GRAVITY MODEL FOR BELA OPHIOLITES AT WESTERN MARGIN OF THE INDO-PAKISTAN CONTINENTAL PLATE

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Keywords: *gravity profile, subduction model, Bela ophiolites. Pakistan.*

ABSTRACT

The oroclinal axial fold-thrust mountain belt has notable features in the geology of Pakistan. The southern part of this belt is of particular importance because it includes the southern branch of the main Himalayan ophiolitic zone, the Bela ophiolites, and its continuation into the Arabian Sea. A number of geological models and hypotheses have been proposed for explanation of the tectonic setting of the area based on surface geological investigations. A gravity study was carried out to provide a model for the tectonic setting of the investigated area. The results of interactive gravity modeling point to the underthrusting of a narrow segment of the Arabian oceanic plate (Bela-Hingol micro-oceanic plate) under the western rifted margin of the Indo-Pakistan subcontinental plate, characterized by a well developed accretionary wedge, an ophiolite complex and a tectonically eroded green schist unit derived from the over-ridding continental plate.

INTRODUCTION

Oroclines, arcs and syntaxes characterize Pakistan's geology. There is no other country where mountain belts bend so often, and so severely (Fig. 1). Many ophiolite occurrences are found from the northern to the southern end of the axial fold-thrust belt of Pakistan (Asrarullah et al., 1979). Among them, the Bela ophiolites occur as the southernmost branch of the main Himalayan ophiolite belt. The western and southern borders of this ophiolite zone are covered by alluvium or by the Upper Tertiary sediments; consequently their tectonic setting can be investigated only by geophysical studies. The analysis of the gravity anomalies, pertaining to eastern half of the Bela Plain, has revealed that the Bela ophiolite zone extends southward in subsurface and continues into the Arabian Sea (Zaigham and Mallick, 1994).

In view to understand the geological setting, a gravity profile has been observed along the coastal area across the Bela Plain. This paper describes the results of the interactive modeling of the gravity profile.

Fig. 1 - Index map showing the main geological trends in Pakistan and the location of the study area. Rectangle- study area. Bold dashed line within the frame shows location of the gravity profile.

GEOLOGICAL SETTING OF THE BELA AREA

The mainly north-south trending axial fold-thrust belt of Pakistan includes several ophiolite occurrences. Among them, the Bela ophiolites located at the southern end of this fold-thrust belt, are probably the most widespread.

The Bela ophiolite zone is bounded by: i) the Piaro Ridge consisting of mainly Jurassic carbonate and clastic units, the Bela Plain, and the Haro Range of Hingol trough consisting of accretionary flysch sediments and north-south oriented chain of mud volcanoes and mud diapirs in the west, ii) the tectonically deformed Jurassic rocks of Mor Range and Cretaceous-Tertiary rocks of Pab Range in the east, and iii) the Arabian Sea in the south (Fig. 2). As most of the coastal area is covered by the Quaternary sediments, therefore, the correlation between the land geological structures and the submarine geological features has become difficult.

The main stratigraphic units recognized in the Bela area are shown in Fig. 3. The Jurassic Ferozabad Group forms the bulk of the Mor Range and the Piaro Ridge. Lithologically, it consists of carbonates and subordinate amounts of sandstones and shales, which are gradationally overlain by a Cretaceous sequence (Anwar et al., 1991). The Cretaceous sequence can in general be divided into five lithologic units particularly in the east of the Mor Range, i.e. the Sember Formation, the Goru Formation, the Parh Formation, the Mughalkot Formation and the Pab Formation in ascending order (Fatmi, 1977). The upper four formations are missing in the west of Mor Range in Bela ophiolite area and the Sember Formation represents the only Cretaceous formation above the Ferozabad Group. The Sember Formation consists of monotonous sequence of interbedded shales and mudstones. The Sember Formation is overlain by the Bela melange (Sarwar, 1992).

The Bela melanges consist of a chaotic mixture of small clasts to huge mountain-size blocks of a variety of rocks embedded in a dominantly shaly matrix (Sarwar and DeJong, 1984). The clasts are derived from ophiolitic as well as con-

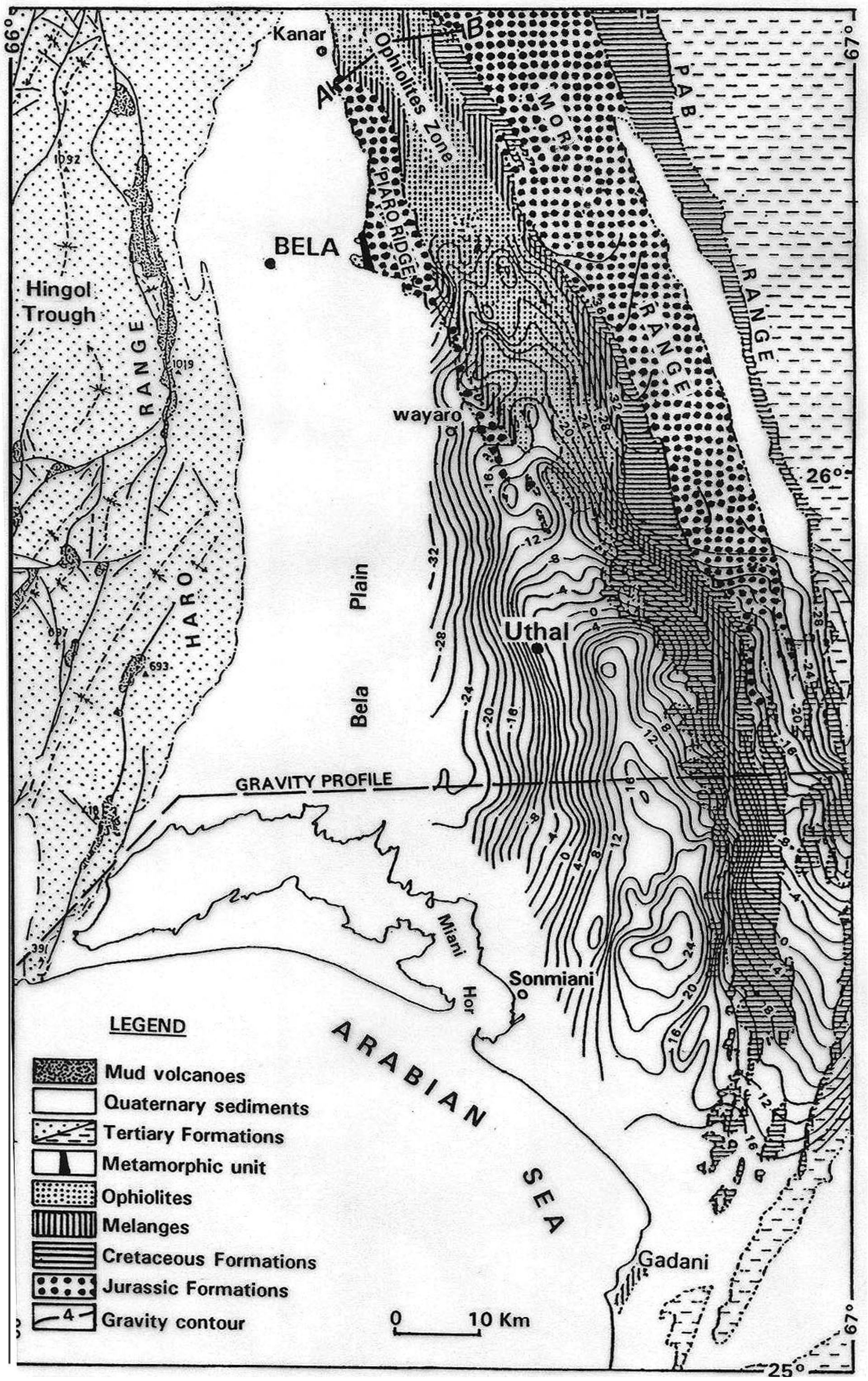

Fig. 2 - Overlay of the Bouguer gravity anomalies over the geology of southern part of the axial fold-thrust belt of Pakistan. Interval of gravity contours is 2 mGal. Map shows locations of the gravity profile of Fig. 7 and the geological profile AB of Fig. 4.

tinental rocks, the latter are mainly represented by the underlying Mesozoic and older sequence of the continental margin, including pink granite basement of the Indian shield (Gansser, 1979). The youngest fossils recovered in the clasts are Maastrichtian forams indicating Late Cretaceous age (Sarwar, 1992). Regionally, the melange zones are exposed in two narrow linear belts of variable width along the western slope of Mor Range (4.5 km wide) and along the eastern slope of the Piaro Ridge (2 km wide). The eastern melange zone extends in the south discontinuously up to the Arabian Sea. In the southern most area, the melange is exposed in the coastal area of Gadani village and also at the mouth of Hub River in Ratti Hills outside the study area about 20 km south of Gadani. The western melange about 20 kilometers east of Bela Town, along the eastern slope of Piaro Ridge, is partly covered by alluvium, but further southward about 20 km north of Uthal Town, it is completely covered and no exposures are known. Similarly, the outcrops disappear northward under the alluvium near the Kanar locality (Fig. 2).

The Bela melange is tectonically overlain by the Bela ophiolites which were emplaced during Paleocene-Early Eocene times (Allemann, 1979). In the east, the shear zone, about 25 m wide, between the outcrops of the Bela ophiolites and the Mesozoic sedimentary sequences is character-

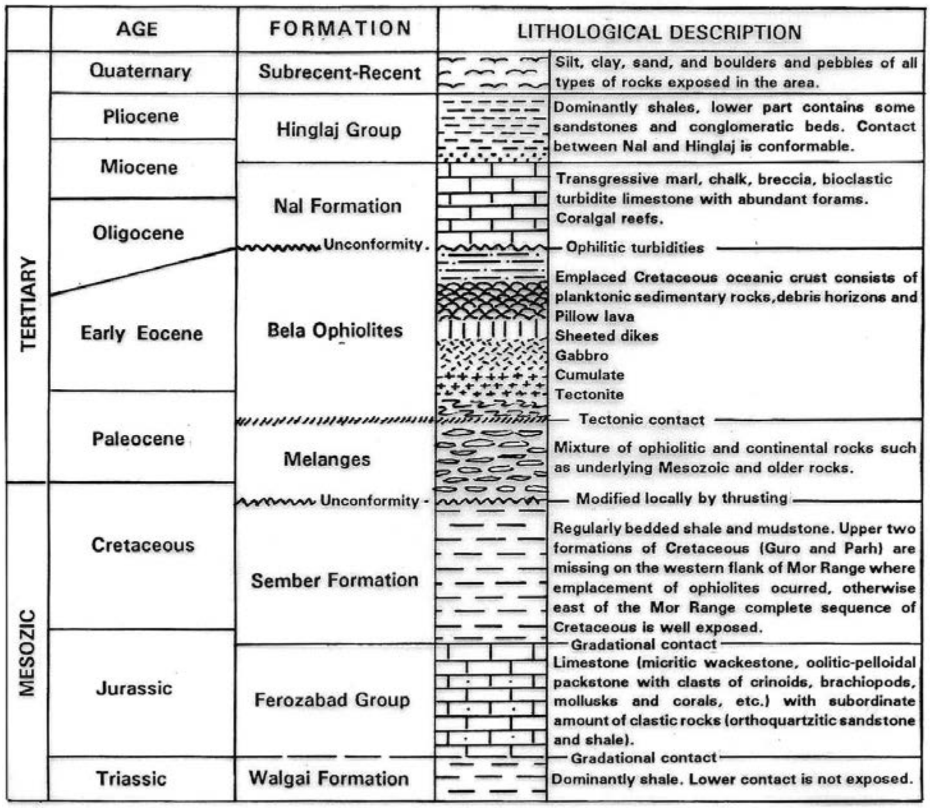

Fig. 3 - Major stratigraphy and tectonic units exposed in the Bela area (source: HSC, 1960; Sarwar and DeJong, 1984; Sarwar, 1992; Ahsan and Rizvi, 1997; Gnos et al., 1997).

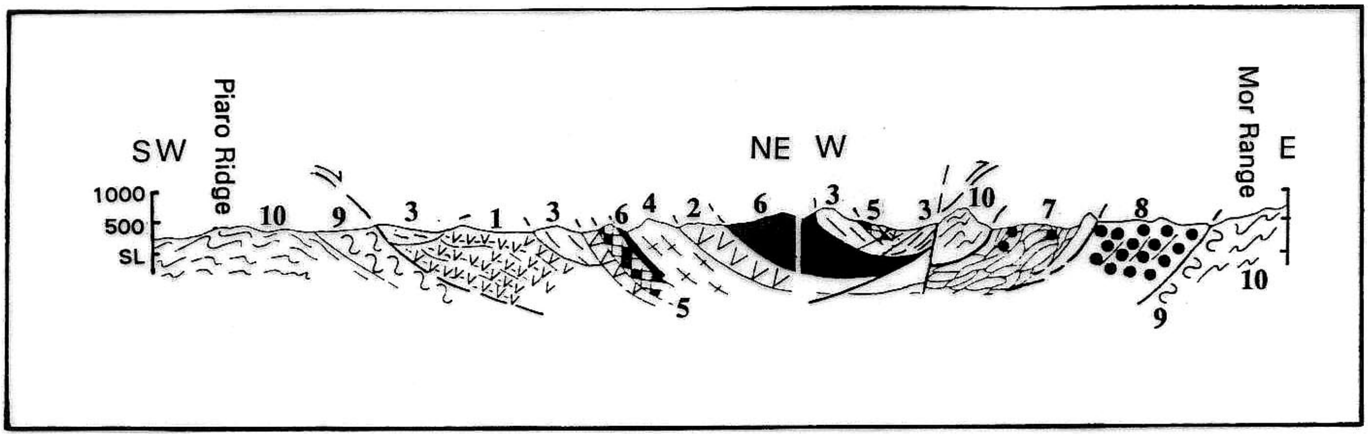

Fig. 4 - Geological cross section of Bela ophiolite zone near Kanar locality (after DeJong and Subhani, 1979). Location of the geological profile is shown in Fig. 2. 1. Pillow lavas with sediments; 2. Pillow lavas without sediments; 3. Sediments+pillow lavas+dolerites; 4. Sediments+gabbroic sills, Melange (locally named Kunno); 6. Ultramafics with gabbro; 7. Melange (locally named Kanar); 8. Agglomerate, 9. Mesozoic shales; 10. Mesozoic limestones.

ized by strongly foliated shales, boundinaged limestone, slices of diabases, gabbros and slates (Gansser, 1979). The western border of the Bela ophiolite zone is also characterized by shear zone where boundinaged Jurassic and Cretaceous limestones, foliated shales, gabbro and diabase slices occur. In the east of the Bela, the ophiolites occur as synclinal nappe (Fig. 4) near Kanar locality (DeJong and Subhani, 1979; Sarwar and DeJong, 1984). In general, all ophiolitic rock types of the Bela ophiolite zone occur as slices measuring from few dozen meters to more than 20 kilometers in length (DeJong and Subhani, 1979). The southern zone mainly consists of pillow lavas. The rock types associated with the ophiolites include pelagic sedimentary rocks with many doleritic or gabbroic intrusions. Due to severe tectonics, the primary relationships between the different lithologies of the ophiolite sequence are not preserved. According to Ahsan et al. (1988) a typical ophiolitic sequence (ultramafic tectonites, ultramafic cumulates, mafic cumulates, sheeted dike complex, basalts) is exposed about 150 km in the north of the study area.

During Oligocene-Miocene times, neoautochthonous carbonates (Nal Limestone) were deposited on the Bela ophiolites. Allemann (1979) has described a 300 m thick section of the Nal Limestone, rich in foraminiferal-coralgal fauna, located 15 km north of Kanar locality. Conformably, the clastic sediments of Miocene-Pliocene Hinglaj Group are overlying the Nal Formation (HSC, 1960).

The Bela ophiolites differ both in structural style and age of emplacement from the Oman and Iran ophiolite nappe, which were emplaced before the Late Maastrichtian (Stocklin, 1977). The Bela ophiolite zone was emplaced in the Paleocene-Early Eocene time (Allemann,1979; Sarwar and DeJong, 1984), as well as the Iranian ophiolites cropping out east and north of Neyriz (Stocklin, 1977). According to

Allemann (1979) and Sarwar and DeJong (1984), the northward migration of the Indo-Pakistan subcontinental plate began to reduce the Tethyan sea and the Bela ophiolite emplacement belonging to this oceanic crust, not before the Paleocene and not after the Lower Eocene time occurred. Differently from the Iranian sub-belt, the Bela zone is characterized by many huge ophiolite slabs. Their north-south extension can be a dozen kilometers or more, but their width is generally less than a few kilometers. Conspicuous melange zones generally border the large ultramafic masses along steep and highly tectonized contacts.

GRAVITY DATA ANALYSIS

Gravity Anomaly Map

The study of the Bela ophiolite zone has been performed using gravimetric data and available geological information. Bouguer anomaly map of the Bela region covers an area of about 4000 km^2 between latitude 25º 15¢ to 26º 15¢ N and longitude 66º 30¢ to 67º 00¢ E. Present cross-sectional interpretation is based on a gravity profile observed across the Bela Plain along the coast of the Arabian Sea. Fig. 2 illustrates the relationships of gravity anomalies with the exposed geological units. The relatively smaller anomalies in the extreme northwest corner appear to be associated with the ophiolite units that crop out to the east and northeast of Wayaro village. All other anomalies are in areas covered by the Quaternary sediments extending from the coast of Arabian Sea to Uthal. The predominant trend on the Bouguer gravity map, is a north-south trending zone of gravity high anomalies, bounded by relatively steep gradients to the east and the west. It is inferred that these anomalies are due to the presence of ophiolites at depth under the Quaternary/Upper Tertiary deposits. To the north of Uthal smaller gravity high anomalies with northwest-southeast trends and bounded by relatively steep gradients, appear to be associated with exposures of the Bela ophiolites. The presence of steep gradients on either side of the north-south striking gravity highs, suggests probable tectonic emplacement of the ophiolites along a complex system of faults/fault zone.

On the west side of the map, there is a north-south striking gravity low, which indicates a sedimentary basin filled with Quaternary/Upper Tertiary sediments. To the east of the zone with high gravity anomalies, a narrow zone of low gravity anomalies is noted which coincides with the exposed sedimentary sequence of Cretaceous/Jurassic age just east of the tectonic contact between Bela ophiolite zone and the Mesozoic sediments. In general, the trend of this zone is almost north-south, but about 20 km to the northeast of Uthal town, one of these gravity low anomalies shows a northwest-southeast change in the general strike of the zone and before returning to the regular north-south trend. The kick in the strike of this gravity anomaly agrees with the tectonic offset of geological structures on the regional scale. A relatively high gravity gradient on the eastern side of the central zone of gravity high anomalies almost coincides with the eastern zone of the ophiolite-sedimentary melange throughout the area, which also indicates a relatively high angle zone of thrusting. A significant deviation of this gravity gradient in its north-south strike trend, similar to the eastern zone of low gravity anomalies, is also seen. This change in strike indicates the tectonic offset of Bela ophiolitic zone towards the west with respect to buried ophiolites south of Uthal. The gravity and geological data also suggest that the Kirthar Range is a thick wedge of sediments underlain by crystalline basement (Zaigham, 1991).

Isostatic balance of Earth's crust in the Bela Region

Fig. 5 illustrates the relationships between Bouguer anomalies and their respective elevations (average topography) in the Bela region. The anomalies decrease with increasing elevation at an average rate of 77 mGal/km in the area. In localities of isostatic equilibrium the rate of change of Bouguer anomalies with elevation is calculated as 152 mGal/km. This difference implies a local isostatic undercompensation. In some tectonic contexts, the question of equilibrium must be re-framed in more dynamic terms than the classical concept of isostasy. According to the classical concept of isostasy, the crust initially was imagined to float passively upon the fluid-substratum (upper mantle), but now the same crust is known to be moving as part of the whole plate-tectonic flow. The lower than normal rate of change in Bouguer anomalies with elevation is probably due to relatively shallow intracrustal rock materials associated with upper crustal features along the western margin of the Indo-Pakistan continental plate. The lower gradient of Bouguer anomalies with elevation change also indicates that the upper crustal features are in the process of isostatic balancing at present and indicates existence of an active oblique subduction process in the area.

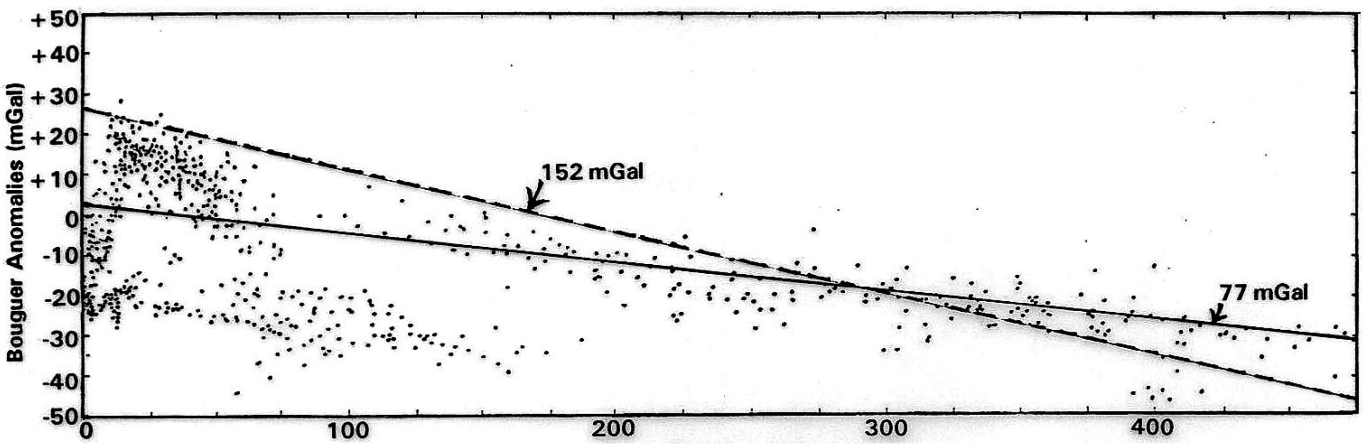

Fig. 5 - Plot of the Bouguer gravity anomalies verses the elevations of observation stations (700 stations at interval of 1.6 km) in the Bela region of Pakistan covering an area of about 4,000 km^2.

Gravity Modeling

The Bouguer gravity anomaly map presented in Fig. 2 covers only the portion associated with the ophiolite zone in the eastern half of the Bela Plain. In order to model deep crustal structures, it was considered necessary to obtain a complete picture of the continuation of gravity data in the western part of the Bela Plain. An east-west oriented gravity profile has been observed for interactive two-dimensional modeling across the southern most part of the Bela Plain almost parallel to the coast (Fig. 2). Gravity modeling was done using the `MAGRA' interactive modeling program for gravitational and magnetic anomalies (Thorarinsson, 1985). Interpretation of basement depth and the gross structural configuration from the analysis of aeromagnetic data and power spectrum of wave number versus the logarithm of the Bouguer gravity anomalies for representative profiles (Zaigham, 1991), provide the basic parameters of the polygons for two-dimensional gravity modeling. Rock samples were collected from the Bela ophiolite zone and Mesozoic outcrops to determine densities. For gravity modeling, the density of the Precambrian basement rocks is assumed within the range of 2.7 to 2.75 gm/cm^3.

The Bouguer gravity profile is similar to the predicted gravity anomaly over the completely eroded orogen for the schematic model of obducted crustal structure (Fig. 6) suggested by Karner and Watts (1983). According to this model, the gravity anomaly is characterized by a positive-negative couple in which the gravity low is due to deformation of the lithosphere and the gravity high is related to the excess mass of the buried load. Similar cases of gravity anomaly “couple” were also found over the Alps, the Appalachians, and outer and inner gravity signature of the Himalayas. These couple anomalies were described by the calculated models in which the lithosphere was deformed by flexure due to surface and subsurface loads emplaced during orogeny.

Similarly, the calculated model for the Bela area (Fig. 7) shows a correlation between the observed Bouguer anomaly profile and the calculated gravity anomalies by theoretical modeling of sub-surface geology. The inner gravity high, with reference to model of Fig. 5, is related to Bela ophiolite zone. The outer gravity low is related to the shape of the flexural depression of the Hingol trough. The gravity low along the continental slope suggests a dynamic downwarp of the oceanic crust. The exotic granite blocks of crystalline massif in the Bela ophiolite zone, green schist slivers and the Mesozoic rock units (e.g. the Piaro Ridge) represent parautochthonous to allochthonous material emplaced as a result of obduction of the Bela ophiolites, tectonically eroded from the western margin of the overriding Indo-Pakistan continental plate. The present gravity model indicates the presence of crystalline basement, related with the western rifted margin of the Indo-Pakistan continental plate beneath the Kirthar Range east of the Bela ophiolite zone. The Bela area continental crust, unlike the full thickness of continental crust (about 40 km) from stable Indian craton just south of the main collision zone of the northern Himalaya, is interpreted to be thinner and implies that the Kirthar Range is undergoing an early stage of convergence in southern Pakistan. It appears from the calculated earth model that the crystalline crust of the Indo-Pakistan subcontinent has obliquely overridden the subducting Bela-Hingol micro-oceanic plate (a segment of the Arabian oceanic plate). The present model also implies the following geological events related to sedimentation of rock units in the basins of the foreland and the hinterland:

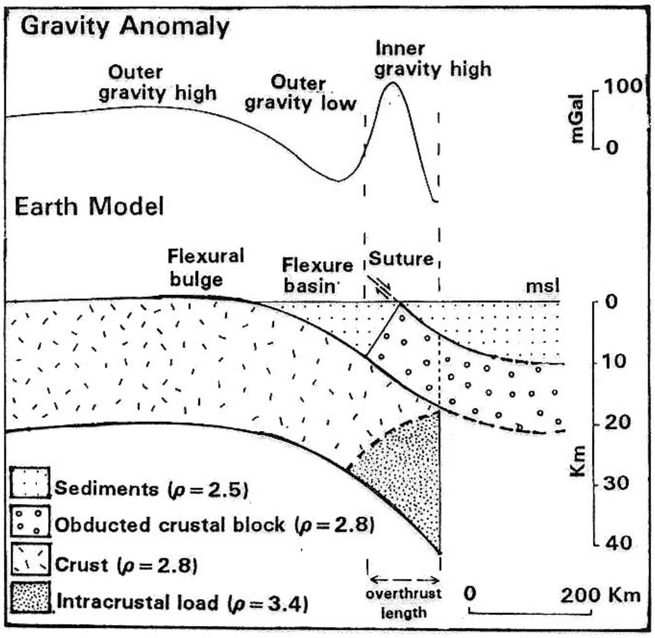

Fig. 6 - Calculated gravity anomaly profile for the emplacement of load onto the continental lithosphere at mountain ranges (after Karner and Watts, 1983).

- The Kirthar Range consist of a thick sedimentary wedge underlain by tectonically deformed crystalline basement with an eastward slope of about 23°- 25°. The thickness of the sedimentary wedge appears to increase to the east.
- The crystalline crust is dissected by normal faults into tectonic blocks, that indicate the presence of a rifted western margin of the Indo-Pakistan continental plate.
- The Bela ophiolite zone was emplaced from an oceanic plate by obduction process. The oceanic plate is obliquely subducting eastward under the western margin of the Indo-Pakistan continental plate with a steep angle of about 20°.
- A sizable zone of the metamorphic complex emplaced during the ophiolite obduction, indicates deformation and tectonic erosion also at deeper levels.
- The descending oceanic plate shows a gentle slope of about 2° west of the middle of the Bela Plain and then steepens eastward with a slope of 20°.
- A block of high density material has been interpreted beneath the flysch sequence accreted on the floor of the descending oceanic plate. This high density material is inferred to be the lower part of a metamorphic layer or a fragment of subducting oceanic plate. From the presence of active mud volcanoes and huge amount of thrust ophiolite blocks, it is concluded that the rate of convergence of the descending plate was greater than the rate of sedimentation in the trench. This resulted in deformation at the base of the hanging wall of the overriding plate. In the setting where the convergence rate was high and a change in the dip of the subducting plate was taking place, the accreted materials would have been removed as is currently happening in the Peru-Chile trench system.
- The flysch sediments of the Hingol trough have considerable thickness (8,000 m approx.) on the gentle slope of the descending oceanic floor. Upward thrusting of high density block along the floor of the descending plate appears to be related to overpressure within the flysch sediments during the development of a discrete, radiating im-

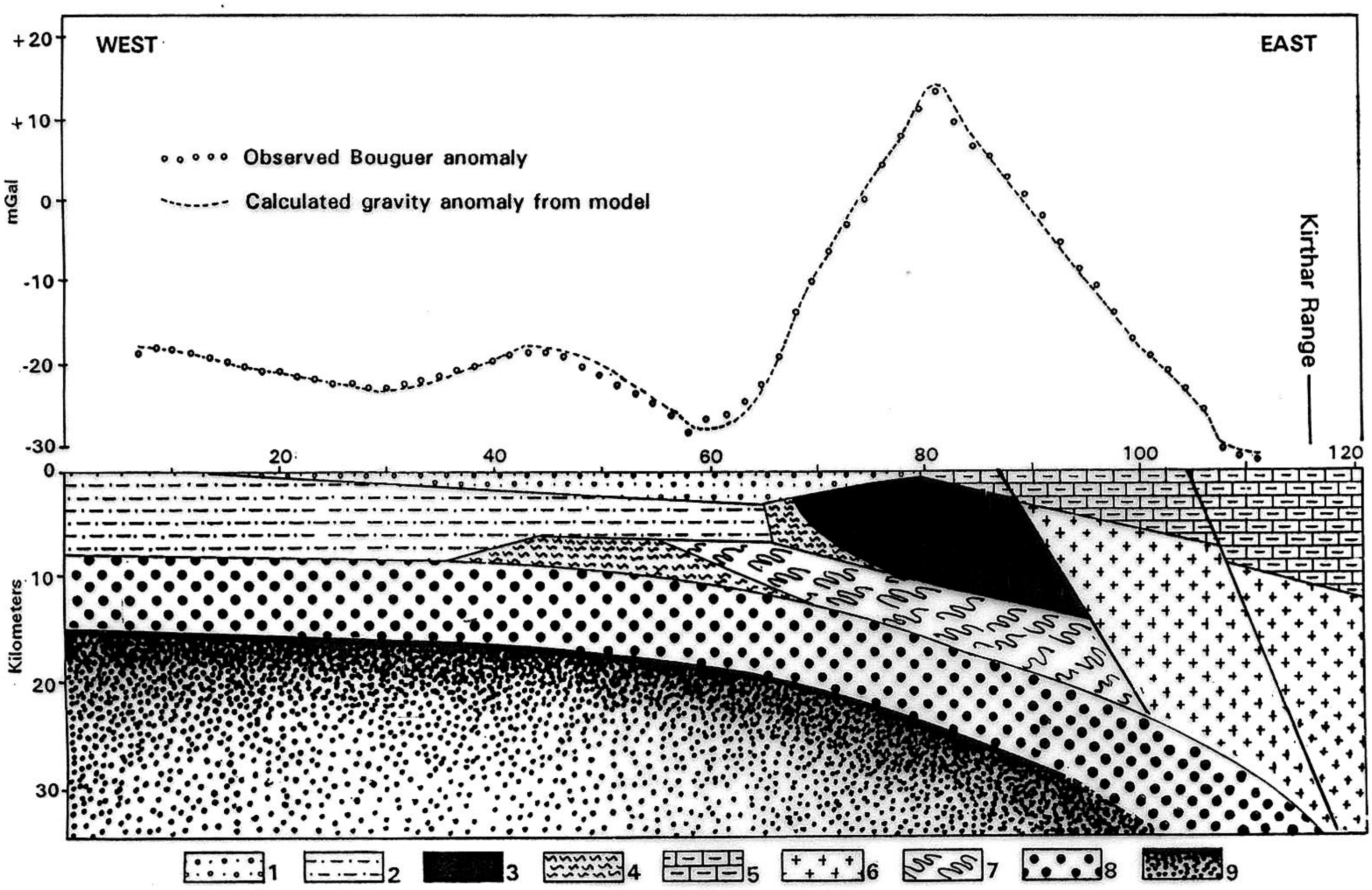

Fig. 7 - Bouguer gravity anomaly profile and calculated earth model across the southern Bela Plain along coast of the Arabian Sea. 1. Quaternary sediments; 2. Hingol flysch sediments of Late Tertiary age; 3. Obducted Bela ophiolites and melanges; 4. Green/blue-schist units; 5. Mesozoic-Tertiary sediments; 6. Rifted continental basement rocks; 7. Intracrustal units; 8. Subducting Neo-Tethyan oceanic plate; 9. Upper mantle.

bricate thrust fault system. The presence of a chain of mud volcanoes along eastern margin of the Hingol flysch basin is the surface indications of the overpressure that is presumably due to intense tectonic movements.

- Quaternary deposits appear to have accumulated in an asymmetrical basin below the Bela Plain. The eastern slope on the top of the complex is steeper (about 11°) than that of western slope (about 2° to 3°) over the flysch sediments.
- The suture line passes through Miani Hor into the Arabian Sea in almost north-south direction delineating the western limit of the Indo-Pakistan subcontinental plate.

CONCLUSIONS

The tectonic model calculated from the gravity data, delineates the subduction tectonics in the Bela region which is concluded below:

1. A segment of the Arabian oceanic plate (Bela-Hingol micro-oceanic plate) has been underthrust beneath the western-rifted margin of the Indo-Pakistan subcontinental plate. As a result of this subduction, an accretionary prism has been developed towards western part, which consists of a north-trending chain of mud volcanoes and mud diapirs along thrust faults. The accretionary prism is composed of flysch sediments of late Tertiary age.
2. A high-density, lower part of metamorphic zone or a part of oceanic plate, has accreted down to a depth of 8 km on floor of descending oceanic plate beneath the flysch sequence causing eruption of mud volcanoes along imbricate thrust faults due to over-pressure.
3. On the eastern side, the obduction complex, consisting of Bela ophiolites and tectonic melange zone, has tectonic thrust-contact with the accretionary prism. A poorly exposed metamorphic complex composed of green schist marks this thrust-contact. Blue schist has not been reported in the area, but the inferred model indicates possible presence of blue schist at depth along the ridding edge of the Indo-Pakistan continental plate.
4. A thick sedimentary wedge, comprising of Mor, Pab and Kirthar mountain ranges, is underlain by the crystalline basement that is dissected by normal faults into tectonic blocks. This tectonic complex represents the over-ridding western margin of the Indo-Pakistan continental plate.
5. Continuation of the gravity anomalies associated with the buried ophiolites beneath the Bela Plain, indicates that the suture zone passes through Miani Hor into the Arabian Sea in almost North-South direction.

Acknowledgments

The authors are thankful to the Director General, Geological Survey of Pakistan, for extending facilities available in the department. They are also indebted to Mr. Anwaruddin Ahmed, Ex-Chief Geophysicist, Mr. I. H. Quraishi, Director (Geology), and Prof. Dr. K. A. Mallick, University of Karachi, for critical discussions and reviews of the manuscript. Authors are also thankful to the `Anonymous' referee for his critical review of the manuscript.

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Received, April 10, 1998
Accepted, November 14, 2000