Bouguer Reduction with Lateral Variable Surface Densities- A Model Based Case Study in Geologically Complex Frontier Area

Paramjit Singh*[1], R.S.Pandey[1], S.K.Gupta[1], N.C.Nainwal[2], Manoj Asthana[1]
[1]Oil and Natural Gas Corpn. Ltd., India
[2]GNB Garhwal University, Srinagar, India

Summary

The Bouguer corrections are applied with two assumptions that "the slab is of uniform density" and "the Bouguer slab is an infinite horizontal sheet". Neither is really valid in geologically complex areas. Serious errors occur in the areas where lithological changes are abrupt and the local relief is sufficient to cause significant errors in the gravity reductions. An attempt is made to counter these assumptions by reducing the field gravity data by actual near surface densities and use terrain correction (TC) where required. The analysis of tectonically complex area of Surinsar anticline in Outer Himalayan thrust fold belt is selected where number of thrusts outcrop on the surface with formations of varying densities, lithologies and ages. Analysis is carried out on a square grid of 25x30 km in this area. The seismically constrained gravity model is generated and analyzed along a selected profile. The application of variable Bouguer densities is suggested where elevation changes are significant. The datum for reducing the data may be selected at the minimum of the elevation to resolve the shallow anomalous features. This methodology can improve the sub surface models in the geologically complex areas where seismic alone is inconclusive.

Introduction

Reduction of gravity field data measurements to MSL or any datum is often done with an average Bouguer reduction density in a basin due to lack of knowledge of near surface rock densities, thus, two assumptions are made in deriving the Bouguer correction; first that the slab is of uniform density and second that it is of infinite horizontal extent. Neither is really valid (Telford et al, 1988). In order to modify the first, one would need to have considerable knowledge of the local geology as to rock type and actual densities. The second is taken care of in the terrain correction.

A lot of work has been done on density contrast varying with depth (Cordell, 1973), (Murthy and Rao, 1979), (Rao, 1990) and (Zhang et al., 2001). A little emphasis is given to the lateral density variation for the near surface layer to be removed for reducing the data on single reference level while processing the gravity data under one investigation or complete basin. Vazk, R (1956) elaborated the idea but remained a non starter to apply on the real field data in complex domains.

The density of sedimentary rocks often varies with depth and laterally owing to the effects of stratigraphic layering, facies variations, compaction, diagenesis, cementation, faulting, folding, thrusting and igneous intrusion. Marked lateral density variation due to reasons mentioned above leads to inaccuracy in quantitative analysis and sometimes put severe constraints on the resolving power of gravity analysis for local structures.

In this paper, geologically complex Frontier area of thrust fold belt of Surinsar anticline in Outer Himalayas is selected to explain the reasons in variation of near surface densities of rocks and application of this methodology is demonstrated in improving interpretation. The variable Bouguer correction densities are applied in a square grid of 25x30 km on each and every gravity station individually and corrected for terrain effects. The results are analyzed and its implication on shape and position of observed anomaly having considerable bearing on exploration objectives are discussed. It is worthwhile to mention the realities of reducing the data to Mean sea Level (MSL) or other convenient datum incorporating actual near surface rock densities.

Reasons of near surface rock density variations

Most of the Gondwana Basins in India exposes different formations laterally and each lithology exposed on the surface has a faulted contact. These faults have acted as a conduit for igneous intrusions during Cretaceous period and as a result, sills/dykes either exposed or concealed cause marked lateral variation of densities in the near surface (Fig.1).

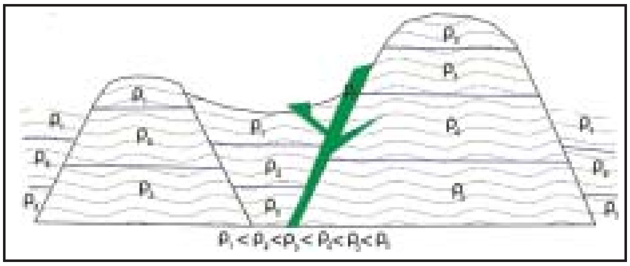

Fig.1: Varation of surface density due to faulting and igneous intrusions.

Similarly in thrust fold belt areas, the surface density may vary significantly within a short area due to the different lithological character of rocks forming different parts of the topography due to emergence of the thrusts (Fig. 2).

There may be areas where fault propagated folding or vice versa is the main factor in forming the topographical relief. In such areas the higher blocks have higher average densities than the lower ones (Fig. 3).

If the erosion cuts the same fold into individual topographical highs of about the same relative elevation, they may have different density values (Fig.4).

A combination of faulting, igneous intrusion, folding, erosion and lithological changes may complicate the density distribution in the near surface rocks in the complex geological areas where seismic also remains inconclusive due to the said reasons (Fig. 1-4). The integration with nonseismic offers a possible solution for generation of an optimum geological model for hydrocarbon exploration. Before applying this technique on the real field gravity data and finding its implications it is better to understand why variable density is required to be applied in such areas.

Why variable Bouguer density?

Bouguer gravity anomaly values are significantly affected by topography. To remove this effect it is necessary

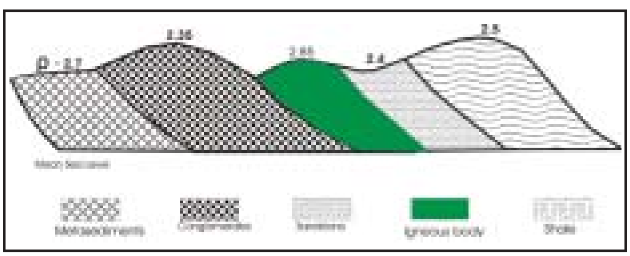

Fig.2 Variation of surface density due to change in lithology

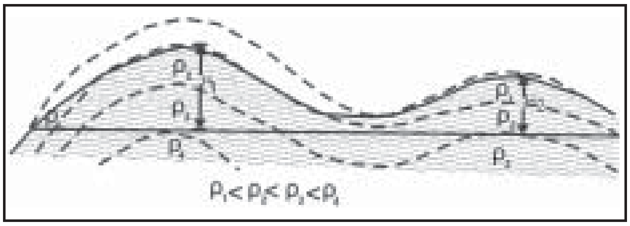

Fig.3 Variation of surface density due to folding and erosion (after Vazk, R 1956)

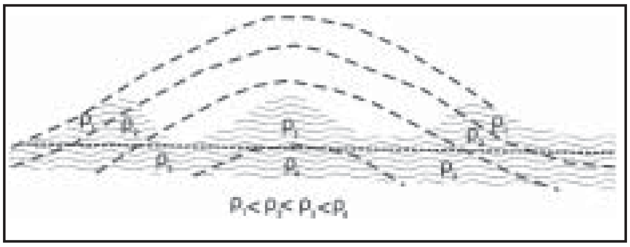

Fig.4 Variation of surface density due to the erosion of an anticline (after Vazk, R 1956)

to know the absolute height and density of the near surface layer i.e. the density FF of formation lying between the exposed surface and the reference datum (usually MSL). Correct choice of the density value for near surface layer is particularly important while preparing maps from the data of semidetailed/ detailed/high-precision gravity surveys for hydrocarbon exploration to take a note of the local structures. The variation in density distribution of the near surface layer is determined by the lithological composition of the near surface layer.

When the effect of the near surface layer density (FF) is under/over estimated while investigating the local anomalies of small amplitude causative, it may generate fictitious positive and negative anomalies with a displacement of the features of interest. For example, the Bouguer anomaly is altered by 0.42 mGal by a change of 0.1 gm/cc in the mean density of the near surface layer in an area with an average height of 100 meters. Errors would be more pronounced in the areas of sharper variation in elevations. It has been suggested that in some situations it might be necessary to assume different values of FF for different sections of the profile, but this obviously requires more geological information than would normally be available (Nettleton, 1976). It must be remembered that inaccurate selection of the density value for the near surface layer affects the calculation of Bouguer anomalies causing errors in geological interpretation. It is also not out of the context to mention that variation in near surface abrupt changes in velocities is also a big constraint in seismic data processing. This is especially true in regions where the surface materials are of low-density unconsolidated sediments or poorly lithified sedimentary rocks and local relief is sufficient to cause significant errors in the gravity reductions due to incorrect surface density assumptions (Hinje, 2003). In case topographic variations are severe, the spatial variation of lithology from surface and borehole data should meticulously be incorporated to arrive at correct density value of the near surface layer.

The application of lateral variable Bouguer density and terrain correction is applied on a rectangular grid in the geological complex thrust fold belt of Himalayas for which the following methodology is adopted:

Methodology in the geological complex areas

The major challenge in exploration is to generate a consistent and reliable model of the given geophysical/ geological system, integrating independent data sets with different meanings, acquisition scale, resolving power and quality etc. This aspect becomes more relevant in the geological complex areas of Himalayan thrust fold belt, especially where the confidence in reflection seismic data is poor.

The area of Surinsar anticline in the Himalayan Thrust Fold Belt is selected for analysis of gravity data where seismic imaging is inconclusive due to the steep dips and complex thrust fold geometry (Fig.5). The type of rocks on all the gravity stations are identified by the field party and are recorded in the computation registers (Trehan et al, 1968). The field party has also used the variable densities which they picked up from the boreholes in Jwalamukhi area and are on the lower side for Upper and Middle Siwaliks.

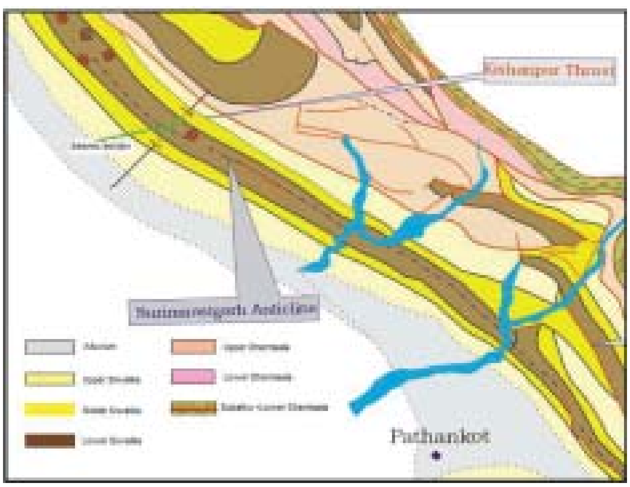

Fig. 5 Geological map of Surinsar area of Outer Himalayas

Himalayan foothills are highly affected by thrusts causing near surface lateral density variation due to juxtaposition of different formations/lithologies. The rocks of different ages and formations (unconsolidated Gravels, Upper, Middle & Lower Siwaliks and Dharamsalas) with varying degree of compaction and compression are exposed on the surface (Fig.6). A Bouguer anomaly map with an average density of 2.3gm/cc in a grid of 25x30 km is processed which is used in all the Himachal Pradesh area to generate a regional gravity map (Fig.7). The necessary terrain correction (TC) on all the gravity stations with varying densities is also applied. Their may be negligible discrepancy

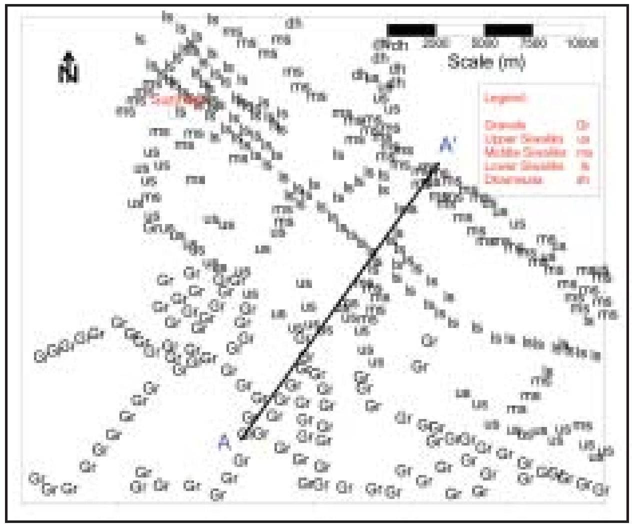

Fig. 6: Map showing type of rocks exposed on the surface in the Surinsar-Mastgarh area of Outer Himalayan Thrust Fold belt. The density of symbols also shows the gravity station location.

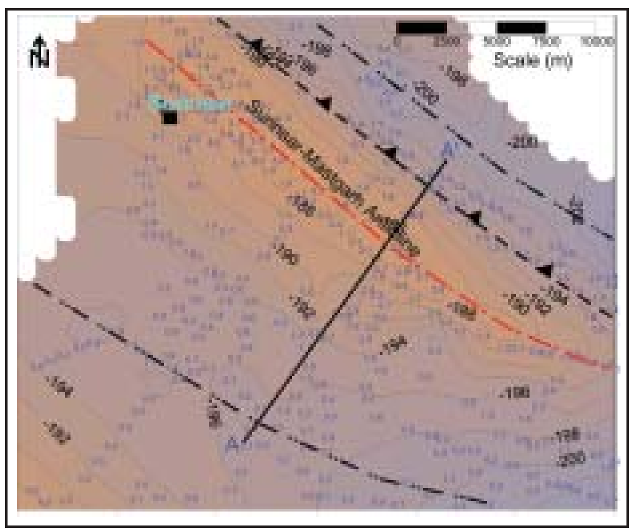

Fig.7: Bouguer gravity anomaly map of the Surinsar anticline. The gravity anomalies are processed with an average Bouguer slab density of 2.3gm/cc and the datum is MSL. The terrain corrections computed station by station with variable densities is superimposed.

in computing the TC in Upper Siwaliks where density of the slab is taken as 2.1gm/cc instead of 2.3gm/cc in the present study.

The dry and saturated bulk densities of exposed rock samples are studied in the laboratory of Oil and Natural gas Corporation Limited (ONGC). The depth of water table in the sub surface is beyond the control of this study where rocks will be saturated and due to this reason an average of the dry and saturated densities measured are used for Bouguer correction. The gravity anomalies are computed by applying lateral variation in surface density for the reduction of Bouguer slab and generated gravity anomaly maps at MSL & at 250m above MSL (i.e. near the minimum elevation in the area), terrain corrected (Fig. 8&9 respectively). The variation in reduction of the data with an average and variable slab density along a profile AA' at a convenient datum and at MSL is evaluated (Fig. 10). The seismo-geological model is generated along this profile by using interval velocities from sonic log of the borehole drilled at the Surinsar anticline and tested the efficacy of the model by gravity forward modelling (Fig.11).

Discussions

The gravity anomalies are oriented parallel to the Siwalik hills and is the manifestation of Himalayan orogeny which created thrust propagated anticline. The gravity

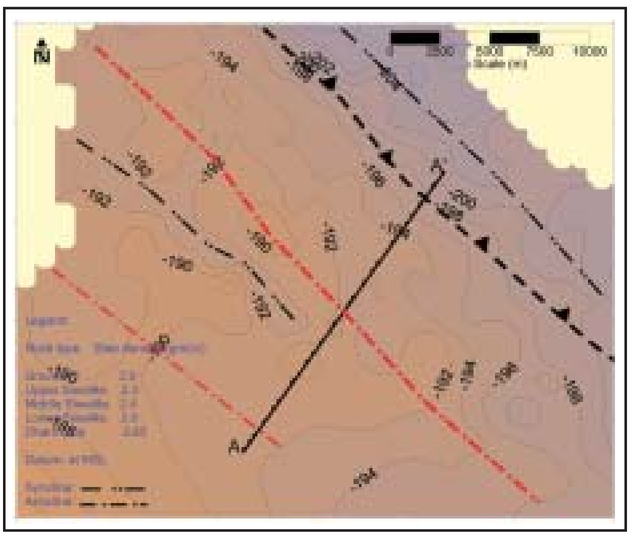

Fig. 8: Bouguer gravity anomaly map on the Surinsar anticline. The gravity anomalies are processed with lateral variable Bouguer slab densities (shown above in the legend in blue colour) and the datum is at MSL. The Surinsar gravity high has decomposed into gravity high and a gravity low on the south with the same trend with the use of the actual Bouguer density correction. The terrain correction applied is posted on the map above (see Fig. 7)

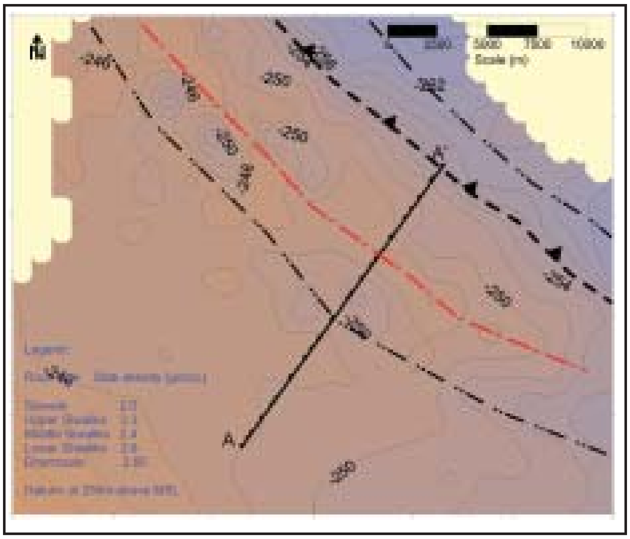

Fig.9: Bouguer gravity anomaly map on the Surinsar anticline. The gravity anomalies are processed with lateral variable Bouguer slab densities (shown above in the legend in blue colour) and the datum is at 250m above MSL. The Surinsar gravity high has decomposed into gravity high and a three local gravity lows. The purpose of reducing the data at a datum of 250m above MSL (minimum elevation of the area) is to avoid stringent correction in the thrust fold area. The change in the vertical relief of the anomaly showing highs and lows are due to the sudden change in the lithology outcropping along the thrust faults. The terrain correction applied is posted on the map above (see Fig.7). Analysis along the profile AA' is given in Fig. 10.

contour map is expected to show influence of the local and sharp features due to the thrusts coming up with different type of rocks having a considerable variation in densities. The gravity anomaly map with an average Bouguer slab density processed at MSL shows a smooth major gravity high at Surinsar area in the Himalayan strike. The congestion of contours on the northeastern part shows a thrust fault (Kishangarh Thrust) and a broad gravity low in the SW of the major gravity high (Fig. 7). The overall anomaly map is smooth which is beyond the expectations due to known geological complexities.

After the application of lateral variable density (densities used are shown on the gravity map, Fig.8) few local features have cropped up with a narrow gravity low on the SW of Surinsar high. The axis of the gravity high at Surinsar is displaced to the SW side. Further, the data is processed at a datum of minimum of the elevation in the area (250m above MSL) to resolve the shallow features (Fig. 9). These features can be analyzed more explicitly along a profile AA' (Fig. 10). The free air anomaly almost obeys the topography as expected. The gravity high between 10-16 km of the profile on the anomaly map generated with average density of 2.3 gm/cc also follows the topography. It appears

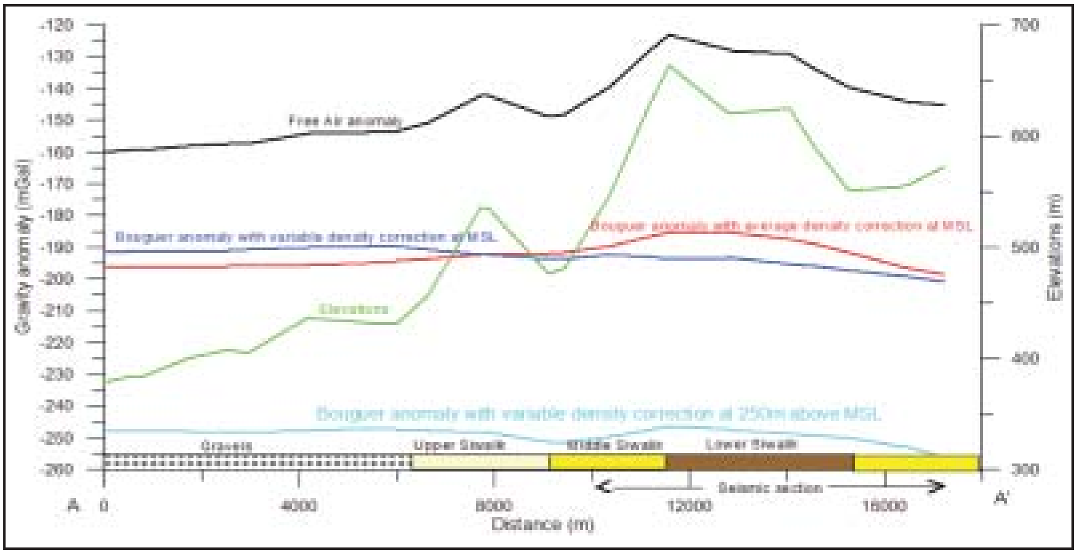

Fig.10: Analysis of the variable densities applied for the Bouguer correction along the profile AA'. The Free Air anomaly is the exact replica of elevation changes which is expected. The Gravity anomaly (in red colour, processed at MSL) shows a high over the topographic high at Surinsar with the application of average density (2.3gm/cc). After applying the actual Bouguer density correction, the effect of topography over the gravity high becomes less pronounced over the topographic high. The Bouguer anomaly processed with varying density and reduced to 250m above MSL shows pronounced highs and lows at the lithological boundaries, thereby indicating thrust fold faults which have emerged with different lithologies on the surface. Bouguer reduction with lateral variable surface densities

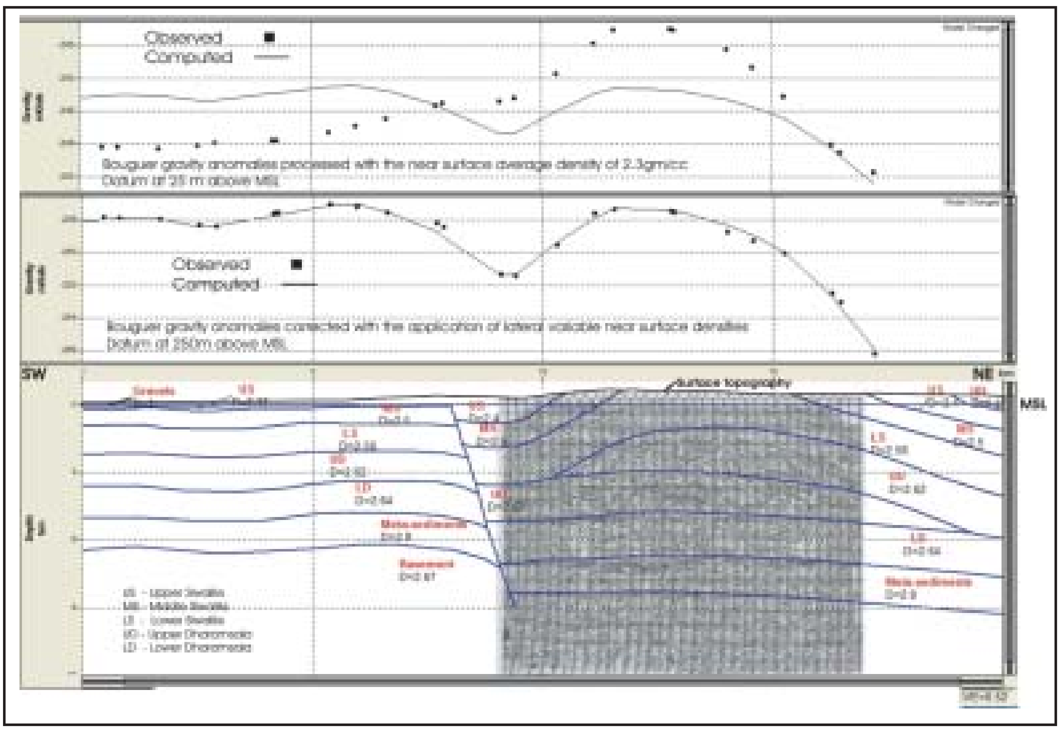

Fig.11: Forward gravity model along a profile AA'. Part of the profile passes over the seismic line. The seismic section is used as a bit map for guidance in the thrust fold geometry. The depth from seismic section is computed by using the interval velocities from Sonic log in a nearby borehole drilled over the same Surinsar structure. The computed gravity response of the seismo-geological model matches very well with the observed gravity values reprocessed with lateral variable near surface densities, whereas it does not match with the gravity values processed with an average density. The densities used for various lithologies are posted in the cross-sectons. These densities are taken from density log of the nearby borehole on the same Surinsar structure.

that the correction is under estimated where rocks of Middle & Lower Siwaliks are exposed whose densities are 2.4 and 2.6 gm/cc respectively. The low density Gravels (2.0gm/cc) are exposed from 0-6 km of the profile. It appears that the Bouguer anomalies are over compensated due to the application of the higher density correction (2.3 gm/cc). The variation of the gravity anomaly with variable density processed at MSL (in blue colour) shows less pronounced gravity high between 10- 16 km of the profile. A gravity high is expected due to the presence of high density Lower Siwaliks. This expected gravity high can be seen along the curve (in sky colour) when the data is processed at 250m above MSL (i.e. at the datum of minimum elevation of the area). The curve in sky colour shows expected relief in the form of lows and highs from the area along the profile where the lithology is changing. This change in the vertical relief of the anomaly is interpreted as thrust faults which have been cropped out with different lithologies on the surface. The gravity response of the seismo-geological model matches excellently with the reprocessed gravity anomaly data with lateral variable near surface densities (Fig.11). It shows a mismatch with the gravity anomaly data processed with an average density of 2.3gm/cc which a customary in Himalayan thrust fold belt. A difference of 2-9 mGal in the vertical relief of the anomaly could have caused a significant error in depth estimation. The most apparent feature is a large normal fault that causes the ramping of the Surinsar structure.

The first assumption in deriving the Bouguer correction that the slab is of uniform density is attempted to set aside by using variable horizontal density of rocks. To set aside the other assumption that "The Bouguer slab is an infinite horizontal sheet", terrain correction to each gravity station is applied. It is concluded that Bouguer correction with varying densities should meticulously be applied and may select the datum at a convenient level to resolve and preserve the shallow features of interest. By using this methodology, the sub surface models can be improved in the geologically complex areas where seismic alone is inconclusive.

Conclusions

In the area of Outer Himalayan Thrust fold belt we are able to mark the boundaries of different lithologies which have been thrusted on the surface and faults are identified. The gravity model integrated with the seismic and borehole data indicates the need of using the true densities for processing the field gravity data.

The pronounced density changes in the area may introduce errors of several mGal by using the average density instead of the true density values even in areas with moderate topography. In order to eliminate the effects of the topography, a Bouguer correction to the level of the lowest point of the topography is sufficient in gravity prospecting for hydrocarbons to resolve the shallow features of interest. The complete Himalayan Thrust fold belt needs a fresh look by applying the above methodology. Using this methodology, the interpretation can be improved for local structures of exploration interest in other Frontier basins as well through improved geological models.

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Views expressed in this paper are those of the authors only and may not necessarily be of ONGC.

References

Cordell, Lindrith., 1973. Gravity analysis using an exponential density-depth function-San Jacinto Graben, California. Geophysics, 38, 684-690.

Hinje, J.William, 2003, Short note on Bouguer reduction density, Why 2.67 ?, Geophysics, 68, No.5, 1559-1560.

Murthy, I.V.R and Rao, D.B., 1979. Gravity anomalies of two dimensional bodies of irregular cross-section with density contrast varying with depth. Geophysics, 44, 1525- 1530.

Nettleton, L.L., 1976. Gravity and magnetic in oil prospecting, McGraw-Hill, Inc. New York, USA, p.464.

Rao, Bhaskara.D., 1990. Analysis of gravity anomalies of sedimentary basins by asymmetrical trapezoidal model with quadratic density function. Geophysics, 55, 226-231.

Sazhina, N., Grushinsky, N., 1971. Gravity Prospecting. MIR Publishers, Moscow, pp.491 (translated from the Russian by A.K.Chatterjee)

Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A., 1988. Applied Geophysics.

Trehan, D.K et al (1968-69), Gravity magnetic data acquisition and interpretation in Surinsar area of J&K. (Unpublished report of ONGC).

Vajk, R., 1956, Bouguer corrections with varying surface density: Geophysics, 21, 1004-1020.

Zhang, J., Zhong, B., Zhou, X., and Dai, Y., 2001. Gravity anomalies of 2-D bodies with variable density contrast: Geophysics, 66, 809-813.