Estimation of Geological Boundary and Source Depth Locations Using Seismic, Gravity, Magnetic and Geochemical Data in Assam-Arakan Basin in Mizoram State of N-E India

G.K. Ghosh*, K. L. Mandal and G.V. J. Rao
Oil India Limited
Email:gk_ghosh@yahoo.com

Abstract

This paper demonstrates an integrated interpretation approach using sparse seismic, potential field (gravity-magnetic) and other geo-scientific data (geological and geochemical) for risking hydrocarbon exploration in geologically and logistically complex areas in parts of Assam-Arakan basin in the state of Mizoram in the north-eastern India. Attempts have been made to estimate critical extent of subsurface lithologies for hydrocarbon resources. The exploration venture for hydrocarbons in the region has always been challenges for acquiring meaningful geoscientific data. It has been difficult for subsurface imaging in this complex terrain, deprived regular geometry and ray steering for seismic, environment constraints/ regulations and complex subsurface geology and deeper basement depth (>12 km) *proved inadequate.* However, acquisition of 2D/3D seismic in the area has been carried out along crooked lines and the same has been integrated with ground gravity-magnetic data and state-of-the-art geochemical surface samples analysis for detailed modelling of this area. Radial average power spectral analysis has been used for direct basement depth estimation using potential field data. Integrated interpretations along three seismic lines using 2D Euler deconvolution and 3D Euler depth solutions for direct source depth estimation show the basement depth could vary from 4 km to 12 km in the study area. The geochemical data analysis also suggested the high probability hydrocarbon zone. TDR, TDX and Cos(θ) analysis have been used for marking source boundary for identifying the thrust/fault locations. These derived results are corroborated well with the other geological evidences. The integrated interpretation could reliably image the regional intra-sedimentary thrust/fault systems along with the basement lineation in encouraging exploration venture of high investment in the area. The present study provides more information for extensive understanding of thrust/fault boundaries and source depth locations for better hydrocarbon exploration and encouraging investment is such high risk-high reward exploration and production ventures.

Introduction

So far, the hydrocarbon exploration in the state of Mizoram has poor to negligible due to inherently difficult logistics, mountainous hill ridges and deep gorges with surface elevation varying from 200 m to 1700 m in Indian side. Recent information on discoveries of hydrocarbon around Mizoram area i.e. Cacher, Tripura and Bangladesh, have also been instrumental in drawing attentions of many explorers and entrepreneurs to divert their exploration focus towards this area (Figure 1). ONGCL (Oil and Natural Gas Corporation Limited), an Indian national upstream company initiated exploration for hydrocarbon in Mizoram by initiating 2D seismic survey in the Kolasib district during the year 2002 and discovered hydrocarbon in Mizoram through subsequent drilling. Five years later, OIL (Oil India Limited) the only other Indian national upstream company, started its exploration by implementing its first 2D seismic survey campaign in Aizawal, Serchip and Lunglei districts of Mizoram during the year 2007 and acquired more than 1300 GLKM of 2D seismic, 2500 gravity-magnetic observations and 700 geochemical samples have been interpreted using advanced Gore's technology (Gore and Associates, 1996) for hydrocarbon exploration. In such a situation, the integrated approach presented in this paper, could render improved confidence for pursuing exploration by reducing uncertainties and minimizing exploration risk in the area.

Geology and tectonics

The Tripura-Cachar-Mizoram-Myanmar fold belt owes its origin to the collision among the Indian, Tibetan and West Burmese Plates in Late Eocene-Oligocene period. This also led to the advancement of an unconformity in the Mizoram area and development of a large fluvio-deltaic system across the whole Bengal-Assam area. In the Late Eocene to Oligocene the Burmese Plate closed over the Assam Shelf, which generates the updated lithological shape. Chittagong-Mizoram-Tripura fold-thrust belt of India, Burma and Bangladesh covers an area of about 24000 km^2.Two interpreted seismic sections viz: seismic line-x and line-y have been shown with different levels of horizons and geological formations (Figure 2).

The Mizoram block comprises a series of curvilinear east dipping thrust with Oligocene and Miocene sediments mutilated into a series of fault propagation folds. There are numerous potential source rocks in this area belonging to Disang Group, Barail Group and Bhuban Formations. Various potential reservoir rocks existed namely Disang Group, Renji Formation, Lower Bhuban Formation, and Middle Bhuban Formations. The Upper Bhuban and Bokabil Formation are also the reservoir rocks.

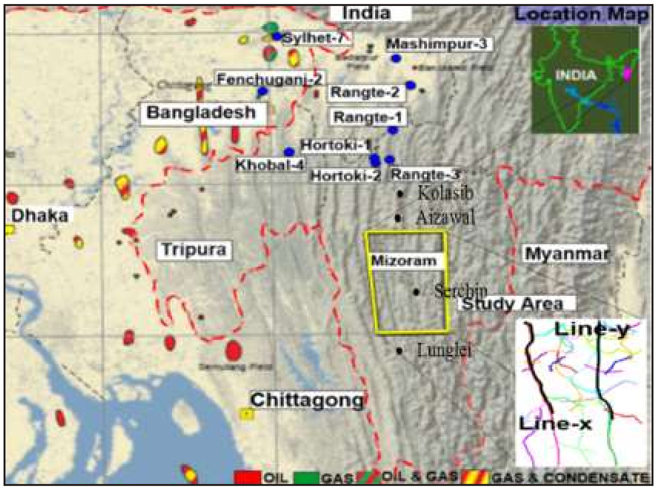

Fig. 1: Location map of the study area surrounded by oil and gas discovered field.

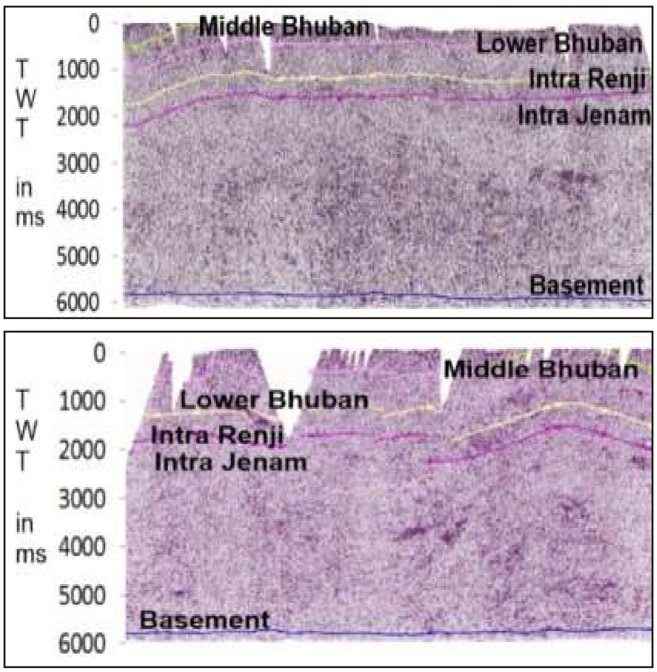

Fig. 2: Two interpreted seismic lines (Line-x and Line-y) as shown in the location map (Figure 1) oriented in the N-S direction. The basement depth indicated more than 5000 ms (TWT).

Methodology and Theoretical approach

The magnetic data has been acquired by OIL in collaboration with National Geophysical Research Institute (NGRI) Hyderabad with the specified grid interval varying from 0.5 to 1km along the available roads, foot tracks around the block using Scintrex Magnetometer (SM). The data has been processed further to reduce in the mean sea level (MSL). The accuracy of the data is 0.1 nT. Diurnal and International Geomagnetic Reference Field (IGRF) corrections have been applied to the magnetic data. In this study, it has been briefly discussed total horizontal derivative (THDR), tilt angle derivative (TDR), horizontal tilt angle derivative (TDX), Cos() map and 3D Euler deconvolution for source depth location to delineate the thrust / fault boundaries identification.

Total horizontal derivative (THDR) has been defined by Grauch et al., (2001) as

$$THDR = \sqrt{(\partial T/\partial x)^2 + (\partial T/\partial y)^2} \qquad \text{(i)}$$

Where $\partial/Ty\partial$ and $\partial/xT\partial$ are the horizontal derivative in x and y directions and $\sqrt{(\partial T/\partial x)^2 + (\partial T/\partial y)^2}$ is total horizontal derivative of the magnetic field T. In general, total horizontal derivative (THDR) has been used here for edge detection.

Tilt angle is the ratio of the vertical derivative (VDR = $(\partial T/\partial z)$) (to the absolute value of the total horizontal derivative (THDR) which improves large and small amplitude anomalies (Miller and Singh, 1994). Further, Verduzco *et al.,* (2004) expressed in the generalized way for both profile and gridded dataset. TDR can be expressed as

$$TDR = \tan^{-1}\left(\frac{VDR}{THDR}\right) \qquad \text{(ii)}$$

The horizontal tilt angle (TDX) was introduced by Cooper and Crown (2006) by using THDR using absolute value of VDR.TDX is varying with the angle $+\pi/2 > TDX > -\pi/2$

$$TDX = \tan^{-1}\left(\frac{THDR}{|VDR|}\right) \qquad \text{(iii)}$$

Cos(θ) is the ratio of THDR and normalized analytical signal |A| (Wijns et al., 2005).

$$Cos(\theta) = \frac{THDR}{|A|} \qquad \text{(iv)}$$

Where

$$A = \left|\sqrt{(\partial T/x\partial)^2 + (\partial T/\partial y)^2 + (\partial T/\partial z)^2}\right| \qquad \text{(v)}$$

Where |A| is the amplitude of the 3D analytical signal.

The 3D Euler deconvolution technique has been used for direct source depth estimation for magnetic source bodies. This has been applied both gravity and magnetic data with the help of homogeneity equation as expressed by Thompson (1982) in equation (vi)

$$(x-x_0)\frac{\partial f}{\partial x} + (y-y_0)\frac{\partial f}{\partial y} + (z-z_0)\frac{\partial f}{\partial z} = -N(f-B) \qquad \text{(vi)}$$

Where, x, y and z represent the coordinates at the points; x_0, y_0 and z_0 represent the coordinates of the sources as a function of. B is called as "background" term, describing the constant contribution of the regional field. The x axis point denotes north, y axis point denotes east and z axis denotes vertical field.

The radial average power spectrum of the gravity-magnetic data (Spector and Grant, 1970; Ghosh and Shaw, 1999) used to estimate the depth to the statistical ensemble of sources can be expressed as

$$Depth = S/4\pi \qquad \text{(vii)}$$

Where S is the slope between the plots of Ln (power) spectrum versus wavenumber for each segment slope provides the average depth estimation of the ensemble of source lying at different depths.

Integrated interpretation

The block area shows surface elevation varying from 200-1700 m (Figure 3a). The Bouguer gravity anomaly varies from -97mGal-17 mGal and decreasing from westward to eastward direction (Figure 3b). However, the total magnetic intensity anomaly shows scattered response with N-S orientation throughout the area. Magnetic field changes significantly in the southern part which might be due to tectonic resettlement process and the upliftment of crystalline basement rocks (Figure 3c). The regional geomagnetic field (IGRF) and the effects of diurnal magnetic variation were removed based on 1974 IGRF epoch (Figure 3d). The reduction to pole (RTP) process has been applied to ensure that the anomaly would be the one as measured at the north magnetic pole where the induced magnetization and the ambient field both would be directed vertically. The RTP corrected magnetic anomaly map shows N-S trend with higher values at the centre and lower values either side of the high (Figure 3e).

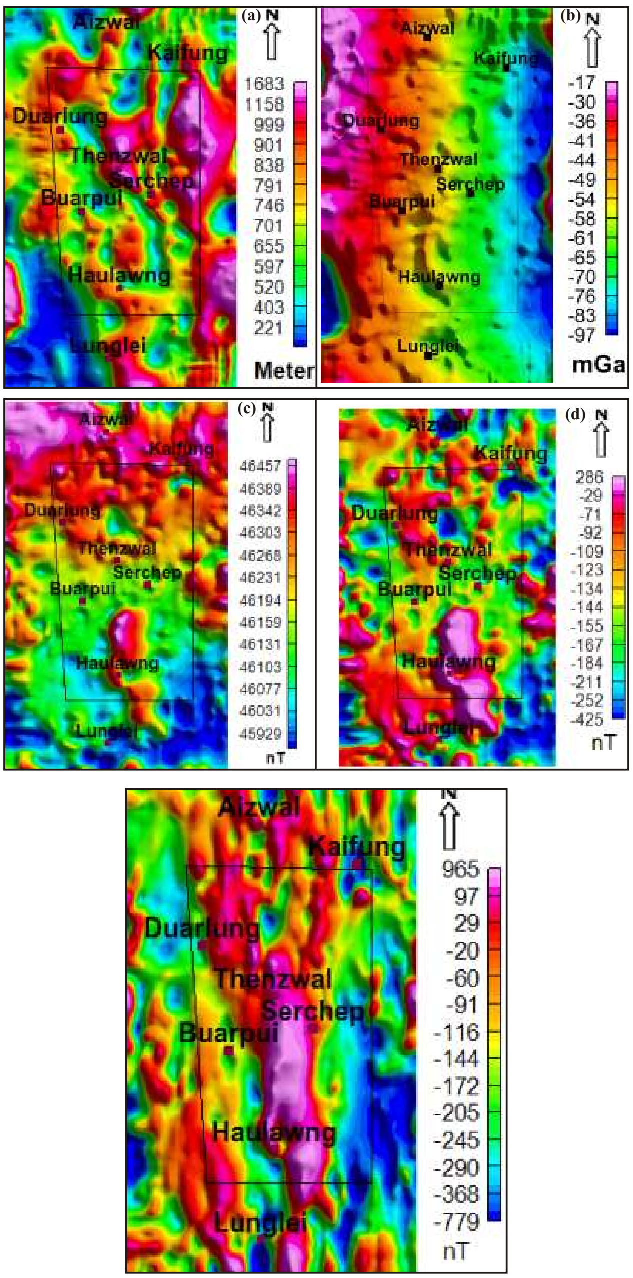

Fig. 3: Maps show the (a) elevation, (b) Bouguer gravity anomaly, (c)total magnetic anomaly, (d) magnetic anomaly (IGRF corrected) and (e) reduced to pole (RTP) data.

Gravity-magnetic data have been interpreted in frequency domain using radial average power spectrum. The log of Power versus wave number plot from Bouguer gravity data suggests an average basement depth at 12.6 km and two Intra-sedimentary depths at 3.08 km and 1.59 km respectively (Figure 4a). Using magnetic data, average basement depth is estimated to be around 11.6 km and two intra-sedimentary depths are at 3.1 km and 1.4 km respectively (Figure 4b) (Spector and Grant, 1970).

Seismic interpretation suggests ambiguity for prospect locations due to lack of consistent horizon marking and basement identification. However, integrated interpretation using gravity, magnetic, seismic and geochemical data have reduced the ambiguity and improved better correlation. Three seismic lines (Line a, linea1 and linea2) have been selected (Figure 5) for the integrated study. The gravity magnetic profiles have been drawn along some seismic lines and simultaneous interpretations have been carried out using 2D Euler deconvolution (Thompson, 1982) for basement depth estimation.

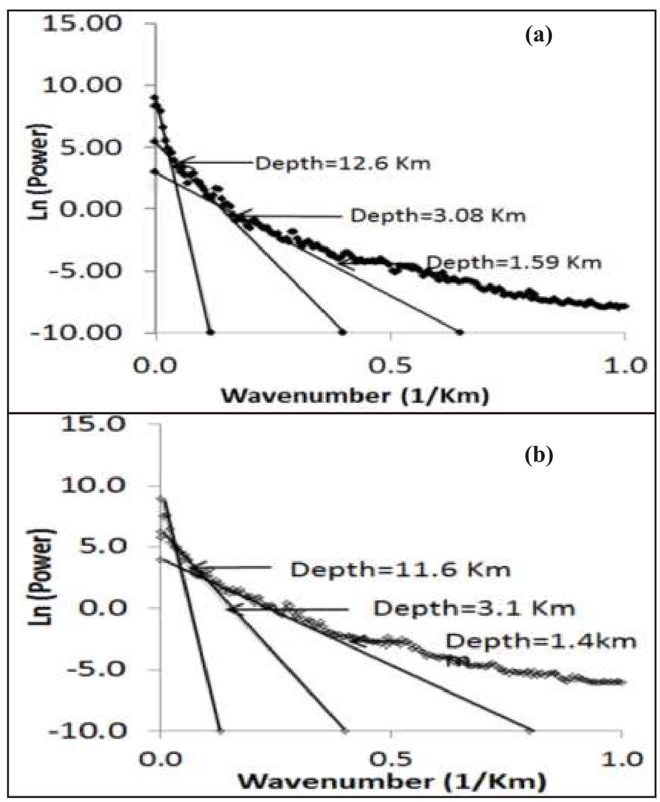

Fig. 4: Radial averaged power spectrum of Bouguer gravity data (a) and magnetic data (b). The slopes indicated basement depth and intra-sedimentary depths.

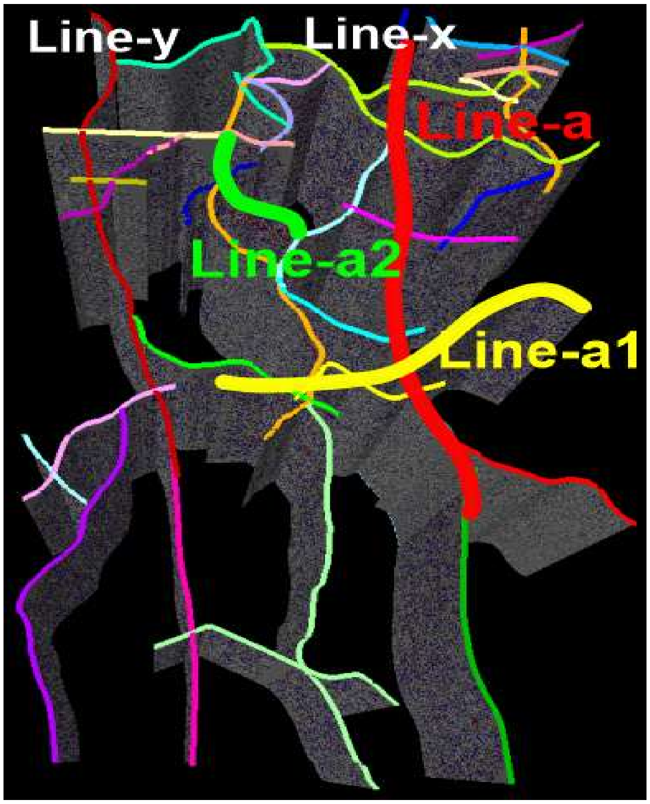

Fig. 5: Three seismic lines (Line-a, line-a1 and line a2) are selected here for integrated approach.

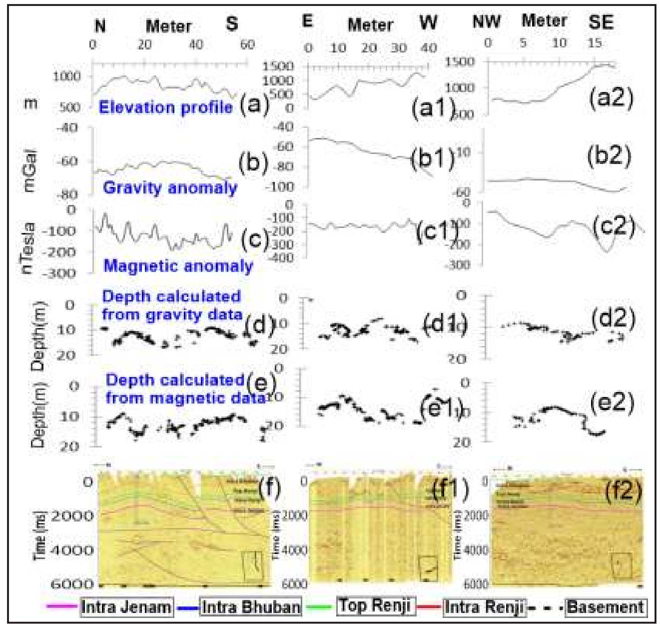

Fig. 6: Top to bottoms are elevation profile (a, a1 and a2), gravity profile (b, b1 and b2), magnetic profile (c, c1 and c2) Euler depth along the gravity profile (d, d1 and d2), Euler depth along the magnetic profile (e, e1, e2) and the interpreted seismic line (f, f1 and f2) for the simultaneously three line a, line a1 and line a2 respectively.

Seismic interpretation provides information only for the shallower part whereas Euler deconvolution provides structural configuration of the deeper formations. It is noted that the basement depths at different locations varying more than 11 km at places which was not decipherable from seismic data and mapping of the deeper strata including basement from seismic was not plausible. These results have been correlated and integrated with seismic data through joint interpretation along the three profiles for identifying prospects for further exploration (Figure 6).

The geochemical sample analysis (Gore and Associates,1996) shows areas with anomalies due to high concentration of higher fractions of hydrocarbons (C3 and above) (Figure 7) which is matching with the seismic and gravity-magnetic joint interpretation (Figure 6). To understand the source depth in this area, 3D Euler deconvolution has also been applied to gravity and magnetic data using different structural index (SI) and window size (WS) (Reid, 1990; Stavrev, 1997).

Various combination of SI and WS are applied, however best suited are SI=2 and WS=20x20 for gravity data and SI=3; WS=20x20 for magnetic data used here for source depth estimation indicated up to 12 km (Figure 8) is super imposed with the identified thrust/fault locations (as marked by white lines) from geological field study. The 3D Euler source depth solutions also calculated from gravity

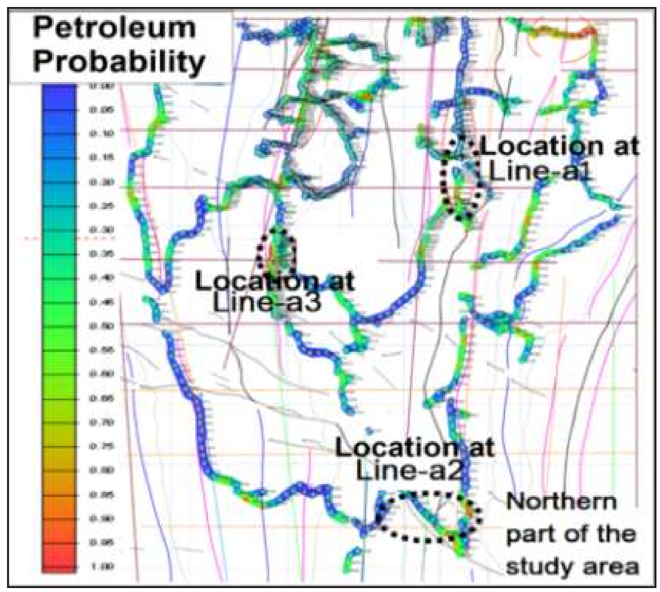

Fig. 7: Geochemical sample analysis shows the priority of hydrocarbon indicator and proposed for drilling locations

data are super imposed to TDR and TDX map (Figure 9a and Figure 9b). Similarly, the TDR and TDX are calculated using magnetic data and superimposed with the identified thrust/fault locations along with 3D Euler source depth solutions as shown in Figure 10a and Figure 10b respectively.

To understand the automatic thrust and fault locations in the hilly terrain mountainous area, tilt angle (TDR)

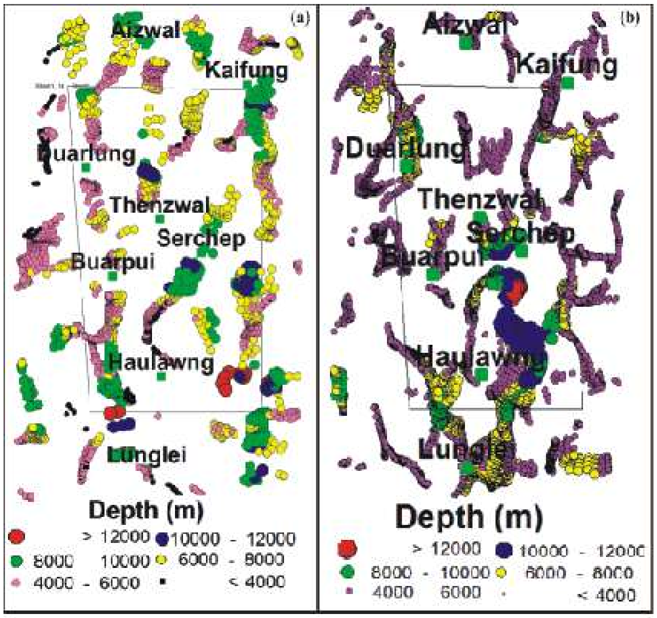

Fig. 8: 3D Euler source depth locations for gravity (a) and magnetic data (b).

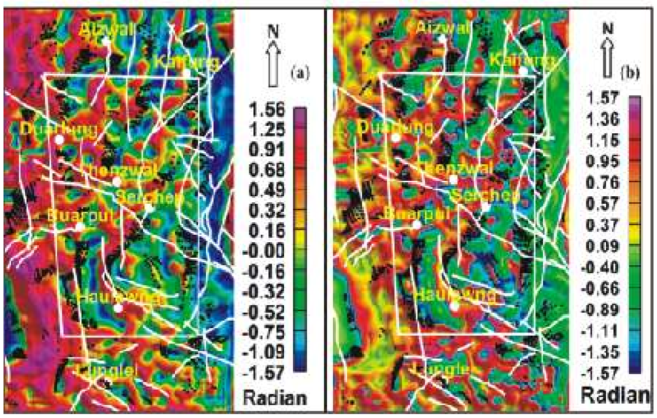

Fig. 9: TDR (a) and TDX (b) map superimposed with thrust/fault locations and 3D Euler source depth solution using gravity data.

(Verduzco *et al.,* 2004) and horizontal tilt angle (TDX) (Cooper and Cowan, 2006) have been interpreted using gravity and magnetic data. The tilt angle generally varies from -90 to +90 degrees. The tilt angle is positive over the source bodies and negative outside the source bodies. It is zero over or near edge where vertical derivative is zero and horizontal derivative is maximum. TDX is varying with the angle -90 to +90 degrees similar to tilt angle method. TDX responds for shallower and deeper bodies and also delineates the edges of the bodies. Both the methods TDX and TDR show a contrast variation along the sharper boundary. The TDR and TDX calculated using gravity data

Cos(θ) map has been derived from the magnetic data as shown in Figure 11. Cos(θ) vales are changes from 0 to 1. The Cos(θ) plot suggests that the map is delineating in the N-direction. The maximum values are indicated where Cos(θ) is 1 is the thrust/fault boundaries and provided additional information.

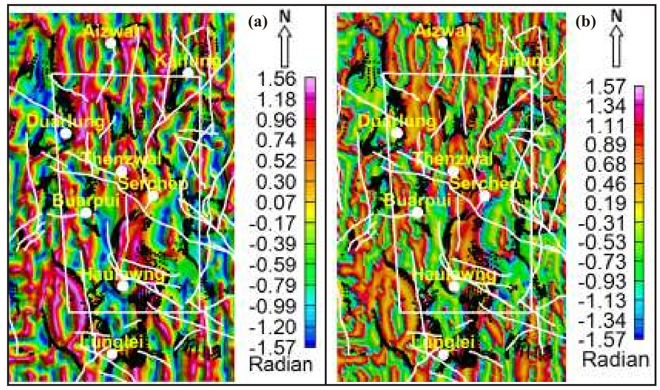

Fig. 10: TDR (a) and TDX (b) map along superimposed with thrust/fault locations and 3D Euler depth solution using magnetic data.

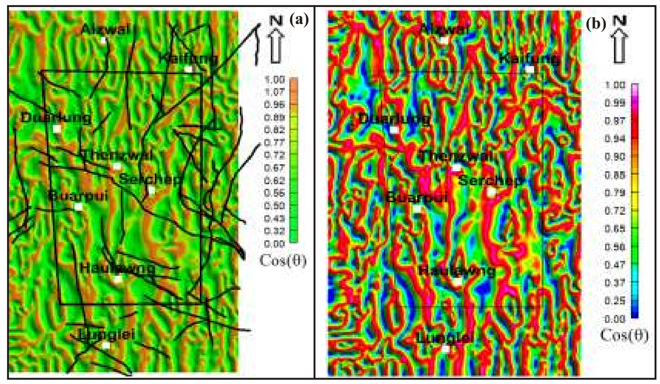

Fig. 11: (a) Cos(θ) map shows values 0 to 1 and (b) Cos(θ) map superimposed with the thrust and fault locations derived from field studies indicated well correlation. However Cos(θ) map shows additions thrust fault locations as indicated by red colours.

Conclusions

Hydrocarbon exploration in geologically complex area coupled with the deeper basement depth of about 11 km or more as that of the Mizoram in Himalayan frontal thrust-fold area has always been challenging from operational and techno-economic point of view. In such situations where seismic data finds its limitations, integrated interpretation approach using potential field data, geochemical information and other geo-scientific information have resulted in raising exploration and production confidence. In this study the use of radial average spectral analysis for direct basement depth estimation from gravity and magnetic data has rendered remarkable results in deciphering particularly the basement configuration. Geochemical sample analysis using Gore's technology has added to the probability of success; thus encouraging investment which is expected to be huge. Integrated interpretations along three seismic lines using 2D Euler deconvolution and 3D Euler depth solutions for direct source depth estimation shows the basement depth could vary from 4 km to 12 km in the area of study. TDR and TDX analysis used for direct source boundary for identifying the thrust/fault locations corroborate well with the other geological evidences. The present study provided more information for extensive understanding of thrust/fault locations and source depth locations for better hydrocarbon exploration and encouraged investment is such high risk-high reward exploration and production ventures.

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