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Sequence stratigraphy of a Post Rift sedimentary succession: An Example from Kachchh Basin, India

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Abstract: The sequence stratigraphy of a post-rift basin fill succession of the Jhuran Formation (Kimmeridgian- Tithonian) in the Kachchh Basin is investigated. The integrated analysis of sedimentology, palaeontology and regional stratigraphic correlation of marker beds provides a comprehensive understanding of post rift sediment succession. The Dhosa Oolite Member (Jumara Formation) serves as a good stratigraphic marker bed across the basin. It contains extensive and dense occurrence of trace fossil Zoophycos, suggesting a slow sedimentation rate, dysoxic bottom water, and low energy deep marine conditions, thus corresponds to Maximum Flooding Surface (MFS). Above this MFS, HST-1 represented by a thick prodelta shale deposit of Lower and Middle Rudramata shale members. In HST-1, Early and late HST can be easily distinguished by a complete transition from fossiliferous mudstone to nodular and hetreolithic facies. The HST-1 is overlain by TST-2 represented by thick bedded sheet geometry sandstones and multiple fossiliferous beds, containing Ammonites of Tithonian Age. In the western Kachchh basin, the entire fossiliferous unit indicates a transgressive package with the landward shifting parasequence sets. In the remainder basin, it is represented by subaerial unconformity. The HST-2 represented by thick cycles of coarsening-up and thickening-up parasequences overlies TST-2. The top of HST-2 is exposed and marks subaerial unconformity (SB2).

Keywords: Sequence stratigraphy, Post-rift, Kachchh basin.

Introduction

Sequence stratigraphy is a powerful predicting tool for understanding the Spatio-temporal distribution of depositional environments and stratigraphic framework in a sedimentary basin (Martins-Neto and Catuneanu, 2010). The stratigraphic sequence technique is successfully applied in hydrocarbon exploration to identify and predict the location of hydrocarbon source, reservoir and seal rocks. The methodology's success lies in its adaptability to a wide range of data types and scales, including seismic sections, well logs, outcrops, and cores. The concept of sequence stratigraphy was initially described by Sloss (1948) to understand unconformity bounded lithostratigraphic units in the North American cratonic interior. Later these unconformities bounded stratigraphic units were recognized as the result of cyclic sea-level changes, and the concept was also applied in interpreting seismic sections. From 1960 to 1970, a team led by Vail at Exxon Production Research developed the fundamentals of seismic stratigraphy and subsurface interpretation techniques. Subsequently, they published AAPG Memoir 26 entitled Seismic Stratigraphy-applications to hydrocarbon exploration in the year 1977. The success ratio of finding viable hydrocarbon reserves has significantly improved as the sequence stratigraphic idea has advanced. The stratigraphic sequence framework comprises three stratigraphic sequence units: sequences, systems tracts, and parasequences (Catuneanu et al., 2010). The sequence stratigraphic framework can distinguish between allogenic and autogenic control on sedimentation. Allogenic control identifies system tracts in a broad sense, whereas autogenic processes, like delta lobe switching, observe at a smaller scale. Tectonics, sea-level changes (eustatic and local), climatic variations, and availability of accommodation space are all important elements that influence sedimentation and the ensuing sequence stratigraphy. The concept of the sequence stratigraphy was developed for passive margin settings. In contrast, sedimentary succession in rift basins is often controlled by a complex interplay of accommodation history linked to mechanical subsidence, local sediment supply (e.g., horst), and the effect of sea-level change on the horst and graben. In a rift basin,the sequence stratigraphy is governed by the combined effect of regional and local factors. The purpose of the paper is to evaluate sequence stratigraphy in a post rift setting, especially when periods of rapid mechanical subsidence (Syn-rift stage) are followed by periods of tectonic quiescence (post-rift), during which the available accommodation space is filled up and consumed (Martins-Neto and Catuneanu, 2010).

Basin architecture and geological setting

The Kachchh Rift basins evolved along western continental margins of India, offering evidence of the breakup of India with Africa. The Mesozoic sedimentary architecture and basin-fill are strongly influenced by the fault system and connected horst and grabens (Biswas, 2016). The Kachchh rift basin is an East-West oriented fault bounded basin, with Nagar Parkar ridge on the north and Kathiawar horst along the south forming its rift shoulders. It truncates at the Radhanpur arc (a basement high) in the east, and opens up to the offshore Kachchh. The rift extended from north to south during its early stages, forming three distinct half grabens (a) Rann Half Graben (b) Banni Half Graben and (c) Gulf of Kachchh Half Graben (Biswas, 2016).

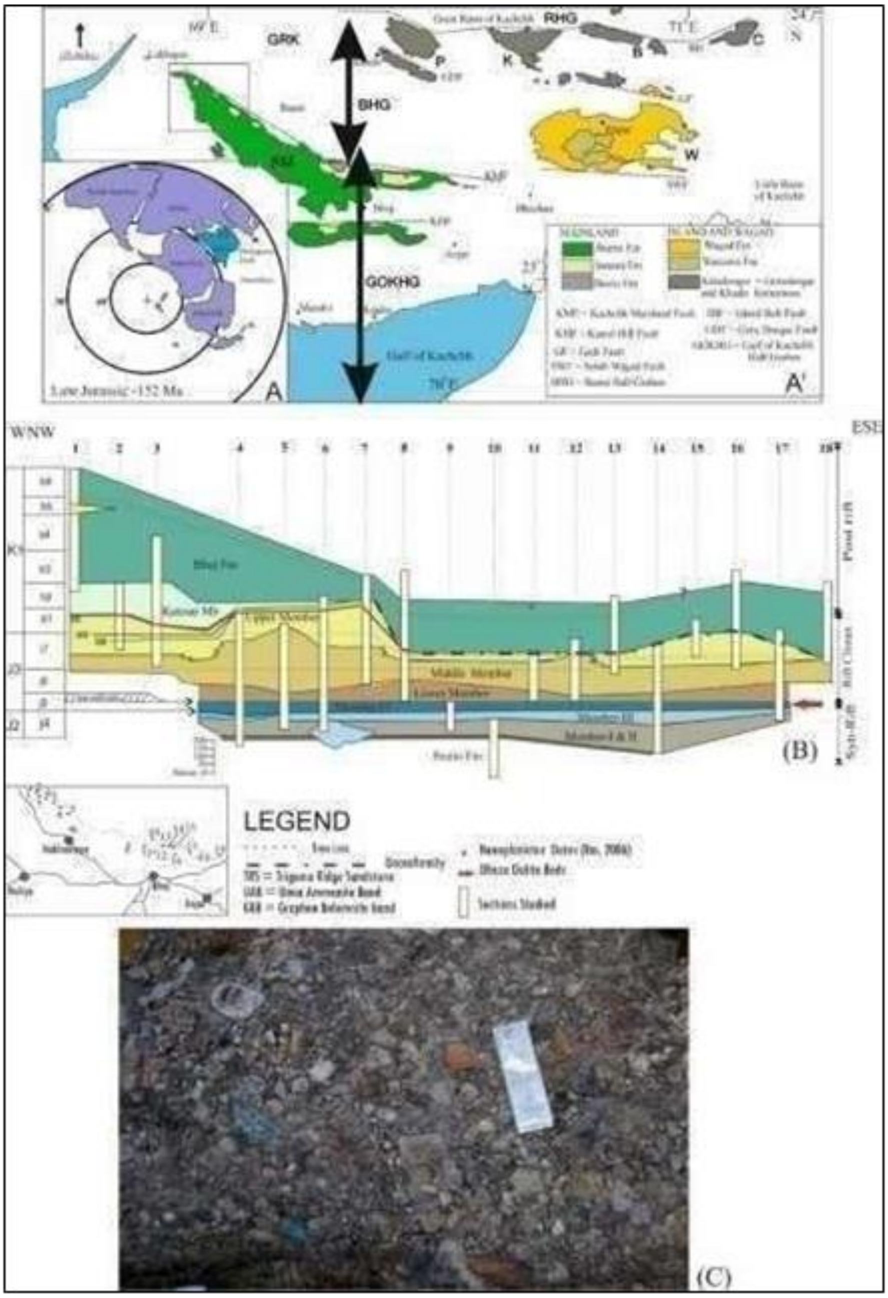

Fig. 1. Location map of the Kachchh Basin (A) Position of the Indian subcontinent during Late Jurassic Time. (A') Geological map of Kachchh Basin (inset) modified after (Desai and Biswas, 2018) indicates study area; (B) Geological Correlation of studied sections throughout the Kachchh basin; (C) Granite-cobble conglomerate beds exposed at Chariyabet in Khadir Island, Kachchh Basin.

The rift basin is asymmetric in its geometry with a south-westerly depocenter and maximum sediment thickness (Fig. 1 A-A'& B). In addition, each of these half grabens acted like a different sub- basin, preserving its own sedimentary facies and getting filled only during periods of transgression or high sea levels. In the Kachchh basin, rift-onset unconformity between pre-rift and syn-rift rocks is marked by Granite-cobble conglomerate beds (Fig. 1C) exposed at Chariyabet in Khadir Island (Biswas and Deshpande, 1968). Onlapping these rift-onset unconformities are the series of the syn-rift strata comprising of shales, claystone, sandstones and minor limestones of Nirona, Lodai and Luna formations (Rhaetian to Bajocian) in subsurface Banni Half Graben (DGH, 2019) and Kaladongar and Goradongar formations (? Aalenian to Bajocian) on the surface in Banni Half Graben (Biswas, 2016a). Thus, these subsurface and surface sedimentary successions represent initial transgression and Transgressive System Tract (TST) and Highstand System Tract (HST) at basinal scale. According to Fürsich et al. (2001), Kachchh Mesozoic succession is represented by TST and HST deposits, while the LST deposits are not preserved, but reworked and incorporated in early TST. Additionally, in Kachchh basin the sequence boundary coincides with transgressive surface (Fürsich et al., 2001). Thus,the middle Jurassic transgressive system tract cycles culminate at maximum flooding surface at the top of Early-Middle Oxfordian Dhosa Oolite Member (Fürsich et al., 1992; Krishna and Pathak, 2011, Biswas, 2016a)(Fig. 2). The upper Jurassic Jhuran Formation is divided into four members: Lower, Middle, Upper, and Katesar (Biswas, 2016). Of which, the Katesar Member and upper part of Upper Member are present only in western Kachchh, while in the remaining part of basin, they are represented by an unconformity.

Methodology

The Kachchh post rift sedimentation sequence is achieved through integrated analysis of sedimentology, ichnology and regional stratigraphic correlation of marker beds. Ichnology is a well- established tool to decipher (a) recognition of key surfaces, such as substrate-controlled trace fossils (Glossifunguites ichnofacies surfaces), and (b) recognizing depositional environments based on ichnological successions (Pemberton and MacEachern, 1992). The present study focuses on ichnology to (a) identify key surfaces (Glossifunguites Ichnofacies surface, Omission surfaces, etc), (b) delineate flooding surfaces, (c) identifying parasequence and its lateral and vertical relationships. In addition to ichnology, sedimentology is also integrated, using data from grain size, physical sedimentary structures. This combined data is laterally correlated based on its occurrence with local and regional marker beds.

Sequence Stratigraphy

Basinal scale Unconformity and MFS: Top of Dhosa Oolite Member

The Dhosa Oolite Member, is the youngest member of the Jumara Formation, is a marker bed with comparable lithological and paleontological characteristics throughout the basin. It comprises Oolitic limestone beds alternating with shale (Fig. 2a). Based on ammonites, the Dhosa Oolite Member biostratigraphically ranges from Early-to-early Middle Oxfordian (Krishna, 2017). The extensive and dense occurrence of trace fossil Zoophycos (Fig. 2b) and other diverse trace fossils are found throughout the outcrops of the Dhosa Oolite Member (Patel et al., 2009). Ichnogenus Zoophycos is an excellent indicator of low sedimentation rate, a dysoxic bottom water environment and low energy conditions. The topmost bed of the Dhosa Oolite Member represents a condensed unit with hardgrounds and Omission surface (Fürsich et al., 1992). The ammonites from the early and middle Oxfordian are mixed up in the highest beds due to omission and hardgrounds. The Wagad area compensates for the lack Middle to Upper Oxfordian sediments in the mainland Kachchh by a continuous (ca 200 m thick) succession near the basin margin. Thus, the top of the Dhosa Oolite Member corresponds to the Maximum Flooding Surface (Singh, 1989) overlapped by a brief period of Early HST.

High stand System Tract (HST)-1

Overlying the above discussed basinal scale unconformity and MFS is The HST deposits Jhuran Formation ranging in age from Upper Oxfordian to Lower Kimmeridgian. These deposits are represented by progradational parasequence sets corresponding to early HST. Outcrop analysis of Lower Member of Jhuran Formation across the basin suggests the occurrence of shallower facies upward in the parasequence set (Fig. 2). Individual flooding surfaces correspond to the occurrence of fossiliferous layers (e.g., Jhuran belemnite Marls). The lowest parasequence along the proximal half of the basin contains offshore facies. The Kachchh basin was in a post-rift setting during the Kimmeridgian period. As a result, no new accommodation space is expected to be created. As a result, the rate of sedimentation will outpace the amount of available accommodation space, which is quickly filled by sedimentary facies that exhibit net seaward movement. Early HST corresponds to the stratigraphic unit covering Lower and Middle Rudramata shale members. During the early HST phase, thick deposits of prodelta shales were deposited. The prodelta shale facies show the complete transition from fossiliferous mudstones to nodular and heterolithic facies. Shales are rich in particulate organic matter and common throughout the parasequence, while fossiliferous mudstones occur at the bottom of the parasequence and contain thin-shelled bivalves with low bioturbation (Desai and Biswas, 2018). Heterolithic facies predominate as the parasequence progresses, with thinner, non-erosive bedding and thicker, massive siltstones with accompanying water escape structures. These prodelta shales are interpreted to be deposited in low energy settings as a part of the distal prodelta environment; in the distal part of the basin; outcrops around the base of the Jara Mara cliff section show the complete changeover of progradational in the distal half of the basin.

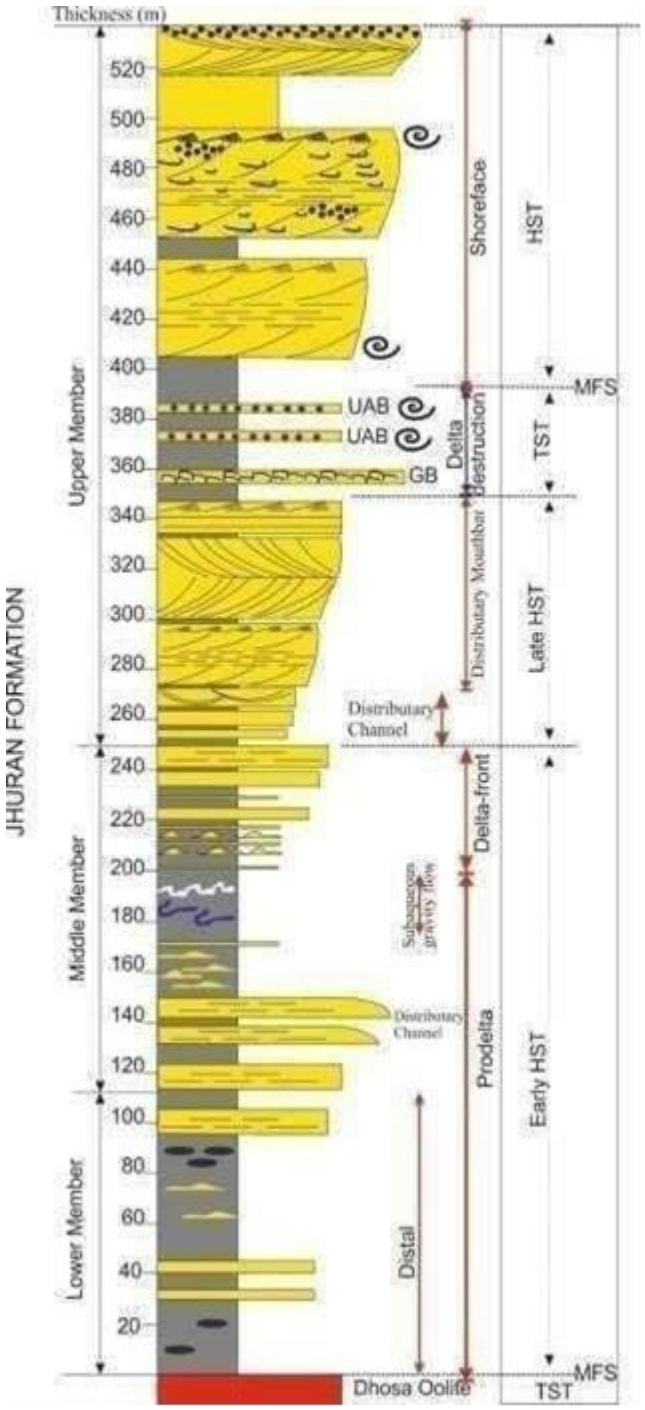

Fig. 2. Composite lithological column of the Jhuran Formation (GB= Gryphaea Band, UAB-Umia ammonite band, MFS Maximum flooding surface, TST- Transgressive systems tract, HST- Highstand systems tract) (modified after Desai and Biswas, 2018).

However, organic-rich facies in the deltaic plain may result from the vertical accumulation of sediment representing pure aggradation of the delta plain (Myers, 1996). Smaller patches of organic- rich facies may emerge during progradation and abandonment of delta lobe, while thick regionally extensive organic-rich facies may form following abandonment of delta lobe that causes sediment starvation (Myers, 1996). Organic-rich facies on the deltaic plain, on the other hand, may emerge from the vertical buildup of material reflecting pure delta plain aggradation (Myers, 1996). Smaller areas of organic-rich facies may emerge during delta lobe progradation and abandonment, while thick regionally broad organic-rich facies may form following delta lobe abandonment that results in sediment starvation (Myers, 1996). Additionally, the proximal prodelta shale of the Kachchh basin contains several subaqueous gravity flow deposits. These contain normal graded units, scour conglomerates, massive sands containing floating mudstones clast, Chaotic sand layers, and a millimeter thick sand layer encased in thick mud are sigmoidal folds (Desai and Biswas, 2018). Such gravity processes indicate a high sedimentation rate along with the delta front settings. In contrast, the Late HST is characterized by a sandstone succession that is several meters thick and corresponds to the distributary channel and distributary mouth bar sandstones (Fig. 3). Lowering the base level promotes subaerial exposure of the land and advancement of the distributary channel systems during the Late HST. This results in (a) increased erosion in the sediment source area, b) and sediment re- distribution as channel and mouth bar deposits. Distributary channels in the Kachchh basin are broad "U" shaped with extensive erosional depression, thin lateral wings, and are laterally stacked. The channel fill sediments comprise an erosional base overlain by pebble-sized and coarse to medium-size particles fining up to medium-sized sediments.

Similarly, among the prodelta and delta-front facies, the distributary mouth bar facies are the coarse, with marked thickening upward and coarsening-upward cycles (Fig. 3A-C). Wave ripples, plane laminations, and marine trace fossils also occur in the distributary mouth bar facies. Thus, the top of the Middle Rudramata Shale Member marks the end of Early HST in the Kachchh basin, while the coarsening-up, thickening-up sequence at the base of the Upper Member marks the beginning of Late HST. Ideally, the top of HST will be marked by an eroded unconformity formed due to the initiation of sea-level fall combined with an increase of siliciclastic supply (Catuneanu et al., 2011). Similarly, transgressive deposits mark the top of the HST in the Kachchh basin, which may have obliterated all other evidence.

Fig. 3. (A) Section showing condensed horizon, Maximum Flooding surface and sequence boundary (SB)in Kamaguna Section, Jhura Dome, Kachchh. (B) Trace fossil Zoophycosin Dhosa Oolite member, Kachchh Basin. (C) Contact between Lower Jhuran and Upper Jhuran in Southern flank of Lodai plug, Kachchh.

Transgressive System Tract-1

The transgressive systems tract defined by thick-bedded sheet bed geometry and multiple fossiliferous strata (ascending order, Gryphaea sandstone bed, and two greenish Oolitic ammonite marlstone bands -UAB), that overlie the prograding distributary mouth bar succession (Fig. 4). The Gryphaea sandstone bed is characterized by small lenticels of disarticulated and bored Gryphaea shells, as well as bored belemnites, ammonites and gastropods. The glauconitic Oolitic ammonite bands are glauconitic and rich in fossils. Oolite comes in a variety of shapes and sizes, ranging from perfectly circular to fractured and regenerated, with twisted kinds also being prevalent. The ammonites found in these deposits are Tithonian inage.

These fossiliferous units serve as important marker beds in the western (distal) part of the basin, but in the rest of the basin, they are represented by an unconformity. The entire fossiliferous facies indicate transgressive packages with the landward shifting of parasequence sets (Fig. 4). The top of the unit is interpreted as a Maximum Flooding surface (Fürsich and Pandey, 2003; Fürsich et al., 2013).

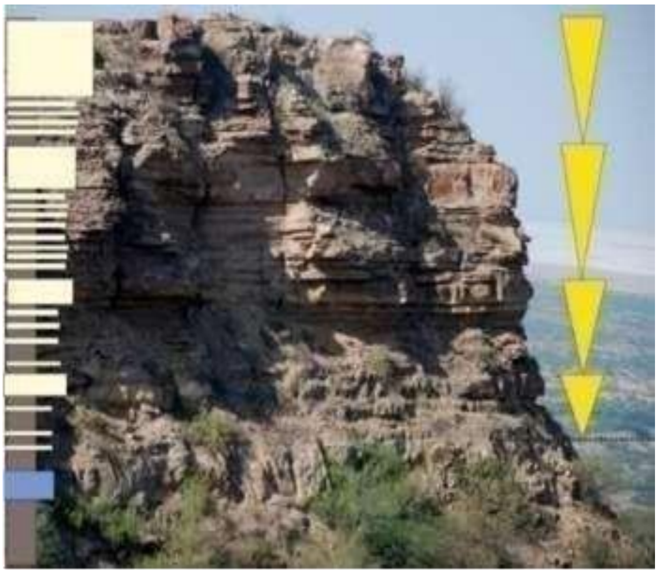

Fig. 4. Outcrop view showing coarsening and thickening-upward cycles of prograding distributary mouth bar succession. Each cycle begins with shales and concludes with sandstones that are thicker. The summit of Jara mara Cliff portion is exposed, the coarsening-up cycles are indicated by triangles (Adapted from Desai and Biswas, 2018).

Fig. 5. Near Lakhpar, a panoramic view of the section along the ridges shows continuous exposure from two Umia Ammonite Bands (UAB), top of Maximum flooding surface (mfz) overlain by HST succession, which shows prograding parasequence with three levels of Trigonia Ridge Sandstone (TRS) indicative of shoreface deposits (modified after Desai and Biswas, 2018).

High stand System Tract (HST)-2

The HST-2 comprises the prograding parasequences of coarsening-up and thickening–up cycles of fossiliferous coarse-grained quartz wacke deposited in the shoreface environment (Fig. 5). These shoreface deposits contain abundant thick-shelled bivalves, Pisotrigonia, Indotrigonia, Ophistotrigonia, and Graviella. Shell beds are mapped stratigraphically and are characterized by disarticulated, disoriented, abraded and altered shell fragments. Primary sedimentary structures comprise planar cross- stratification in cross-section and 2D straight crested oscillatory dunes. As a result, the coarse-grained sandstones are envisaged to be deposited in storm-prone areas with high wave energy.

Discussion and conclusions

The availability of accommodation space is in a sedimentary basin is a function of tectonics, eustatic sea levels, and sedimentation rate. The interplay between sedimentation and availability of the accommodation space creates three types of rift basin fills, namely (a) under filled phase, (b) filled phase, and (c) overfilled phase (Martins-Neto and Catuneanu, 2010). The sedimentation rate in the underfilled phase is insufficient to match the available accommodation space. Such situations are expected during the syn-rift stage, when the rift basin often experiences episodic subsidence, fault activation and extension regime. Several discrete normal faults emerge during early rifting (Withjack et al., 2002), resulting in various accommodation spaces.

Hence, the rapid development of accommodation space outpaces the sediment supply. Furthermore, as rifting progresses, many associated fault systems emerge, enlarging the basin (Withjack et al., 2002). The transition of the syn-rift stage to the post rift stage is also marked by the transition from underfilled phase to filled phase to overfilled phase. The exposure of the uplifted areas like horst and rift shoulders may act as a source of local sedimentation in such a setting (basal conglomerates, Fig. 1C). In contrast, the post rift is marked by a sharp reduction in tectonic and extension activity, without creating an additional accommodation space (Martins-Neto and Catuneanu, 2010). This will result in progradational parasequence sets, transforming the sedimentation into overfilled phase. The entire Jhuran Formation in Kachchh is a river-dominated deltaic system indicating a higher sedimentation rate (Desai and Biswas, 2018). As a result, it can be envisaged that no new accommodation space was being created. Tithonian eustatic sea-level rise causes the occurrence of transgressive system tract (TST-1) between two HSTs. During the Tithonian period, the Indian subcontinent (Kachchh, Jaisalmer basin) experienced, a phase of rapid sea-level rise, which coincided with the emergence of new seaway (Pandey et al., 2012; Jain and Garg, 2012; Desai and Saklani, 2014). Based on ichnofabric analysis, Tithonian sediments in the neighboring Jaisalmer basin are interpreted as high energy stacked aggradational shoreface deposits. Fürsich and Pandey (2003) have inferred Tithonian sediments as strongly asymmetric, coarsening-upward cycles with shell beds as higher-order HST-TST cycles, and complete absence of LST as the sequence boundary coincided with the transgressive surface.

Thus, the presence of TST-1 in the Kachchh basin is due to eustatic sea-level rise. However, due to the geometry and configuration of the rift basin, the transgressive deposit is present only in the western region of Kachchh, whereas the central and eastern region of the basin experience regional erosion and unconformity. Thus, the transgressive surface is represented by an uneven erosional contact in the eastern and central Kachchh basin. Similarly, the overlying HST-2 is developed in the western Kachchh basin (distal part), and is represented by an erosional or subaerial unconformity in the remainder basin. Based on the above discussion, it may be concluded that eustatic or local sea-level changes play critical role in post-rift stratigraphic architecture and basin-fill. During HST, the post-rift phase of the Kachchh basin creates several progradational parasequence sets belonging to the river-dominated deltaic system. The occurrence of fossiliferous TST-1 package is governed by Tithonian eustatic sea-level rise, and it is overlain by coarsening-up and thickening–up shore face cycles of fossiliferous sandstones. Thus, the Kachchh basin offers ideal outcrops for studying the complex interplay between accommodation space, sediment supply and tectonics during the post rift stage.

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