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Seismic Constrained Gravity Inversion for Sub-basalt Exploration in West Coast, India

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SUMMARY

Exploration in sub-basalt reservoirs is challenging because conventional seismic fails to image the structures below basalt. Advanced seismic acquisition using long offsets and low-frequency sources as well as improved processing are the possible way-outs. Use of non-seismic data, e.g., Gravity, Magnetic and Magneto-Telluric (MT), along with seismic is being considered as an option to improve subsurface image below basalt. The present work is an integrated approach for better imaging of the sub-basalt structures. We performed a model study over the geological set-up of a west-coast basin of India. Above basalt velocity model derived from seismic method is converted into density model and is used as constraint in gravity inversion to delineate the below-basalt density structures. The use of additional constraints from MT is found useful to reduce the uncertainty in gravity inversion. The technique is then used to invert satellite gravity data along the same profile to obtain the base basalt and sub-basalt density structure.

Introduction

During continental break-ups, sedimentary basins which may have hydrocarbon prospects get covered/trapped by consecutive lava flows. Most of these volcanic rock formations are basaltic. The sedimentary layers located beneath basalt are termed as sub-basalts and the layers trapped within basalt are called intra-basalt. Standard seismic acquisition and processing fail to image sub-basalt layers due to several reasons which include internal scattering due to rough interface, severe transmission loss because of huge velocity contrast, mode conversion and the presence of inter-bed multiples. For the last couple of years, geophysicists are in search for an appropriate technology to image through basalt. The possible and to some extent proven ways to improve seismic images below basalt are the use of a low-frequency seismic source, wide-angle long-offset data and use of advanced data processing techniques. An integrated use of seismic with different non-seismic methods, viz., gravity, magnetic and magnetotelluric (MT), which do not have the limitation to image through or below basalt - can help to obtain a better sub-basalt picture. In the present work we used gravity inversion, constrained with seismic, well log and MT data, to resolve the sub-basalt structure of a west coast basin of India. The above-basalt p-wave velocity structure, obtained from seismic, is converted into density model using the p-velocity – density relationship derived from available log data. We keep this over-burden density structure constrained for gravity inversion and determined the sub-basalt density structure for a synthetic model. In the synthetic study, the sediment thickness obtained from MT inversion is also used as an extra constrain which further reduces the inherent ambiguity of gravity inversion. Apart from the synthetic study, we inverted the satellite gravity data over the basin along the same profile where seismic and well-log constrains are available.

Geology of West Coast, India

The West Coast of India is a rifted volcanic continental margin evolved after the break-up of the Gondowana super continent during the mid-Cretaceous. The area experienced two major Precambrian magmatic events at about 678 Ma and 550 Ma ago (Chandrasekharam, 1985). In the late Cretaceous period (85-90 Ma) the area experienced another magmatic event. Further, the Deccan basalt erupted from the Reunion hotspot (68.5-62 Ma) is found as continental flood basalts on the western Indian shield which extends through the entire western margin of India. The western continental margins of India consist of a number of major sedimentary basins, which include the Kutch Basin, Surat Basin, Laxmi Basin, Bombay Basin and Kerala-Konkan Basin. Out of these, the Bombay Offshore Basin is the major hydrocarbon containing basin of India. These basins are formed during the time of separation of Madagascar from India (85-90 Ma) and have several north-south trending grabens separated by basement highs (Campanile et al., 2008) which provide structures suitable for trapping of hydrocarbon. Oil and Natural Gas Corporation (ONGC) of India drilled several wells in the southern part of Bombay basin, but despite the favorable condition of a petroleum system, they experienced no success (Chatterjee, et al., 2006). However, none of these wells have penetrated through the basalt into the sub-basalt Mesozoic sediment. Because the Cenozoic sediment above basalt does not contain hydrocarbon reserve, the exploration in this area focuses mainly on identifying sediments below basalt and to evaluate its thickness. As seismic alone fails to image the sub-basalt structure, the present work is an attempt to address the problem using gravity inversion, constrained by seismic and MT.

Constrained Gravity Inversion

The gravity method was the first geophysical technique used for oil exploration in Nash dome (Texas) at the beginning of twentieth century. Later, although it has always been used for reconnaissance, the tremendous success of seismic technology in exploration over-shadowed the gravity method. Recently the gravity method regained its importance in oil exploration, particularly for the areas where the targets of interest are below a high-velocity zone such as basalt. Gravity method, unlike seismic measurements, is an effective tool to map low-density sedimentary layer, especially when it is trapped between high-density basalt and basement.

The major disadvantage of gravity inversion is its inherent ambiguity and unconstrained gravity inversion can lead to an unrealistic geological model. The only way to reduce uncertainty is to use all the available constraints to restrict the search within realistic geological limits.

For the present work, a seismic line along a western off-shore basin has been selected. The available seismic section images clearly the layers above-basalt, whereas, below basalt is hardly visible. Neither base basalt nor basement can be identified from the seismic data. The purpose of the present study is identifying and mapping base basalt and basement. Based on available log data, we established a velocity-density relationship and converted the available above-basalt velocity model (from seismic) to the density model. For below basalt, we assume a single sedimentary layer between basalt and basement (figure 1) and the thickness of the basalt is varied within 500 m to 1800 m (Gombos et. al., 1994). Synthetic gravity anomaly over this model is simulated using the 2D polygon method for arbitrary shape body (Talwani, et al., 1959) where each layer is assumed to be one polygon. The anomaly due to known over-burden is subtracted from total anomaly to obtain the residual. Since, the over-burden is known a-priori from seismic interpretation, the aim of gravity inversion is to delineate the base of basalt and the top of basement and thus, the depths of these two layers are treated as unknowns. The synthetic anomaly has been corrupted using 2.5% noise to make the study more realistic and the density values of the two unknown layers are allowed to vary within strict limit (±10% of actual) to reduce the uncertainty of gravity inversion.

For inversion, simulated annealing (SA) – a well established global optimization technique has been used. The working principle of SA is based on the theory of thermodynamics (Sen and Stoffa, 1995). The advantages of SA over the gradient-based technique are (i) SA does not require any close-to-real initial model, (ii) with certain probability, it has the ability to avoid stacking in local minima and (iii) along with the best-fit model, it produces a number of models having similar degree of misfit (least-square error), which can be used for uncertainty analysis.

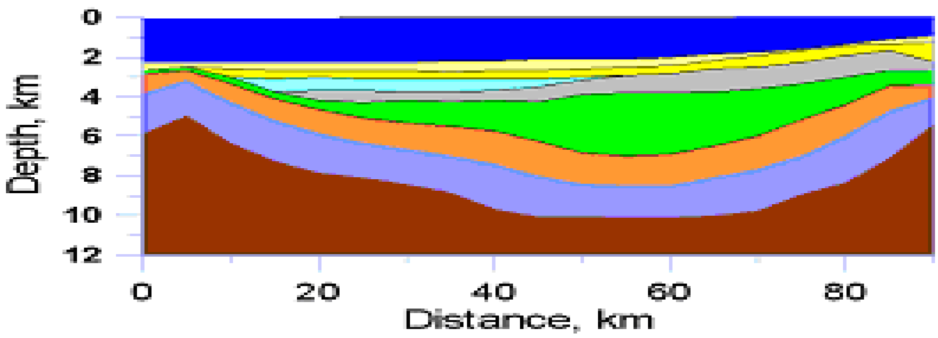


Figure 1 *The density model of the study area.*

We specified a realistic initial range of depth values for each corner of the bodies and the best-fit result is shown in figure 2(a). The agreement between observed and computed data is quite good and the inverted base basalt and basement also resemble the original model. To visualize the uncertainty present in the depth, we performed statistical analysis of all the models having same degree of misfit and have plotted the variance at each depth point (vertical bars at figure 2a). The result shows high variance at some of the places which is expected because the depth of the two layers can always be adjusted to obtain the same gravity effect. But almost all the models follow the specific trend of the actual model.

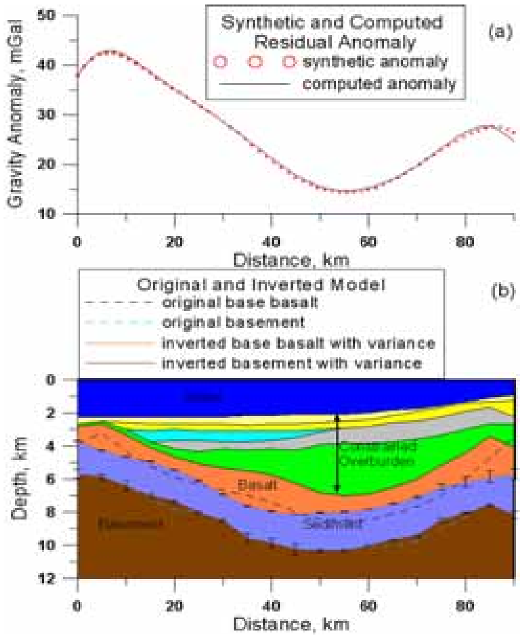


Figure 2 *Gravity inversion constrained by Seismic. (a) Observed and simulated anomaly and (b) Inverted model.*

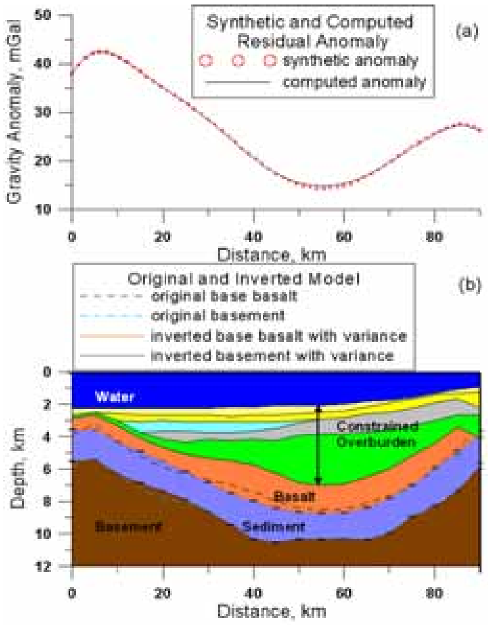
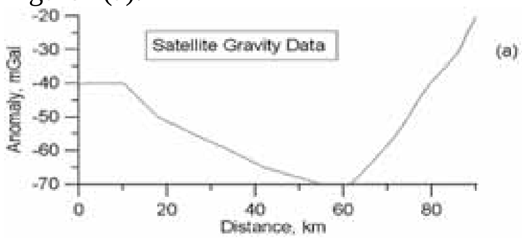


Figure 3 *Gravity inversion constrained by Seismic and MT. (a) Observed and simulated anomaly and (b) Inverted model*

The only way to reduce this uncertainty is by incorporation of more information. As Magnetoteluric (MT) method is sensitive to the conducting sediments, it is quite capable of mapping the sediment thickness. So, next, we assumed that the sediment thickness is known a-priori from MT inversion. Now, base basalt is the only independent variable. Figure 3 shows the best fit and the variance of each depth values for the MT-constrained inversion and we observed uncertainty is much less than previous one.

Inversion of Satellite Gravity Data:

The satellite gravity data (Sandwell and Smith, 1997) along the same profile is shown in Figure 4(a).



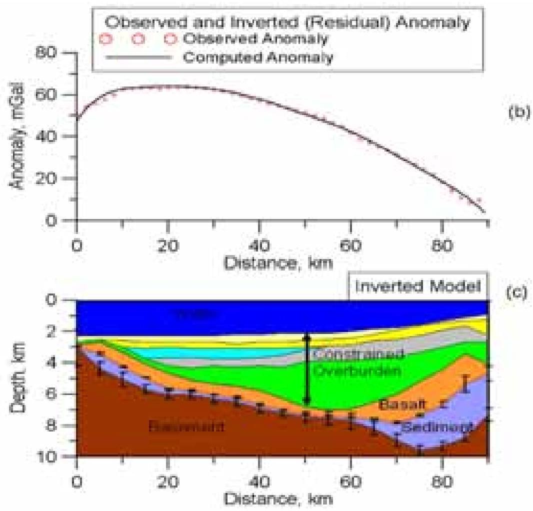


Figure 4 *Inversion of Satellite Gravity Data (a) Satellite gravity data along the study profile. (b) Observed and inverted residual gravity anomaly and (c) Inverted density model.*

The density of basalt, sediment and basement are assumed a-priori to be 2.85 gm/cc, 2.45 and 3 gm/cc respectively. The anomaly due to overburden is subtracted from the observed anomaly to get the residual (Figure 4b), which is inverted to delineate the base-basalt and sub-basalt structures. The misfit of the data and the inverted model is shown in Figure 4b and 4c. The inverted model shows a thick layer of sediment towards the coast (East), however we see almost no sediment in the middle part and moderate sediment in the western part of the profile. The low variance values of base basalt show that this layer is better delineated with less ambiguity whereas, high variance values of basement reflects the uncertainty present in estimating the depth of basement. Due to the absence of MT data other constraints, like sediment thickness, could not be used to reduce this uncertainty.

Conclusions:

The study shows the potential of cooperative gravity and MT inversion, constrained with seismic information, for sub-basalt exploration. Seismic technology, as is well known, can image the above-basalt layers with reasonable accuracy, but can not reveal any sub-basalt sediment. MT is the best technology to identify the existence of the conducting sedimentary layer, but basement mapping is difficult with MT. Gravity, in contrast to MT, as it depends on the density difference, is able to map the low-density sedimentary layer as well as high-density basement. Even in the absence of MT, gravity can be used to provide a rough estimate of the depth of base basalt and basement. The use of MT, to constrain the sediment thickness, shows a remarkable reduction of uncertainty in the results of gravity inversion. The satellite gravity data over the same profile is inverted (without MT constraint) using the same over-burden. The result shows thick sediment towards the east (coast) with thin to moderate sediment towards the west. The uncertainty of basement is moderately high, where as, base-basalt has been delineated more uniquely. The result is encouraging and shows promise for better delineation of sub-basalt structure in the presence of additional constraints from MT and/or magnetic technology.

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