Imprints of Strike Slip Movements in the Middle Eocene-Miocene Sequence of Western Indian Continental Shelf: Implications for Hydrocarbon Exploration and Production Strategy.

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Summary

Bombay Offshore Basin developed over western Indian Shelf, is characterized by Passive Continental Margin structural affinities. Multicyclic Carbonates of Middle Eocene to Miocene post rift sequence developed in the shelf, harbour major part of discovered Indian Petroleum Reserves. Structural fabric in the basin is characterized by three sets of faults, (i) NW-SE, (ii) N-S or NNE-SSW, (iii) NE-SW or ENE-WSW, co-relatable with ancient structural studies inferred rift related block faulting and subsidence as main genetic mechanism for structural evolution. With increasing 3D seismic coverage, imprints of a subtle NNE to ENE-SSW structural trend, are evident in almost entire basin including Bombay High field. Over Bombay High, this trend is characterized by series of tight linear undulations accompanied by numerous small en-echelon fault traces. In vertical section these are expressed as space accommodation ‘bulges’. Their amplitude and diameter increases upwards and invariably their edges are marked by structural dislocation, depicting typical geometry of ‘positive flower structures’. In the adjoining structural blocks, similar faults have resulted in moderate to strong positive structural inversion of Eocene-Oligocene strata at number of localities. This trend coincides with the transform faults active during the ocean floor spreading in the Arabian Sea, and hence inferred to be related to reactivation of pre-existing fault planes by strike-slip movements during northward movement of Indian Plate in Tertiary period. These faults may have important role in creating the reservoir heterogeneity, which could affect fluid migration, entrapment and production behavior.

Introduction

Bombay offshore basin developed on western Continental Shelf of India (figure-1) is characterized by typical passive continental margin affinities (Biswas et al., 1982; Naini and Talwani, 1982). Its tectono-sedimentary history has been correlated and described by Rao and Talukdar (1980), Basu et al. (1980, 82), Nair et al. (1993, 1993), Zutshi et al. (1993), Parida et al. (1997) and others. Stratigraphic column comprises of Paleocene-early Eocene synrift sequence predominantly of clastic origin and post rift Middle Eocene to subrecent carbonate-clastic sequence (figure-2).

Middle-Late Eocene and early Middle Miocene periods are represented by two megacycles of platform carbonate sedimentation, which harbor rich hydrocarbon accumulations in Bombay High and its satellite fields in the basin.

Structural fabric is constituted by rift related basement horst and graben features draped by carbonate-clastic sediment cover strongly disrupted by multiple sets of faults. Most pre-dominant fault orientation observed over shelf area are: (i) NW-SE faults primarily associated with initial rifting process, (ii) N-S or NNE-SSW faults mostly coeval to earlier trend and considered to have been evolved during rifting (iii) NE-SW or ENE-WSW faults genetically younger to other two trends and invariably show strike-slip movements. These fault trends have been correlated with ancient structural grains of Peninsular India namely Dharwar, Aravalli, and Narmada respectively (Biswas, 1982) and therefore, are considered to owe their origin to reactivation of pre-existing structural planes under the influence of stresses prevailing in Tertiary period.

The NE-SW or ENE-WSW fault trend, which has been established in Tapti-Daman and Panna-Bassein block over number of structures such as Neelam, B-173, B-55 was not hitherto known over the Bombay High field. However, 3D seismic data has revealed the presence of NE-SW fault trend over the field. The present paper aims to demonstrate the presence of this fault system over the Bombay High field and its adjoining areas and its impact on future exploration and exploitation strategy in the area.

Regional Framework

Strong structural control of NW-SE Dharwarian trend is evident in demarcating the boundaries of main structural elements developed in the western continental shelf as brought out by gravity magnetic data (figure-3, modified after T.S. Balakrishan, 1997). Further north of Cambay Basin the pre-dominant structural grain is characterized by NE-SW Aravalli trend. Arabian Sea transform fault system also has strong fault planes oriented in NE-SW trend and some of the faults apparently exhibit the strike slip component extending right up to shelf areas (figure-3). Regional structural map based on extensive 2D/3D seismic data also suggest strong NE-SW and ENE-WSW fault trend present all over the shelf area affecting even the Paleocene and Miocene hinge zone (figure-4). The trend is equally pre-dominant across the

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Fig. 1: Location map showing major oil and gas fields of Bombay Offshore basin.

Fig. 2: Generalised Stratigraphic Chart Showing major Stratigraphic Units developed in and around Bombay High.

Fig. 3: Regional Tectonic Element Map derived from gravity & magnetic data showing predominant NE-SW fault pattern (modified after, T.S. Balakrishnan, 1997)

Fig. 4: Regional Fault Map of Western Continental Shelf derived from seismic data (compiled by Zutshi and Parida; 1995, 1997). Strong NE-SW fault trend is apparent in the shelf area with manifestations of Strike-Slip movements.

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Central Ridge System (Parida et al. 1995) and displaced by strike-slip movements.

**Structural Attributes**

Structural seismic attributes such as “dip-azimuth”, “dip” and “edge-detection” (Landmark Seiswork) generated on the mapped horizons at Basement Top, L-I, L-IV, L-III and L-II Tops indicate the presence of strong NE-SW lineaments, which are co-relatable to the structurally disturbed zones in vertical section (figures-5a & b). On dip azimuth maps these lineaments are apparently caused by the presence of linear “ridges” with incipient en echelon fault traces clustering longitudinally along these structural features and show a tendency of broadening in terms of their diameter at stratigraphically shallower levels (figures-6a & b). These features are highlighted when lighted from NE quadrant. When direction is changed to SE quadrant, E-W features namely median and southern graben fault system become more visible (figure-7a &b).

Eastern Margin Fault system is conspicuously displaced by number of these oblique (NE-SW) fault traces as clearly brought out by structural attribute images (figures-6a & b). At basement Top level, presence of master fault is seen on edge detection image (figure-8), which inferred to be responsible for the development of most of the lineaments exhibited at shallower levels.

**Fault geometry**

In vertical section seismic events are disrupted by sub vertical planes often associated with compressive "bulges" having convex upwards geometry (figures-5a & b). Sense of dip-slip often reverses at shallow stratigraphic levels with a tendency of merging of fault planes at deeper levels. Mild to moderately strong structural inversion is developed in number of places particularly along the Eastern Margin Fault System in Bombay High South as well as along few oblique (NE-SW) main faults. On plan, most of NE-SW faults are en echelon and form interlacing pattern in broader fault zones (figure - 10a, b & c).

**Basement Configuration**

Structural configuration at Basement Top is constituted by number of sub linear ridges or, horsts flanked by grabens. Orientation of lows and highs is controlled by basement composition ranging from Archean Granite, phyllite schist, quartzite and Cretaceous Paleocene Deccan Trap Basalt, Aravalli Trend, superimposed by rift related faulting, during Cretaceous-Paleocene, in turn controls spatial distribution of different basement rocks (figure-9). Strong NE-SW trend is evident in Bombay High south and central part, whereas in northern part strong NW-SE trend is exhibited by number of linear ridges and grabens punctuated by faults (figure-9). Incidentally the structurally highest part is occupied by Cretaceous-Paleocene basalts as compared to present day lower structural areas without basalts cover, implying thereby a structural inversion of northern part due to local compression built-up in the area.

**Spatial Fault Pattern**

Fault pattern as brought out by 3D seismic data is marked by a strong NE-SW trend over Bombay High structure at all the mapped levels including Basement Top, L-IV, and L-III & L-II tops. Changes in their magnitude and frequency are observed at different stratigraphic levels. At basement top, frequency of faulting is relatively higher and almost evenly distributed (figure-10a). At shallower levels faults tend to cluster along few linear tracts forming a kind of 'shear zones'...
Fig. 6 (A-B): Dip Azimuth images of horizons at Basement Top and L-III Top (Early Middle Miocene) mapped over Bombay High Field. Strong NE-SW lineament trend is observed in both the images with slight change in the frequency and magnitude of the structuring. The lineament trend is interpreted as 'space accommodation bulges' developed over the field under the influence of strike-slip movement during post-Miocene tectonic impulses. For inferred fault pattern please see figure-9a&b.

Fig. 7 (A-B): Dip Azimuth images of the horizons mapped on Basement Top and L-III Top (Early Middle Miocene) respectively lighted from SSE direction. East-West fault trend is highlighted. Bombay High Eastern Margin Fault trace appear to be segmented by number of oblique (NE-SW) faults.

Fig. 8: Structural Attribute image (Edge Detection) on Basement Top showing major faults over Bombay High Structure. A major oblique fault is seen to cut across Bombay High South.

Fig. 9: Basement Composition Map, showing the distribution of Archean and Cretaceous-Paleocene Deccan Trap flows over the Bombay High.
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Fig.10: (A,B&C) Interpreted Fault Pattern, superimposed on the structure Maps at Basement, L-IV and L-III (Early Middle Miocene) Tops respectively strong NE-SW fault trend is observed at all the levels with slight variation in the magnitude. Preferential clustering of fault trace at L-IV and L-III tops along NE-SW orientation has resulted in to formation of shear fault (Shfz) 1,2 & 3. For structural attributes please see figures-6-7 & 8.

This is inferred to be resulted due to general fault kinematics under strike-slip regime, where master faults at deeper levels tend to evolve in to broader linear tracts comprising interlacing en-echelon fault traces sub parallel to master faults. Three main shear zones are identifiable over Bombay High field namely, Shfz1, Shfz2, and Shfz3, Southern graben fault system forms the causative for Shfz1 and is well developed at all the levels. However, Shfz3 is relatively less developed at L-IV (figure-9c) and L-V levels. Relative magnitudes of shear zone development vis-a-vis different stratigraphic levels suggest a tendency of northwesterly shift in the principal strike-slip axes with geological time.

Eastern Margin Fault is affected by sinistral along number of NE-SW faults (figures-6a & b), which in general corroborates with anticlockwise rotational component generated during the movement of Indian Plate in Tertiary, as inferred by earlier workers (Naini and Tawani, 1982, 1987). Sinistral movement has resulted into positive structural inversion along Eastern Margin Fault Zone (figure-5).

Fluid Flow Behaviour

The secondary leaching and inter-granular porosity network primarily control fluid flow within L-III and other Miocene carbonate reservoirs over Bombay High structure. As the main reservoir is multi-layered, separated by intervening shale horizons the vertical permeability across successive layers is generally considered insufficient to allow cross stratigraphic migration of fluids, except in the areas of lacking shale thickness. The oil-water contact across the structure varies to the extent of ~90m between crestal part and flanks of the structure and OWC is encountered in stratigraphically younger units as we move towards the flanks.

To explain the temporal variation in the oil-water contact, earlier workers proposed model (figure-11) based on (i) tectonically controlled inclined oil-water contact, and (ii) stratigraphically controlled layer wise oil-water contacts for each layer. However, these models are not able to explain the causative for gravity-in-equilibrium (in case of inclined oil-water contact) and cross stratigraphic fluid flow behaviour (in case of layer wise contacts).

Lately, strong exploitation challenges have emerged in Bombay High field in terms of water break through in the crestal part of the field, oil by-passing and high well sickening rates, and in spite of adequate voidage compensation and other measures taken to boost the production, it has been increasingly difficult to sustain the production rates. This has warranted, a re-look into the fluid flow model in the field.

In light of the new fault pattern revealed by 3D seismic data, it is likely that these faults have an impact in controlling the fluid flow behaviour in terms of creating preferential anisotropy in spatial and temporal permeability distribution in the main reservoir, and as such warrant consideration in modeling the fluid flow behavior in the field.

Preliminary studies indicate correlation between the NE-SW fault pattern and fluid flow behaviour as indicated by preferential trend of (i) high water cutting wells, and (ii) and apparent segmentation of oil-water contact by main NE-SW fault zones (figure-11c, 12). Further analysis and validation of the structural framework with production data is required to establish more realistic and workable model for future strategy formulation.
Conclusions

- 3D seismic data has revealed the presence of predominant NE-SW fault over Bombay High field.
- On regional scale it is correlatable to the strike-slip fault system present in the Western Continental Shelf of India.
- Manifestations of Strike-Slip movements like structural inversion, incipient flower geometry and related features are seen over Bombay High as well.
- In light of the observed fault system, an alternative fluid flow model is envisaged for Bombay High field.
- Detailed analysis of the production data-vis-a-vis structural framework and alternative fluid models is required to validate the envisaged model.

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