Maiden Deepwater Sub-basalt Resistivity Image of Kerala-Konkan Basin, India using Integrated Controlled Source Electromagnetic (CSEM) and Marine Magnetotelluric (MMT) methods

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Abstract

Deep water Kerala-Konkan (KK) is a sub-basalt basin and extremely challenging as it is seismically difficult, mostly unexplored and geologically complex. Reliance Industries Limited (RIL) took the challenge and carried out integrated Marine-Magnetotelluric (MMT) and Controlled Source Electromagnetic (CSEM) survey on the block KKIIID2 during April-May 2010 to delineate the sub-basalt formations. The integrated MMT and CSEM survey used a new workflow to study the deep-water sub-basalt basins and has been used for the first time in this sub-continent. This is also the first commercial MMT survey in India. The survey successfully maps the top of the basalt layer and maps the base of basalt. Results indicate that the top basalt of deep-water KK is thin and there is a conductive zone below the resistive top basalt layer.

Introduction

Sub-basalt basins are difficult for seismic imaging which make it risky for hydrocarbon exploration. Kerala-Konkan (KK) deep-water basins (Figure 1) are unexplored and the nature of basin below the basalt cover is grossly unknown. Reliance Industries Limited (RIL) decided to acquire resistivity image of the sub-basalt formations to mitigate the risk. An integrated marine electromagnetic (EM) survey was planned combining Marine-Magnetotelluric (MMT) and Controlled Source Electromagnetic (CSEM) for resistivity imaging of sub-basalt KK. This is a unique algorithm and the first of its kind in this sub-continent to image sub-basalt. Magnetotelluric (MT) is a proven sub-basalt investigation tool (Colombo et al., 2007; Sinharay et al., 2008) and already been used to image sub-basalt structures below Deccan Traps (DT) by different workers. CSEM is generally used to identify hydrocarbon saturated resistive thin layers within the saline water saturated conducive sedimentary environment (Constable and Weiss, 2006). Using CSEM as a sub-basalt exploration tool was a new thinking and intensive object-oriented feasibility study was carried out prior to adopt it in survey workflow. Joint MMT and CSEM survey was carried out in April, 2010. This commercial integrated CSEM and MMT study for sub-basalt exploration is the first of its kind in Indian deep water though MMT was introduced in India in 2009 in Gulf of Kutch (Harinarayana, 2009).

Geology and Challenges

Reliance KK blocks are deep-water sub-basalt basin in the south-western tip of India. The shallower part of the basin is covered by thick Cenozoic sediments but no hydrocarbon reservoir has been discovered in it. Cenozoic sediments are underlined by basalt layer with thickness varies from few hundred of meters to about 2 Km (Singh et al., 2006). The general geology of Indian west coast, Madagascar, Seychelles and Africa suggests that KK is potential for sub-basalt exploration (Roberts et al., 2008). Thick basalt layers pose a great challenge to hydrocarbon exploration in this region as they allow very less seismic energy to penetrate below it. Conventional reflection seismic, thus, produces poor images below the top basalt

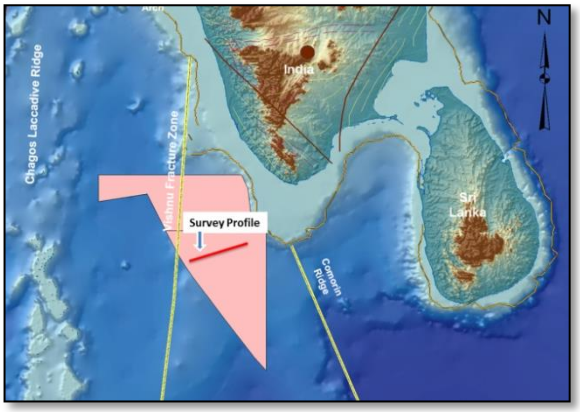

Figure 1: Profile for integrated CSEM and MMT survey

layer and unable to map the sub-basalt geology with certain degree of confidence. Integrated EM surveys have been carried out over the study area mainly to answer the following questions: 1) how thick is the top basalt layer, 2) is there any sediment below the basalt layers, and 3) how thick is the sub-basalt sediment (if present).

Methodology

CSEM is a towed steamer sea-bed geophysical technique for mapping electrical resistivity beneath the sea floor (Edismo et al., 2002: Ellingsrud et al., 2002). Numbers of sea-bottom EM receivers are dropped on the seafloor along a profile (Figure 2) and a horizontal electric dipole (HED) is towed about 30-50m above the receivers. The HED transmits controlled frequency EM signals commonly varying from 0.05–10 Hz. The transmitted primary EM signals penetrate below the seabed and sea-bottom EM receivers continuously record the signals. The amplitude and phase of the processed signals are then inverted to create electrical resistivity image below the sea-bed. CSEM is very sensitive to horizontal resistive layers even if it is thin (about 20 m) and capable to map basalt layers if it is thin (<500 m). CSEM loses sensitivity below thick basalt layers.

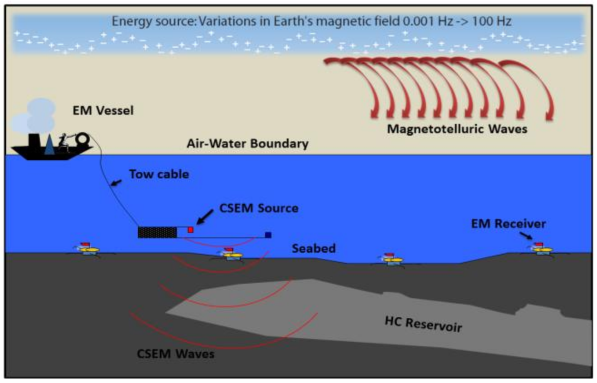

Figure 2: CSEM and MMT survey layout

MMT is a passive source EM technique which measures Earth's natural time-varying EM fields of frequency about 0.0001-1 Hz using seafloor receivers. The inversion of recorded electric (E) and magnetic (H) fields provide deep resistivity images of the study area along the profile. MMT is highly sensitive to the conductive layers and a tested tool to detect the presence of saline water saturated sediments below resistive basalt cover (Hughes et al., 1987; Whiter et al., 1994). MMT can image efficiently even if the basalt layer is very thick (>500 m) However, MMT fails to detect resistive basalt layers if they are thin and especially when sandwiched between two conductive layers. Hence, joint application of CSEM and MMT complements each other's limitations and can efficiently map the thin top basalt layer, conductive sub-basalt sediments (if any) and resistive basement of the basin.

EM Survey Details

Joint CSEM and MMT survey was planned along a 50 Km long North-East (NE) to South-West (SW) profile as shown in figure 1. Conventional seismic method efficiently maps the sedimentary structures above the top of the basalt layer of Cretaceous-Tertiary (KT) age. But the seismic images below KT boundary remain unclear and uncertain. Total 19 EM receivers were deployed along the profile with spacing of about 3 Km for both MMT and CSEM data acquisitions. However, only 17 EM station data found usable as one receiver was lost and another one was very noisy. CSEM signal used extra low base frequency of 0.08 Hz to penetrate sub-basalt structures. The quality of acquired CSEM data was very good and it was possible to achieve the maximum offset up to 20 Km (Figure 3a). Each MMT station was captured for more than 3 days to assure the best possible quality (Figure 3b) in this deep water block. However, MMT data were significantly affected by low signal strength due to low solar activity during the survey and the considerable elevation difference of the oceanic crust and continental shelf.

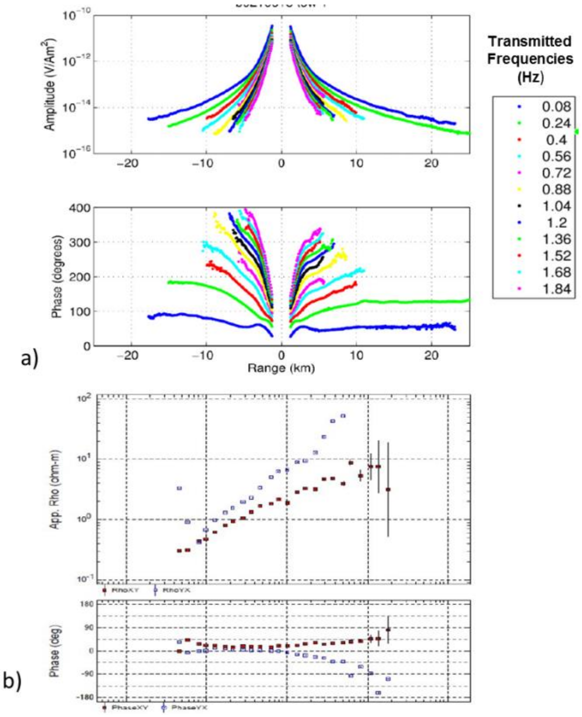

Figure 3: a) CSEM amplitude and phase plot and b) MMT apparent resistivity and phase plot

Results and Discussions

The sub-basalt resistivity structures are delineated using MMT survey. 2D inversion (Groot-Hedlin and Constable, 2004) of MT data is carried out for both apparent resistivity and phase of 13 MMT stations along the profile. Inversion result has been presented in Figure 4. Result shows that MMT fails to detect the top basalt layer (mapped by seismic survey). This is a clear indication that the top basalt layer is thin in nature and overlying on a conductive zone. The deeper resistivity zone in MMT section is anticlinal in nature. This resistive zone is massive and no conductive layers or pockets are detected below it. This deep resistivity zone is possibly the basement**.**

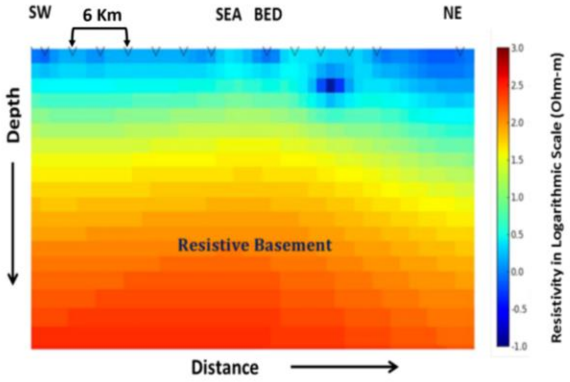

Figure 4: MMT 2D inversion result along NE-SW profile

The preliminary normalized magnitude versus offset (NMVO) plots of CSEM data show that the resistivity structure is relatively flat in smaller offsets but takes anticlinal shape as offset increases (Figure 5).

Processed CSEM data were inverted by 1D inversion algorithms (Key K., 2009) in next stage to obtain the initial resistivity model of the basin. The stitched model along the profile (Figure 6) shows the presence of multiple resistivity layers as indicated by (1), (2) and (3). The structure over the area is not 1D in nature. So, in next stage 2D constrained inversions (Abubakar et al., 2008) are carried out for both amplitude and phase of 17 CSEM stations along the profile. CSEM inversion result has been presented in Figure 7. CSEM result clearly maps the resistive top basalt layer with varying thickness. The resistivity of basalt layer varies from 20 to 40 ohm-m and its thickness is about 150 m in NE which gradually thickens up to 600 m in SW. Below the top basalt layer, a prominent conductive zone is detected. The conductivity zone is several times thicker than the basalt layer and the thickness well as conductivity increases in the NE end of the profile. CSEM results also map the bottom of the conductive zone with an underlying thick resistivity layers with resistivity about 1000 ohm-m. The nature of this resistive zone is difficult to interpret as CSEM loses sensitivity in greater depth.

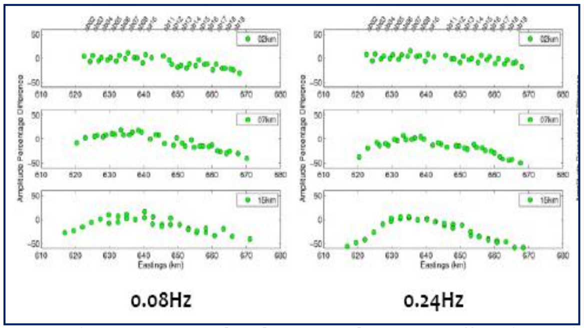

Figure 5: CSEM normalized magnitude versus offset (NMVO) plot along the profile for two lowest frequencies and three different offsets (2 Km, 7 Km & 10 KM from top to bottom respectively).

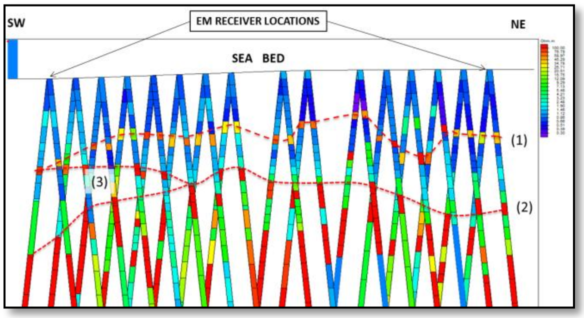

Figure 6: 1D inversion results of both in-tow and out-tow for 16 CSEM stations along the profile. Transmitter was towed from SW to NE. Three resistive interfaces (1,2& 3) have been marked along the profile.

The unique design of this survey provides the opportunity to carry out Joint Inversion (JI) of both CSEM and MMT data for integrated resistivity imaging of sub-basalt structures with greater details. Joint CSEM and MMT inversion (Virgilio et al., 2009) have been carried out along the survey line with constrained top of basalt. The JI algorithm assigns more weight on CSEM data for delineating the shallower sections whereas MMT data are given higher weight for mapping the deeper structures. Joint inversion result has been presented in Figure 8. Joint CSEM and MMT inversion result indicates increased conductivity and thickness of the sub-basalt layer with respect to CSEM-only inversion results. The resistivity of sub-basalt conductive layer is about 3 ohm-m. Such sub-basalt conductive layers below basalt may be Mesozoic sediments which have been reported in some part of Deccan Trap by Harinarayana et al., 2007 and Gorain, 2012. The top of basement is mapped in the 2D resistivity section.

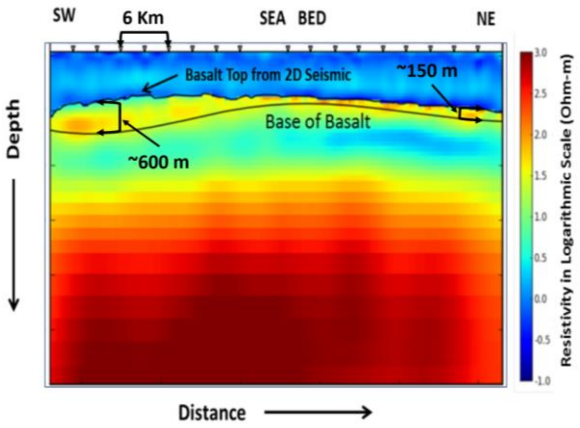

Figure 7: Constrained 2D CSEM result with base basalt

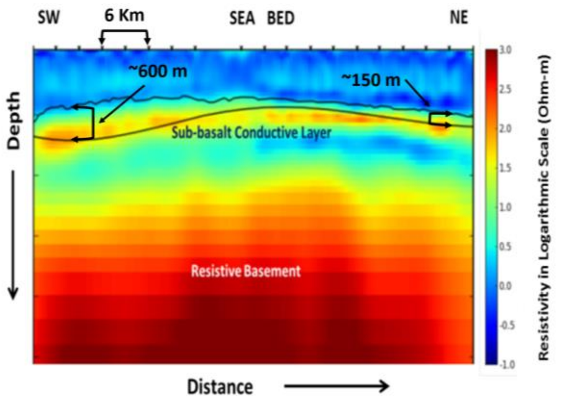

Figure 8: Joint CSEM and MMT result with seismic constrained top and interpreted base of top basalt layer

Conclusions

The maiden integrated CSEM and MMT studies in Indian deep water prove valuable for sub-basalt studies. It successfully concludes that the top basalt layer in the study area is thin and a conductive layer is present below the basalt. The sub-basalt conductive layer may be sedimentary in nature. This study also proves that the joint CSEM and MMT workflow adopted is efficient for sub-basalt exploration for deep water basins.

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