Asymmetric rift basin related to multiple extensional events during India-Gondwanaland tectonic separation, in southern Kutch-Saurashtra Basin

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Abstract

Extensive field research in Kutch onshore basin, commencing from the mid-late 20th century, has unveiled significant information about geology and evolutionary history responsible for creation of its unique present day geomorphology. It is characterized by Mesozoic ridges, outcropping in W-E trend of the Precambrian Delhi fold-belt, separated by Cenozoic flatlands. Exploratory wells Banni and Nirona drilled in mainland Kutch encountered conglomeratic Rhaetian sediments overlying Precambrian Basement, suggesting an earliest episode of rifting in Late Triassic. Seismic API projects in Kutch offshore basin unveiled an existence of NNW-SSE trending horst-graben structures in Mesozoic section, the rendition of which is seen in overlying Cenozoics. However, poor seismic image of Mesozoic strata which is overlain by 1500m-2500m thick basalt of Deccan Trap volcanism and limited well control eluded exploration geoscientists from mapping a definite pre-rift horizon. In southern Kutch Offshore basin, recently acquired 8 km long offset 3D broadband seismic data, processed with RTM technology, showed an improved sub-basalt image of the Mesozoic section. The dip transects of this volume were characterized by high amplitude inclined reflectors representing the tilted fault blocks of an asymmetric rift basin, bounded by west dipping extensional faults, striking along the Dharwarian grain. In the present study, a pre-rift horizon corresponding to rifted Middle Jurassic strata was mapped in the southern Kutch offshore basin to define the present day pre-rift geomorphology. Seismo-geological transects, across the drilled wells, were prepared along the dip sections to define the structural configuration of the Mesozoic rift and hypothesize the depositional environment of overlying Jurassic-Cretaceous synrift sediments which have emerged as major hydrocarbon plays in the basin.

Introduction

Kutch-Saurashtra basin is a legacy of complex and multi-stage tectonic events which began when Indian Plate initiated its separation from Gondwanaland in Late Triassic-Early Jurassic, travelled northwards while drifting over Reunion hotspot at K-T boundary resulting in formation of one of the most extensive large igneous provinces (LIPs) on Earth, and eventually collided with Eurasia in Miocene. Stratigraphically, the basin consists of Mesozoic strata, from Late Triassic to Late Cretaceous, unconformably deposited over Precambrian Basement, outcropping as E-W trending ridges in Kutch onshore basin. In offshore basin and Saurashtra horst the Mesozoic rocks are overlain by Deccan Trap basalt. Cenozoic rocks are unconformably deposited over Mesozoic strata within the intervening basins facing uplifted Mesozoic ridges in the Banni Graben region. At present, these basins occur as extensive flatlands of Banni Grassland and the Great Rann of Kutch (Figure 1c). In Kutch Mainland, offshore and Saurashtra horst block the Cenozoic strata is unconformably deposited over Deccan Trap basalt. A stratigraphic disposition and structural configuration of Cenozoic basin is widely comprehended from seismic volumes and drilled wells,

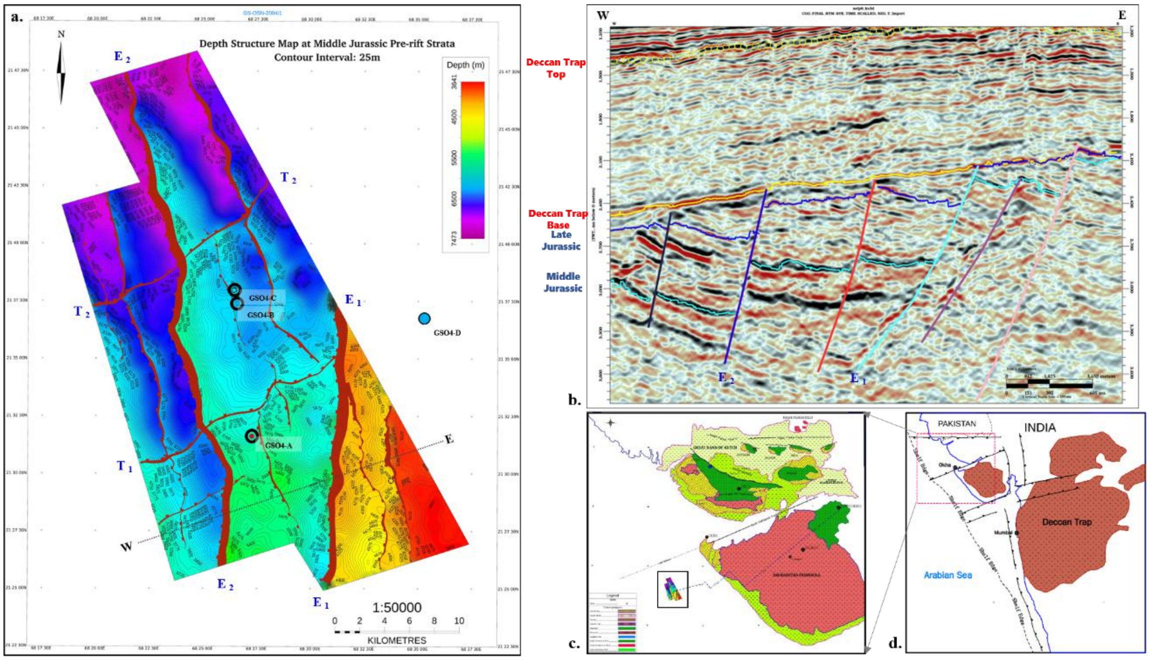

Figure 1: a. Study area denoted by depth map of Pre-rift strata (Middle Jurassic); b. Seismic line along the dip of study area (annotated W-E in Fig 1a), with interpreted horizons and faults; c. Geological map of Kutch-Saurashtra onland basin with study area in shallow-water offshore, denoted by the depth relief map of pre-rift strata; d. Index map of Western Continental Margin of India (WCMI) with Kutch-Saurashtra basin annotated as *box*.

exploration geoscientists are evaded from unambiguous perception of sub-basaltic Mesozoic strata due to poor seismic image and fewer well control.

Vintage literature limits Mesozoic basin of Kutch within two principle uplifted rift shoulders i.e. Nagar Parkar ridge in north and Saurashtra horst or Kathiawar block south, bounded by Nagar-Parkar fault and North Kathiawar fault respectively (Figure 1c). Although, offshore well GSO4- A located south of offshore extension of North Kathiawar fault encountered presence of gas bearing Late Jurassic sandstones while well GSO4-D drilled in the east encountered coarser Early Jurassic and Late Triassic sediments (Figure 1 & 5b).

Recently acquired 3D broadband seismic data, processed with RTM technology, showed an improved image of sub-basalt Mesozoic strata and unveiled the existence of a NNW-SSE trending asymmetric rift basin in the study area (Figure 1a & b). Pre-rift horizon was mapped and seismo-geological transects were constructed along dip lines of the area to define present day structural configuration of the basin. This revealed that hydrocarbon bearing Early Cretaceous and Late Jurassic sediments are encompassed within a NNW-SSE trending half graben. The findings not only augment pre-established hydrocarbon potential of the area but also provides leads for updating existing perception about extent of the sub-basalt Mesozoic basin and supports the significance of Dharwarian trend in basin building history. Occurrence of Mesozoic sediments, south of offshore extension of North Kathiawar fault, within a NNW-SSE trending half graben bounded by rift shoulder in the east composed of coarse grained Middle Jurassic and older clastics, explores possibility of two major episodes of rifting during India-Gondwanaland separation. This study aims to: 1. Establish present-day topography of pre-rift Middle Jurassic strata based on seismic and well data, in southern Kutch-Saurashtra Basin; 2. Demonstrate structural disposition of sub-basalt Mesozoic rift basin from local and regional seismo-geological dip transects and explain its tectonic evolution; 3. Summarize on gross depositional set-up of Late Jurassic and Early Cretaceous synrift sediments.

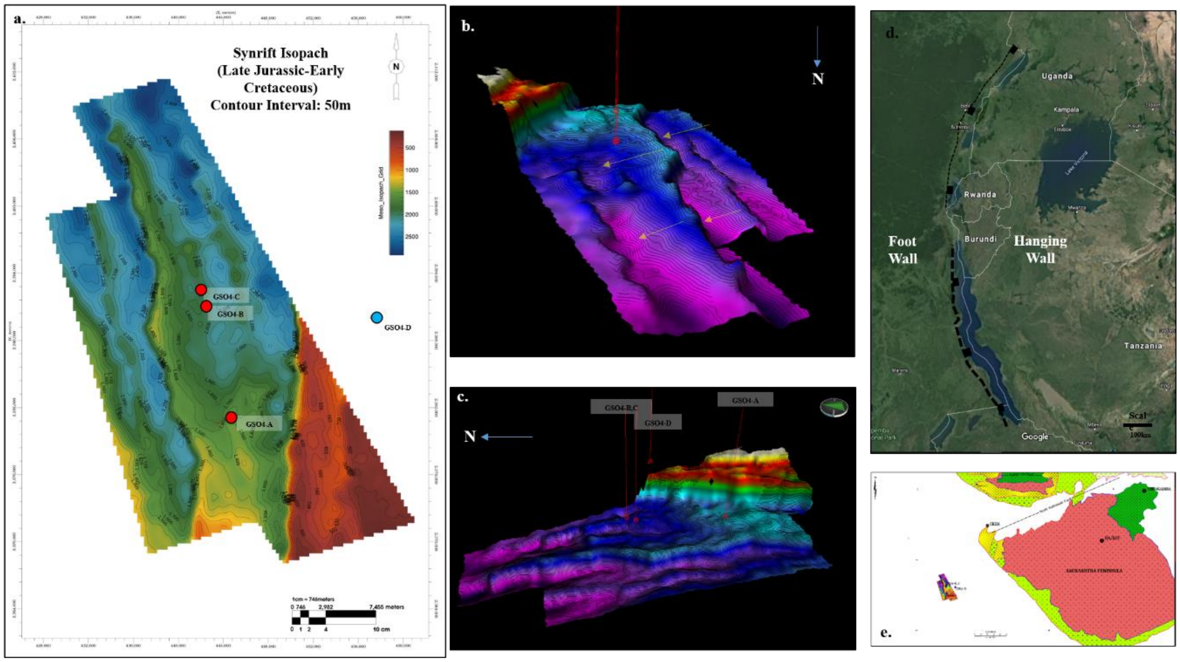

Figure 2: a. Isopach map of Late-Jurassic and Cretaceous sediments i.e. synrift; b. 3D view of depth relief of pre-rift strata from north, hanging wall dip-slope annotated with *dashed arrows*; c. 3D view of depth relief of pre-rift strata from west; d. Satellite image (Google Earth) of Lake Tanganyika and associated lakes of Great African Lakes, bounding fault annotated with *dashed line*; e. Index map.

Rift basin in southern Kutch Offshore Basin

Dip sections of 3D broadband seismic data, processed with RTM and FWI technology show presence of tilted blocks bounded by an array of westward dipping extensional faults which is characteristic of an asymmetric rift graben (Figure 1b). These high amplitude reflectors are a representation of rifted Middle Jurassic carbonates and occur due to high impedance contrast between carbonates and enveloping clastics. Well GSO4-D, drilled in the uplifted eastern block, encountered 80m of oolitic limestone belonging to Middle Jurassic (Figure 3a & 5b). Peak of these high amplitude reflectors was mapped as a horizon close to Middle Jurassic top in the 3D Broadband seismic volume (Figure 1b). The depth relief map revealed presence of sub-parallel uplifted rift shoulders trending in primordial Precambrian Dharwarian trend, having steep gradient of the fault escarpment facing south-west and gentle gradient of hanging wall flexure towards east to north-east, which is the textbook topography of sub-parallel half grabens in an asymmetric rift basin (Figure 1a, 2b & c). Depth structure map of Middle Jurassic strata shows NNW-SSE sub-parallel inter-fingering rift shoulders. Extensional faults displace the pre-rift strata with maximum throw of ~ 1.1 km in north and ~ 1.4km in the south (Figure 1a). Faults are listric in nature resulting in larger heave in displaced pre-rift strata. Magnitude of subsidence is highest in the north, where the pre-rift strata occurs at the depth of ~7.3 km. Area south of transfer fault TT' is structurally higher and shows higher density of graben bounding extensional faults.

In the half grabens, thickest synrift sediments occur on the hanging wall adjacent to the fault escarpment. Regional dip of the basin is due north wherein the rift basin deepens (Figure 2 a, b & c). The uplifted footwall highs act as provenance for graben fill sediments which are deposited on the eastward dipping hanging wall flexure in palaeo-current direction transverse to the axis of rift while axial drainage occurs parallel to the rift axis aided by the longitudinal trend of the grabens. The rift basin is intersected by NE-SW trending transfer fault, coinciding with the Precambrian Aravalli trend (Figure 1a).

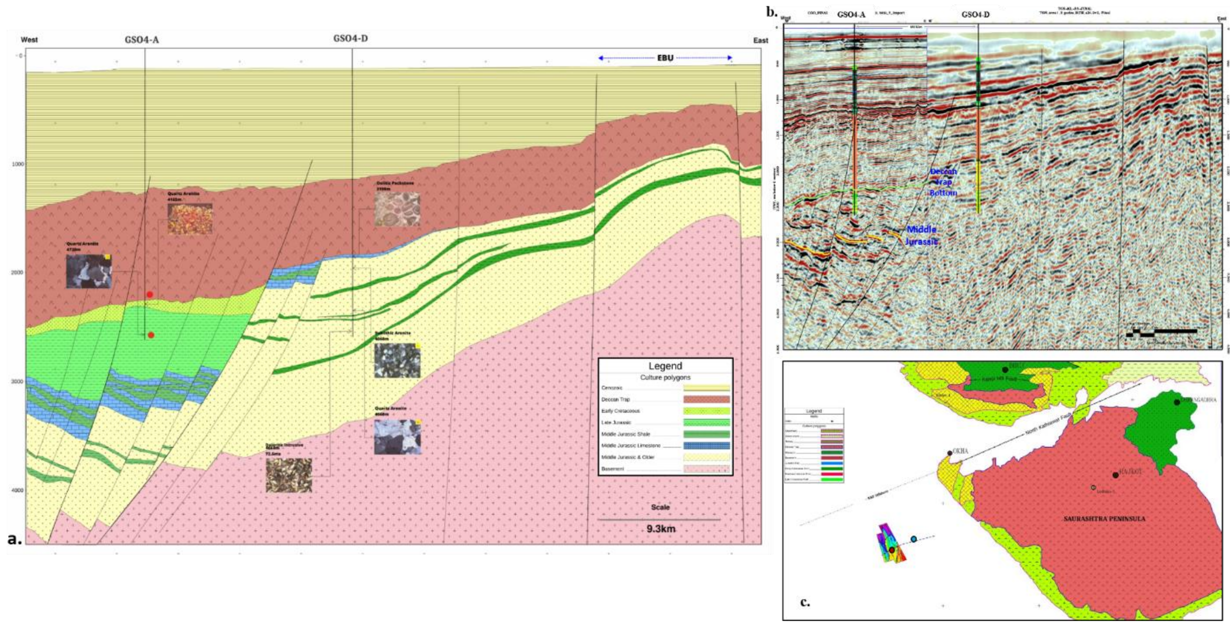

Figure 1 a. Seismo-geological profile along drilled wells GSO4-A and GSO4-D, i.e. the dip section of the study area, Eastern Basement Uplift annotated as *EBU*; b. Seismic line passing through wells GSO4-A and GSO4-D with interpreted faults; c. Index map.

Four Mesozoic wells were drilled in the study area, well GSO4-A (drilled depth: 4887m), drilled south of the block, encountered ~80m of Early Cretaceous sediments belonging to Berriasian age, underlain by Late Jurassic clastics belonging to Tithonian-Kimmeridgian age (Figure 1, 3a & 5b). Well GSO4-B & C (drilled depth: 5157m & 4836m), drilled 10-13 km north of GSO4-A, encountered ~350m thick succession of Early Cretaceous sediments belonging to Berriasian-Hauterivian age, underlain by Late Jurassic clastic sediments belonging to Kimmeridgian-Tithonian age (Figure 1 & 5b). Well GSO4-D (drilled depth: 4865m), drilled east of GSO4-A, encountered Middle Jurassic oolitic limestone underlying Deccan Trap basalt, followed by the clastic sediments of Middle Jurassic, Early Jurassic and Late Triassic (Figure 1, 3a & 5b). In Kutch Basin, oolitic grainstones and packstones are characteristic of Middle Jurassic sequences, viz. Jhurio and Jumara formations, precipitated in clastics starved, transgressive-neritic environment (Pandey and Dave, 1998). Similar oolitic limestones have also been dated Middle Jurassic in well GK-29A located in northern part of Kutch Offshore. Presence of oolitic limestone belonging to Middle Jurassic in GSO4-D is distinctive from GSO4-A, B & C, wherein, younger Early Cretaceous sediments were encountered underlying Deccan Trap (Figure 5). Younger sediments in the basinal direction (west) and older marine sediments in, structurally higher, landward direction (east) suggests that eastern block is present as an uplifted rift shoulder (Figure 1 & 2 b &c) and remained an area of positive relief post Middle Jurassic. While the younger Late Jurassic and Early Cretaceous sediments were deposited in the subsided half grabens in the west (Figure 2a & 3).

In Saurashtra horst block, 215km east of well GSO4-D, well Lodhika-1 encountered clastics of Late Cretaceous Wadhwan formation and Early Cretaceous Dhrangadhra formation, underlying Deccan Trap basalts. Early Cretaceous fluvial sands are underlain by undifferentiated coarse grained Late Jurassic sediments. Volcanics in form of Dolerite intrusion and welded tuffs occur at the base of the well (Figure 4a). Recently acquired 2D seismic revealed eastward dipping divergent seismic reflectors at well area and significant lowering of gravity anomaly (Figure 4: b & c). These observations affirm that well Lodhika-1 was drilled in a graben formed during a rifting episode congruent with that of the western offshore graben of GSO4 area, accommodating Jurassic-Cretaceous synrift clastics as graben fills. The Jurassic volcanics are interpreted to have originated as rift related volcanism in transcontinental rift set-up margin based on Sr-Nd

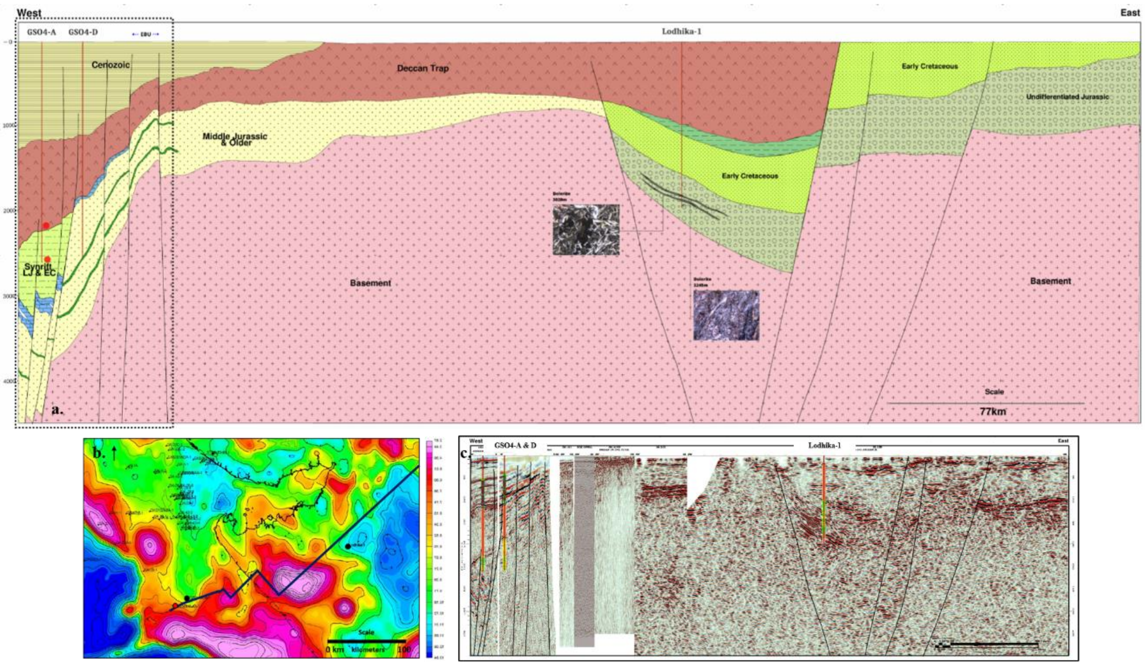

Figure 2 Seismo-geological section along seismic line from offshore well GSO4-A, GSO4-D and onland well Lodhika-1 depicting presence of rift graben in the east wherein drilled well Lodhika-1 encountered Cretaceous and Jurassic sediments, seismo-geological section of figure-3 annotated by *dashed rectangle*; b. Index map-Gravity anomaly map of Kutch-Saurashtra Basin with seismic line annotated as *solid line*. c. Seismic section along drilled wells GSO4-A – GSO4-D to Lodhika-1.

isotopic signatures (Rathore et al., 2019). The basaltic glass of Deccan Trap, as anticipated, is categorized as MORB type basalts with least or no continental interaction. The block between GSO4-D and Lodhika-1 is a horst block with uplifted basement showing increased gravity anomaly (Figure 20 a, b).

Discussion and Future Scope:

Presence of basin wide carbonates, belonging to Callovian-Oxfordian age, attributed to their onland type section of Jhurio and Jumara formations, overlying Late Triassic to Middle Jurassic clastics suggests a period of quiescence in tectonic activity which allowed these shelfal carbonates to be precipitated. Four stages of basin evolution are envisaged:

1. Initial rifting during Late Traissic and deposition of 1st synrift graben fill sediments of Late Triassic-Middle Jurassic followed by a phase of tectonic quiescence and precipitation of basin-wide Middle Jurassic carbonates.
2. Rifting during Middle Jurassic-Late Jurassic resulting in rifting of Middle Jurassic strata observed as tilted fault blocks bounded by westward dipping extensional faults.
3. Late Jurassic to Early Cretaceous synrift sedimentation.
4. Uplift of southern area during India-Madagascar tectonic separation (~90ma) or India-Laxmi ridge separation (~71ma) and erosion of synrift strata in south of the study area followed by Deccan Trap eruption at K-T boundary.

Analogous basin congruent to the proposed tectonic evolution occurs in UK-Norwegian central graben, characterized two phases of rifting in its evolutionary history. Older NNW-SSE trending rift, bounded by Late Triassic extensional faults, was subjected to reactivation due to second phase of extension in Late Jurassic, at an axis 10^{o} orthogonal to Late Triassic rift strike (Roberts et al., 1990).

Gas bearing Early Cretaceous sediments occur as texturally, moderately to well mature, quartz

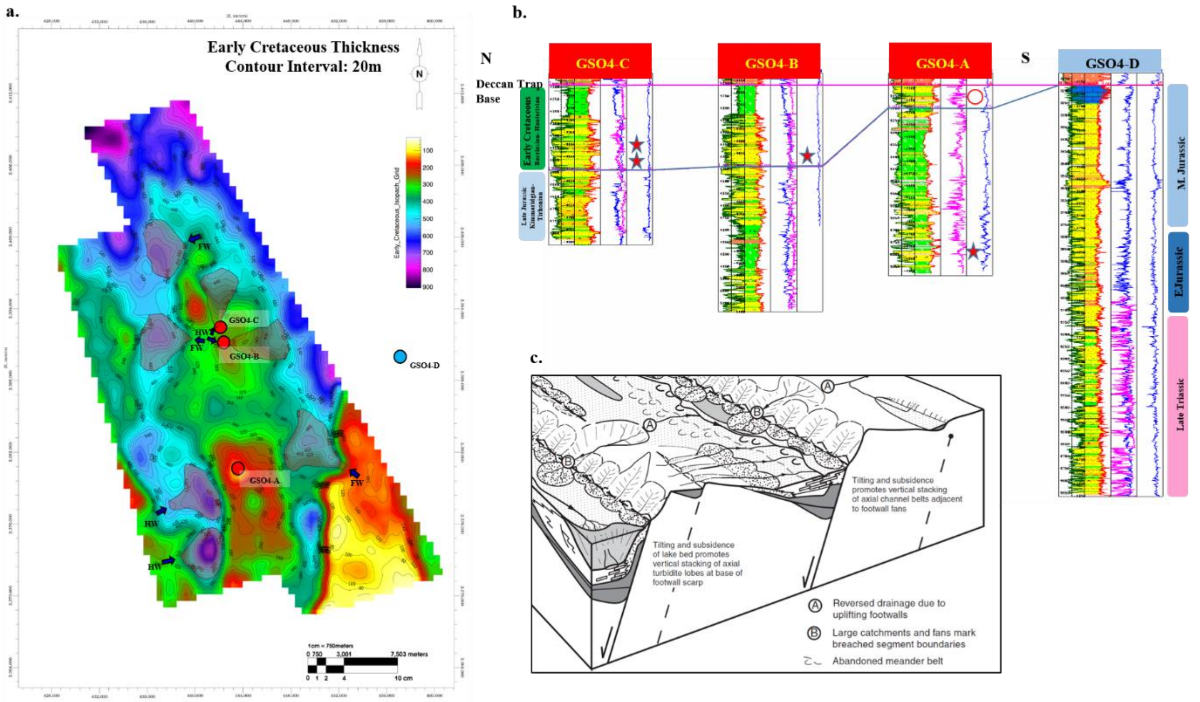

Figure 3 a. Early Cretaceous iso-pach map, foot-wall sediment inlets annotated as *FW* & hanging-wall sediment inlets annotated as *HW*; b. Electro-litho-log correlation along drilled wells GSO4-AD, A, B & C; c. Generalized depositional set-up in an asymmetric rift basin (*Gawthorpe & Leeder*, 2000).

arenites, showing blocky and fining up log-motifs indicating progradational to aggradational depositional set-up (Figure 5b). The high textural maturity of Early Cretaceous sediments can be attributed to reworking of sediments in marginal marine set-up which is also evident from significant bioturbation reported in conventional core. Isopach map of Early Cretaceous shows thinnest sediments overlying pre-rift footwalls. Evidences of transverse drainage, from footwall breaches are observed, these are areas of sediment inputs to graben depocentres from both uplifted footwall (*FW*) and hanging wall flexures (HW) (Figure 5a) . Delineating the depositional locales will assist in de-risking studies for future exploration in the gas bearing Early Cretaceous play.

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Views expressed are those of authors only and not necessarily of the organization.

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