearc basin beneath the Kharan Desert. No other sediments crop out and the nature of the basin fill will remain conjectural until drilling takes place. However, deep-water turbidites, volcaniclastics and reworked flysch might be anticipated.

Makran Accretionary Prism

Subduction of the Neo-Tethys Ocean beneath the southern margin of the Eurasian plate commenced in the late Cretaceous. This is currently continuing as the oceanic crust underlying the Arabian Sea is undergoing subduction beneath the Makran Accretionary Prism (Fig. 2) at approximately 5cm/year (Khan, Raza and Alam, 1991). Marine seismic work (White and Klitgord, 1976), indicates an approximate 1° northerly dip for the oceanic crust seaward of the accretionary wedge. The top of the oceanic crust in this area is estimated at a depth of 8km. Earthquake data from the Balochistan region support the interpretation of a gently dipping oceanic lithosphere under the Makran Ranges for approximately 200km inland from the present coastline where the dip steepens (Dykstra and Birnie, 1979). This increase in dip occurs beneath the Kharan Desert and the oceanic crust is thought to be over 100km deep beneath the deformed magmatic arc/continental margin where contemporary volcanic activity, as exemplified by the Koh-I-Sultan volcano, occurs.

The subduction process resulted in the obduction of marine flysch and ophiolite remnants onto the southern margin of the Eurasian Plate. Within the northern part of the Makran Range (Siahan Flysch Belt), deep water flysch sediments of Miocene age form the first belt of accreted material. These sediments are all of turbidite and slope mud facies and the outcropping flysch deposits become younger towards the coast. The Makran Accretionary Prism is largely emergent and a set of imbricate north dipping

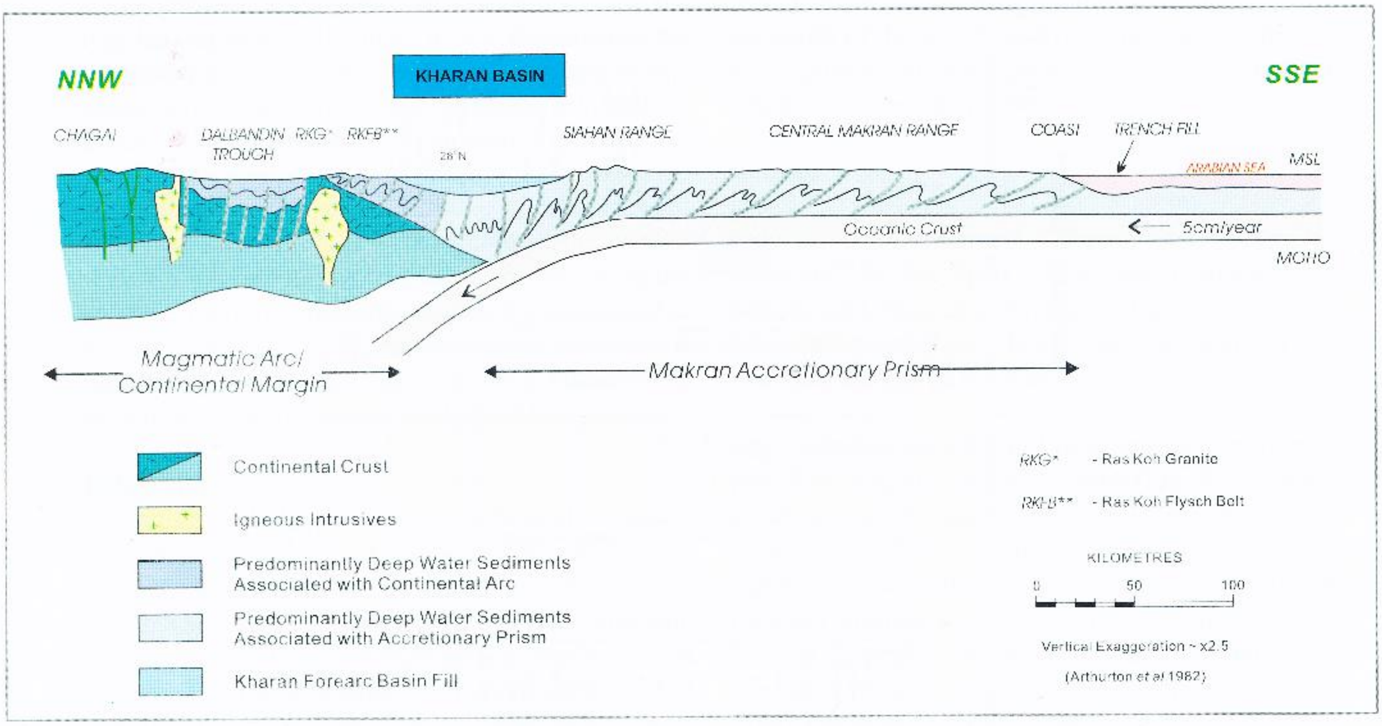

Fig 2 - Schematic Cross-Section from Offshore Makran to Chagai

thrusts has resulted in the creation of a series of east-west trending ridges. The outcrop of supposed ophiolite to the west of Washuk is present within one of these imbricate thrust sheets. It has been estimated (Nigel Press Associates, 1998) that the thrusting has been responsible for shortening of between 50-70% (*i.e.* +/- 200km).

Offshore, low amplitude frontal folds extend to a distance of 150km from the coast out to the abyssal plain

During the mid to late Miocene the Siahan Range began to be uplifted, either due to thrusting related to the sinistral movement along the Chaman Fault or by underplating of subducted oceanic lithosphere. Erosional products, derived from the uplifted area, may have been deposited within the Kharan forearc basin as a series of prograding shelf sandstones and slope mudstones. These deposits are expected to rest unconformably over thrust slices of interbedded flysch turbidites and mudstones.

REGIONAL STRATIGRAPHY

Pre-Tertiary

The presence of Palaeozoic sediments within the region is unproven and only a few remnants of Mesozoic aged sediments remain in NW Balochistan. Upper Cretaceous volcanics are abundant in the Chagai and Ras Koh areas where they are referred to as the Sinjrani and Kuchakki Groups respectively (Fig. 3). These sequences consist of volcanics and thin beds of shale, sandstone and limestone. Grey, green and black agglomerates and volcanic conglomerates are the dominant rock types but variegated fine-grained tuffs and porphyritic andesitic lava flows are also present. The maximum thickness measured in the field is 1,200m as the lower contact is not exposed (Kadri, 1994) but it is reported that the entire section may be up to several thousand metres thick within the Chagai Arc.

On the flanks of the Chagai Arc, the Sinjrani Group are overlain by the Humai Formation, which largely consists of shallow water fossiliferous limestone,

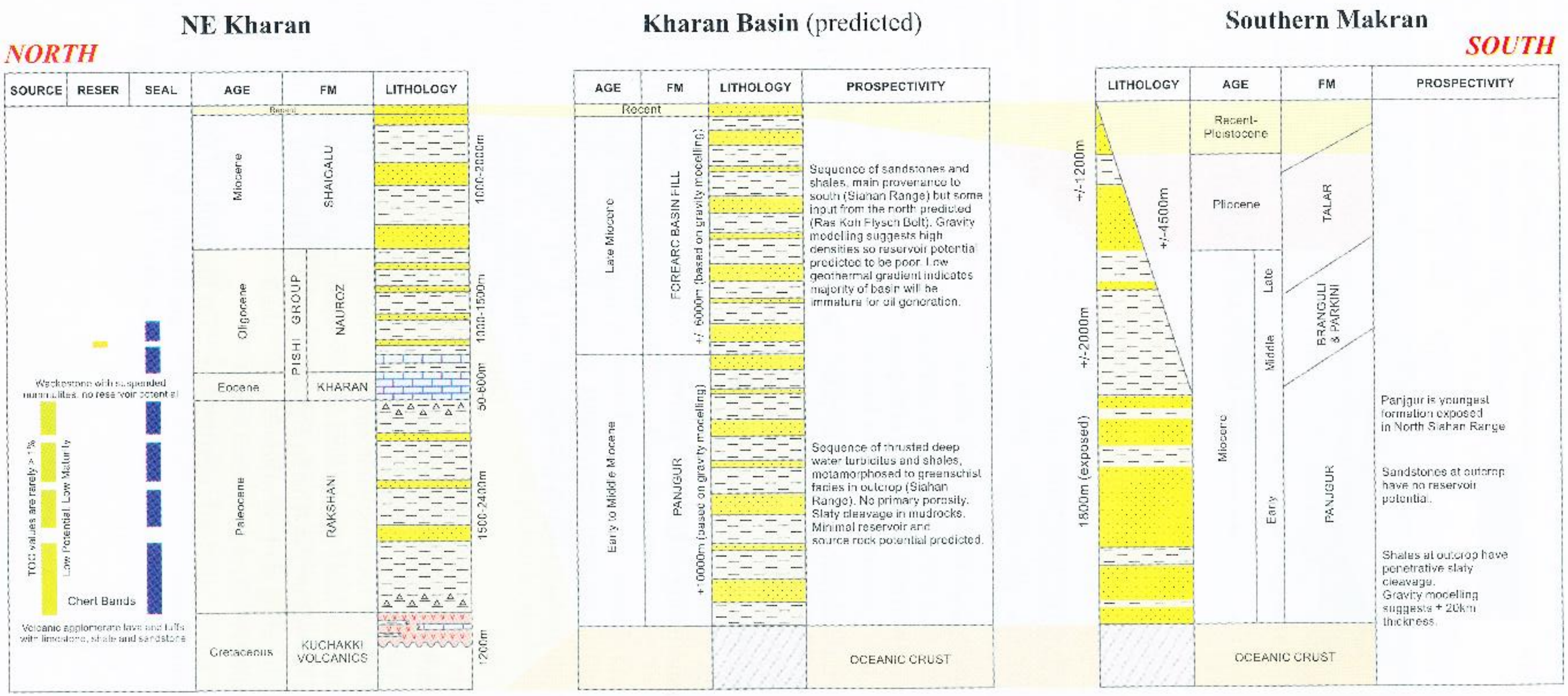

Fig 3 - Western Balochistan Generalised Stratigraphy shale, siltstone and occasional volcanics. Near the type locality at Koh-i-Humai, in NW Balochistan, the formation is composed of greenish grey and purple shales, calcareous sandstones, siltstones, thin-bedded limestones and volcanic conglomerates in the lower part and massive, dense, fossiliferous limestone in the upper part. A thickness of 300m is reported from Mazenen Rud (Kadri, 1994). Although the contact with the Sinjrani Group is unconformable along the southern margin of the Chagai Hills it is conformable everywhere else. The Humai Formation has not been recognised within the Ras Koh area but may be present at depth below the Rakhshani Formation.

Paleocene

During the Paleocene the Dalbandin Trough, developed between the Chagai and Ras Koh arcs. Several thousand metres of marine mudstones with thin limestones, conglomerate lenses volcanic boulders and localised tuffaceous horizons, all attributed to the Rakshani Formation, accumulated therein (Fig. 3). The clastics and subordinate limestones occur throughout the formation whilst the cherts and agglomerates have only been observed near the top and base of the formation. Within the upper part of the the formation evidence of shoaling is demonstrated by the presence of reefal/oncolitic limestones and cross-bedded sandstones. The thickness of the formation varies considerably from 150m to a maximum of 2,400m south of Robat (Kadri, 1994).

The Rakshani Formation includes a number of igneous intrusions within the Ras Koh Range. These consist of syenodiorite and granodiorite which mainly form large discordant masses up to several kilometres wide. Smaller scale, semi-concordant pods and more continuous lenses of occasionally serpentenised ultrabasic rocks are also present. Individual lenses up to 1.5km long and 15m wide are reported (Hunting Survey, 1960). Whilst some of these appear to cross-cut stratigraphy and have an intrusive origin, others are clearly concordant and may represent sea-floor basalts.

During the Paleocene, obduction of the deep water (Ras Koh) flysch sediments, that were deposited to the south of the Ras Koh Arc commenced. The Ras Koh ophiolite assemblage was thought to have been emplaced at the same time.

Eocene

Relatively undeformed Eocene to Oligocene sediments of the Pishi Group that comprises the Kharan and Nauroz Formations (Fig. 3) overly the Rakshani Formation. These are exposed on the southern margin of the Ras Koh Range.

The early Eocene Kharan Limestone is a medium to dark grey nummulitic wackestone (Fig. 4a) which is generally thick bedded (up to 2m thick) and occasionally massive. Interbeds of grey to brown calcareous shale and grey to greenish brown, fine to medium grained sandstones are also present. The Kharan Limestone is reported to attain a maximum thickness of 600m (Kadri, 1994) although it is only 50m thick at Kharan Kalat where it forms a prominent ridge. The Kharan Limestone was deposited in a deep marine basin as a series of calci-turbidites (MPOC internal report, 1999).

Neogene

The overlying Nauroz Formation forms an area of low relief and is shale dominated with subordinate sandstones, limestones and conglomerates. The shales weather to a dark green or maroon colour but on fresh surfaces they are grey. The sandstones are up to 3m thick and are fine to coarse grained and generally calcareous, weathering to a dark brown colour. Sandstones are more common towards the top of the succession as the formation coarsens and thickens upwards. The lower part of the formation is believed to be middle Eocene in age, based on foraminiferal assemblages, whilst an Oligocene age for the upper part is inferred (Hunting Survey, 1960). The Nauroz Formation is some 1,000-1,500m thick and is thought to have been deposited in a deep marine basin.

During the Oligocene, the arc complexes underwent considerable uplift. Subsequent deposition is thought to have been restricted to the Dalbandin Trough where estuarine/fluviatile sediments of the Shaigalu Formation accumulated. These sediments do not impact the prospectivity of the Kharan Basin and are not discussed further.

To the south of the Kharan Basin thick packages of diachronous Neogene sediments present problems in terms of stratigraphic terminology and correlation. Furthermore, being syn-orogenic sediments that have accumulated in an accretionary wedge, extensive reworking has taken place. The Neogene sediments, which comprise the Makran Accretionary Prism, have been differentiated on the basis of four main facies associations (Platt *et al.*, 1985). Only the oldest, the Panjgur, is exposed in the Siahan Range that flanks the southern edge of the Kharan Basin (Fig. 1). Detailed examination of the Panjgur Formation in the vicinity of Washuk revealed two main lithofacies, namely:

Lithofacies 1

This lithofacies consists of massive to thickly bedded (up to 5m), buff or light grey, tight, quartz rich, fine to medium grained sandstones (Fig. 4b). Individual beds are often of uniform thickness and laterally continuous over 100's of metres, commonly occurring as stacked, multi-storey sand bodies up to 75m thick. The bases of the beds are loaded and invariably show sole marks that indicate palaeo-flow directions towards the west. Pebble size mud intra-clasts are present in some of the massive sandstones and are generally observed at or near the base of the bed. The beds fine up through parallel laminated centres to current-rippled tops.

Lithofacies 2

This lithofacies comprises thinly bedded, laterally continuous, fine grained sandstones within a mudrock-dominated sequence. Individual beds vary from 5-50cm thick but are commonly less than 10cm. They have flat, sharp bases and wavy tops formed by asymmetric current ripples that define the local flow direction. Internally the central part of the bed is parallel laminated and occasionally the tops are gradational. Sandstone lenses are also common in this lithofacies. In general, Lithofacies 2 coarsens and thickens up beneath Lithofacies 1.

The sedimentary features of the Panjgur sandstones indicate rapid deposition. The lateral continuity of the sandstones (Fig. 4c), the presence of a marine fauna and the unidirectional flow direction indicated by sole structures are consistent with a turbidite origin. This facies is interpreted as a submarine fan complex derived from the rising axial foldbelt that developed along the Chaman Fault Zone located approximately 200km to the east.

The Panjgur Formation passes conformably upwards into the Parkini Formation, which comprises slope mudstones, via a transitional facies association known as the Branguli Formation, of middle Miocene age. These sediments, and the Plio-Pleistocene Talar Formation were deposited many kilometres to the south of the Kharan Basin and did not contribute to the forearc fill.

To the north of the Makran Accretionary Prism, volcanism resumed in the Pleistocene, possibly as a result of an increase in the rate and angle of subduction. The Koh-i-Sultan volcanic centre and other volcanoes to the west in Iran were responsible for the extrusion of andesitic lava flows. Magnetic data indicates the probable presence of thick deposits of volcaniclastic sediments within the northwestern part of the Kharan Basin.

POTENTIAL FIELDS DATA

Potential fields data available over the Kharan area are summarised in Table 1.

In 1999 Carson Services Inc., on behalf of MPOC acquired airborne gravity and magnetics data over the Kharan Basin south of 28°N. Due to the large difference in elevation across the area data, was acquired at two different flight altitudes. The flight elevation was 1,036m above mean sea level in the northern part of the block and at 2,310m above mean sea level in the south, with an overlap of between 6 and 12km. The lines were flown in a NE-SW and NW-SE orientation with a 6km spacing. This grid

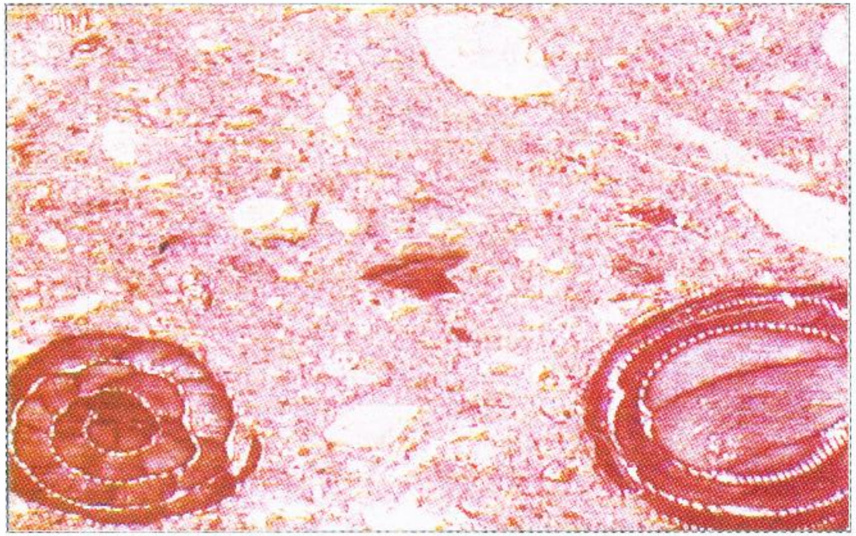

Fig 4a - Photomicrograph of nummulitic Kharan Limestone, near Kharan Kalat

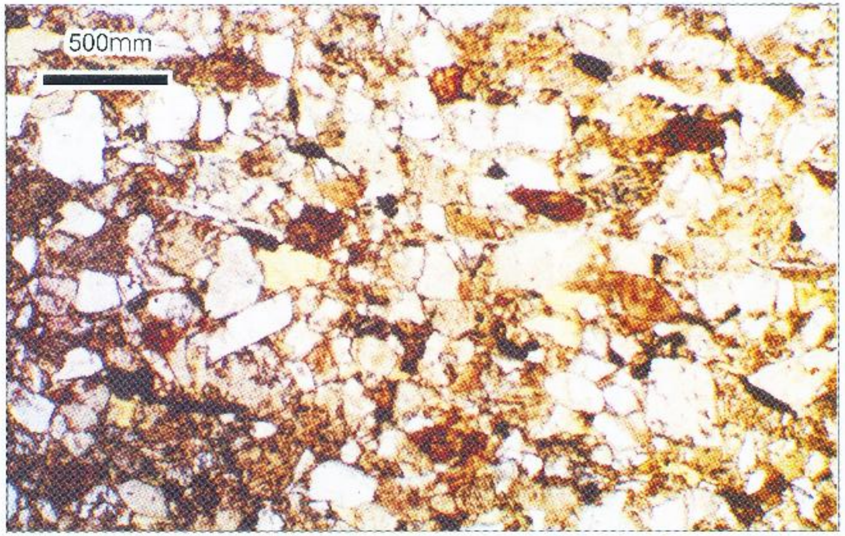

Fig 4b - Photomicrograph of fine-grained Panjgur sandstone, near Washuk

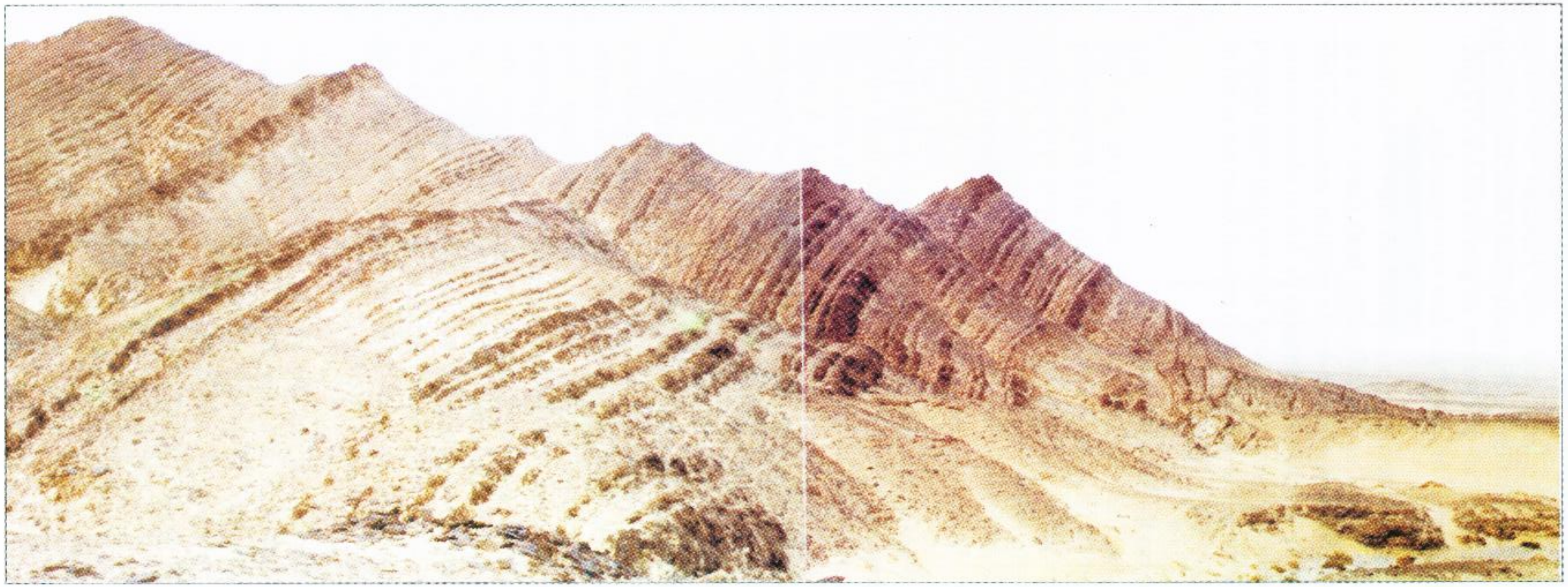

Fig 4c - Photograph of Panjgur sandstones and shales (Lithofacies 1), near Washuk was chosen to coincide with the regional dip and strike directions and was expected to resolve anomalies with wavelengths greater than 3km. A total of 7,359 line kilometres of gravity and 8,772 line kilometres of magnetics data were recorded.

The proprietary data acquired for MPOC has been interpreted and modelled by both Carson Services Inc. and Ark Geophysics. In addition, magnetics data compilation was undertaken by Ark in which the data from the large Canadian (CIDA) project were merged with the Carson data set to provide coverage north of 28°N.

Gravity Interpretation

The Carson Bouguer gravity map (Fig. 5) was produced using a Bouguer density of 2.67gm/cc for the terrain correction. Bouguer gravity values range from -50 milligals in the north to -110 milligals in the southwest, this substantial difference being attributed to density contrasts in the deep crust.

A broad, low frequency 30 milligal gravity high, trending E-W, dominates the northern limit of the survey area which is located to the south of the Ras Koh Range and beneath the Kharan Desert. A broad gentle low is observed to the south and east along the North Siahan Range, creating a distinctive gravity gradient

Both the Bouguer and mathematical residuals show similar characteristics. The 5km upward continued residual map (Fig. 6) is believed to represent changes in density contrast within the uppermost few kilometres of the sedimentary section and is therefore of great interest. In the eastern half of the survey area NE-SW trending anomalies are interpreted as representing thrust related structures, parallel to the Ras Koh and Siahan Ranges. These anomalies are segmented by cross-cutting faults that broadly parallel the Chaman Fault Zone.

A broad NE trending gravity high is located in the north of the area near the 28°N and 64°E intersection. This high is thought to represent the Amiri Belt (Spector *et al.*, 1985), an old, deeply buried volcanic arc system running to the south of the Ras Koh Range. For modelling purposes this anomaly has been assumed to mark the location of the suture zone between the accretionary prism complex to the south and the deformed continental/magmatic arc to the north.

A long, relatively narrow, positive anomaly is located near Washuk, in the eastern part of the survey area. The asymmetric nature of the anomaly, with its segmented NE-SW strike, may be interpreted as a thrusted basement block parallel to the Siahan Range. The segmentation represents several, smaller, younger faults that trend almost parallel to the Chaman Fault Zone. Several elongated narrow lows surround these highs.

The predominant strike direction in the central part of the survey area swings from E-W to NW-SE in the direction of Iran. The areally large negative anomaly located in the southwestern part of basin was considered as representing a possible sedimentary basin and this was the basis for locating one of the profile models.

Magnetics Interpretation

The magnetic anomaly map (Fig. 7) shows similar characteristics to the gravity maps, with the more extensive merged magnetic data clearly demonstrating the regional NE-SW trend. The large long wavelength magnetic anomaly straddling 28°N is thought to represent a major intra-basement magnetic susceptibility contrast, which is interpreted as the suture zone.

In detail, the residual magnetic anomaly map (Fig. 8) shows that there is significant variability in magnetic susceptibility within these broad trends. This observation is supported by the small positive anomaly southwest of Washuk that, through MPOC fieldwork, is known to reflect an ophiolite body within a thick pile of clastics.

The residual magnetic anomaly map is also useful for the identification of near-surface igneous rocks. These are concentrated to the north of 28°N where they appear as numerous high frequency, narrow residual anomalies

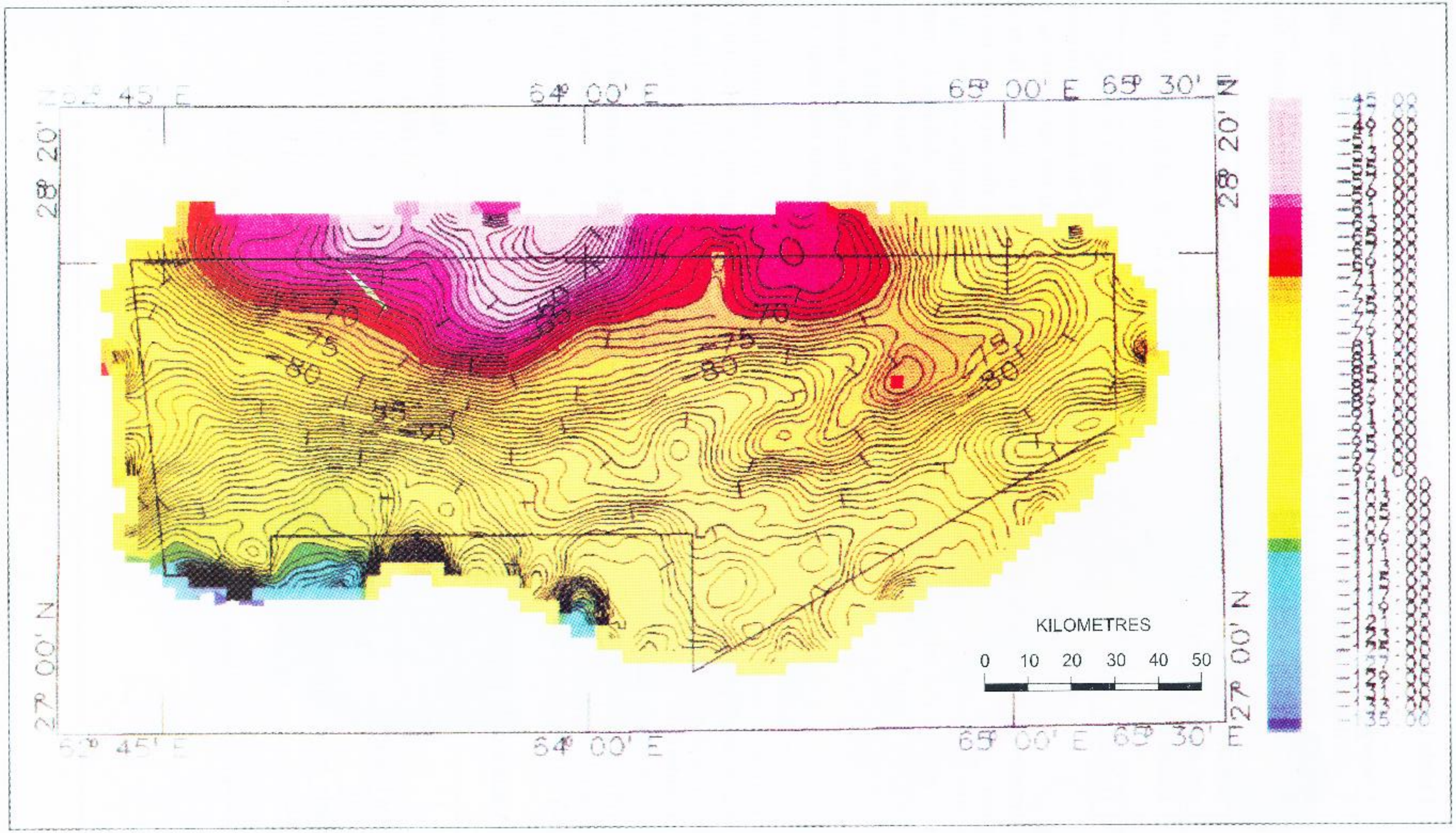

Fig 5 - Bouguer Gravity Map, values in mGals.

Table 1: Potential Fields Data within The Kharan area.

Type	Coverage	Comments
Airborne Gravity	7,359 line km, 6x6 km grid, flight elevation 1,036m and 2,310m above mean sea level.	Acquired by Carson for MPOC in 1999.
Airborne Magnetics	8,772 line km, 6x6 km grid, flight elevation as above.	Acquired by Carson for MPOC in 1999.
Airborne Magnetics	125,000 line km, line spacing 800m to 1,600m, elevation 1,200m to 3,300m above ground level.	Canadian aid project in 1976-77.
Airborne Magnetics	Unknown.	USSR aid project in 1962-63.
Land Gravity	Unknown, but within the Nauroz Kalat area.	GSP project in 1986?

Depth Modelling

Magnetic depth estimates assume that igneous (and some metamorphic) rocks produce magnetic responses while sedimentary rocks generally do not. The depth estimation process also relies on gradients and inflections along the flanks of the magnetic anomalies, regardless of the rock type producing them.

Access to the CIDA magnetics data has allowed Ark to provide depth estimates for the area (Fig. 9). However, the number of depth estimates was limited by the availability of anomalies with well-defined inflection points on individual flight lines. Taking the Kharan Basin as a whole, depths to magnetic basement in the northwest are thought to be shallow, with calculated values of approximately 2km; basement in this area may represent shallow volcanic bodies. The central part of the basin is characterised by depths up to 7km, whilst the more extreme values (up to 11.5km on Fig. 9) are derived from such a large wavelength anomaly that they must be treated with caution. This area is thought to be the site of the suture zone between the deformed magmatic arc/continental margin and the Makran accretionary prism. The shallow depths calculated for the southern part of the area are due to the presence of localised ultrabasic rocks within the Siahan Range.

The Euler's depth estimates for magnetic basement were used for constraining the gravity data in the profile modelling. Two profiles (Figs. 10a & 10b) were modelled by Ark, both constrained to some extent by surface geology. The main objective of the modelling was to ascertain the nature and thickness of the Kharan forearc basin. The assumed density values used in the modelling are listed in Table 2.

Table 2: Density Values used in gravity modelling.

Layer	Density (gm/cc)	Magnetic Susceptibility (nT)
Accretionary Prism Complex	2.59 to 2.72	0.002 to 0.011
Ras Koh Flysch Belt	2.67	0.001 to 0.013
Deformed Magmatic Arc/Continental Margin	2.73 to 2.76	0.010 to 0.059
Oceanic Lithosphere	2.87	0

Note. Magnetic susceptibility values are zero below the Curie isotherm which is at c.16km

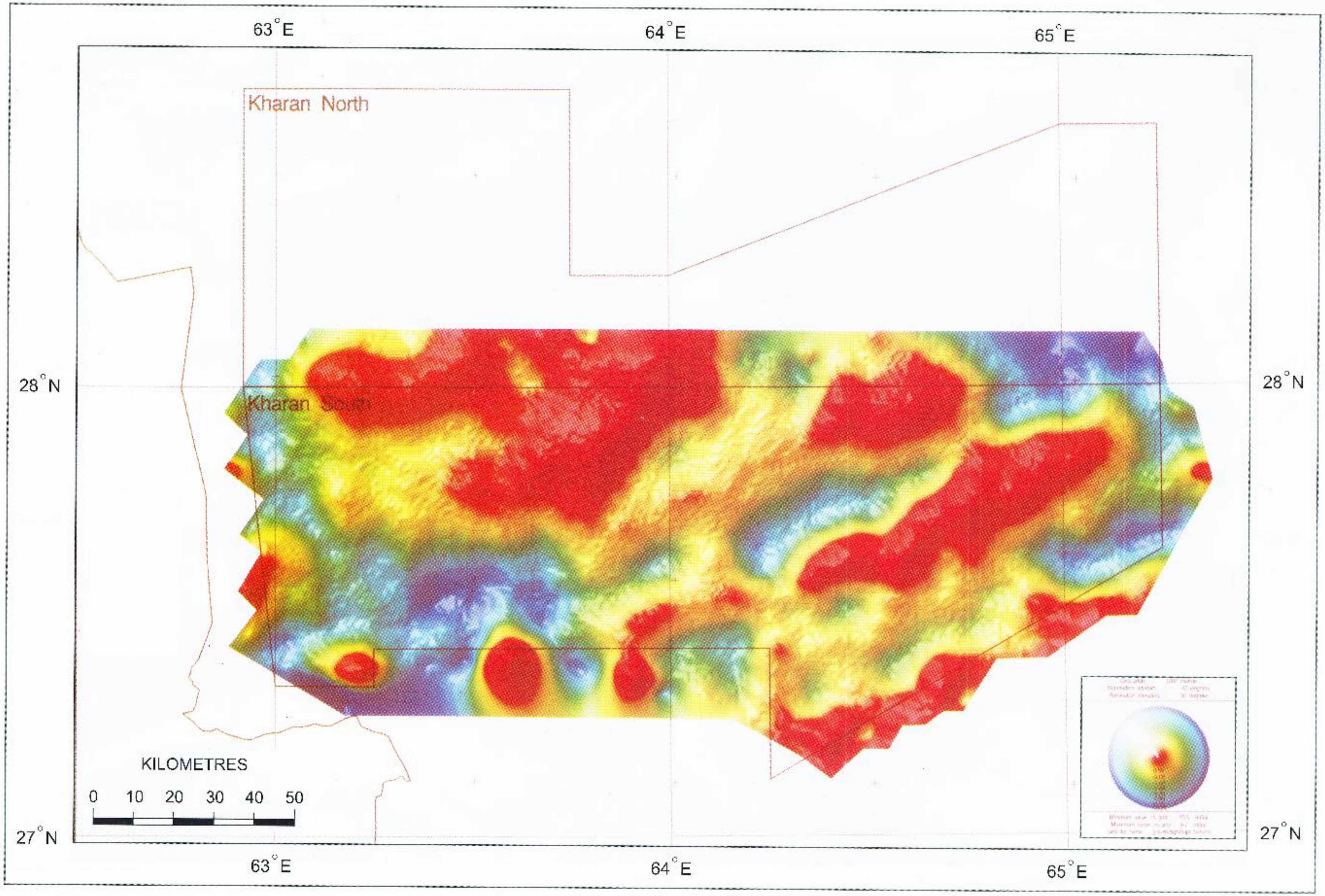

Fig 6 - Residual Bouguer Gravity Map (5 km upward continued), values in mGals, in range -15.3 (blue) to 9.7 (red). Illumination azimuth -45 deg.

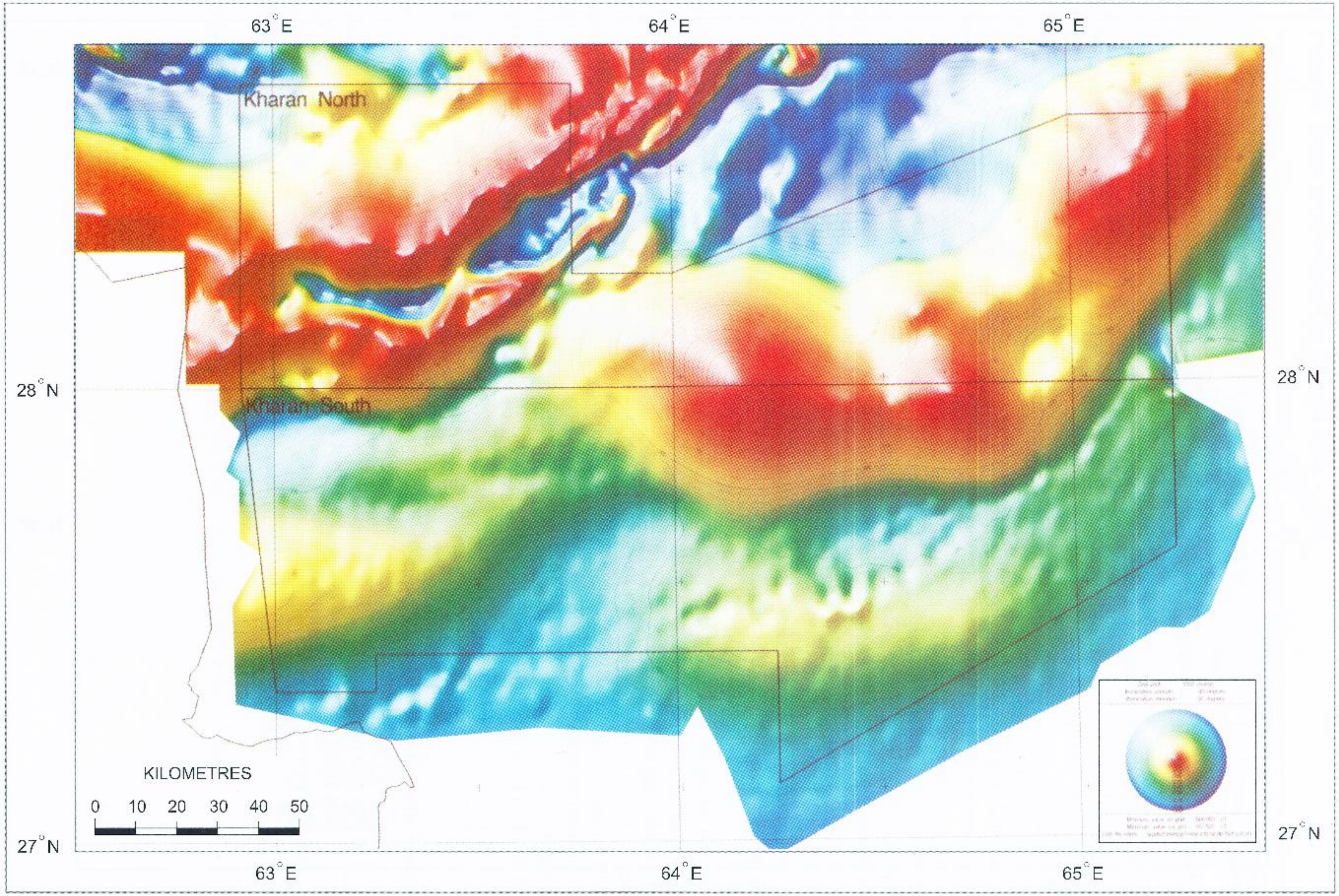

Fig 7 - Magnetic Anomaly (RTP). Values in nT, in range 606 (blue) to 857 (red). Illumination azimuth is -45 deg.

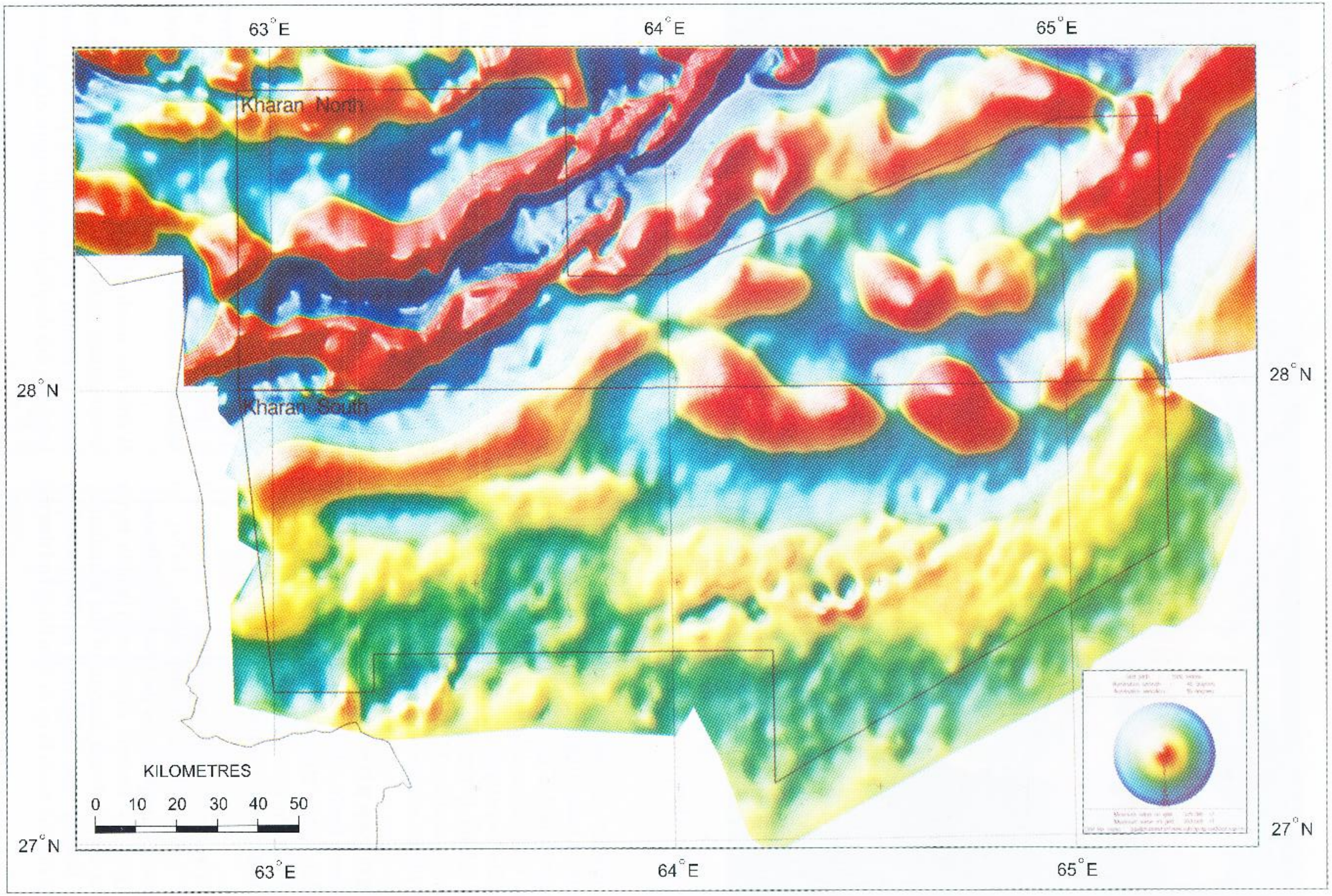

Fig 8 - Residual Magnetic Anomaly (RTP). Values in nT, in range -326 (blue) to 654 (red). Illumination azimuth is -45 deg.

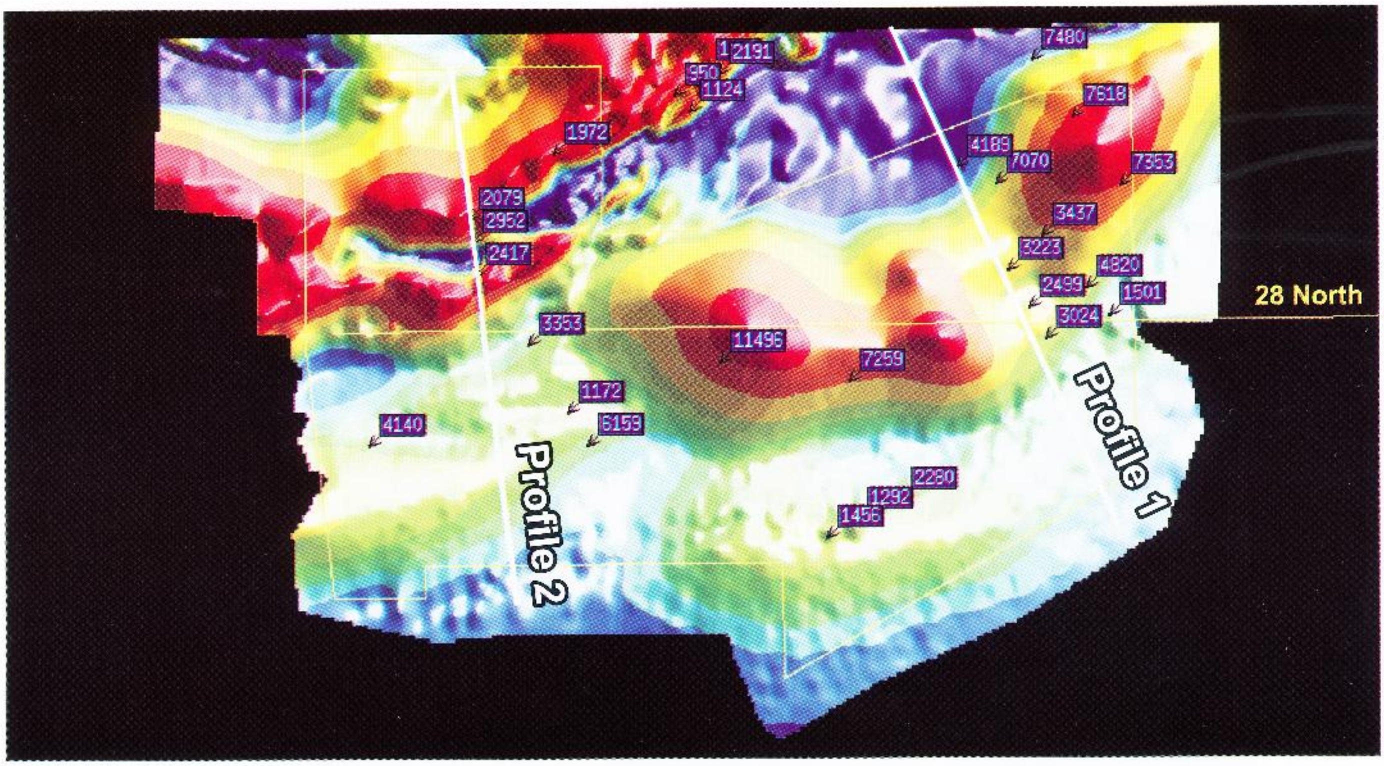

Fig 9 - Magnetic Anomaly Map (RTP) with depth estimates in metres to magnetic basement below survey elevation.

Both profiles suggest that the forearc sediments within the Kharan Basin have high density values in the range 2.63-2.67gm/cc. Attempts to model the profiles using a lower density value of 2.45gm/cc for this section were unsuccessful. The implication from the modelling is that the section lying above the suture zone contains high density sediments that are unlikely to be effective reservoirs.

HYDROCARBON POTENTIAL

The Kharan Basin is believed to have formed during the middle to late Miocene when erosional products, derived from the recently uplifted Siahan Flysch Belt were transported northwards. The basin is referred to as a residual or constructed forearc basin (Dickinson and Seely, 1979), an interpretation supported by the presence of ultrabasic rocks (possibly oceanic lithosphere) within thrust slices at the landward margin of the accretionary prism. Gravity and magnetic profile modelling indicate that the basin is up to 7km thick and that the sedimentary fill will consist of high density material.

SOURCE POTENTIAL

Forearc basins and associated convergent plate margins are generally characterised by young, immature to marginally mature source rocks and low geothermal gradients. The geothermal gradient for the Makran Accretionary Prism is approximately 2°C/100m (Raza *et al.*, 1981), this estimate derived from the following well measurements:

Ketch Band #1	2.4°C/100m
Garr Koh #1	2.6°C/100m
Jal Pari #1	1.4°C/100m

The top of the oil window is expected to lie between 3,500-5,500m. In the absence of well data it is assumed that the Kharan forearc basin will be similar.

Within the north Makran and Kharan areas, field investigations by the GSP and several oil companies failed to identify any oil seeps or potential source intervals, this despite historical reports of an active oil

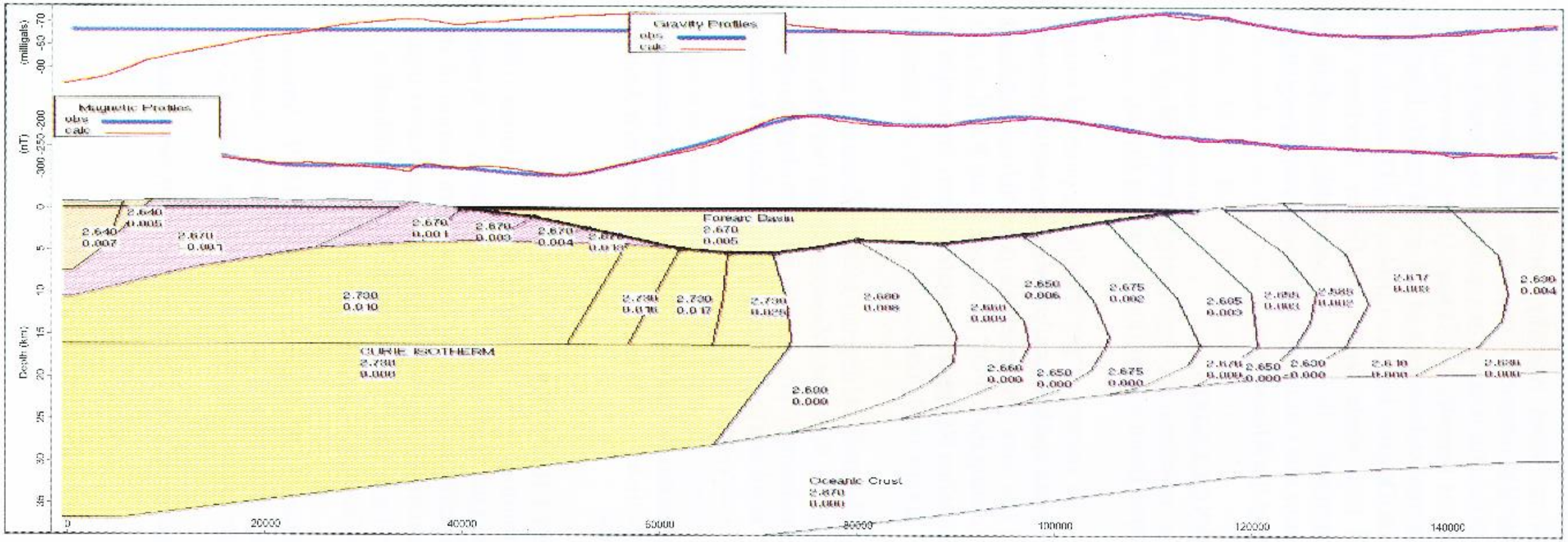

Fig 10a - High Density Model - Profile 1

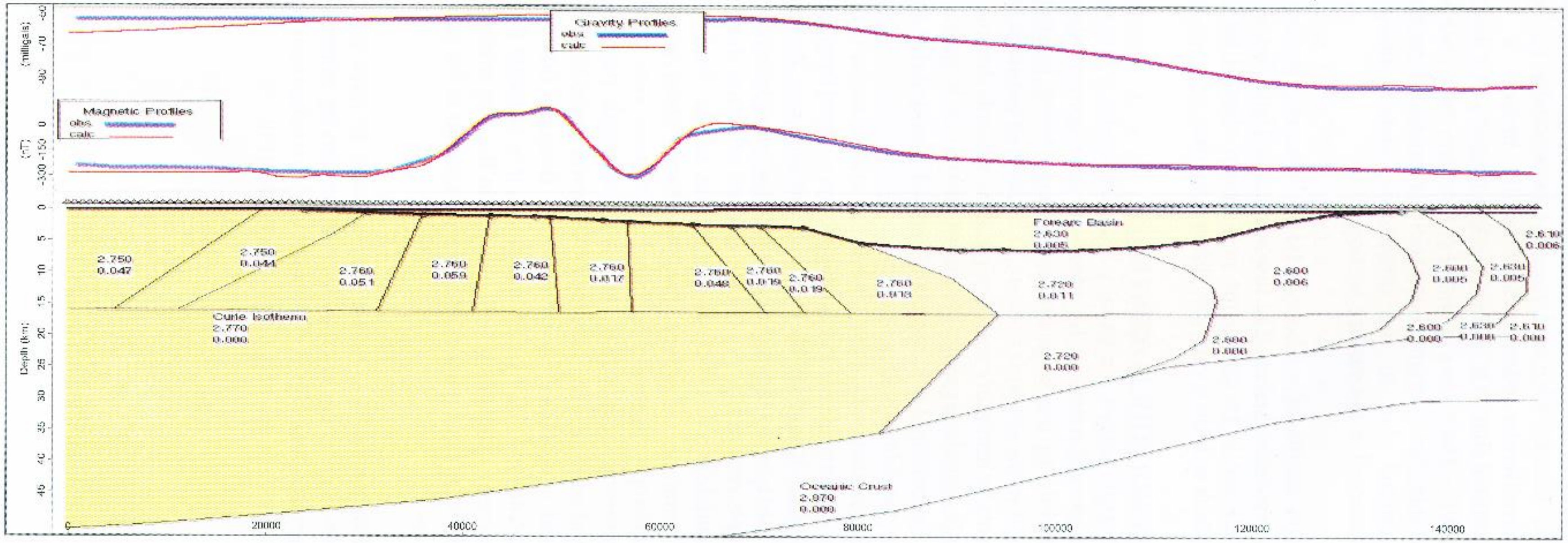

Fig 10b - High Density Model - Profile 2 seep near Kwash (Hunting Survey, 1960). Although the Eocene Kharan Limestone occasionally has a petroliferous odour when freshly broken, it is reported that TOC values are less than 1% (OGDC, 1995). The source potential of the deep-water shales within the Panjgur Formation is predicted to be minimal due to the greenschist metamorphism observed in the surface section.

The results of a Thermal Basin Screening Project were inconclusive. The few anomalies identified are believed to be due to the presence of alluvial fans, which exhibit a very low thermal inertia.

RESERVOIR POTENTIAL

Forearc basins are usually associated with a low to moderate potential for reservoir development, due mainly to the sediment provenance being located within the volcanic backarc. The derived sediment is usually immature and dominated by volcanic detritus, which includes a significant amount of clay minerals. Depositional foci are also frequently shifted due to tectonic instability.

In contrast, within the Kharan forearc, the majority of sediments are believed to have been sourced from the Siahan Range of the Makran Accretionary Prism. Uplift during the middle to late Miocene is thought to have resulted in significant erosion of thrust sheets containing thick clastic sequences of the Panjgur Formation. However, the sandstones observed at outcrop within the Siahan Range have very poor reservoir quality (Fig. 4b), with negligible porosity and permeability. Macroporosity never exceeds 1.5% and is restricted to rare sinuous fractures that are locally infilled by clay minerals. It is possible that some microporosity remains within the clay mineral networks but permeabilities are expected to be very low.

The Kharan Limestone also appears to have poor reservoir potential, the wackestones having minimal primary porosity and no observable development of secondary porosity due to fracturing (Fig. 4a).

TRAP POTENTIAL

Forearc basins typically contain abundant, fault-controlled structural traps but in the absence of seismic data it is not yet possible to identify such features beneath the Kharan Desert. However, the structural style to the east, an area formerly licensed to OGDC, has been confirmed by 2D seismic data and high angle faults and flower structures are recognised. It is not unreasonable therefore to assume that similar structures are present along strike within the Kharan area.

CONCLUSIONS

In conclusion, the hydrocarbon potential of the Kharan Basin is considered to be low due to:

- The absence of any identifiable potential source rocks and hydrocarbon seepages within the area.
- The very low reservoir potential as evidenced during the MPOC fieldwork in the Ras Koh and Siahan Ranges and inferred from the results of gravity modelling.
- The probable absence of any sedimentary section older than the Miocene flysch section, thus reducing the scope for developing plays involving pre-Tertiary source rocks and reservoir intervals.

Due to this lack of encouragement MPOC decided to relinquish the Kharan (South) Concession in January 1999.

REFERENCES

Arthurton, R. S., A. Farah, and W. Ahmed, 1982, The Late Cretaceous-Cenozoic History of Western Balochistan, Pakistan: The northern margin of the Makran subduction complex; in: Trench and Forearc Geology, Legget, J. K, (ed), Special Publication of the Geological Society, v.10, p. 373-385.

Dickinson, W. R., and D.R.Seely, 1979, Structure and Stratigraphy of Forearc Basins; American Association of Petroleum Geologists, v. 63, p.2-31.

Dykstra, J.D., and R.W. Birnie, 1979, Segmentation

of the Quaternary subduction zone under the Balochistan region of Pakistan and Iran; in: Dynamics of Pakistan, Farah and De Jong, eds., Geological Survey of Pakistan, Quetta, p.319-323.
Hunting Survey Corporation Limited, 1960, Reconnaissance geology of part of West Paksitan, Maracle Press Ltd., Toronto, Ontario, 550p.

Kadri, I. B., 1994, Petroleum Geology of Pakistan, published by PPL, 275p.

Khan, M.A., H.A. Raza, and S. Alam, 1991, Petroleum geology of the Makran Region: Implications for hydrocarbon occurrence in cool basins; Journal of Petroleum Geology, v. 14(1), p.5-18.

Nigel Press Associates, 1998, (Unpublished), Kharan Licence Pakistan Structural study.

OGDC, 1995, (Unpublished), Kharan Exploration Licence, Prospectivity Assessment.

Pearce, J. A., et al., 1984. Characteristics and tectonic significance of supra-subduction zone ophiolites; in: Marginal Basin Geology, Kokelaar and Howells, eds, Special Publication of the Geological Society, v.16.

Plains Resources, 1995, (Unpublished) Report on sampling of oil seeps and rock formations from The Jongle Banglow, Bansur, Jhai, Warro, Gish Kuar and Kulak areas of Balochistan.

Platt, J. P., J.K. Leggett, J.Young, H. Raza, and S. Alam, 1985, Large-scale sediment underplating in the Makran accretionary prism, southwest Pakistan; Geology, v.13, p.507-511.

Raza, H. A., R. Ahmed, and S.M. Ali, 1991, A new concept related to structural and tectonic behaviour of Balochistan Basin, Pakistan and its implication on hydrocarbon prospects; Pakistan Journal of Hydrocarbon Research, v.3, p.1-17.

Spector, A., et al., 1985, Application of aeromagnetic data to mineral resources exploration, Baluchistan, Pakistan; in: Utility of Regional Gravity and Magnetic Anomaly Maps, Hinze, J.W., ed., SEG Publication.

Vrendenburgh, E.W., 1901, A geological sketch of the Baluchistan desert and part of eastern Persia; India Geological Survey Memoirs, v31, p.179-302.

White, R. S., and K.D. Klitgord 1976, Sediment deformation and plate tectonics in the Gulf of Oman; Earth and Planetary Science Letters, v.32, p.199-209.

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