Modern Sub-Basalt Seismic Imaging - Deepwater Realm Offshore Southwest India

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Abstract

This paper describes contemporaneous efforts undertaken in the seismic imaging of sub-basalt features offshore the South West coast of India particularly focused in the Kerala-Konkan Basin. Data for this basin study originates from a modern 3D seismic survey integrated with long regional 2D seismic lines and with joint regional investigations comprising of gravity, magnetic, electro-magnetic and MT data to form the basis for the geological assessment of the key components of deep-water petroleum systems, both along the Tertiary overburden above basalt and, below it, the critical imaging of the Mesozoic lithology. The modern marine 3D Q-surveys conducted with long spreads and processed with state-of-art migration algorithms brought in remarkable improvements for the imaging resolution and coherence of sub-basalt structures these interpreted by pairing images of pre-stack time and depth migrated lines.

Kerala-Konkan basin lies South of the Mumbai Offshore area, the main productive oil province of India. Key to the exploration of this vast deepwater region is the assessment of its petroleum systems in Mesozoic strata buried under late Cretaceous flood basalts. Regional geology re-constructions and interpretation of its Mesozoic depositional history was done through our set of regional lines that cover outer shelf, slope, rise and ocean basin providing insight on the nature of continental and oceanic crust layers of Mesozoic lithology under basalt. To focus on risked prospect plays several 3D surveys were carried on so that sub-basalt exploratory drilling locations could be derived from mapping of structural dip and fault seismic closures under basalt and associated stratigraphic traps.

Interpretation mapping of the PSTM/PSDM paired images provides for new enhanced domain with 3D structure and stratigraphic features correctly placed in depth. The methodology of time/depth imaging allows for significant sub-basalt recognition of structural planes, focuses faults paths displacements and rectifies horizons continuity. For the purpose of seismic interpretation the sub-basalt velocity model derived from data also provides for better confidence on the structural dynamics of the seismic section.

In this paper we present results of seismic interpretation of an "over-under" modern data set acquired in the deepwater realm of Kerala-Konkan Basin. These data were integrated with ancillary geophysical regional lines for the purpose of understanding the nature of sub-basalt hydrocarbon prospects.

Introduction - Southwest Offshore India

Kerala-Konkan Basin developed after the break-up of West Gondwana into Madagascar and Indian continents. A series of linear rifts, horsts and grabens developed parallel to the dominant basement fabric NNW-SSE (see Figure 1).There were significant tectonic events that affected the imprint of the newly formed western Indian basins such as: a) the rifting away from Madagascar; b) the reorientation of drainage system from East to West which affected the sediment supply to the West coast; c) uplift, extension and subsidence caused by the Deccan/Reunion mantle plume; d) the northward drift of India and development of its western coast carbonate systems and finally; e) the collision of India with the Himalayas.

The rifting between Madagascar and India led to development of clastic deposition over an already developed sag basin. With progressive rifting the basin went through a shallow marine stage which was disrupted by volcanism, uplift, extension and subsidence associated with the Deccan/Reunion mantle plume (Biswas, 1982). Continuous rifting took place as India, drifted into higher latitudes,

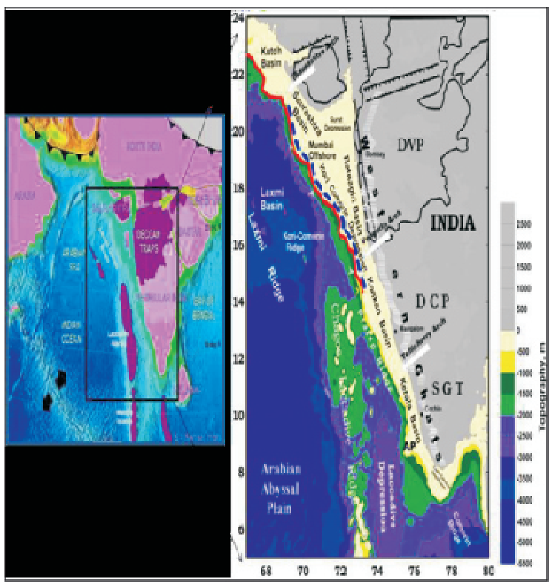

Fig. 1: Location and morphology of the western offshore (Left Panel) and morphotectonic framework (Right Panel) of the of the West coast showing the location of Kerala-Konkan Basin (adapted from Kharak Singh et al., 2007). The basin is affected by the basalt flood events near its K/T boundary.

contemporaneous with development of carbonate systems off the western coast. Afterwards, during mid-Eocene the collision of the Indian and Asian tectonic plates occurred, the Himalayan uplift and reactivation of the western coast basins of India also took place.

These events led to a period of clastic sedimentation over the rift basin followed by a five million year long span of volcanism, that originated the depositional environment of carbonates in the west coast, as opposed to the very active clastic sedimentation offshore the East coast still active nowadays. The Mesozoic sediments under the so-called Deccan basalt in the western flank of India are in actuality covered by flood basalts that were intense at the Tertiary-Cretaceous boundary and which have impacted the whole of West India. Interpreting the structuring of Mesozoic sediments under basalt either by seismic surveys or well drilling has been difficult due to homogenous and massive nature of the basalt. Deccan basalt blankets the Kutch, Saurashtra, Bombay and Kerala-Konkan basins. Our DISCover surveys are fundamental for the comprehensive seismic interpretation all along the western flank of the Indian peninsula deepwater realm.

Gravity Image Map of the Western offshore

The satellite derived free air gravity anomaly map (Figure 2) of the western offshore correlates well with various morphological features and reveal the typical bi-polar gravity anomalies associated with shelf and slope areas of the margin (Sheena et al., 2007). The free-air anomalies in general are negative throughout the eastern Arabian Sea, except in certain areas of the shelf. The gravity field seems to be disturbed perhaps due to the presence of several basement ridges and isolated bathymetric features (Radhakrishna et al., 2002) in the central of the margin. A NW-SE trending gravity low of ~ −40 mGal correlates well with the Laxmi ridge, whereas, the Laxmi Basin as a whole is characterized by a broad regional gravity high with a prominent NNW gravity low at the center associated with the crest of the Panikkar Ridge (Krishna et al., 2006). The Laccadive Ridge is associated with positive gravity field and further East, in the basin between the Laccadive Ridge and Sri Lanka, prominent NS trending gravity lineaments along 75°E joins the West coast at 10°N and is probably the trace of the Vishnu fracture zone (Norton and Sclater, 1979).The gravity trends of fracture zones along the Carlsberg ridge can be clearly seen in the South West corner of the gravity anomaly map.

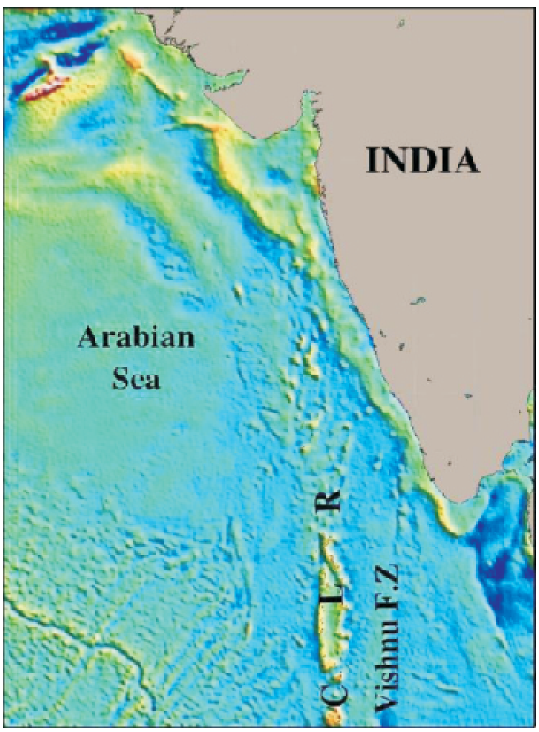

Fig. 2: Satellite derived free air gravity anomaly map of the deepwater Western offshore region

Deepwater Stratigraphy

The litho-stratigraphy of the basin explains two different events of sedimentation before and after the Deccan basalt eruption, these are: (i) Sandstone dominated continental deposition (ii) Sandstone, shale and coal dominated deltaic/ marginal marine deposition (iii) Sand, shale and limestone dominated marine deposition (Shah et al, 2009). Sediments which are above the basalt are alteration of clastic and carbonate sediments. Lithology is mainly affected by marine transgressions, regressions pulses and Tertiary column sedimentation is mostly under the influence of Himalayan uplift.

It is interesting to note the divergence of the sedimentary columns between East and West India offshore basins (Figure 3). In the East coast basins of India the sediments are strikingly similar all with successive sequences of open marine clastics laid down during Upper Cretaceous, Tertiary and Plio-

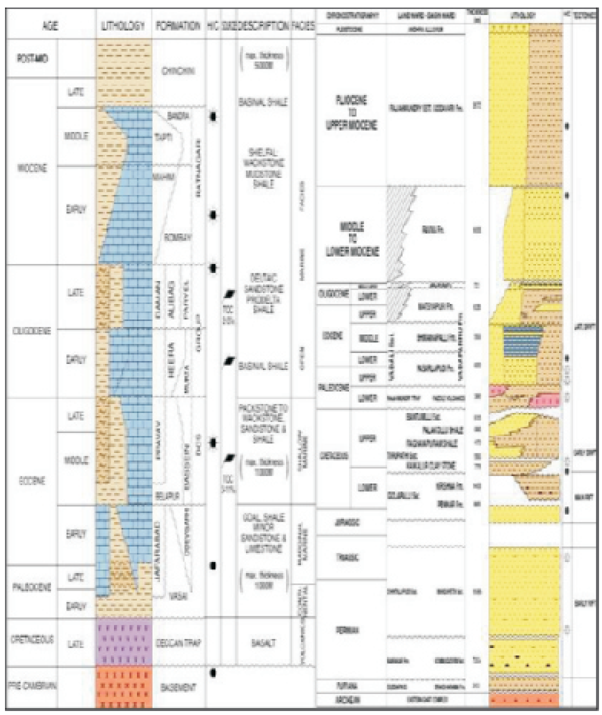
Fig. 3: Generalized stratigraphy of the West coast Mumbai High consisting mostly of carbonates and shales, differs greatly compared with the dominant clastic stratigraphy of the East coast Krishna-Godavari Basin.

Pleistocene. This stratigraphy differs from the West coast due to the remarkable predominance of carbonates in these basins, which were starved during the Tertiary (Fainstein et al., 2008).

In the sub-basalt section, oil migration from source to reservoir requires pathways that are through windows of seals below reservoirs. Faults should provide the conduits that permit migration of oil from source to reservoir. In the western coast the predominant reservoirs are carbonates above basalt and carbonates and sands below basalt. These were deposited in several pulses of marine transgression associated with vertical uplift of the basins. The most important basin offshore in the West Coast is the Mumbai basin the main producing area in India containing the giant Mumbai High field, This field discovered in 1974 by ONGC is geologically unique its main producing reservoirs are Miocene carbonates. Deepwater wells are yet to be drilled in this province.

DISCover Technology

Main benefit of the revolutionary DISCover technology is with respect of its low frequency enhancement. This additional bandwidth is needed for appropriately imaging sub-basalt lagers.

In the DISCover Acquisition Technique, 6 (six) streamer cables over and 2 (two) streamer cables under are pulled around a V-frame flip-flop 50 meter spaced source. Maximum offset achieved so far is 8 (eight) km (Kalra, 2011).

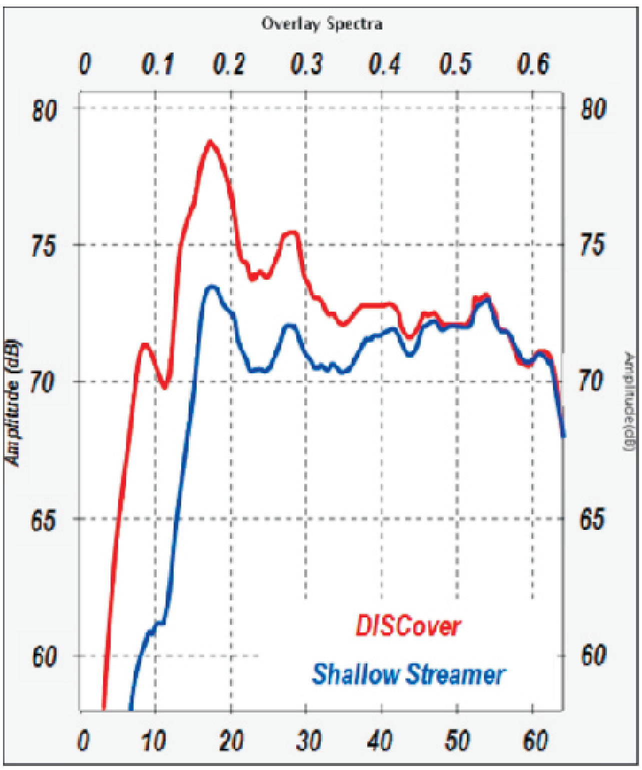

Fig. 4: Amplitude spectra of DISCover is displayed in red and compared with the amplitude spectra of shallower depth streamer in blue. Clear gain of low frequencies benefit imaging of deeper sub-basalt Mesozoic strata.

Upon processing a combination of upper and lower cable undergo generalized surface multiple prediction, inverse Q for phase, COMFI interpolation and regularization, isotropic Kirchoff PSTM, radon de-multiple, inverse Q processing for amplitude and final stacking velocities applied on a 500 meter grid w/ SCVA.

Filter panel comparisons of DISCover streamer combination versus shallow cable receiver streamer demonstrates a remarkable gain in low frequency bandwidth (see figure 4).

It is interesting to note that the high frequency end of the bandwidth remains essentially the same (Fig. 4). By contrast remarkable signal/noise ratio gain in decibels is realized at lower frequency, these benefit imaging and may be applied to seismic inversion modeling.

Prestack Time and Depth Imaging

Deepwater subsurface imaging resolution and the target identification of subtle structured and stratigraphic features remains limited by seismic imaging leading to the best sub-basalt geological interpretation model (Fainstein et al., 2009; Fig. 4).

In the time migration (post-stack or pre-stack) geophysical programs retrieves the velocity profile at the CMP and either computes the travel time via the DSR equation (straight ray) or ray traces through this local model (curved ray) but no lateral velocity changes are comprehended, the ray path is always symmetric for a flat event (1D velocity model). Upon depth migration a full travel time table is build externally. The travel time generator program involves velocity changes vertically and laterally. The ray path can be non symmetric even for a flat reflector (3D velocity model).

3D DisCover Technology Interpretation

The DISCover technique applied in the data acquisition at Kerala Konkan basin (Fig. 6) consisted of an over-under seismic acquisition technique that deployed 6 cables over at 7 meters depth, 100 meters separation and 8 km offset; and 2 cables under at 20 meter depth and 300 meter separation. The source acquisition standard was a flip-flop V-frame source, 50 meter interval.

The DISCover processing sequence consists of mixing the bandwidth of upper and lower cables, applying a generalized surface multiple prediction procedure, inverse Q phase adjustment followed by interpolation and regularization. At this point the isotropic Kirchoff migration algorithms are run followed by de-multiple and amplitude inverse Q adjustment. Final stacking velocities are produced within a fine 500m grid.

In essence, and after processing this forefront suite of new data represents the very first deepwater images of the Mesozoic structuring under basalt that can be interpretable and where correlations from line to line could be made so as to

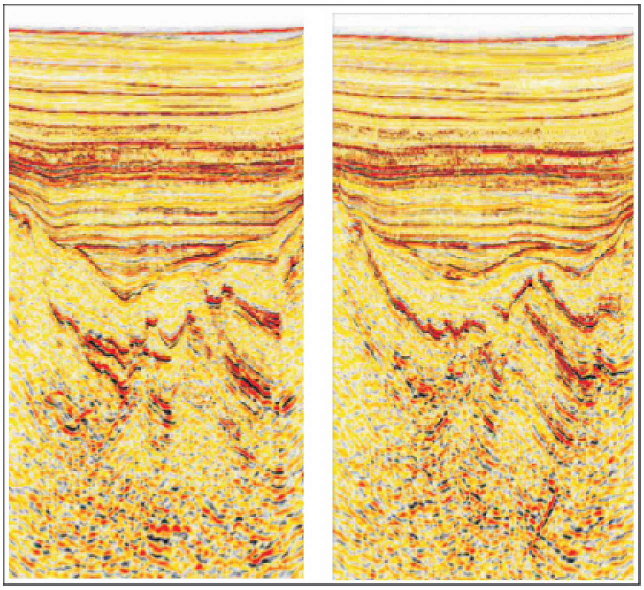

Fig. 5: Successive cross-lines undertaken on the 3D over-under survey in the West-coast off India display numerous features under basalt such as the sag basin, fractures, faults and folding. K-T boundary layer is clearly seen as major change in frequency content. Deeper bright amplitudes may be related to the Reunion volcanic event.

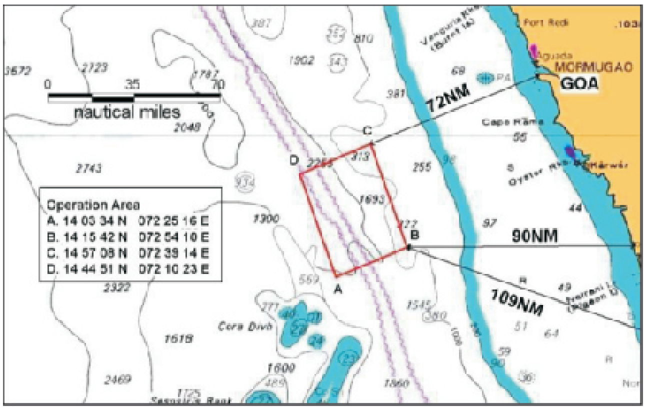

Fig. 6: Acreage of Kerala-Konkan deepwater basin in the West coast of India is being evaluated by modern 3D surveys. WesternGeco has developed the innovative DisCover methodology of seismic data acquisition, ideal for sub-basalt imaging.

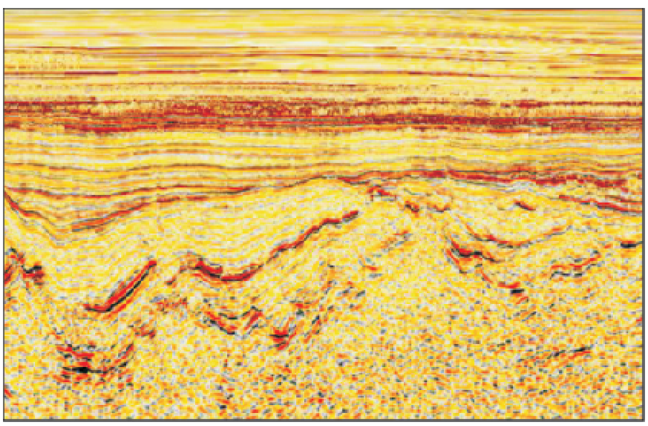

Fig. 7: The wonderful imaging of Mesozoic strata under basalt is clearly demonstrated in this in-line seismic section. A sizable anticline structure is delineated under an erosion unconformity represented by the Cretaceous/Tertiary boundary. Numerous faults compartmentalize sedimentary strata. High-amplitude anomalies on Mesozoic may represent earlier lava flowage (Reunion) event.

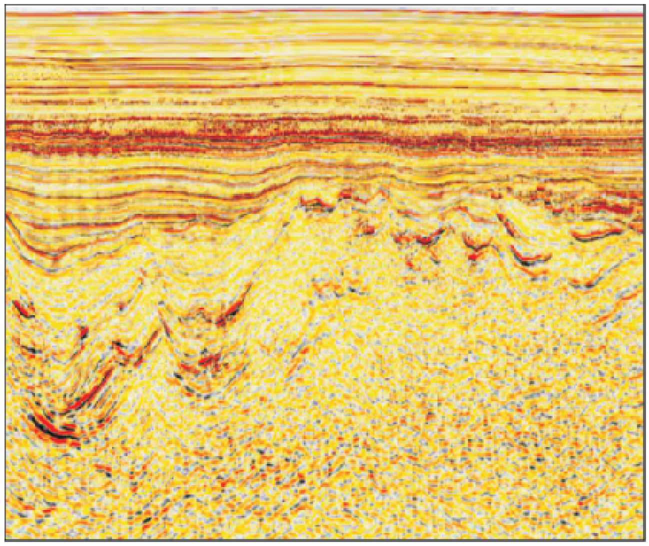

Fig. 8 : South West- North East line displays a volcanic ridge dome and the adjacent marginal Mesozoic basin. Tertiary cover is uniform the high amplitude reflection is the signature of carbonate platform. Shallow to deepwater subsidence of the basin occurred recently. Tertiary sequences are detached from Mesozoic sequences.

produce plausible structure and stratigraphy models for the sub-basalt in the Kerala-Konkan Basin.

The imagery resolution gain under basalt is readily appreciated when a comparison is made between the over-under technique and the single streamer (Fig. 9).

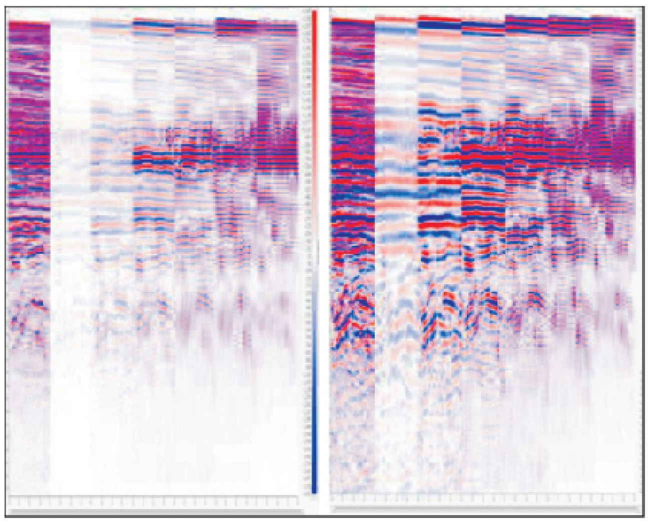

Fig. 9 : Filter panels of shallow streamer only (left) compared with the DISCover over-under filter panel. These panels display all frequencies and 0-5 Hz, 5-10Hz, 10-15 HZ, 15-20 HZ, 20-25 HZ and 25-30 HZ. Imagery bandwidth enhancement gain is readily seen in the low frequency end of spectrum.

Role of Regional Data

In deepwater there are therefore two very distinct lithologies that were shaped afterwards and before the Deccan events. It would appear from modern imaging that several compressional events affected the Mesozoic strata, whereas the Tertiary column is unaffected by compression.

Regional seismic lines, gravity modeling and magnetic data need be coherently integrated for suitable understanding of significant episodes of the Kerala-Konkan basin geologic reconstructions. However, although the regional seismic data pertaining to the south-western tip of India have been interpreted in time and in depth domain, there are nuance geologic interpretation issues that need full suites of additional ancillary data (Roy et al., 2009).

Recognition of slope, rise and ocean basin prospects in the deepwater Kerala-Konkan sub-basalt basin relies on data addition to PSTM/PSDM pairs these are refraction seismic, gravity, magnetics and electrical methods. One of the critical issues concerns the precise determination of the continental ocean boundary (COB) (Figs. 10 & 11).

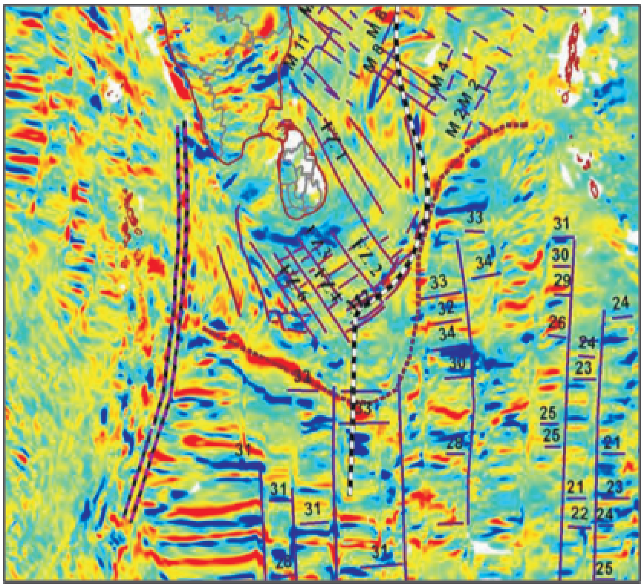

Fig. 10: South of India, patterns of magnetic anomalies from satellite imagery may be recognized relative to events of sea-floor spreading. realm defining therefore the transition boundary between continental and oceanic crust bordering Kerala-Konkan basin (figures 10 & 11).

These ancillary data sets are integrated for the purpose of determining magnetic and gravity patterns so that the COB could be recognized, hence prospect focus definition could be done.

With further utilization of ancillary data resistive and conductive layers beneath basalt can also be defined, hence providing for the understanding of the best velocity model combination yield for seismic at prospect levels these combined with gravity and magnetic data inversion models that enhance regional interpretation. Data therefore is subject to iterative interchange enhancement for sub-basalt imagery of Mesozoic strata, wherein structural prospects are identified and mapped. Several prospective areas are seen in the slope, rise and basin, rift and inversion tectonism are apparent in several areas this is caused by the transform margin at the southwestern tip of India (figure 11). The challenge therefore is to properly map Mesozoic sedimentary structures as opposed to effects caused by the profuse lava flows.

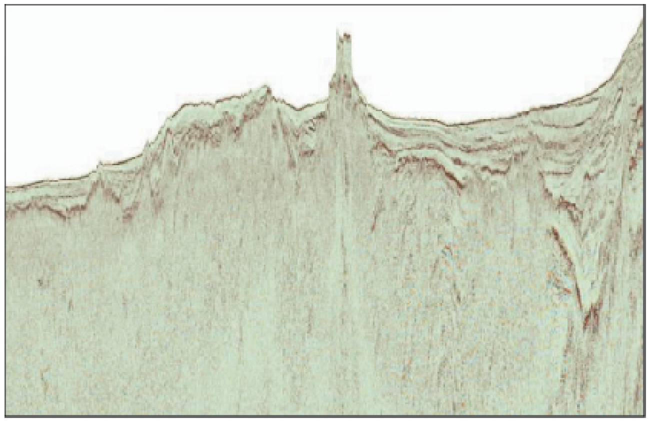

Fig. 11: A regional view of the Kerala-Konkan basin encompassing on the coast side (East) the continental crust half-graben, deepwater continental slope and rise, the deepwater oceanic crust basin realm dissected by fracture zones (COB?) and on the western side the pure oceanic crust with SDR's.

Tectonism has been identified as active ranging since the Aptian and /the Albian times to the Santonian and/Maastrichian immediately under the flood basalts at K/T boundary. Flattening of interpreted horizons provides for a rather precise understanding of tectonic inversion. Erosion at structure tops are also clearly demonstrated by pene-planation near the K/T boundary that may have occurred prior to the lava extrusion. It is important as well to determine the geochemical composition of the so-called basalts these comprise a wide range of distinct minerals and crystallography that inherently influence micro and macro anisotropy.

The deepwater basin underwent abrupt collapse during the Tertiary, where sediments are dominantly deepwater marine clastics intercalated with minor carbonate events. Source rocks should be encountered in the deeper Mesozoic lithology this is demonstrated by the previous links of India and Madagascar. The velocity models for sub-basalt stratigraphy must account for compaction diagenesis, consequently identify areas of high velocity that are sediment dominated as opposed to lava. Identification of the continental-ocean boundary is needed for risk evaluation of deepwater prospects (Figure 11), and relationships source-reservoir-seals in the Mesozoic sequences under basalt.

Conclusions

Kerala-Konkan Basin offshore South West India is one of the largest un-explored sub-basalt basins in the world. This basin is now attracting strong interest from exploration companies as proven by the recently concluded NELP IX acreage bid round. To properly evaluate the deepwater realm an integrated geophysical approach is deemed necessary, it involves adequate 3D anisotropic time/depth seismic migration for prospect focusing, coupled with ancillary 2D regional seismic, gravity, magnetic and EM/MT. key to exploration are the regional seismic identification of seaward dipping reflectors, the continental-oceanic boundary, the mapping of deeper sub-basalt horizons, proper interpretation of Mesozoic erosion surfaces, flood basalts, dykes and sills, understanding of basin evolution in the rift environment and prospects that involve tectonic inversion. Gravity is interpreted synergistically with seismic and provide the density response for models of magma chamber formation in the deep crust. Magnetics identifies sea-floor spreading events and fracturing of Mesozoic substratum by dyke feeders. EM/MT are fundamental tools that contrast the resistive vs conductive nature of layers beneath the basalt flood surface and are selectively compared with velocity profiles for improved parameters of velocity inversion under basalt.

During the final analysis of this DISCover dataset, similar to plotting of amplitude spectra analysis (shown in Fig 4), the recorded frequency spectrum was split into panels comprising of various ranges in order to understand the lowest usable frequency that got recorded. It was very encouraging to observe the frequency panels which clearly demonstrated that lowest usable recorded frequency was ranging from 2.5 to 5 Hz and beyond up to 10 Hz. Along with these, the higher frequencies was almost unaffected as shown in Fig 9.

In this paper we have focused on regional assessment of the Kerala-Konkan basin and on display imagery improvements of its sub-basalt Mesozoic strata that are obtained with the 3D over-under DISCover technique.

Acknowledgments

The authors are thankful to ONGC and to WesternGeco for providing data for this article. Data involves suites of surveys of 2D regional and 3D, both of these with long-spread for proper valuation of long offsets. Data modeling of ancillary potential field data complements these suites, IIT (India Institute Technology Mumbai, India contribution is also gratefully acknowledghed .

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