Rift graben related to India-Gondwanaland tectonic separation, in sub-basalt Mesozoic basin, Southern Kutch Offshore Basin, India

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Abstract
The Western Continental Margin of India (WCMI) has been subjected to various phases of extensional tectonics from Late Triassic to Early Palaeocene. The resultant lithospheric stretching due to these extensional events has left geological imprints on WCMI in form of rift basins and associated extensional structures. One such imprint of lithospheric extension has been observed and studied in Block of Kutch Offshore Basin. Recently acquired, 3D broadband seismic data, processed with RTM technology and FWI velocity, has substantially improved the sub-basalt image. G&G data from four wells drilled in the study area has been analyzed and three seismo-geological sections i.e. two along dip profile and one along strike profile, have been prepared along the seismic lines passing through the drilled wells. Based on their analysis, the present-day basin architecture of study area has been conceptualized. The study area consists of a half-graben, which is part of a larger rift basin that has been sculpted during India-Gondwanaland separation event beginning in Early Jurassic. The graben structure shows an array of westward dipping listric faults, which have displaced the pre-syn-rift Middle Jurassic and older strata. These normal fault arrays and the resultant uplifted rift shoulders have largely controlled the rift fill sedimentation in the study area. Deccan Trap is underlain by Early Cretaceous sediments towards north and Late Jurassic sediments towards south indicating differential rate of subsidence along the rift axis from south to north.

Introduction
The Western Continental Margin of India is a pericratonic rift or a passive margin petroliferous basin, which has attained its present shape due to sequence of tectonic events along three prominent Precambrian trends viz. Dharwar trend, Aravali-Delhi trend and Satpura trend. Kutch basin owes its origin to break-up of the Indian sub-continent from Gondwanaland along the Precambrian Dharwarian trend and subsequent rifting of the Kutch Block along the Delhi-Aravali trend, during Late Triassic-Early Jurassic (Biswas, 1987). Rift basins are manifestation of lithospheric stretching resulting in shallow depths of Moho, high heat flows and associated magmatism and elevated rift margin topography. The elevated margins serve as dominant provenance for syn-rift and post-rift sedimentation (Allen & Allen, 2013). In the present study, the authors have attempted to explain the present day rift basin-architecture of the study area.

The study area is a part of NELP Block GS-OSN-2004/1, located in southern extremity of Kutch Offshore Basin, on the northern flank of E-W trending Saurashtra Arch (Figure 1). In the study area, commercial gas pools are established in Early Cretaceous and Late Jurassic sedimentary sequences. A marginal gas pool has also been discovered in fractured basalt. (Figure 2 & 3).

Figure 1 Study area showing drilled wells and proposed locations

The objective of this study is to interpret the improved seismic data and available well data to prepare seismo-
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general sections and demonstrate the present day structural style of Mesozoic basin in the study area.

Theory and Methodology

Four wells have been drilled in GS-OSN-2004/1 area with an objective to explore hydrocarbon potential of Mesozoic sequence (Figure 1). Well-A, encountered Late Jurassic sediments underlying Deccan Trap while the wells, C and D, located north of Well-A (Figure 2 & 3), encountered Early Cretaceous sediments underlying Deccan Trap (Singh et al., 2018). Well-B, located east of Well-A in the adjacent fault block, encountered Late-Middle Jurassic sediments underlying Deccan Trap (Saxena, 2016) (Figure 2 & 3).

Due to poor resolution of sub-basalt image in the pre-existing seismic volume, the present broadband data was acquired, with an objective to enhance the seismic image in sub-basalt Mesozoic sedimentary sequences. The acquired data was processed using 3D APre-STM and APre-SDM with RTM technology. The final velocity model was updated with FWI technology.

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1. Seismo-Geological Section along NE-SW Dip Profile:

Well-B, which is located at the landward side (NE) relative to Well-A, encountered oolitic limestone (Figure 3, 4 & 10), below Deccan Trap. In Kutch Basin, oolitic grainstones and packstones are characteristic of Middle Jurassic sequences viz, Goradongar, Jhurio and Jumara formations, deposited in clastics starved, transgressive-neritic environment (Dave and Pandey, 1998). Similar oolitic limestones have also been dated Middle Jurassic in the exploratory wells located in northern part of Kutch Offshore. Well-A, which is located towards the basinal side, encountered younger Late Jurassic sediments below Deccan Trap (Figure 3 & 4).

Presence of younger sediments in the basin direction (SW) and older marine sediments in the, structurally higher, landward direction (NE) indicates that eastern block was uplifted and remained an area of positive relief (Figure 4). Well-C and Well-D located north of Well-A are structurally lower than the latter at Mesozoic Top level and consists of Early Cretaceous sediments underlying Deccan Trap. The seismo-geological section (Figure 4) shows a half-graben basin structure formed due to extension associated
with India-Africa rifting towards end of Middle Jurassic, with its axis in present day NNW-SSE direction. Absence of Early Cretaceous sediments in Well-A and Well-B corroborates this theory.

2. Seismo-geological section along E-W Dip Profile:

Well-C, which is located on the basinal side of the study area, encountered Early Cretaceous sands underlying Deccan Trap. Well-B, located towards the landward side of Well-C, encountered oolitic limestone underlying Deccan Trap (Figure 2, 5 & 10). This seismo-geological section shows similar basin architecture as depicted in the NE-SW section. A marked increase in sediment thickness implying increased accommodation space in the rift depo-centre is observed in this section, compared to the NE-SW section (Figure 4- NE-SW & 5). Presence of younger Early Cretaceous sediments in the northern wells (Wells C & D) indicates a higher rate of subsidence in the northern part of the rift relative to the south. Similar basin structure has been observed in the Rhine Graben in Central Europe, wherein the rift fill sedimentation began in the southern extremity of the graben and continued northwards. As the rifting in the south waned, the northern part continued to subside and receive the younger rift fill sediments (Frisch et. al., 2011). This seismo-geological section shows a possible detachment fault associated with asymmetrical rifting (Figure 5). This detachment fault has even displaced the younger Deccan Trap and a part of Cenozoic sequence, which is because of its reactivation due to Cenozoic tectonic events (Figure 5).

3. Seismo-geological section along N-S Strike Profile:

The wells, C and D, located north and in a structurally lower area at Mesozoic Top level (Figure 2), have encountered Early Cretaceous sediments underlying Deccan Trap. Well-A, located south and in structurally
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higher area (Figure 2 & 4), has encountered Late Jurassic sediments underlying Deccan Trap. A relatively thinner, 50m un-fossiliferous interval, consisting of sandstone below Deccan Trap may belong to Early Cretaceous (Figure 4). The seismo-geological section (Figure 6) shows that Early Cretaceous sequences are thinning out towards south, terminating close to or at Well-A. This section is prepared along the rift axis, with the Well-C and Well-D located in the rift depo-centre towards the north. This depo-centre received sediments from structurally higher Jurassic flanks located in the south (Well-A) and the east (Well-B). The Jurassic sequences are intruded with numerous doleritic intrusives.

Towards the south of Well-A, the sequences again appear to be structurally lower at Late Jurassic level (Figure 6). This may have facilitated deposition of Early Cretaceous sediments overlying Late Jurassic sediments in the southern part of study area.

Discussion

Rift grabens comprise of a central axial depression flanked by elevated shoulders that plunge steeply towards the central axis (Figure 4 & 5). They are formed in the areas where the lithosphere is extended and subsequently thinned. The extension can occur due to convective mantle plume acting on the base of lithosphere, pulling it apart or due to unspecified tensional stresses triggering the failure of continental lithosphere. Rift graben is characterized by an array of listric faults having their strikes parallel to the rift axis (Figure 4 & 5). These faults are created due to brittle deformation of the shallow crustal lithosphere (0km-15km), while ductile plastic deformation occurs at greater depths (Frisch et.al., 2011).
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The study area consists of a graben, axially trending in NNW-SSE direction (Figure 8), which also corresponds to the present day Precambrian Dharwarian trend. The width of graben increases towards north of the study area, which has repercussions on sediment thickness and their age range. Seismo-geological section along E-W direction, which cuts the northern part of the study area, shows a greater thickness of sub-trappean rift-fill sediments, belonging to Late Jurassic and Early Cretaceous (Figure 5). In contrast, the NE-SW seismo-geological section which cuts the southern part of the study area, shows a relatively lesser thickness of sub-basalt rift-fill sediments, belonging to Late Jurassic (Figure 4).

An array of westwards dipping normal faults, having listric geometry typical of extensional basins, striking parallel to the rift axis, controls the sedimentation style of syn-rift Late Jurassic sediments. The elevated rift shoulders, comprising of Late Jurassic and older strata are present in the western and southern part of the study area, as indicated by high relief in time map within Late Jurassic sequence (Figure 9a, 4 & 5). Well B also lies on the rift shoulders as it encountered much older, Middle Jurassic sediments underlying Deccan Trap (Figure 4, 5 &8). The graben center comprises of younger post rift, Early Cretaceous sediments underlying the Deccan Trap (Figure 9b, 5). The extent of these sediments will continue to the north of study area (Figure 9b). The displacement along the master fault initiated from the southern part of the basin resulted in creation of elevated graben shoulders, during Early-Middle Jurassic. The subsidence of graben began from the south and steadily continued northwards, resulting in creation of accommodation space for younger Late Jurassic and Early Cretaceous sediments. This resulted in present day basin architecture, wherein, the older Late Jurassic sediments occur on the elevated graben flanks and the Early Cretaceous sediments were deposited in the deeper graben center (Figure 9c).

Conclusion

Rift basins occurring worldwide have complex basin geometry, with varied magnitude of subsidence and lithospheric extension along the rift axis. To envisage the petroleum system of such complex rift basins, understanding of the present day basin architecture and its evolution is of paramount importance. Newly
acquired and processed 3D broadband data of the study area has facilitated significant improvement in the interpretation of sub-basalt seismic image. The present study area depicts a typical half-graben basin geometry. Enhanced seismic image and well biostratigraphy studies reveal that Middle Jurassic and older sediment sequences are vertically displaced by an array of west-ward dipping listric faults, while the overlying Late Jurassic and Early Cretaceous sediment sequences appear to be stable and unaffected by the normal faults. Occurrence of oolitic limestone belonging Middle Jurassic sequence in the structurally higher, terrestrial side of the study area reveals that these rock sequences are present as the elevated shoulder flanks on the footwall of the rift basin. These Middle Jurassic sequences also appear as high amplitude seismic signatures underlying the syn-rift and post-rift, Late Jurassic and Early Cretaceous sediments, respectively, in the rift depo-centre. This observation along with improved seismic image indicates that the half-graben structure is fragment of a larger and wider rift basin, shaped during a major tectonic break-up of Indian subcontinent from Gondwanaland in Early Jurassic.

The high amplitude seismic signatures observed in the dip sections, underlying the Late Jurassic sequences, may be the Middle Jurassic carbonates, similar to one encountered in Well-B. The resource assessment study attributes 768 MMTOE of YTF reserves to Middle Jurassic sequence. These unexplored seismic signatures occur at structurally higher rising flanks, at shallower depths in the western part of study area and investigating them by drilling can throw light on their hydrocarbon prospectivity in the future.

The Mesozoic sequence in the Kutch Basin has been intruded by numerous igneous bodies. Magmatism in passive graben system, i.e. which is not associated with hotspot activity, is dominantly of alkaline composition, i.e. silica undersaturated melts. Active graben systems, like mid-oceanic ridge, is dominantly emplaced with tholeiitic basaltic melts (Frisch et al., 2011). Measurement of bulk chemical composition of these magmatic intrusives can aid us to delineate the emplacement events related to Deccan volcanism, which was associated with hotspot activity, from the emplacement events related to older passive lithospheric extension episodes. This will lend greater clarity in our understanding of the tectono-stratigraphic evolution of Kutch Basin.

References


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