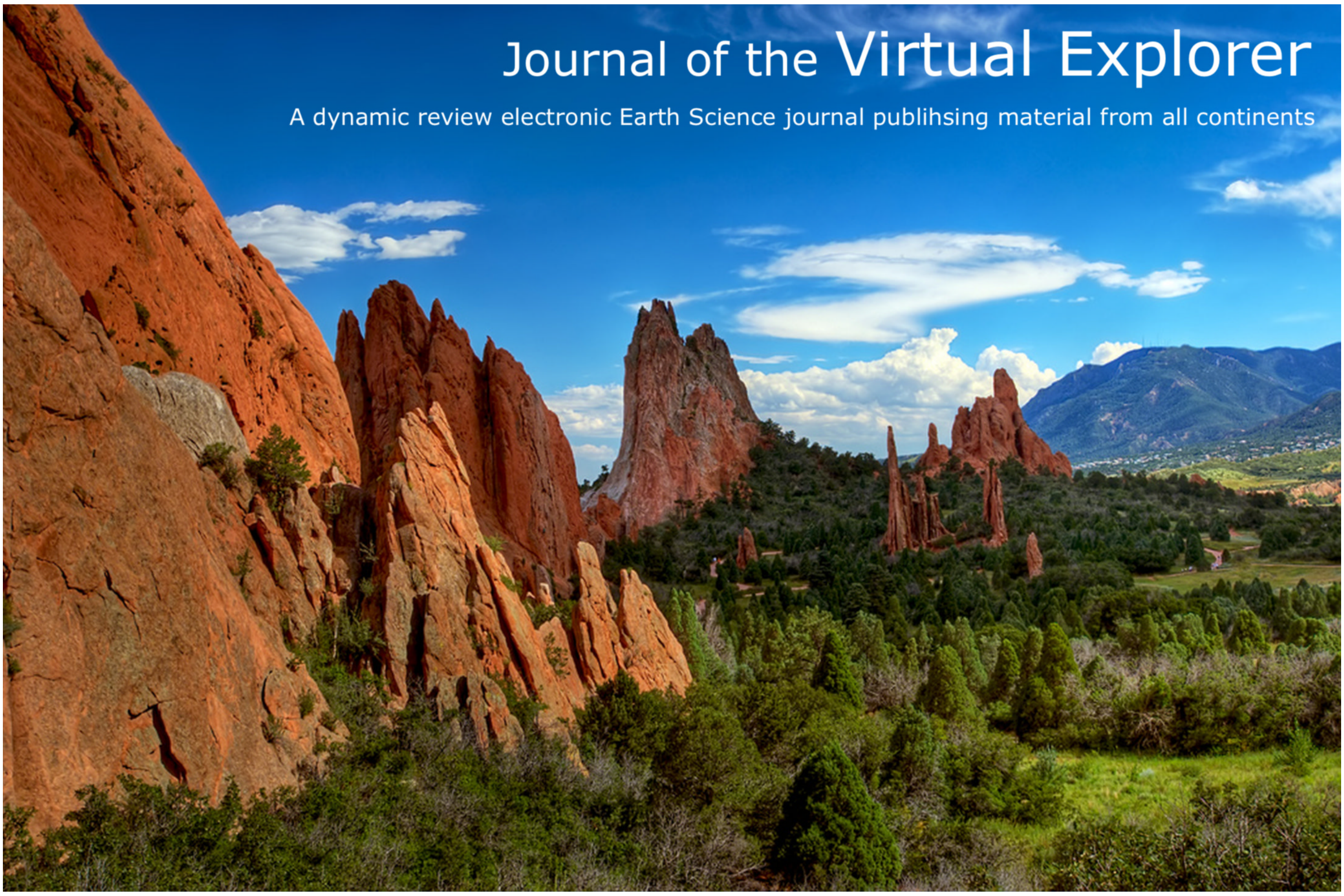

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Abstract: Integrated geophysical studies facilitate to delineate the deep crustal structure of the earth worldwide. In the present study, gravity, magnetic, bathymetry and deep seismic reflection data was used to obtain a geologically plausible model from the deep crustal structure and also for the hydrocarbon prospects in Indus Offshore basin of Pakistan beneath the seismic line PC/9074-86. Steep positive gravity gradient towards southwest of the area, above thick sedimentary strata (greater than 10 Km) in the offshore depression area, 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 northeast is reduced to 6.5 Km on the mantle rise and it may be the area of transitional crust. 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 shows 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.

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Introduction

An integrated geophysical study (IGS) involves the use of the several geophysical techniques in the same area to investigate a subsurface feature or phenomenon. Since every geophysical method has its own limitation in the type of information it provides, a combination of two or more geophysical methods generally yields extra information, which may help to reduce the ambiguity inherent in the interpretation of some types of geophysical data. In exploration for minerals, it has been a common practice to employ a number of geophysical methods so as to take advantage of the widest possible range of physical properties possessed by hidden prospects. The use of multiple geophysical techniques in problems of crustal structure and dynamics has grown considerably over the past two decades. The theory of plate tectonics has also been developed by the integration of evidence from seismology, gravity, heat flow, the magnetic field, paleomagnetism, and other related disciplines (Sharma, 1987).

In oil exploration the combination of gravity and magnetic reconnaissance with seismic follow-up for detail is well established. In prospecting for metallic minerals, the best combination of various geophysical methods is not so definite because of the great variety of targets and detection methods available (e.g., gravity, magnetic, and various types of electrical and electromagnetic methods). Many examples of integrated studies in the form of exploration case histories can be found in several texts on applied geophysics (Dobrin and Savit, 1988; Telford et al., 1986; Sharma, 1987; and Parasnis, 1973).

Integrated geophysical studies have also 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; 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; Qureshi, 1986; Naveed, 1986, 1987 and 1992; Shah, 1996; Direen et al, 2001; and Leucci and De Giorgi, 2005). Seismic reflection methods need to be more refined to show exactly how oceanic and continental crusts merge. However, 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.

Worzel (1965) interpreted a crustal structure across the Bahamas continental margin using gravity and seismic data. The comparison between computed and the Airy's isostatic Moho shows that the continental margin is not strictly in isostatic equilibrium according to the Airy's hypothesis. It is also found that the topography near the slope is very steep thereby giving rise to sharp changes in the Airy's Moho, and such sharp changes at the upper mantle depths may not be present in reality. Rabinowitz and La Brecque (1977) prove that such mantle boundary undulations are mere artefacts of Airy's isostatic assumptions. The model suggests that the computed Moho rises from a depth of about 30 Km to 13 Km in a horizontal distance of about 200 Km with a major change occurring beneath the Km mark 400. Worzel (1965) first pointed out that Atlantic or passive type margins tend to show negative isostatic anomalies (upto -50 mgal) over the slope and adjacent part of the rise even when thick sedimentary accumulations are allowed for. These indicate a deficiency of mass beneath the slope and adjacent part of the rise, and a corresponding surplus of mass beneath the shelf.

Scrutton (1979) used bathymetric, seismic reflection, gravity and magnetic data to obtain a detailed structure of the crust and upper mantle at Goban Spur. Using a 29 Km thick crust at the coastline as a guide, an Airy's type 2D-isostatic model of the crust was constructed and a general agreement could be obtained between the predicted and observed crustal thickness. The free-air gravity effect of the isostatic model was not in very good agreement with the observed because the difference in calculated levels over the inner continental margin and outer margin plus oceanic provinces was 15-20 mgal less. This discrepancy is confirmed by extending the two-dimensional approach to a three-dimensional approach to the whole of the survey area. There must, in effect, be a slight isostatic imbalance with respect to the Airy's model assumed. Crustal density variations, crustal thickness difference and variations in upper mantle density across the margin could be its possible causes.

Qureshi (1986) interpreted gravity data of Morocco using the results of deep seismic soundings with the intention to delineate the crustal structures and interpret their isostatic behaviour and relation to the tectonics of the area. The results revealed that the crust is the thickest in the High Atlas region and attains a value of 36 Km, whereas it thins out to about 24 Km towards the Atlantic coast. It is about 30 to 32 Km below the Anti Atlas and the Meseta areas. Another maximum thickness (approximately 34 Km) lies below the Rharb Plains that decreases northwards to about 22 Km near the Alborans coast and 25 Km at the Atlantic coast. The regional and isostatic crustal behaviour was also studied by comparing the Moho depth map with the isostatic Moho depth map and it was observed that most of the areas of Morocco are not compensated isostatically. The High Atlas and the Anti Atlas areas are overcompensated, whereas Rharb Basin is under-compensated. The Meseta behaves isostatically in a reasonable way and is in a good isostatic balance.

A similar study was carried out by Naveed (1986) on the sediment starved continental margin of Goban Spur, NE Atlantic Ocean. In that study, computed Moho has been deduced from the free-air gravity data by using a mean reference crustal thickness of 30 Km towards the continental side. The shallow sedimentary structure was interpreted from a seismic reflection profile CM10. The sediment density was based on the seismic interval velocity data. The other parameters such as mean crustal thickness and the densities of the crust and upper mantle were interpreted from nearby seismic refraction surveys over the Southwest Approaches. A steep (free-air) gravity gradient towards the oceanic side from +60 mgal to -15 mgal is attributed to the “edge effect” caused by increasing depth to sea-bed and changes in the Moho depth as one moves towards the ocean along the section. The difference between the observed and calculated gravity fields in the escarpment region gives a negative isostatic anomaly indicating a mass deficiency beneath the escarpment area and it cannot be accounted for by making any changes in the depth to the Moho. This anomaly has been explained by assuming low-density (-0.15 and -0.22 gm cm-3) granitic rocks present in the thinned and attenuated continental crust near surface within the basement (as explained by Scrutton, 1979 and 1985). Using the principles of hydrostatic equilibrium, the Airy’s Moho was calculated which appears to follow the computed Moho. The comparison of the two also implies that some mass deficiency beneath the slope is present indicating that Goban Spur margin may not be in strict isostatic equilibrium according to the Airy’s hypothesis. Furthermore, it must be appreciated that some ambiguity in the interpretation may be due to the two-dimensional assumption of nearly three-dimensional Goban Spur gravity anomalies.

Integrated Geophysical Studies in Indus Offshore Basin

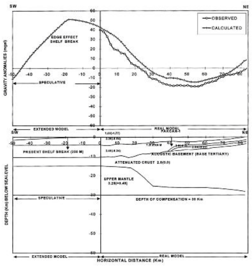
Extensive geological and geophysical studies have been conducted in Indus Offshore basin during the last two decades (Raza et al., 1989 and 1990; Ahmed et al., 1994; Shuaib and Shuaib, 1994; Amir et al., 1996; Siddiqui, 1997; Biswas, 1982; Khan and Raza, 1986; Qadri, 1984; Raza, 1997; Raza and Ahmed, 1990; Bowles, 1997; OGDC-PCIAC, 1986; Naveed, 1987; and Shah, 1996).

The study area, lies between latitudes 23° 15’ to 24° 30’ N and longitudes 66° 30’ to 67° 30’ E, is the part of Indus offshore basin of Pakistan and forms the continental shelf that is about 120 Km south of Karachi city and is situated between the Gulf of Kutch and Murray Ridge spreading over 20,000 square Kms. 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). 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). General stratigraphy of the Indus offshore basin 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. The geothermal gradient in the Indus offshore basin is optimum ranging from 1.5oC/100m to 3oC/100m (Khan and Raza, 1986).

In the present study, multidisciplinary data from seismic, gravity, magnetic and bathymetry was integrated to obtain a geologically plausible model from the deep crustal structure and also for the hydrocarbon prospects in

Indus offshore basin beneath the seismic line PC/9074-86. The overall workflow of integrated geophysical studies in Indus offshore basin has been summarized in Figure 1.

Figure 1. Workflow



Workflow of integrated geophysical studies conducted in Indus offshore basin.

Database for Integrated Geophysical Studies in Indus Offshore Basin

Four deep (15 sec twt) seismic reflection lines (PC/9074-86, PC/9044-86, PC/9027-86, PC/9112-86) shot by PetroCanada during 1986 seismic survey are used in the present study for deep structure across the continental margin along with the gravity, magnetic and bathymetry data. The seismic line PC/9074-86 is approximately 88 Km long and runs northeast-southwest through the OGDCL well, PakCan-1.

Free-air gravity and bathymetry data along the seismic line PC/9074-86 is the integral part of this project. Available free-air gravity data shows a linear negative gravity field westward of the present coastline. The areas located closer to the coast show positive gravity up to 15 to 20 mgal. The Indus Canyon, located to the southeast, shows a negative field, which seems to be strongly influenced by the seabed topography. Besides that some independent lows and several anomalous noses are also observed on the map, which are not related to any bathymetric feature, and might have emerged due to density contrasts within sedimentary strata. To the southwest 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 was compared with the gravity field further to the present shelf break.

In the present study, for the purpose of preparing crustal models along the line PC/9074-86, the 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), and mean mantle velocity is taken as 8.1 Kms-1 (the relationship suggested by Christensen (1966) at 10 Kbar pressure provides a density estimate of 3.28 gm cm-3). Furthermore, mean crustal thickness beneath the innermost shelf regions has been assumed 30 Km as the reference thickness (Naini and Talwani, 1983). Dix (1955) Interval velocities are used to deduce averaged interval velocities which are in turn used in computing bulk densities for each rock type (layer) using Gardner relationship (Gardner et al., 1974). All these density assumptions are comparable to those used by Worzel (1965), Scrutton (1979 and 1985), Donato et al. (1983), Naveed (1986 and 1987); and Siddiqui (1996).

Total-intensity magnetic data along the seismic line PC/9074-86 shows that the magnetic field varies from -100 gammas in the southwest to -50 gammas over much of the northeastern 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 one moves from southwest to northeast. 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.

Discussion

Two-dimensional gravity modelling (Talwani et al., 1959) of the observed free-air gravity data along deep seismic line PC/9074-86 (which is running through well PakCan-1 in the NE/SW direction in Indus offshore basin) predicted different depth models by assuming different background regional anomalies e.g., (0, 0), (40, -0.4762) and (60, -0.7143). However, the model produced in Figure 2 (right half) with background anomaly value (40, -0.4762) 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.

As discussed above that observed free-air gravity shows generally a linear negative gravity field westward of the present coastline. To the southwest of well Pak-Can-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 (right half of Figure 2). 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 (left half of Figure 2). 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; and 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.

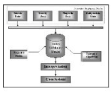
Beneath the mantle rise, the crustal thickness which is approximately 24.5 Km towards northeast is reduced to 6.5 Km, and it may be the area of the transitional crust types. The deep seismic line (15 sec twt) does not show typical lower crustal reflections in the extensional regime of the Indus Offshore, which 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.

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 thickness (30 Km). Maximum attenuation has been observed beneath Km marks 12 to 26 (Figure 2) and this area appears to be the indication of 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.

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 southwest 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.

Figure 2. Depth model and total gravity effects



Speculative true scale depth model (bottom) and total gravity effects (top), by assuming 40 mgal (40, -0.4762) regional background anomaly, along the PC/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 discontinuity). This explains as to why gravity starts to become strongly positive from km mark 22 southward.

Conclusions

On the basis of present study, it is concluded that the deep crustal structure of passive continental margins is best interpreted with the help of geophysical methods such as deep seismic reflection, seismic refraction, gravity, and magnetic data. The results from these methods are combined to obtain a geologically plausible model from the deep crustal structure.

In the present study an integrated interpretation of the results obtained from gravity, magnetic, bathymetry and deep seismic reflection data sets was used to develop the deep crustal picture of Indus offshore basin beneath the seismic line PC/9074-86. This deep seismic profile, 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". The deeper (6 sec twt) parts of the seismic section do not show any evidence of discontinuous seismic events in the extensional regime of the Indus offshore, which is most possibly due to extra-thick sedimentary sequence above the acoustic basement, and weak energy source used in the seismic survey.

Steep positive gravity gradient towards southwest 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. Furthermore, it is speculated from the 2D-modelling of free-air gravity anomalies along the seismic line PC/9074-86 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. 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.

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