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Deep Crustal Studies of Indus Offshore Basin (Pakistan) Using Seismic and Gravity Data

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ABSTRACT: *Deep crustal studies of Indus Offshore basin, using gravity and deep seismic reflection data along the line 9074-86, prognose a speculative crustal picture beneath the seismic line. Steep positive gravity gradient towards south-west of the line, above thick sedimentary strata (greater than 10 Km) in the offshore depression area in the North East, is attributed to a prominent rise in the mantle. Intuitively, extending the depth model beyond the present day shelf break and computing its gravity indicates that the overall gravity effect is one of the typical shelf edge ("Edge Effect") anomalies. The crustal thickness which is approximately 24.5 Km thick towards north-east is reduced to 6.5 Km on the mantle rise and it may be the area of transitional crust. The deep seismic line (15 sec twt) does not show typical lower crustal reflections as shown by COCORP (Consortium for Continental Reflection Profiling) in USA and BIRPS (British Institutions Reflection Profiling Syndicate) in UK. The absence of such reflections in the extensional regime of the Indus Offshore is possibly due to extra-thick sedimentary sequence above the acoustic basement and weak energy source used in the survey. Presence of thick sedimentary rocks of varying lithologies which commonly form source-reservoir-seal trilogies, optimum geothermal gradients, analogies with other basins, oil/gas shows in and around the offshore area, number of structural traps including reefs and "Bright Spots" in sediments ranging in age from Cretaceous to Early Miocene show positive evidence to the presence of hydrocarbons. Furthermore, it is speculated that the younger sediments in the offshore area may have attained maturity, due to thinning of the crust as a consequence of mantle rise in the outermost shelf regions, and may produce hydrocarbons. Lack of data, absence of new technology and equipment, remote and difficult area, high risk and highly expensive zone, and formation pressure hazard may be the main reasons of non-discovery of this hidden wealth.*

INTRODUCTION

Pakistan's Offshore Exclusive Economic Zone (E.E.Z.) extends over an area of almost 2,65,650 sq. Km, bordering the coastline of about 825 Km length in the south of the country between Iran border in the west and Indian border in the east. Offshore Pakistan is divided tectonically into two major divisions (Fig. 1): The Western Makran basin having an oceanic crust (Arabian Plate) and Eastern Indus basin with a continental crust (Indian Plate) with Murray Ridge/Owen Fracture as the dividing line between the two (Raza et al., 1980, 1989 and 1990; Ahmed et al., 1994; Shuaib and Shuaib, 1994; Amir et al., 1996; Siddiqui, 1997).

Biswas (1982) classified the western margin of India as a divergent continental margin whereas, Naini and Talwani (1983) suggested that the margin had evolved from the process of rifting in the late Cretaceous followed by seafloor spreading in the early Paleocene. The Indus Offshore basin falls in the Type IV (Intermediate Crustal type): an Extra-continental Downwarp to Small Ocean Basin combined with Tertiary Delta Basins toward Oceanic Areas of Halbouty (1970) and Klemme (1980) and Extra-continental Trough Downwarp of Riva (1983).

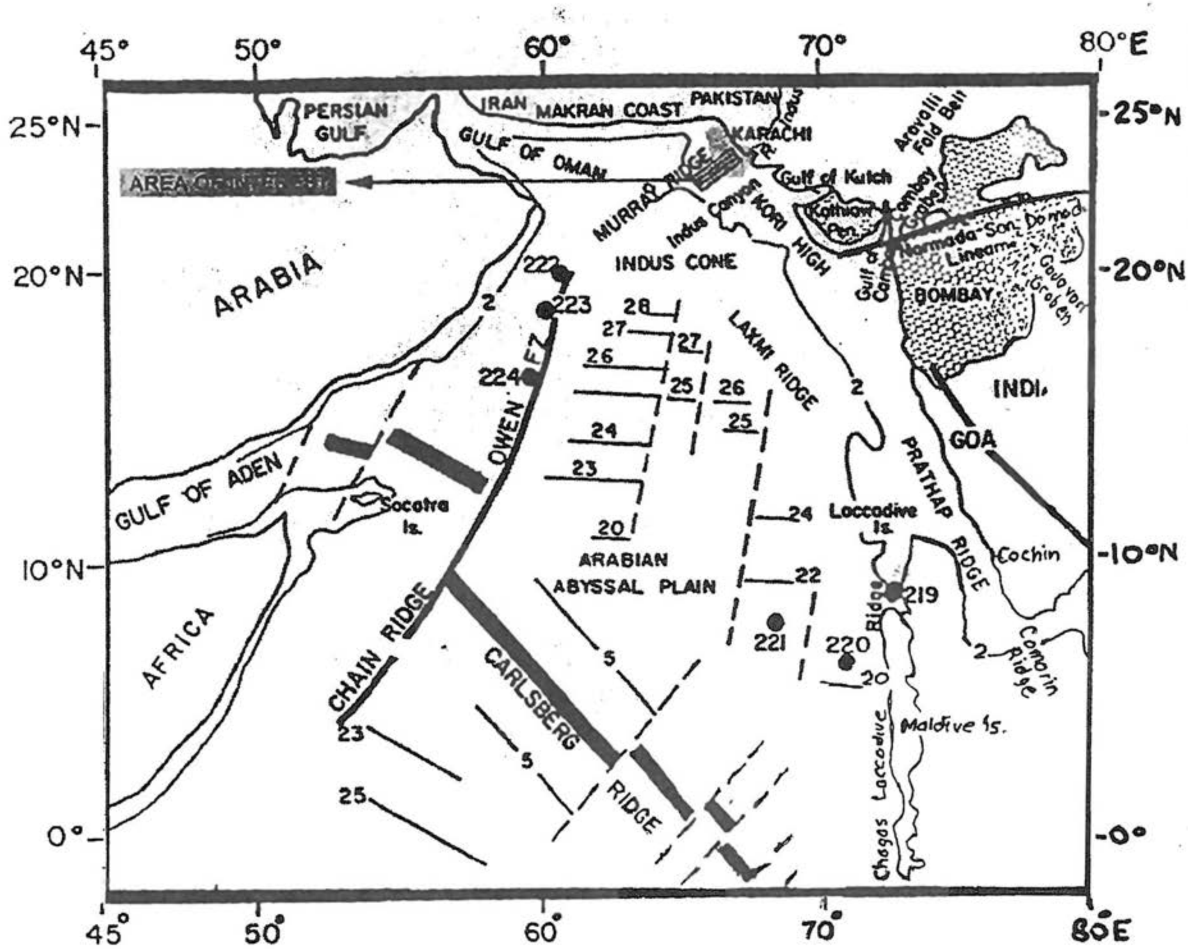

Fig. 1. Generalized map of the Arabian Sea showing various Physiographic features. Thick black bars, offset by dashed lines, represent segments of mid-oceanic ridge crests, and fracture zones (FZ), respectively. DSDP Leg 23 Sites are shown as solid circles. Thin lines with numbers correspond to magnetic anomalies. Two km isobath is shown around continents, islands, plateaus and ridges (After Naini and Talwani, 1983).

The average shelf break to the west of the Indian continent occurs at about 200 m water depth whereas in the study area it is less than 150 m (Naini and Talwani, 1983).

The Eastern Indus Offshore, the southern offshore extension of the Indus basin, is subdivided into three geological provinces (Shuaib and Shuaib, 1994; Siddiqui, 1997): Indus Basin Paleogene Shelf, Miocene Downwarp and Murray Ridge Flank. The Paleogene Shelf is narrow and runs along the present coast line. Fluvial/deltaic clastics followed by carbonate camp were deposited from Paleocene to Oligocene. Fair quality source rocks have been identified in the wells. The Miocene downwarp, located at the trailing edge of the northward drifting Indian Plate regarding deltaic deposition was initiated in this sub-basin during early Miocene. Late Miocene regression caused large scale channelling, followed by transgression, which has filled the channels and blanketed the entire area. Poor to fair quality source rocks of early Miocene age have been recognised. Good quality sandstone of delta plain facies are potential reservoirs. Growth fault related structures are evident on seismic (Siddiqui, 1997). The subsurface structures are related to normal faults in the east and listric normal faults and diapiric structures in the west (Ahmed et al., 1994). The regional seismic lines show the Murray Ridge to be the crest of a major crustal updome which possibly extends onshore where it is expressed as the Bela Ophiolite. On the flank of this updome, seismic correlations suggest the presence of a relatively thin Miocene and diapirically uplifted Lower Tertiary. Indus Marine C1 has been drilled in this province which encountered Eocene section, had hydrocarbon shows, but was abandoned for mechanical reasons.

INDUS OFFSHORE BASIN - A PROSPECTIVE ZONE

General stratigraphy of the Indus Offshore basin (Fig. 2) suggests a number of source rocks in the area (Raza et al., 1990), namely, the shales of Sembar and Goru (Cretaceous), Bara (Paleocene), Laki (Eocene), Nari (Oligocene), Gaj or equivalent facies (Miocene) and the limestones of Mughalkot (Cretaceous). Hard geochemical data from Kirthar Range (Seemann et al., 1988) indicates organic richness (above average TOC values) in samples from Sembar, Goru, Pab, Dunghan, Ghazij and Nari formations in onshore southern Indus basin.

Exploratory efforts in the offshore Indus basin include 34,984 Km of seismic survey and nine wells (Shuaib and Shuaib, 1994), out of which three did not reach objectives due to technical problems while other four appear to have been located on no/inadequate traps though gas shows/traces were recorded in all wells (Table 1). Gas shows were reported from Cretaceous to Eocene section in Sun Oil wells. Wintershall wells also encountered gas shows in Miocene. OGDC's well PakCan-1 was an offshore-wise uneconomical gas discovery in Miocene. It was drilled on a big structural closure during 1985-86 under Canadian Assistance program upto the target depth of 3,701 metres and gas flowed at 3.7 MMCF/day from Miocene sandstone, but was not considered economical and was plugged. Seismic survey of 5,732 Km was completed by OGDC-PCIAC during 1986 in offshore Indus basin, the interpretation of which revealed number of structural traps including nine reefs at depth approximately 2,800 to 5,400 metres and seven "Bright Spot" at depth from 1,250 to 3,350 metres in sediments ranging in age from Cretaceous to Early Miocene (Shuaib and Shuaib, 1994).

The Offshore region of Pakistan is filled with thick marine sedimentary rocks of varying lithologies, which commonly form source-reservoir-seal trilogies (Raza et al., 1990; Ahmed et al., 1994), and reflects sedimentation since rifting of the Indian margin in Cretaceous and earlier times. However, the fan sedimentary sequences have been deposited since Oligocene as a consequence of Himalayan uplifts and sea-level changes. The geothermal gradient in the Indus Offshore Basin is optimum (Khan and Raza, 1986) ranging from 1.5°C/100m to 3°C/100m.

The sands of Miocene age are proven reservoirs in the Indus Offshore basin. Some Eocene possibly carbonates picked on seismic line can prove to be the best accumulators of hydrocarbons. The presence of gas shows and the occurrence of hydrocarbons in the nearby areas are taken as strong evidence for migration (Fig 2). Cretaceous Lower Goru sandstone is proved to be oil and gas bearing in a number of wells drilled by OGDC and Union Texas in onshore Thar Slope in its north-east and east directions (Shuaib and Shuaib, 1994). Paleocene Ranikot sandstone and limestone are also proved to be gas-bearing in Sari, Hundi and Kothar wells drilled by OGDC in onshore Karachi Trough in its north direction. Oil and gas reservoirs were discovered in Bombay offshore of India (Roy and Deshponde, 1982) in its south-east direction in Eocene-Miocene sandstone and

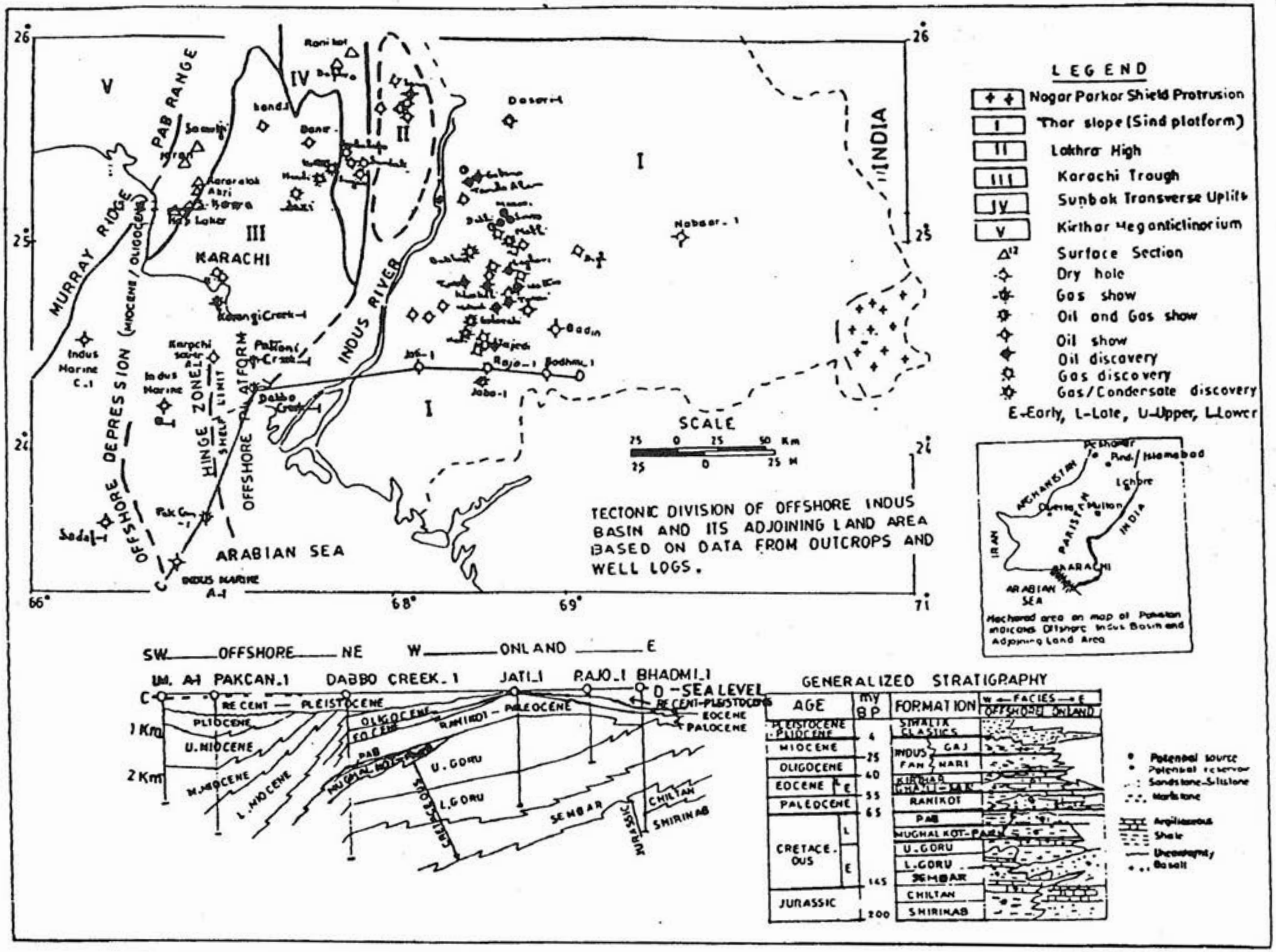

Fig. 2. Generalized stratigraphy of the Indus Offshore Basin and Stratigraphic cross sections along the Regional Seismic Profile (passing through the well, PackCan-I) based on the shown well log locations (After Shuaib and Shuaib, 1994).

TABLE 1. SUMMARY OF DRILLING ACTIVITY IN THE OFFSHORE INDUS BASIN (AFTER QADRI, 1984 AND SHUAIB & SHUAIB, 1994).

Well Name	Company	Year	Location	Objectives Reached	T.D. (Below MSL) in metres	Age/Formation Reached	Status
Dabbo Creek-01	Sun Oil	1963-64	24°20'02'' N 67°16'42'' E	Yes	4354 (-4335)	E.Cretaceous (Sember Formation)	Minor gas shows in Cretaceous, Drilled on down thrown side of the fault. Plugged and abandoned.
Korangi Creek-01	Sun Oil	1964-65	24°42'42'' N 67°04'14'' E	Yes	4140 (-4124)	U.Cretaceous (Mughalkot Formation)	Gas shows in Paleocene-Eocene section. Plugged and abandoned.
Patiani Creek-01	Sun Oil	1964	24°27'00'' N 67°17'30'' E	Yes	2659 (-2643)	U.Cretaceous (Mughalkot Formation)	Gas shows in upper part of Mughalkot. Drilled on the flank of the structure. Plugged and abandoned.
Indus Marine-A1	Wintershall	1972	23°27'28'' N 66°48'26'' E	Partially	2841 (-2831)	M.Miocene (Gaj Formation)	Abandoned due to technical reasons after kicking.
Indus Marine-B1	Wintershall	1972-73	24°15'03'' N 66°45'20'' E	Partially	3804.(-3793)	E.Miocene (Gaj Formation)	Abandoned due to technical reasons after kicking.
Indus Marine-C1	Wintershall	1975	24°36'01'' N 66°18'24'' E	No	1942 (-1932)	E.Eocene (Ghazij Formation)	Formation pressure required mud weight greater than the fracture gradient at the bottom. Plugged and abandoned due to high pressure.
Karachi South-A1	Husky	1978	24°29'08'' N 67°00'30'' E	No	3353 (-3343)	U.Cretaceous (Mughalkot Formation)	Tops of formations were found lower than expected. Abandoned.
PakCan-01	OGDC	1985-86	23°44'33'' N 66°57'36'' E	Yes	3701 (-3684)	M.Miocene (Gaj Formation)	Non Commercial gas discovery in Miocene. Plugged and abandoned. DST-3 flowed, Gas 3.7 MMCF/day from 2743-2747 M.Miocene, Sandstone interval, confirming the presance of hydrocarbons in the area.
Sadaf-01	Occidental	1990	23°44'08'' N 66°23'39'' E	Yes	3981 (-3965)	M/E.Miocene (Gaj Formation)	Dry. Plugged and abandoned.

limestone. Bombay High (a paleo-high) and Cambay graben (Fig 1), which further extends into Pakistan's Panno Aqil graben, are two major oil producing regions of India. These are characterised by high geothermal gradients attributed to the shallowness of the mantle as inferred from seismic refraction experiments (Naini and Talwani, 1983).

The onshore discoveries of Sari and Hundi gasfields in Karachi depression, and oil and gas discoveries of Badin Block (Pakistan) from the Cretaceous Lower Goru deltaic sandstones provide indirect evidence of the prospectivity of the Indus Offshore basin. Therefore, Cretaceous to Miocene sandstone and limestone seem to be the objective reservoirs in Indus Offshore basin. However, Cretaceous sediments become dominantly shaly/marly towards the west from Pakistan shoreline in offshore Indus basin and are deeply buried. These can be explored and drilled onshore at comparatively shallow depths. So, Paleocene to Miocene sandstones/limestones seem to be the main hydrocarbon objectives in offshore Indus basin.

INDUS OFFSHORE BASIN - AN ATTRACTIVE FRONTIER

Pakistan's vast sedimentary basins cover about 80% of the country's total land mass with widespread oil and gas seepage. Despite a long history of oil and gas exploration and an attractive petroleum policy, Pakistani sedimentary basins still contain sizeable areas, which can be classified as frontiers. These areas cover more than 60% of the total prospective area of Pakistan and include the Pishin Basin, the Makran-Kharan Basin, Fold and Thrust Belt parts of the Platform of the Indus Basin and the entire Offshore (Raza et al., 1990; Bowles, 1997; Raza, 1997; Siddiqui, 1997). Uptil now 421 exploratory wells in over a hundred years of Petroleum search have been drilled in Pakistan. Pakistan remains one of the least explored basins, with a well density of less then five per 10,000 sq. Kms, compared to an average of one hundred wells for other similar basins. Vast areas of Pakistan specially the Balochistan Basin and offshore remain virtually unexplored.

No oil or gas has been discovered so far from Pakistani offshore areas. Wildcats have been few, and holes reaching prognosticated reservoirs are rare. Hydrocarbon potential in Pakistani offshore, estimated on the basis of adequate thickness of marine sediments, tectonics and basin analogies, hydrocarbon shows, and the results of field and laboratory investigations in the adjoining coastal areas, is expected to fall between 14 to 16 billion barrels of oil or equivalent gas (Raza et al., 1990). Lack of data, no availability of new technology and equipment, remote and difficult area, high risk and high cost zone ($140,000/day for Offshore whereas it is $14,000/day for Onshore), low business volumes, and formation pressure hazard may be the main reasons of non-discovery of this hidden wealth (Bowles, 1997).

Pakistan desperately needs to exploit new oil and gas potential of the new frontiers for increasing self-reliance. It is high time that sustained exploration efforts are directed towards these frontier areas which if properly explored, may prove to be of great potential. This paper briefly highlights the exploratory status, hydrocarbon potential and deep crustal structure of Indus Offshore basin deduced from the seismic and gravity data. Analogies with other basins suggest that there is significant potential for further hydrocarbon discoveries in these basins of Pakistan. But it requires a commitment from both the oil companies and the government to achieve success. New play concepts need to be utilised with advance technology along with new geological and geophysical studies which highlight the prospectivity of these areas.

After the discovery of Bhit-2 in Lower Indus, Lasmo Oils applied for and was granted exploration licences for Offshore Indus (A & B). British Gas also received exploration licences for Offshore Indus (C & D). A new package of incentives for offshore petroleum exploration based on Production Sharing Arrangement, envisaging royalty holiday, low tax rate, payment of rentals and production bonuses to the exploration companies has also been offered in the new Petroleum Policy of 1997.

GRAVITY, FLEXURE, AND THE GROWTH OF SEDIMENTARY BASINS AT A CONTINENTAL EDGE

Walcott (1972) computed gravity anomalies (free-air), flexural stresses, and vertical displacements that could be expected to occur at a continental edge due to loading by large accumulations of sediments (Fig 3). The modelling provides revealing information regarding the cause of observed gravity anomalies and provides useful estimates for the vertical displacements and the variation in flexural stresses caused by sediment loading at shelf edge. He attributed the initial edge effect anomaly, positive anomaly to load, and the broad negative anomaly to compensation for that load partly produced by the density contrast between basement and sediments and partly by the displacement of mantle material. Bending stresses can be calculated for various thickness and downwarp of the crust (Jeffrey, 1970). The maximum bending stress occurs beneath the positive anomaly, i.e., beneath the point of maximum flexure, near the edge of continental shelf. Maximum value extends over 200-300 Km width.

DATABASE FOR INTEGRATED GEOPHYSICAL STUDIES AND DEEP CRUSTAL STRUCTURES

Integrated Geophysical Studies (IGS) have been carried out in many parts of the world both onshore and offshore to study deep crustal structures of the earth. The deep structure across passive continental margins has been studied in previous years from magnetic, seismic reflection, seismic refraction, and free-air and isostatic gravity data to determine the nature of the Moho and the boundary between continental and oceanic crust types (Davis and Francis, 1964; Grow et al., 1979; Baily, 1981; Hinz, 1981; Worzel, 1965 and 1974; Keen and Loncarevic, 1966; Closs et al., 1969 and 1974; Arayamadhu et al., 1970, Rao, 1970; Walcott, 1972; Kahle, 1976; Rabinowitz and La Brecque, 1977; Scrutton, 1979 and 1985; Naini, 1980; Biswas, 1982; Naini and Talwani, 1983; Naveed, 1986, 1987 and 1992; Zia, 1996). Seismic reflection methods need to be more refined to show exactly how oceanic and continental crusts merge. Gravity interpretation retains some flexibility with regard to densities and therefore cannot provide a unique solution to the problem. The best interpretation, therefore, can be achieved if the results from gravity data are used in conjunction with the results obtained from other geophysical methods such as seismic and magnetic. In the present study, seismic, gravity and bathymetric data (OGDC-PCIAC, 1986) was integrated to interpret the deep crustal structure beneath the Indus Offshore Basin (Fig. 4).

1. Seismic Data

Four deep (15 sec twt) seismic reflection lines (Fig. 5) shot by Petro-Canada (PC/9074-86, PC/9044-86, PC/9027-86, PC/9112-86) during 1986 seismic survey, with a cable length of 2975m, are used in the present study for delineating deep structure across the continental margin along with the gravity and magnetic data. These are different from the conventional multichannel (120 channels) profiles at short interval which was 50m instead of 25m used for normal recording. Other acquisition parameters are the same for all the profiles. Seismic Line PC/9074-86 is approximately 88 Km long and runs northeast-southwest through the well, PakCan-1.

Deep Seismic reflection surveys (15 sec twt) in many parts of the world have been carried out to view the deep crustal structure down to Moho depths. The most sustained efforts in this kind of work are made by COCORP (Consortium for Continental Reflection Profiling) and BIRPS (British Institutions Reflection Profiling Syndicate) in the USA and the UK, respectively. The deep seismic data from the Indus Offshore Shelf region do not show any promising evidence of deep seismic events. It is thought that the deep crustal reflections could be associated with crustal regions which have undergone extension during the rifting phase of the margin development.

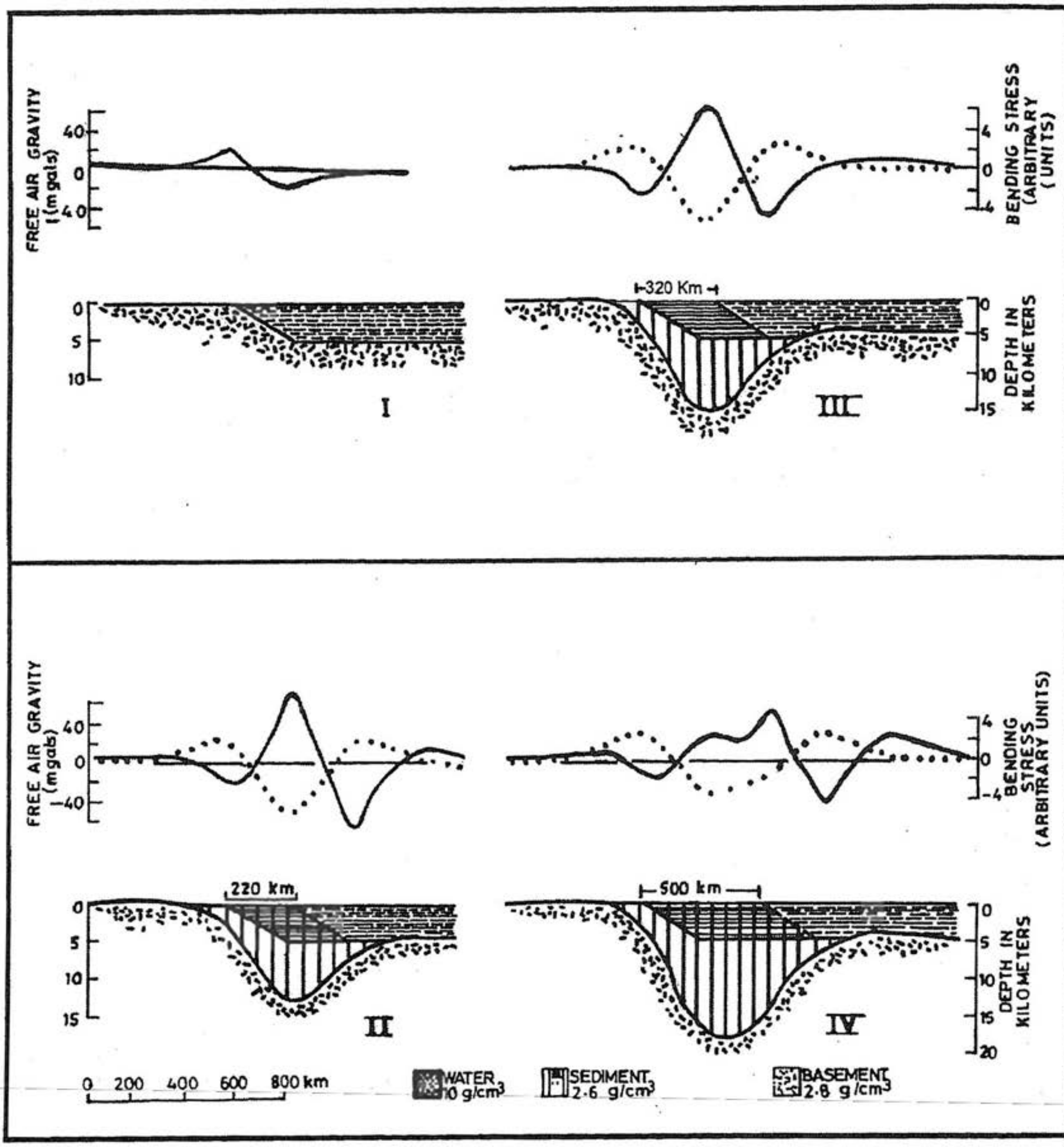

Fig. 3. Calculated gravity (free-air) anomalies and relative bending stresses (dotted) for flexural models of different load widths. Only the upper part of the models are shown, the base of the crust is included in the gravity calculations (After Walcott, 1972).

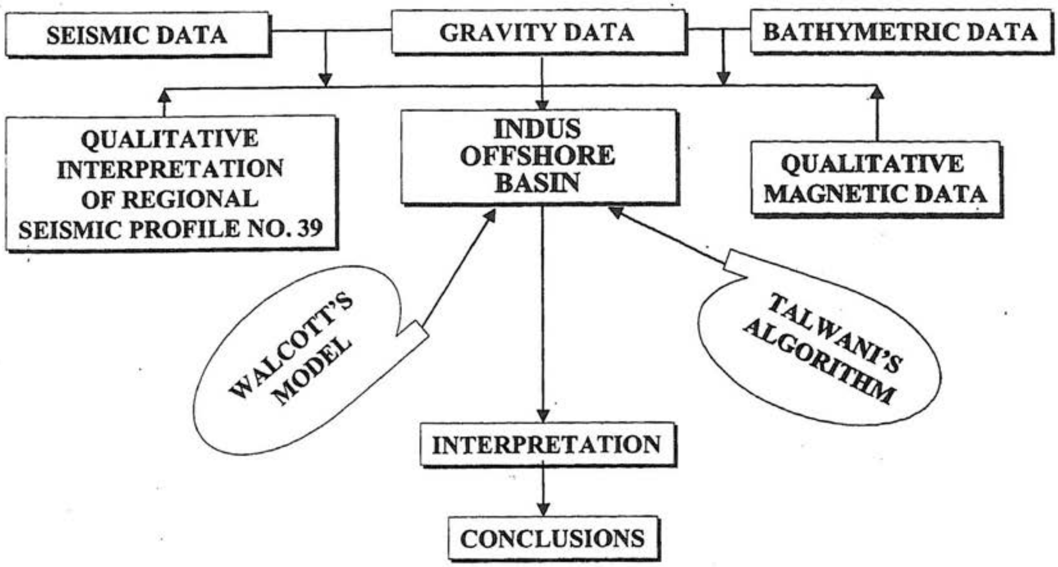

Fig. 4. The frame work of the present study.

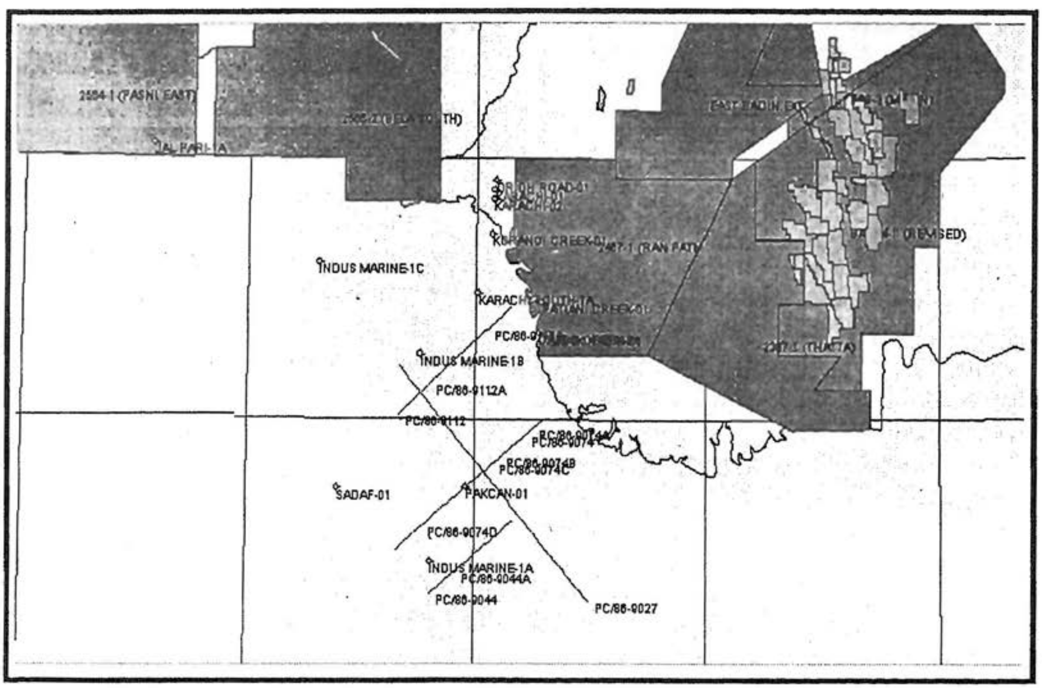

Fig. 5. Indus Offshore Basin, drilled wells and four deep seismic lines (15 sec twt) shot by Petro-Canada in 1986. (Source: EMS, Mathtech Pakistan).

The lack of these deep seismic events in Indus Offshore data could be explained as follow:

1. The absence of sufficiently strong acoustic impedance contrasts within the crystalline basement rocks which do not allow seismic energy to reflect back to the surface. From this, it may be deduced that the crust may be of relatively homogeneous composition.

2. It has been observed (Smith and Bruhn, 1984; Fountain et al., 1984) that the fault planes produce reflections when they are dipping gently or are nearly horizontal. Therefore, the lack of block-faulting in the upper crust in the current data could be related to the absence of deep seismic events.

3. It is possible (Fuchs, 1969; Hale and Thompson, 1982; Blundell and Raynaud, 1985) that the crustal rocks are thinly laminated (as thin as $\lambda/32$) and that the seismic reflections from these occur due to constructive interference. There may be a possibility that the signal frequency deep beneath the acoustic basement becomes too low to seismically resolve the thinly laminated crustal rocks.

2. Free-air Gravity Field and Bathymetry

Available Free-air gravity data show a linear negative gravity field westward of the present coast line. The areas located closer to the coast show positive gravity upto 15 to 20 mgal. The Indus Canyon, located to the south-east, shows a negative field which seems to be strongly influenced by the seabed topography. Besides that independent lows are also present, for example, one is centred at latitude 23° 45' N and longitude 67° E, and the other one at latitude 23° 40' N and longitude 67° E. Several anomalous noses appear on the map which are not related to any bathymetric feature, and might be due to density contrasts within sedimentary strata. To the south-west of well PakCan-1, the area is characterised by a strong positive gravity with an approximate gradient of 1.8 mgal Km^{-1}. Relatively steeper gradients in the field can be noticed close to latitude 24° 30' N, longitude 67° 10' E. In order to understand the cause of this strong positive anomaly, bathymetry (Fig. 6) was compared with the gravity field further to the present shelf break.

PARAMETERS FOR CRUSTAL MODELLING

In the present study, for the purpose of preparing crustal models along the line PC/9074-86, the following parameters have been taken into consideration:

1. Crustal velocity is taken as 6.4 Kms^{-1}. On Nafe and Drake (1963) velocity-density curve this velocity corresponds to 2.8 gm cm^{-3} density.

2. Mean mantle velocity is taken as 8.1 Km^{-1}. The relationship suggested by Christensen (1966) at 10 Kbar pressure provides a density estimate of 3.28 gm cm^{-3}.

3. Mean crustal thickness beneath the innermost shelf regions has been assumed 30 Km as the reference thickness (Naini and Talwani, 1983).

4. Dix (1955) Interval velocities are used to deduce Averaged interval velocities which are inturn used in computing bulk densities for each rock type (layer) using Gardner relationship (Gardner et al., 1974) (Table 2). All these density assumptions are comparable to those used by Worzel (1965), Scrutton (1979 and 1985), Donato et al., (1983), Naveed (1986 and 1987); Rafat (1996).

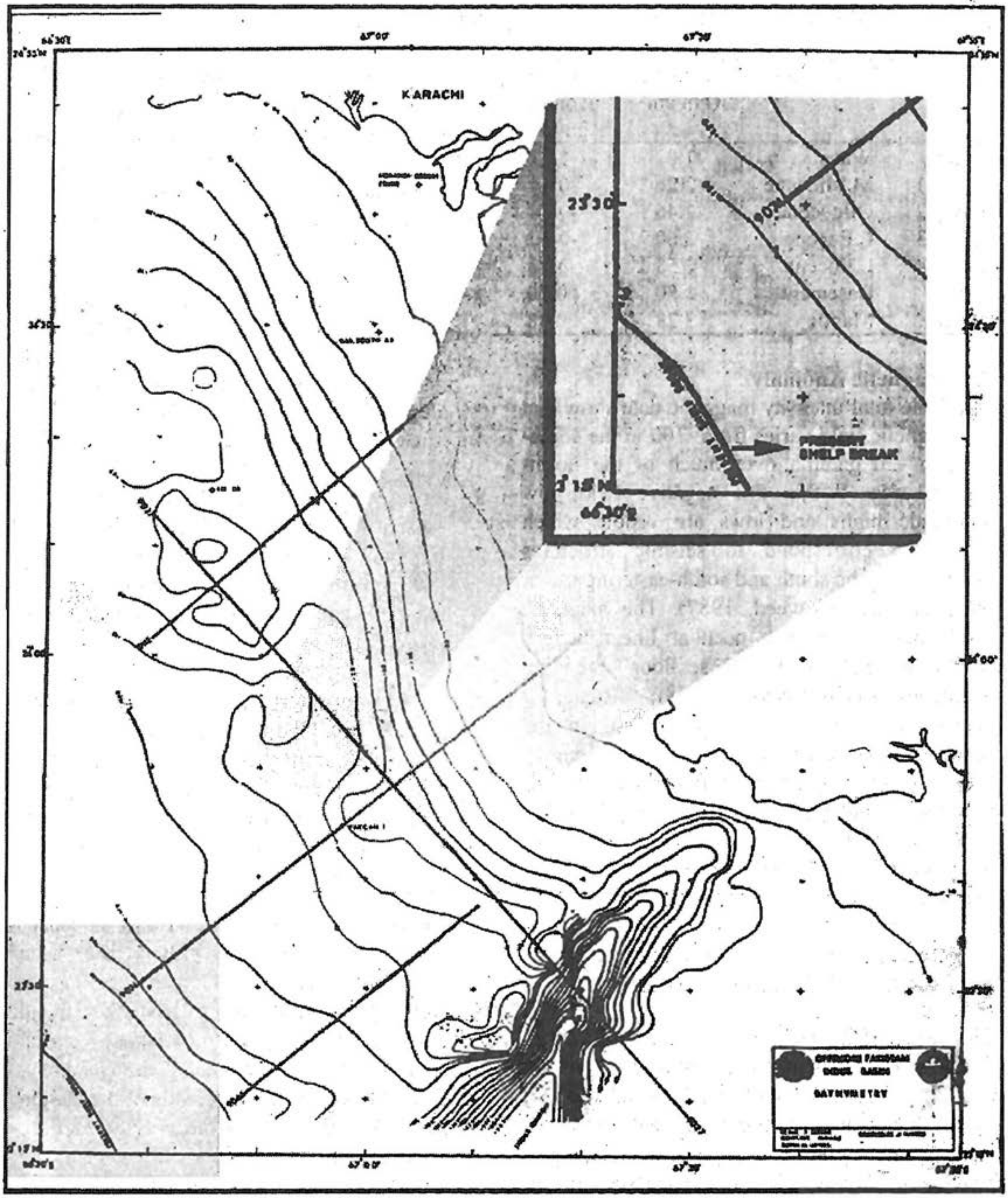

Fig. 6. Detailed bathymetry of OGDC-PCIAC concession area. Contour interval is variable. Fig. also shows the location of exploratory wells drilled todate, present shelf break in the south-west (enlarged view is shown at the right upper edge of the figure), and deep seismic reflection profiles. The most prominent bathymetric feature is the Indus Canyon in the south-west.

TABLE 2. AVERAGE DENSITIES FOR DIFFERENT LITHOLOGIES

Layers	Lithologies	Density (gm/cm^3)	Density Contrast (gm/cm^3)
Water	Water	1.03	-1.77
Layer-1	M.Miocene	2.26	-0.54
Layer-2	Oligocene	2.46	-0.34
Layer-3	L.Eocene	2.60	-0.20
Layer-4	L.Eocene	2.58	-0.22
Crust	Basement	2.80	+0.00
Mantle	Mantle	3.28	+0.48

3. Magnetic Anomaly

Available total intensity magnetic data show that the magnetic field varies from -100 in the south-west to -50 gamma over much of the north-eastern area. Within this negative field, low amplitude highs and lows are visible which appear to correspond to seismic structures delineated in the south and south-eastern parts of the study area (Naveed, 1987). The magnetic field does not show a peculiar linear pattern similar to that of typical seafloor spreading anomalies (Kristofferson, 1978); instead, it appears to show a very gentle rise in the basement surface as from south-west to north-east. The overall magnetic field has a longer wavelength indicating some deep seated source. The short wavelength anomalies, on the other hand, may be representing the supra-basement features.

GRAVITY MODELLING ACROSS THE CONTINENTAL MARGIN

The nature of the deep crust is inferred primarily from methods such as gravity, magnetic, seismic and from laboratory studies of the outcropping rocks which were once buried at great depth (e.g. Ivrea Zone, N.Italy). Geophysical techniques provide an indirect view of crustal structure at varying scales of resolution, ranging from low in the case of gravity and magnetic to relatively high in case of seismic. In the present study, two-dimensional gravity modelling technique (Talwani et al., 1959) has been applied to deduce the crust/upper mantle boundary along the line PC/9074-86 (Indus Offshore Basin) in the following steps:

1. Time to depth conversion of available limited seismic data using Layer-Cake method, after marking good reflectors, assigning ages on the basis of nearby/distant wells and long range land correlation and velocity analysis which are comparable to that of Naveed (1987) and Rafat (1996).

2. Averaged interval velocities were calculated for each interval (layer) in the sedimentary wedge above the acoustic basement and using Gardner relationship the bulk densities were computed (Table 2) for each rock type (layer).

3. From the known bathymetry along the seismic line and using density contrast of -1.77 gm cm^{-3} between seawater of density 1.03 gm cm^{-3} and crystalline crust of density 2.8 gm cm^{-3}, the gravity attraction was computed.

4. The sedimentary structure between the seabed and the acoustic basement was interpreted from the seismic reflection data. The density contrasts used for each seismic sequence have been taken against the crust of mean density 2.8 gm cm^{-3}, and these are shown in the model diagrams.

5. In order to deduce the Moho boundary across the margin using gravity data, mean crustal thickness in the area must be known. Seismic refraction surveys have been found useful in providing crustal thickness, crustal and mantle seismic velocities. Generally, crustal thickness on either side of the margin are required and then the gravity data are used to predict the Moho in-between. The Moho boundary was computed by using density contrast of +0.48 gm cm^{-3} between upper mantle of density 3.28 gm cm^{-3} and the continental crust having thickness (a reference thickness) of 30 Km (Naini and Talwani, 1983) beneath the onshore area (not shown). The procedure involves, first,

the calculation of the gravity effect of seawater and the sediments, and then the density deficiency due to this is balanced by the rise in the Moho (higher density rocks coming closer to the surface) towards the ocean basin. The best possible fit between the observed and calculated gravity fields was achieved by progressively shallowing the Moho boundary towards the ocean basin. The net computed gravity effect due to seawater, sediments and the upper mantle is compared with the observed gravity field. When the margin is in perfect isostatic equilibrium, no residual anomaly will be generated.

6. Different depth models were predicted by assuming different background anomaly values (0, 0) [Fig. 7], (40, -.4762) [Fig. 8], and (60, -.7143) [Fig. 9]. Composite effect of gravity anomalies (Observed, Calculated, and Residual) for all the layers with different background anomaly values are also shown respectively.

7. Partial effect of each layer (Water layer, Layer-1, Layer-2, Layer-3, Layer-4, and Mantle) with different background anomaly values (Figures 10, 11, and 12) are also shown respectively.

8. The residual (isostatic) negative anomaly generated along the profiles could not be explained in terms of any change in Moho depths; instead, it was accounted for by assuming low density rocks near the surface of the basement. This rock possibly corresponds to an older sedimentary unit.

9. A speculative extended depth model (Fig. 13 & 14) along the line is prepared by extending the crustal model backward to present shelf break and beyond to understand the cause of strong positive anomaly in the south-west which starts rising from Km mark 22 steeply to +40 mgal. This model from 0 to -50 Km mark is projected from the right half using same depths for each layer except for the seabed configuration which is plotted using the true values taken from the bathymetric map (Fig. 6).

10. The Isostatic behaviour of the area has been studied by calculating Isostatic Moho for normal crust of 30 Km. Airy's Moho (Airy, 1855) is calculated from Hydrostatic Principle. Computed (Gravity) Moho depth between Km marks 16 and 80 is more than Airy's (Isostatic) Moho. The comparison of the Airy's (Isostatic) Moho and Computed (Gravity) Moho suggests that the area may not be in complete isostatic equilibrium according to the Airy's hypothesis, indicating a deficit of mass conditions.

INTERPRETATION AND DISCUSSION

From two-dimensional gravity modelling (Talwani et al., 1959) of the observed free-air gravity data along deep seismic line PC/9074-86 (which runs through well PakCan-1 in the NE/SW direction in Indus Offshore Basin) predicted different depth models were inferred by assuming different background regional anomalies. Three of them shown in figures 7, 8 and 9 with background regional anomalies (0, 0), (40, -0.4762) and (60, -0.7143) are considered relatively more plansible. However, the model produced in Fig. 8 with background anomaly value (40, -.4762) shows a best match between the observed and calculated anomalies, except for minor residuals, and is preferred to others. These residuals could be attributed to the overall 2D assumption of the earth model.

Observed free-air gravity shows generally a linear negative gravity field westward of the present coastline (Fig. 8). To the south-west of well PakCan-1 the area is characterised by a steep positive gravity above the thick sedimentary strata (greater than 10 Km) with an approximate gradient of 1.8 mgal Km^{-1}. It starts rising from Km mark 22 steeply to +40 mgal. Comparison of bathymetry with the gravity field further to the present shelf break and beyond suggests the true scale speculative depth model of the line PC/9074-86 (Fig. 13 and 14). The model from 0 to -50 Km mark is projected from the right half using same depths for each layer except for the seabed configuration which is plotted using the true values taken from the bathymetric map. It appears from this model that the positive gravity gradient close to the break could be partly attributed to the changing upper mantle and water depths (edge effect - Worzel, 1965; Walcott, 1972; Naveed, 1986 and 1987). This Edge Effect Anomaly is characterised by three parts: (1) The initial edge effect anomaly (2) The positive anomaly to load and (3) The broad negative anomaly to compensation for that load partly produced by the density contrast between basement and sediments and partly by the displacement of mantle material.

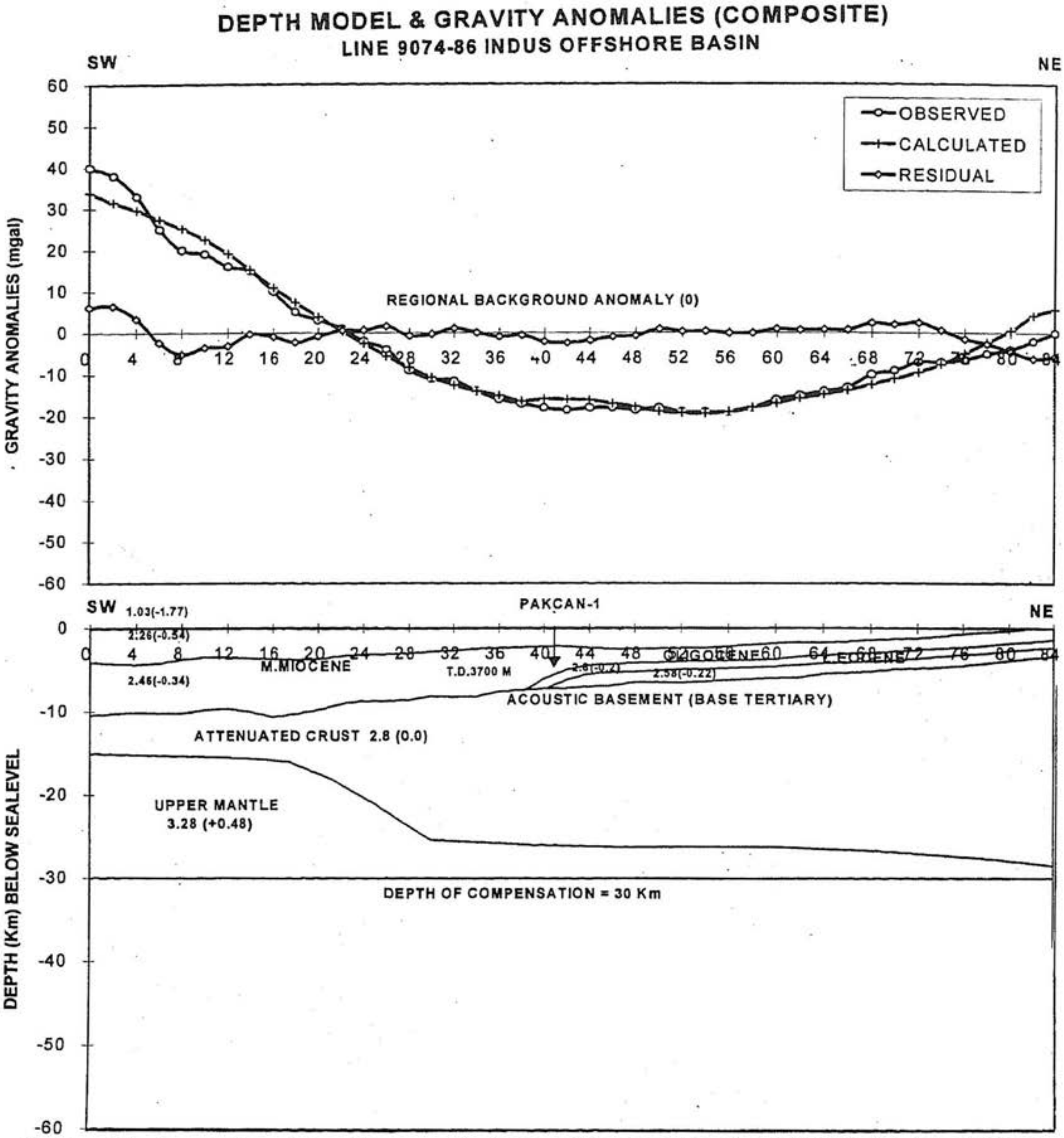

Fig. 7. Depth model and gravity anomalies(composite) along the line 9074-86 (Indus Offshore Basin) as determined from limited seismic reflection data and gravity observations, by assuming zero regional background anomaly.

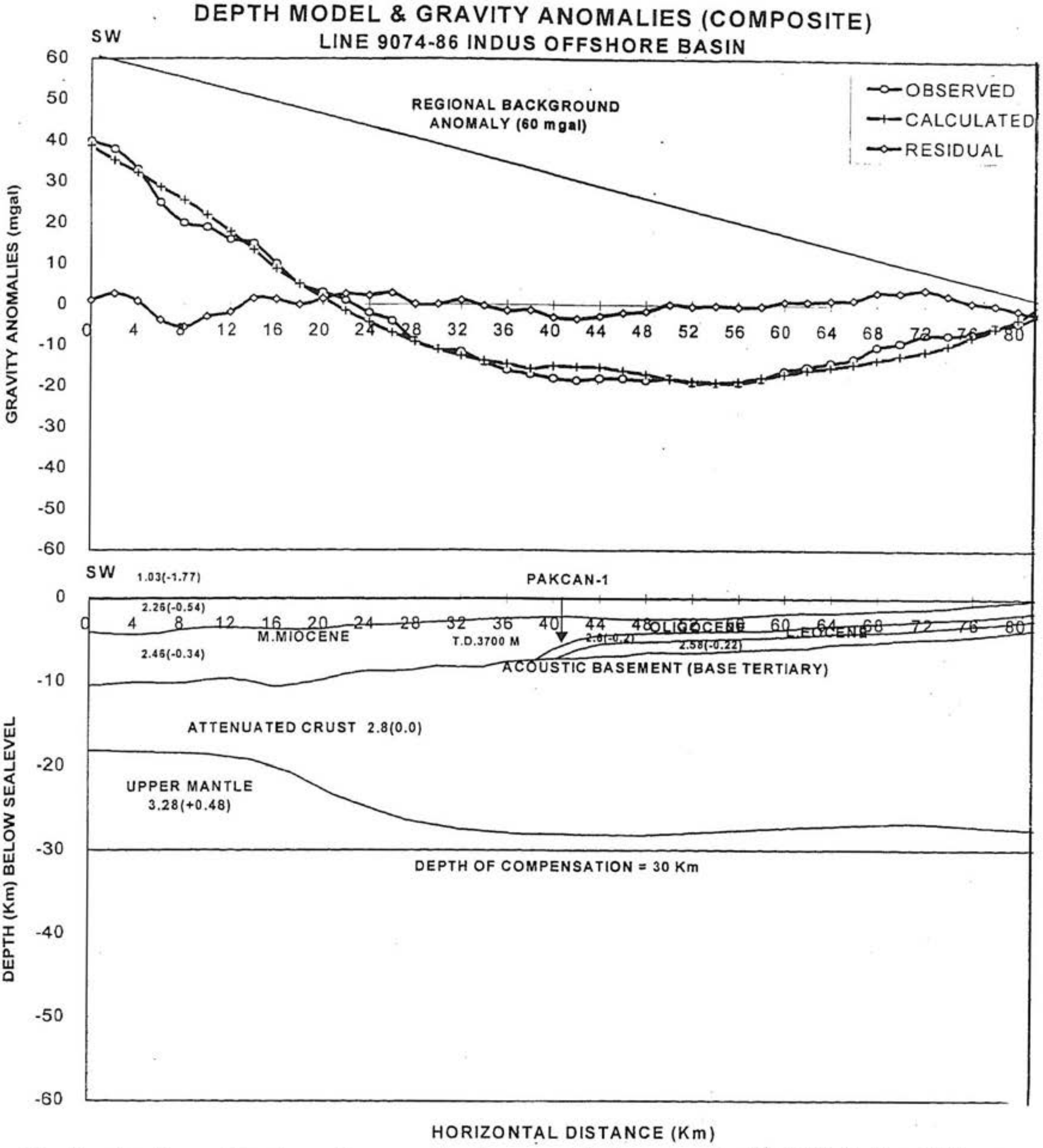

Fig. 8. Depth model and gravity anomalies (composite) along the line 9074-86 (Indus Offshore Basin) as determined from limited seismic reflection data and gravity observations, by assumig 40 mgal (40, -0.4762) regional background anomaly.

Beneath the mantle rise, the crustal thickness which is approximately 24.5 Km towards north-east is reduced to 6.5 Km, and it may be the area of the transitional crust types. The deep seismic line (15 sec twt) does not show typical lower crustal reflections as shown by BIRPS and COCORP. The absence of such reflections in the extensional regime of the Indus Offshore is possibly due to extra-thick sedimentary sequence above the acoustic basement, and weak energy source used in the survey. Therefore, the predicted gravity anomaly between 0 to -50 Km mark which is due to the typical shelf edge and shallowing of mantle boundary explains as to why gravity starts to become strongly positive from Km mark 22 south-west. Clearly, more gravity data beyond the present shelf break is required to strengthen the argument. Furthermore, the isostatic anomaly calculation in this region would show as to how much gravity is due to the edge effect. Near elimination of free-air gravity i.e. zero isostatic anomaly would mean the positive gravity is simply due to edge effect.

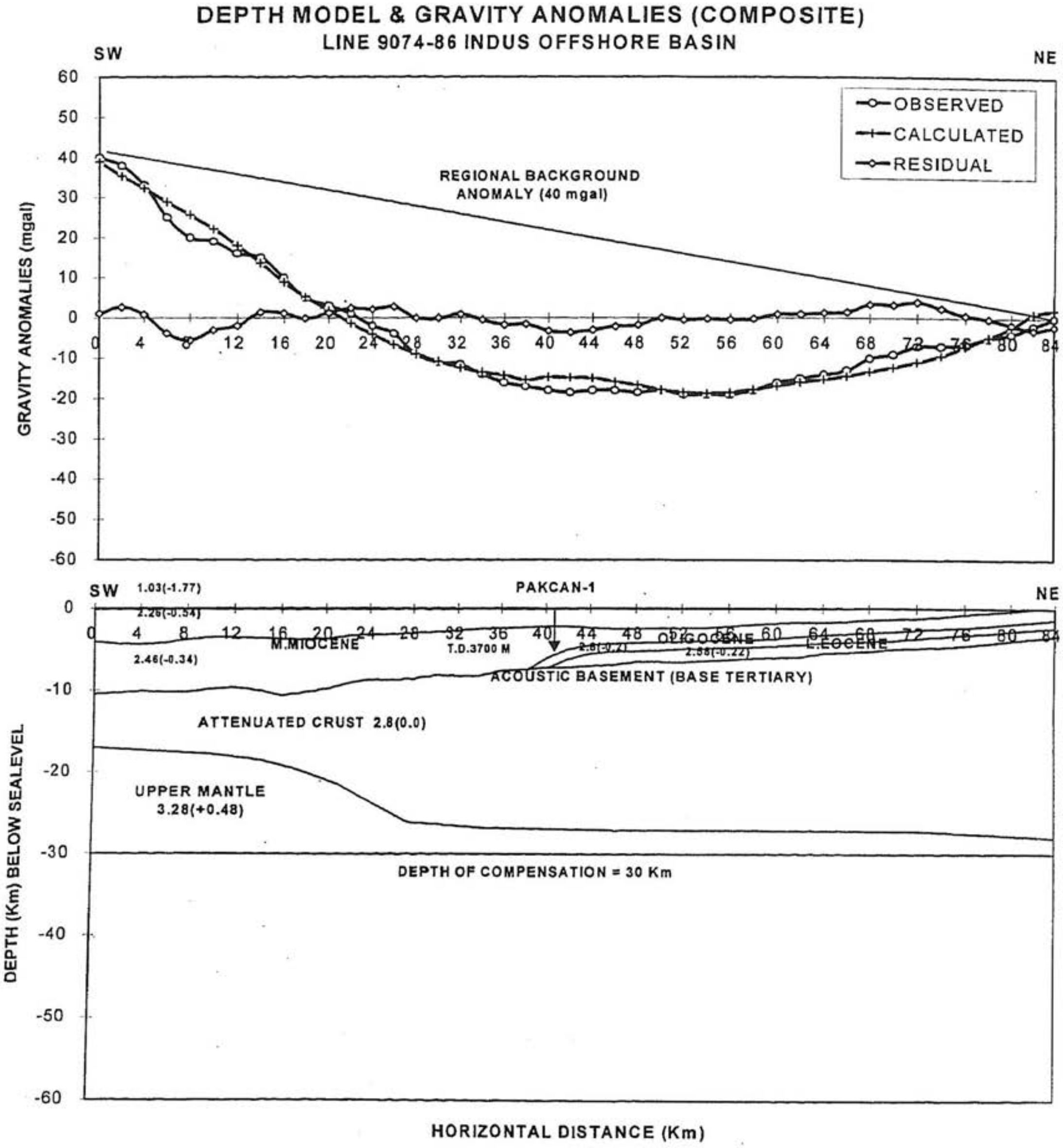

Fig. 9. Depth model and gravity anomalies (composite) along the line 9074-86 (Indus Offshore Basin) as determined from limited seismic reflection data and gravity observations, by assumig 60 mgal (60, -0.7143) regional background anomaly.

The crustal model also shows the magnitude of the crustal thinning as one moves towards the present shelf break region (south-west). The whole crustal attenuation can be measured with respect to its initial 30 Km thickness. Maximum attenuation has been observed beneath Km marks 12 to 26 and this area appears to be the transitional crustal regions.

The magnetic profiles seem to support the gentle north-eastward rise in the basement. The two relatively short wavelength magnetic anomalies located above Km marks 60 and 75 appear to be due to supra-basement features. It is difficult to appreciate any feature related to this on the seismic line owing to the presence of long period multiples. The depth to basement analysis using magnetic profile (Naveed, 1987) suggests that the acoustic basement reflector (possible Base Tertiary) is close to the deduced depths of basement surface.

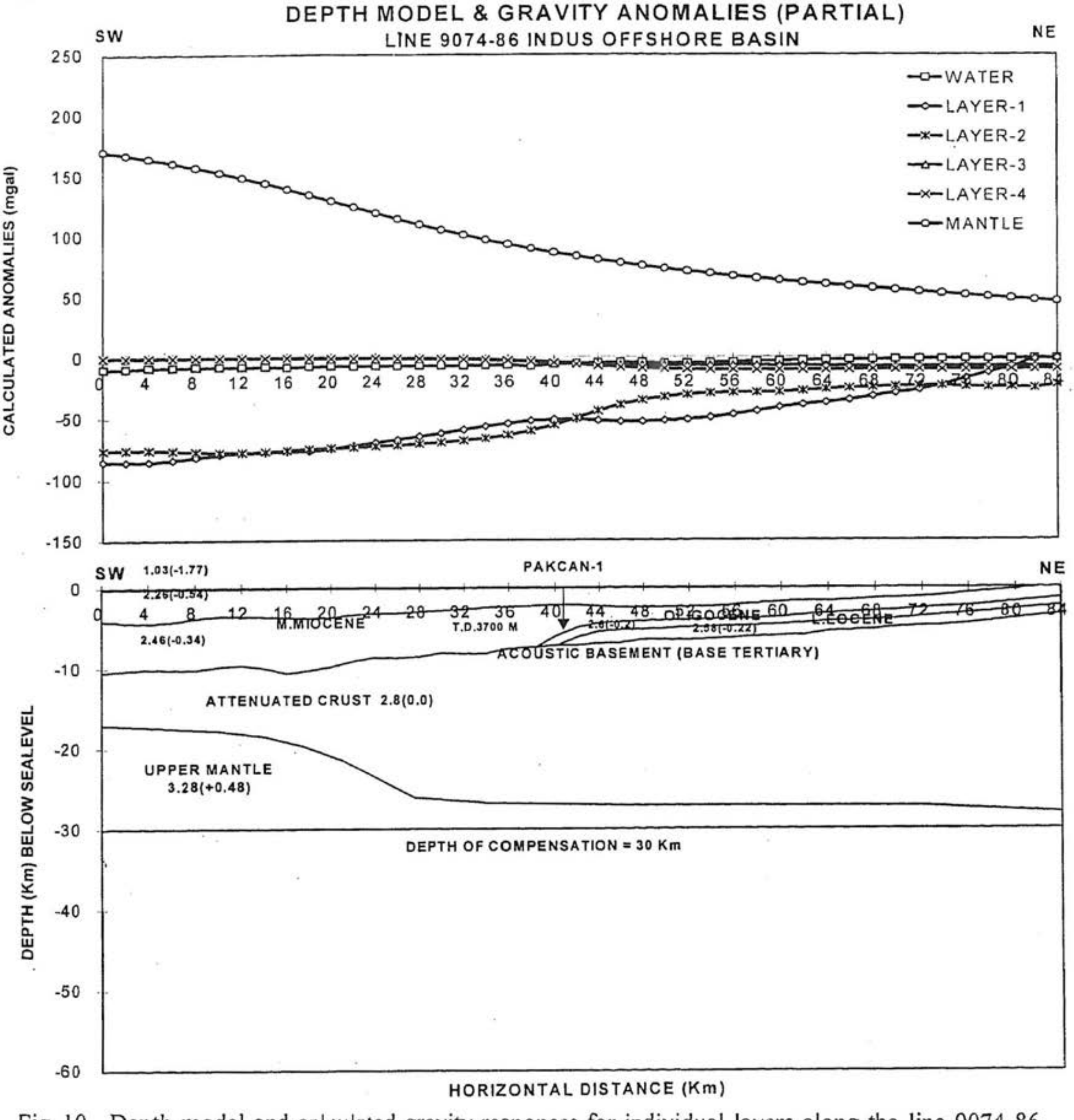

Fig. 10. Depth model and calculated gravity responses for individual layers along the line 9074-86 (Indus Offshore Basin) by assumig zero regional background anomaly.

Bombay High (a paleo-high) and Cambay graben are two major oil producing regions of India and are characterised by high geothermal gradients attributed to the shallowness of the mantle as inferred from seismic refraction experiments. To the north of the study area, the onshore Badin Block (Pakistan) produces oil and gas on a commercial scale from the Cretaceous Lower Goru deltaic sandstones. Also, in the study area steep positive gravity gradient above the thick sedimentary strata (greater than 10 Km) towards south-west of the area is attributed to prominent rise in the mantle.

Therefore, it is interpreted that the younger sediments in the offshore area may have attained maturity, due to thinning of the crust and consequent rise of mantle in the outermost shelf regions, to the stage of producing hydrocarbons.

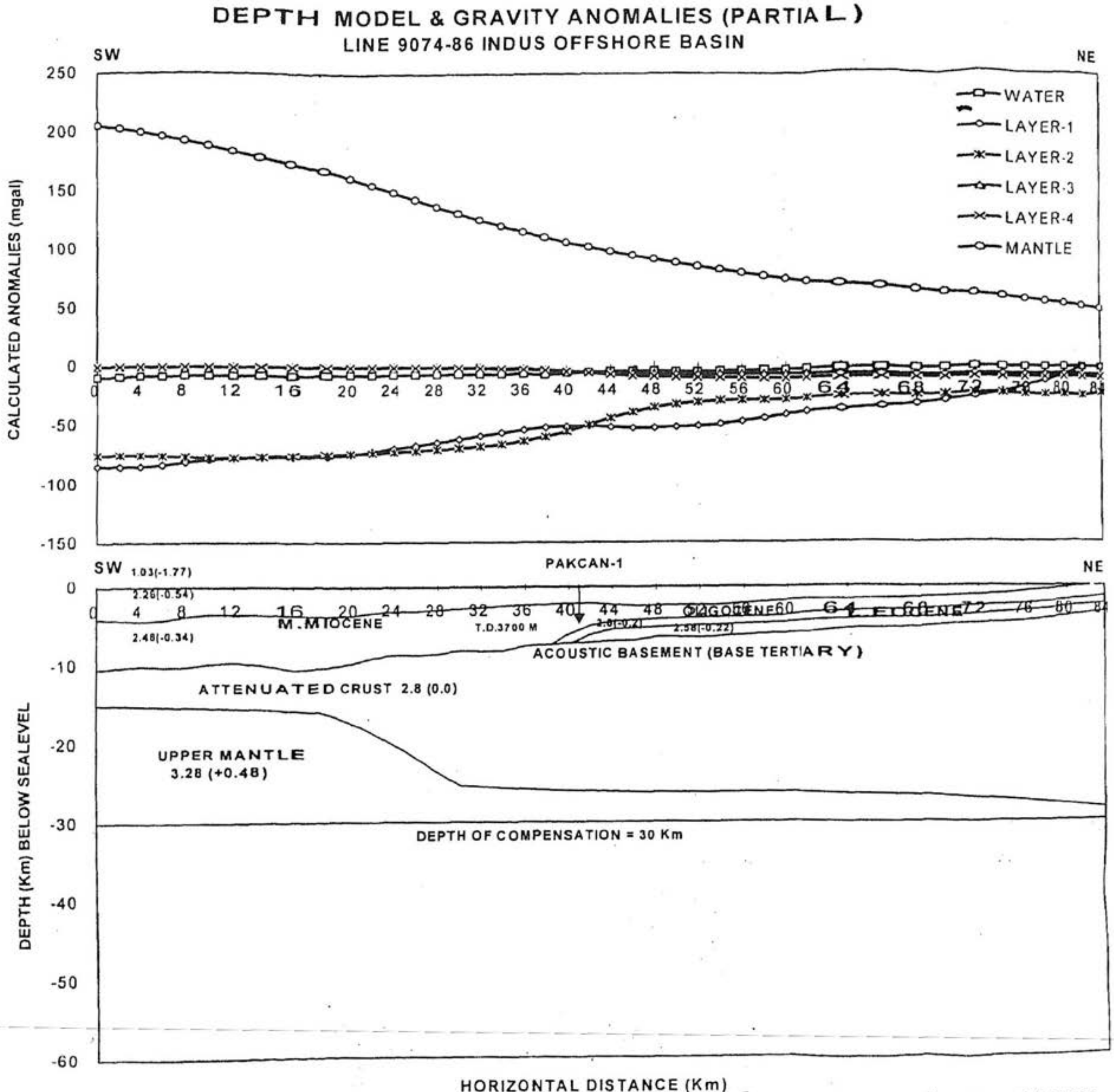

Fig. 11. Depth model and calculated gravity responses for individual layers along the line 9074-86 (Indus Offshore Basin) by assumig 40 mgal (40, -0.4762) regional background anomaly.

STRUCTURAL EVOLUTION OF THE MARGIN

Passive continental margin of the rifted type undergoes a history of predominantly vertical movement during their formation and development. These vertical crustal movements which shape the margin, may or may not be fault controlled. Regional subsidence of the margins without obvious fault control is the most conspicuous form of vertical movement of the crust. The thinned crust beneath the outer shelf and slope regions shows marked subsidence compared to the inner shelf regions in many parts of the World, for instance, the north-west Atlantic Ocean where as much as 10 Km of total sediments were deposited in the Georges Bank Basin, 14 Km in Baltimore Canyon Trough and 12 Km in the Blake Plateau (Grow et al., 1979). The process of continent rifting is thought to comprise stretching (extension) and consequent thinning of the lithosphere (McKenzie, 1978; Bott, 1982). It is generally believed that the initial pre-existing mass of the crust does not rupture instantaneously in response to tensile forces, rather it is stretched over a period of millions of years. The continued extension eventually leads to continental break-up and to the formation of an ocean basin. The evidence of crustal stretching and thinning is derived from geophysical data such as seismic refraction, gravity and from the knowledge of sedimentary basins investigated by seismic reflection profiles.

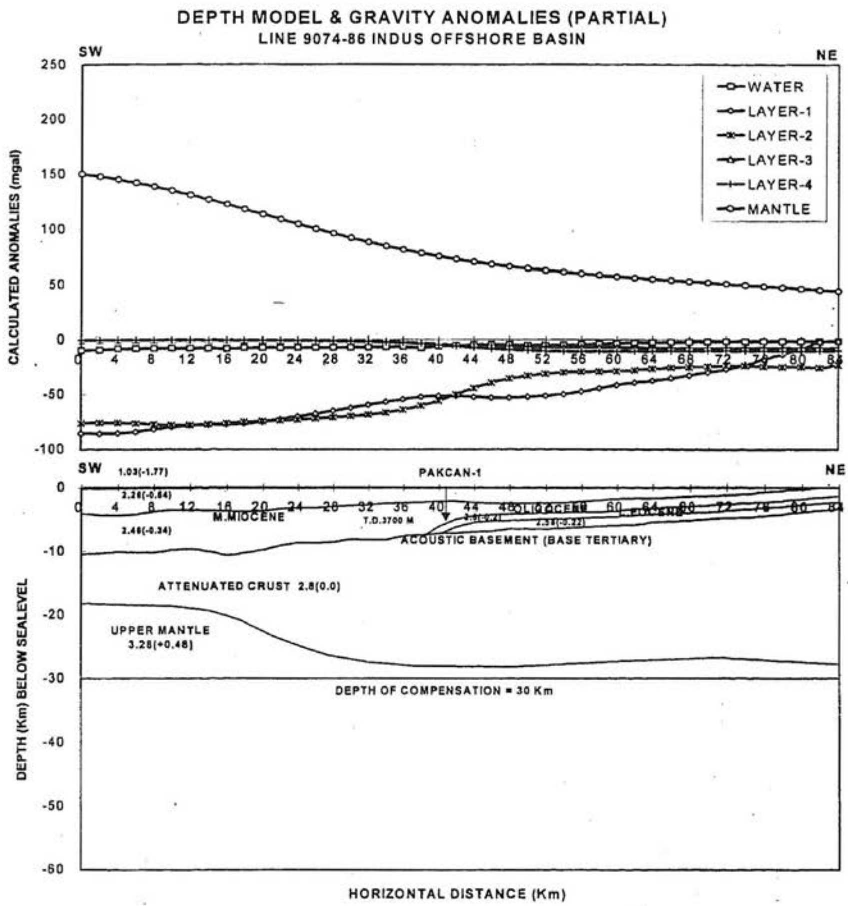

Fig. 12. Depth model and calculated gravity responses for individual layers along the line 9074-86 (Indus Offshore Basin) by assumig 60 mgal (60, -0.7143) regional background anomaly.

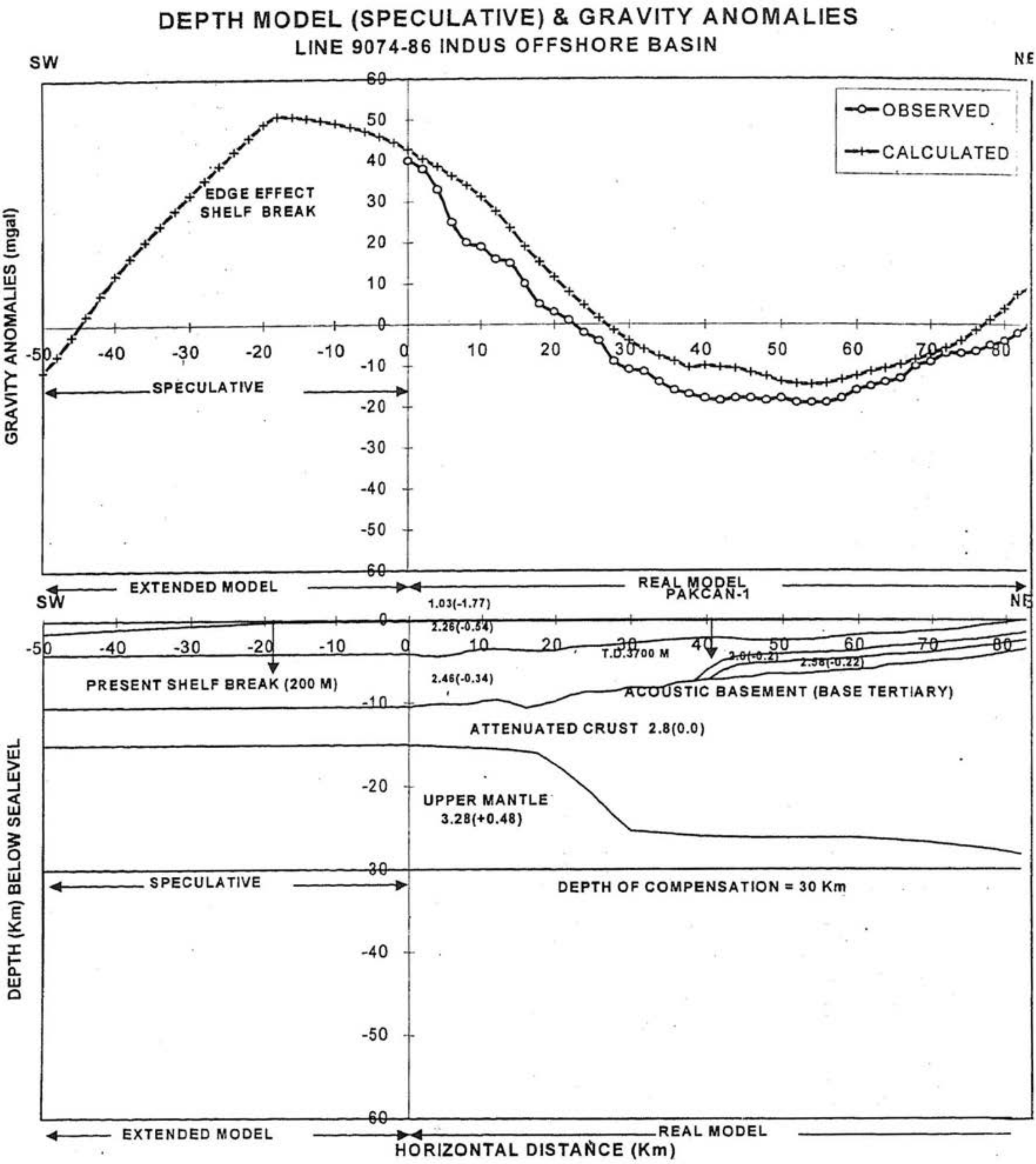

Fig. 13. Speculative true scale depth model (bottom) and total gravity effects (top) along the line 9074-86 (Indus Offshore Basin). The model from 0 to -50 km mark is projected from the right half except for the seabed configuration which is plotted using true values. Note the predicted gravity anomaly between 0 to -50 km mark which is due to the typical shelf edge and shallowing of mantle boundary (Mohorovicic discountinuity). This explains as to why gravity starts to become strongly positive from km mark 22 southwards.

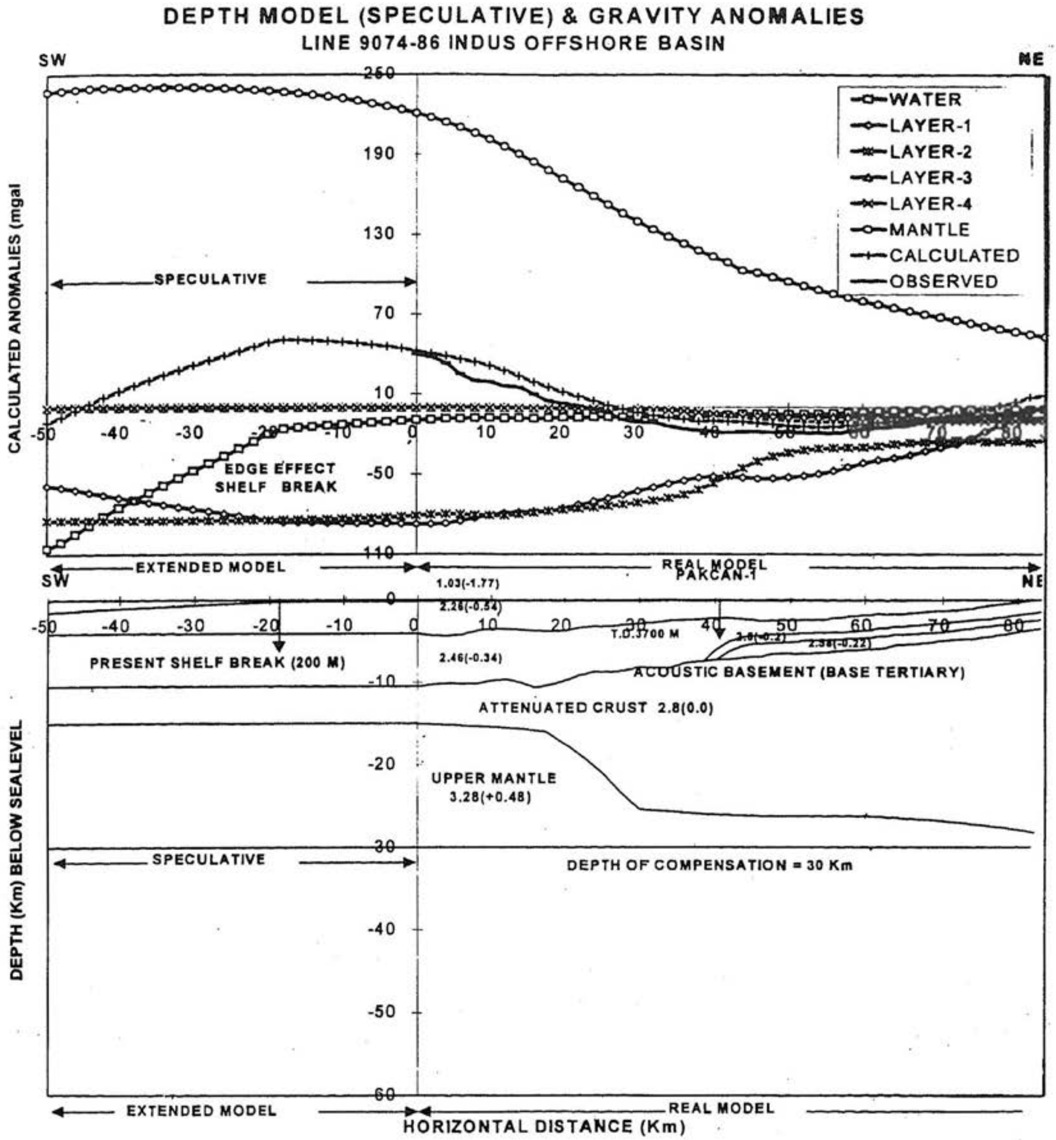

Fig. 14. Speculative true scale depth model (bottom) and calculated gravity responses for individual layers (top) along the line 9074-86 (Indus Offshore Basin).The model from 0 to -50 km mark is projected from the right half except for the seabed configuration which is plotted using true values.

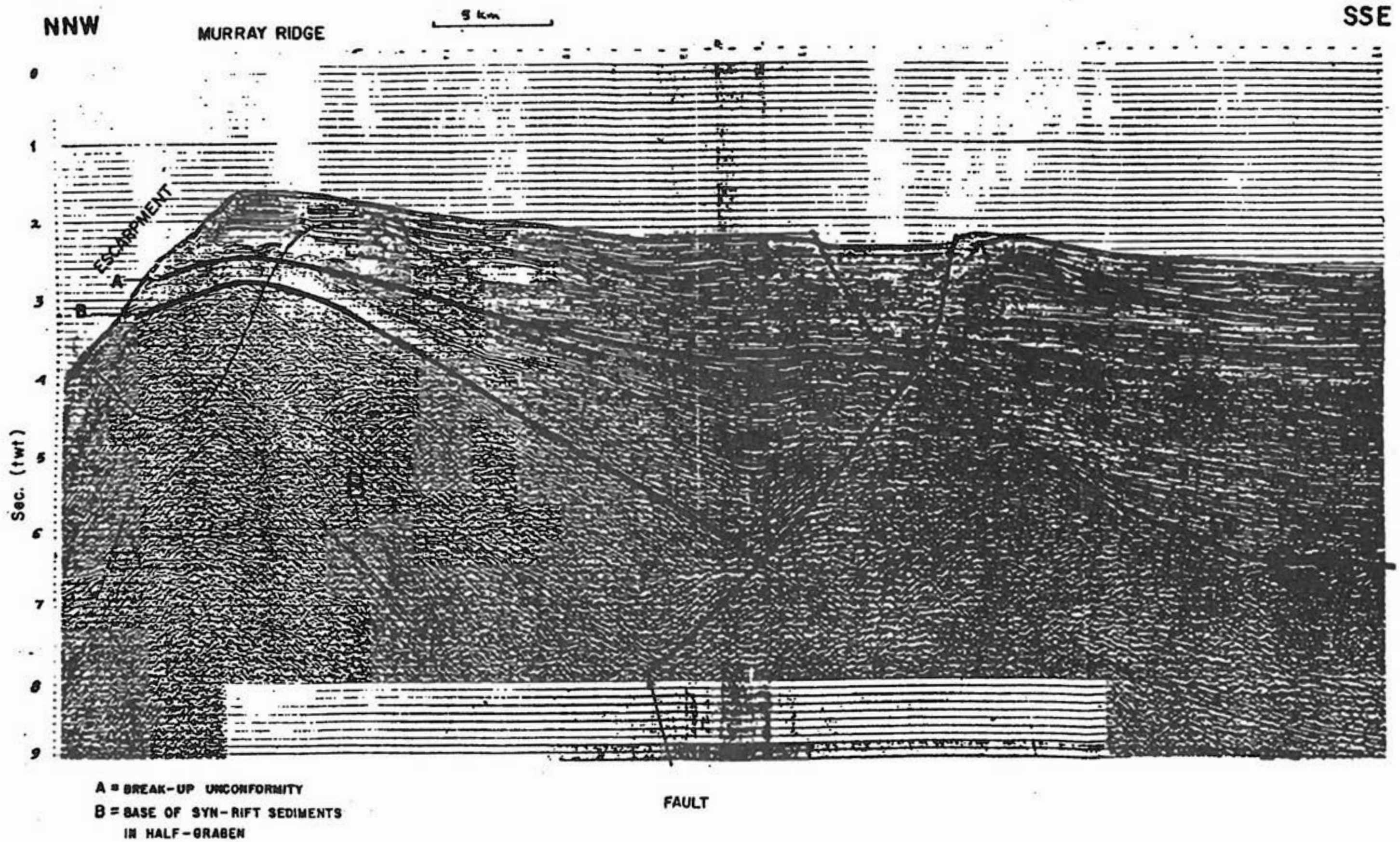

Fig. 15. Unmigrated seismic reflection profile (PAK-16) running north-south across Murray Ridge showing a half garben bounded by a listric fault, and an unconformity "A". The divergent seismic reflection pattern in the wedge shaped syn-rift sequence indicates deposition during the rotation of the basement block. Also note reactivation of the syn-rift listric fault after deposition of the rift-phase sequence (Line from Phillips seismic survey, 1977).

In order to demonstrate an evidence for the rifting process, a seismic line from the Philips (1977) seismic data bas been used (Fig. 15). The north end of this profile extends to as far as the Murray ridge. The interpretation of this line revealed the presence of two main seismic events, viz. "syn-rift" and post-rift". The former occurs in fault bounded sedimentary basin which is wedge shaped in cross-section, and the latter lies unconformably on the top. The divergent pattern of seismic reflections from the strata within the basin suggests that the processes of continental rifting and deposition were contemporaneous. The younger post-rift sequence seems to have been effected by minor reactivation of an older fault. The fault bounding the basin is regarded as normal and listric in form indicating extension and accompanied with rotation of the basement block. The structural evolution of a continental margin is therefore mainly controlled by the amount of initial crustal thinning that occurs during the rifting phase and subsequent tectonic subsidence. The tectonic subsidence is a result of the cooling of thinned lithosphere (thermal contraction). The process of thinning produces a thermal anomaly due to passive upwelling of hot asthenosphere. During the post-stretching event, the heat is lost exponentially with time and slow isostatic subsidence continues. The total amount of subsidence appears to be determined by the amount of crustal thinning and heating that occurs during the rifting phase of the margin development. As the margin subsides due to thermal contraction, sediments accumulate so that the regions of large crustal thinning are usually associated with largest thickness of sediments. The loading of sediment and water may accentuate subsidence (Walcott, 1972).

Naini and Talwani (1983) suggest that the north-eastern Arabian sea has two phases evolutionary history. In the latest Cretaceous, the western margin of India and adjoining eastern basin evolved through the process of rifting. During this phase, Cambay graben, eastern basin and Chagos-Laccadive-Laxmi ridge complex came into existence. Beginning in the early Paleocene, active rifting began along spreading centres (oriented east to west) during which the western basin (located between Laxmi ridge and Owen fracture zone in Fig 1) evolved. The crust beneath the western basin is oceanic type (e.g., area of magnetic anomaly 28 in Fig. 1), and the eastern basin has a crust which is thicker than the normal oceanic and thinner than the normal continental crusts. Naini and Talwani conclude on the basis of seismic refraction experiments that the eastern basin is underlain by one of transitional crust types.

The regional seismic line (Fig 8) clearly shows sediment thickness in excess of 10 Km towards the south-west of the hinge zone. The crustal model prepared along the line shows the extent of crustal thinning and its relationship with the overlying sedimentary succession. It is inferred from these models that the area with largest crustal thinning is associated with maximum sediment thickness. The offshore depression overlying the acoustic basement and the hinge line flexure appears to have been formed without major fault control, due to massive post-rift regional subsidence (thermal contraction). An appreciable component of sediment loading may be present in the observed subsidence. Furthermore, the attenuated crustal areas could be one of transitional crust. The acoustic basement reflection has been mapped as a Base Tertiary event (Naveed, 1987), and this could possibly mark the onset of active seafloor spreading in the area. In order to assess the age of the onset of seafloor spreading, the nature of syn-rift sediments and their paleoenvironments drilling through half-graben located on Line PAK-16 of Philips (Fig. 15) is necessary. This could unravel the evolutionary history of the continental margin.

CONCLUSIONS

On the basis of present study, it is concluded that:

1. The deep (15 sec twt) seismic profile (PC/9074-86) running across the continental

margin (northeast - southwest) suggests a maximum sediment thickness greater than 10 Km to the west of Base Tertiary hinge zone i.e., in the offshore "depression area".

2. On the seismic line PC/9074-86, the acoustic basement appears to be marked by a strong high amplitude more or less continuous seismic reflector and attains depth greater than 6 sec (twt) in the "depression area". The reflection character of this event, when seen on unmigrated profile, suggests that it could be one of continental type of acoustic basement (non diffractive).

3. The deeper (6 sec twt) parts of the seismic section do not show any evidence of discontinuous seismic events similar to the ones reported by BIRPS and COCORP. The absence of deep reflections in the extensional regime of the Indus Offshore is possibly due to extra-thick sedimentary sequence above the acoustic basement, and weak energy source used in the survey.

4. From the 2D-modelling of free-air gravity anomalies along the line PC/9074-86 it is speculated that the area to the west of the Base Tertiary hinge zone suffered maximum crustal attenuation (approximately 24.5 Km thick crust towards north-east is reduced to 6.5 Km on the mantle rise) and this could be one of transitional crustal regions formed during the rifting phase of the margin development. It is further speculated that in the outer shelf regions, where upper mantle rocks are shallower, overall geothermal gradients are expected to be higher than the innermost shelf regions.

5. Steep positive gravity gradient towards south-west of the well PakCan-1, above thick sedimentary strata (greater than 10 Km), is attributed to a prominent rise in the mantle. Intuitively, extending the depth model beyond the present day shelf break and computing its gravity indicates that the overall gravity effect is one of the typical shelf edge anomalies.

6. It is also interpreted that the younger sediments in the offshore area may have attained maturity due to thinning of the crust and consequent rise of mantle in the outermost shelf regions and may produce hydrocarbons. Further, Offshore region of Pakistan is filled with thick marine sedimentary rocks of varying lithologies, which commonly form source-reservoir-seal trilogies. Basins similar to Pakistani offshore basins have mostly been found hydrocarbons producing.

7. The Miocene section has low prospectivity. The Paleocene/Eocene section probably has source potential and may have charged structures on the Murray Ridge Flank.

RECOMMENDATIONS

From the above discussiion, it is recommended that:

1. Regional seismic/well ties are required. More seismic mapping in the most prospective areas, probably Murray Ridge Flank, should be carried out.

2. More gravity and magnetic data be acquired further westward of the study area, beyond the present shelf-break, to predict the continental/oceanic crust boundary and to establish the relationship between gravity, flexure and the shape of the sedimentary basin.

3. In order to have a better understanding of the crustal structure and deeper velocities, seismic refraction experiments should be carried out both onshore and offshore. This would surely help in preparing better 2D-isostatic models across the continental margin.

4. Increase the well densities in the Indus Offshore Basin. Sun, Wintershall, OGDC and Oxy all have drilled for Miocene target, any future campaign should consider older targets as well. Cretaceous-Miocene sandstones and Eocene limestones can be targeted as potential reservoirs associated with fault traps. Probable reef build up in the south-east at Eocene level may also form potential target.

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