CHAPTER - 7
SEQUENCE STRATIGRAPHY

7.1 INTRODUCTION

Sequence stratigraphy is a methodology that helps to decode the paleo depositional setting, facilitating paleogeographic reconstructions and the prediction of facies and lithologies away from control points (Posamentier and Allen, 1999; Catuneanu, 2002, 2006). The continued development of the sequence stratigraphic paradigm in the 1980s and 1990s resulted in a diversification of approaches and the definition of several types of sequence (Catuneanu, 2011). A depositional sequence is defined as a sedimentary unit bounded by subaerial unconformities and their marine correlative conformities (e. g., Vail 1987; Posamentier et al., 1988; Van Wagoner et al., 1988, 1990; Vail et al., 1991; Hunt and Tucker 1992); genetic stratigraphic sequences are defined as a sedimentary unit bounded by maximum flooding surfaces (Galloway, 1989); and transgressive-regressive (T-R) sequences, a sedimentary unit bounded by composite surfaces that include the subaerial unconformity and the marine portion of the maximum regressive surface (Embry and Johannessen 1992). Thus, with this development, a sequence may or may not be genetically related. With this reason in mind, Catuneanu (2009) defined a sequence as a succession of strata deposited during a full cycle of change in accommodation space or sediment supply.

The concept of sequence stratigraphy, therefore, involves the study of the interplay of sediment supply and the change in the accommodation space with a time that results in a particular stratal stacking pattern and serves as a fundamental approach for interpreting and predicting the distribution of sediment bodies. These stratal stack patterns enable us to understand the sequential deposition of sediment in the basin and explain the geometric relationships and the architecture of sedimentary strata (Catuneanu et al., 2011). Stratal stacking patterns and the key bounding surfaces are the main tools for sequence stratigraphic analysis.

The stratal stacking patterns may be defined in relation to or independence of shoreline trajectories. Shoreline-related stacking patterns are defined by combinations of depositional trends that can be tied to specific types of shoreline trajectory: *forced regression* (forestepping and downstepping at the shoreline, interpreted as the result of negative accommodation); *normal regression* (forestepping and upstepping at the shoreline, interpreted as the result of positive and overfilled accommodation); and *transgression* (backstepping at the shoreline, interpreted as the result of positive and underfilled accommodation) (Catuneanu et al., 2011). While shoreline independent may occur in terrestrial conditions like a lake where eustatic sea-level changes have no role or effect on the rate of sedimentation or effect on the change of accommodation space.

The key bounding sequence stratigraphic surface that marks a change in the stratal staking pattern can serve as a sequence boundary. Such surfaces include: (i) *Subaerial unconformity:* Subaerial unconformity (Sloss et al., 1949) is a surface of erosion or nondeposition that forms under subaerial conditions as a result of fluvial erosion or bypass, pedogenesis, wind degradation, or dissolution and karstification (Catuneanu et al., 2002, 2011). (ii) *Correlative conformities**:*** The correlative conformity forms within the marine environment at the end of base-level fall at the shoreline (Hunt and Tucker, 1992). It marks the paleo-seafloor at the onset of forced regression that marks the change in stratal stacking patterns from highstand normal regression to forced regression. (iii) *Maximum flooding surface* (Frazier 1974; Posamentier et al., 1988; Van Wagoner et al., 1988; Galloway 1989): It is a paleo-sea floor that marks the maximum transgression. *Maximum Flooding surface* demarcates the stratal stacking pattern of transgression and highstand normal regression. (iv) *Maximum regressive surface* (Helland-Hansen and Martinsen 1996): It is the paleo-seafloor at the end of lowstand normal regression. It demarcates the change in stratal stacking patterns from lowstand normal regression to transgression. (v) *Transgressive ravinement surfaces* (Nummedal and Swift 1987): It is an erosional surface formed by wave or tidal scouring during transgression. (vi) *Regressive surface of marine erosion* (Plint 1988): It is an erosional surface formed by wave scouring during forced regression.

In general, sequence stratigraphic concepts are mainly designed where the accommodation space is controlled mostly by eustatic sea-level changes in a tectonically stable condition. However, the application of these concepts in rift basins poses a complication where the accommodation space is controlled by the combination of tectonic, either subduction or upliftment and eustatic sea-level changes. Martins-Neto and Catuneanu (2010), postulated a model that defines the dominant stratigraphic patterns that are commonly encountered in this tectonic setting, and provides a framework for understanding the process–response relationship between the controls on accommodation space and the resulting stratigraphic architecture of rift basins. They provide a method for the definition of key surfaces for stratigraphic correlation in rift basins, and it highlights the predictive potential of the observed stratal stacking patterns. A typical rift sequence consists of Transgressive and Highstand Systems Tracts where the Transgressive Systems Tract includes retrogradation and the High Stand Systems Tract includes progradation (Martins-Neto and Catuneanu, 2010).

7.2 GENETIC SEQUENCE STRATIGRAPHY

The genetic stratigraphic sequence is a stratigraphic sequence bounded by maximum flooding surfaces (Galloway, 1989) formed during stages of positive accommodation and does not require stages of negative accommodation (Catuneanu, 2017). The advantage of this approach is that the sequence boundary 'Maximum Flooding Surface' (MFS) can be easily identified in all marine depositional systems and is independent of unconformities. It also does not necessarily include falling-stage and lowstand systems tract, nor any sequence stratigraphic surfaces that are exclusively associated with forced regression (Catuneanu, 2017). Thus, this model overcomes the recognition problems related to correlative conformity and can be built on only during a stage of positive accommodation (Catuneanu, 2002, 2017). The main demerits of this approach are that it includes the subaerial unconformity within the sequence, thereby placing genetically unrelated strata together within the same sequence. Additionally, the timing of formation of maximum flooding surfaces depends on sedimentation, and hence they may be more diachronous, especially along strikes (Martinsen and Helland- Hansen, 1995; Posamentier and Allen, 1999; Catuneanu, 2006).

A classic genetic sequence comprises of Lowstand Systems Tract (LST), Transgressive Systems Tract (TST) and Highstand Systems Tract (HST) with Maximum Flooding Surface (MFS) and the Sequence Boundary (SB). The LST includes deposits that accumulate after the onset of relative sea-level rise, during normal regression (LST wedge), after force regression and is bounded at the base by the subaerial unconformity and/or the correlative conformity (Catuneanu, 2011, 2017). TST comprises the deposits that accumulated from the onset of transgression until the time of maximum transgression of the coast, just prior to the renewed regression of the HST. It is bounded at the top by MFS and exhibits backstepping, onlapping, and retrogradational clinoforms that (in siliciclastic systems) thicken landward (Catuneanu, 2011). The HST includes the progradational deposits that form when sediment accumulation rates exceed the rate of increase in accommodation during the late stages of relative sea-level rise (Catuneanu, 2011). This systems tract is capped by the subaerial unconformity and its correlative conformity *sensu* Posamentier and Allen (1999) and exhibits prograding and aggrading clinoforms.

7.3 SEQUENCE STRATIGRAPHY OF THE STUDY AREA

A model-dependent workflow is adopted for sequence stratigraphic analysis of the peri-cratonic rift-filled succession of Khadir, Bela and Chorar Islands. A typical rift sequence tends to start with relatively deeper water deposits at the base and consists of transgressive (retrogradational shoreline) and Highstand Systems (progradational shoreline) Tract (Martins-Neto and Catuneanu, 2010) separated by maximum flooding surface. The rifting process is marked by stages of rapid mechanical subsidence typically followed by longer periods of tectonic quiescence, when sediment supply gradually fills the available accommodation, showing an overall progradational trend. (Holtz et al., 2013; Martins-Neto and Catuneanu, 2010). Model-dependent *genetic sequence stratigraphy* is the choice of a framework for sequence stratigraphic analysis where the sequence boundary is bounded by intervals of sediment starvation (Galloway 1989) which correspond approximately to the times of MFS (Christie-Blick and Driscoll, 1995).

The Jurassic succession of Khadir, Bela and Chorar Islands are exposed as an isolated uplift along the southern flanks of the Island Belt Fault of Eastern Kachchh. These successions comprise of mixed siliciclastic-carbonate and non-clastic carbonate sediments, recording the relative changes in the accommodation space with respect to eustatic sea-level changes and tectonic movements in time. The genetically related sedimentary successions of these Islands show conformable successions yet varying rates of sediments influx, and accommodation space (both positive and negative) with time in shallow marine conditions. The integration of lithofacies, ichnology, stratal stacking pattern and bed geometries enables us to identify the systems tract and bounding surfaces.

The Jurassic succession of Khadir, Bela and Chorar Islands show two genetic cycles; 1st cycle is represented by LST-I, TST-I where the lowermost systems tract HST-I is not observed due consealed or not exposed; and the 2nd cycle is represented by HST-II where the overlying systems tracts are either eroded or not developed. The Khadir Island succession comprises

LST-I, TST-I and HST-II where the sequence boundary MFS forms at the top of the Hadibhadang Sandstone Member. The succession of Bela and Chorar Islands shows similar sequences where it is characterized by TST-I and HST-II separated by MFS at the top of Hadibhadang Sandstone Member. Hence, the observed systems tract in the Khadir, Bela and Chorar Islands conforms with the model-dependent workflow of genetic sequence stratigraphy. Therefore, the sequential development of the Jurassic succession of Khadir, Bela and Chorar Islands is discussed based on the genetic sequence model in detail in the following subtopics.

7.3.1 Sequence stratigraphy of Khadir Island

The Jurassic succession of Khadir Island comprises 692 m clastic, non-clastic, and mixed siliciclastic-carbonate succession displaying wide lateral and vertical variations and yet recurring in composition, fossil content, and bioturbation structures. The recurring succession is grouped into eight lithofacies which include bioclastic grainstone, bioclastic packstone-wackestone, micritic sandstone, peloidal wackestone-packstone, peloidal packstone-wackestone, polymictic conglomerate, sandy allochemic limestone, and shales. The succession is also bioturbated at varying intensity at various stratigraphic levels having seven ichnoassemblages, *Diplocraterion, Skolithos, Lockeia, Planolites-Palaeophycus, Rhizocorallium, Protovirgularia* and *Hillichnus* that belonging to three ichnofacies, *Cruziana, Skolithos* and *Cruziana-Skolithos*. The integration of the sedimentological and ichnological data shows three genetically related systems tracts which include LST, TST and HST which are described as follows.

7.3.1.1 Lowstand Systems Tract (LST-I)

The Cheriya Bet Member is mainly comprised of conglomerate which is characterized by coarse gravelly sediments of boulders and pebbles of basement-derived clasts deposited during the Aalenian?/Bajocian age. The clasts are highly angular, unsorted, and often show striations suggesting debris flow along the faulted flanks as distal fan deposits (Biswas, 1993; Fürsich et al., 2014) that debouch into the encroaching sea during the early rift phase. These conglomerates mark the beginning of sedimentation in the sub-basin. These conglomerates are overlain by fining upwards succession with pebbles at the base and grades into fine to coarse-grained sandstone (Fig. 4.5c) at the top. The clasts of this graded bedding are angular and poorly sorted suggesting short-lived crevasse play of floodplain deposit (Fursich et al., 2014) in a seasonal fluvial system. The basement-derived sediments characterized by a very poorly sorted, highly angular clast-supported conglomerate marks the beginning of sedimentation in the tectonically controlled rift basin. The adoption of a particular system tract for the fluvial system is complicated and difficult to justify for deposits along the fault flanks as the sediments were dumped as debris or slump deposits (alluvial fan) and lack confined fluvial system or channel flood plain aggradation. However, the LST is adopted on the assumption that accommodation is the main control where the cycles of fining upward sequence represent channel deposits or encroachment of the sea along the distal fan deposits.

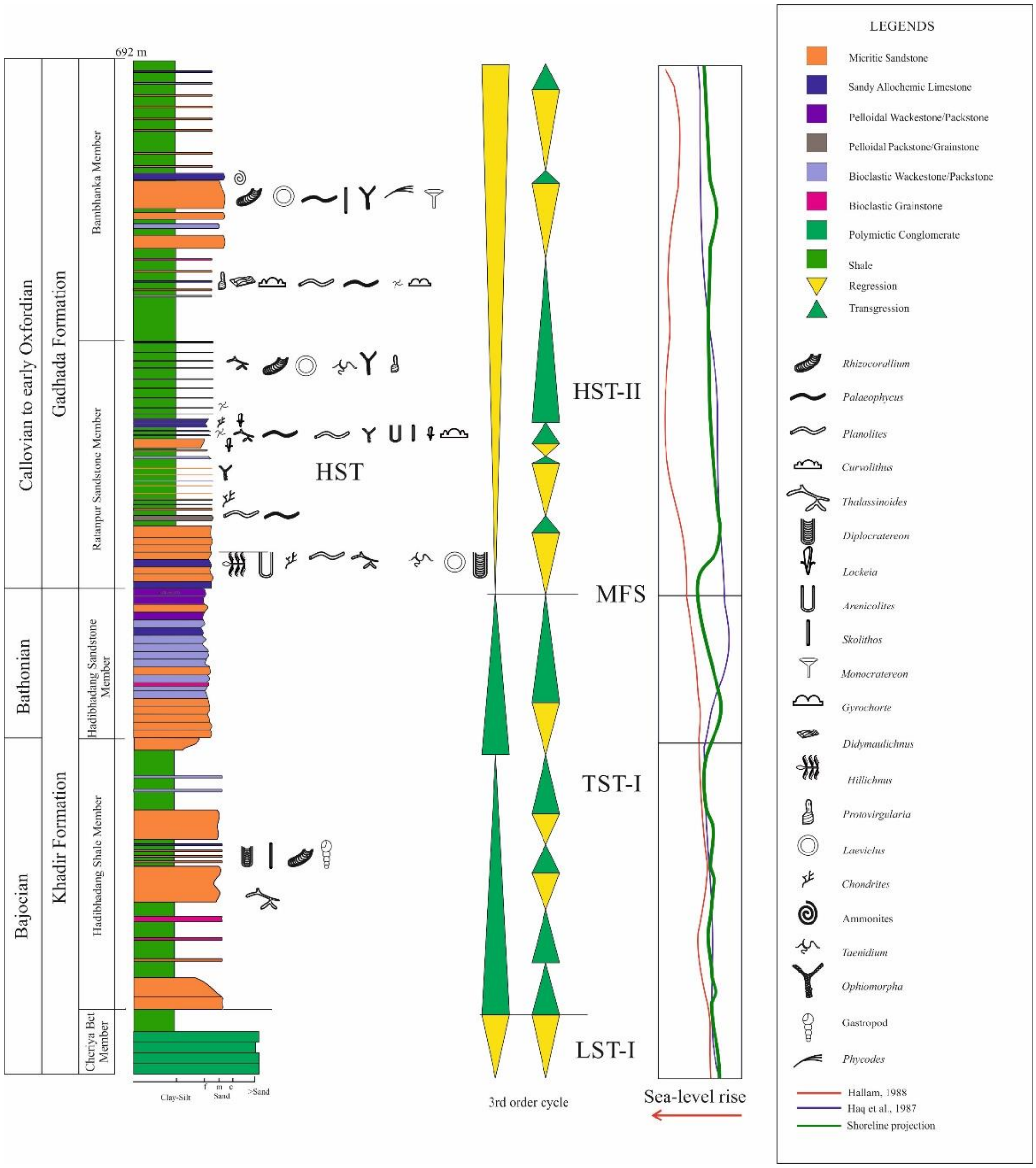

Fig. 7.1 The composite litholog of the Khadir Island showing the distributions of lithofacies, trace fossils, stacking pattern of the sequence and comparison with the global eustatic sea-level curves.

7.3.1.2 Transgressive Systems Tract (TST-I)

Transgressive Systems Tract is formed during base-level rise when the rate of sediment supply is outpaced by the accommodation space. It can be recognized from the diagnostic retrogradational stacking patterns, which result in overall fining-upward profiles within both marine and nonmarine successions (Catuneanu, 2002). The TST-I marks the initial marine influx in the peri-cratonic rift basin of Kachchh. It is observed in Hadibhadang Shale and Sandstone members of the Khadir Formation of Aalenian? /Bajocian to Bathonian age. This coincides with the global transgression (Hag et al., 1988 and Ruban, 2015) with minor regression. The succession is characterized by the deposition of thick shales, often gypseous in nature intercalated with micritic sandstone and non-clastic carbonate rocks. In Khadir Island, Hadibhadang Shale Member is characterized by of 180 m thick shale-dominated succession intercalated with thickly cross-bedded micritic sandstone with thin bands of bioclastic packstone/grainstone sandy allochemic limestone and micritic sandstone, belonging to Aalenian?/Bajocian age. The thinly bedded micritic sandstone is often bioturbated by vertical burrows such as *Diplocraterion*, *Arenicolites* and *Skolithos* forming *Skolithos* and *Diplocraterion* assemblages belonging to *Skolithos* Ichnofacies. The thick shale succession of Hadibhadang Shale Member is often truncated by thickly bedded micritic sandstone with sedimentary structures such as planar lamination and cross-bedding. The occurrences of thickly bedded micritic sandstone and *Skolithos* Ichnofacies in the thinly bedded micritic sandstone suggest a temporal change in sediment supply and energy condition in a pro-delta environment. This thick shale succession pinches out and becomes dominated by micritic sandstone in the west where abundant large size of wood fossils (trunks) are observed. The occurrence of paleochannel fill in the thickly bedded micritic sandstone at the base of the western tip suggests a local rise in the base level due to rejuvenation of the tectonic activity in the sub-basin. However, the stratigraphically equivalent successions towards the east are shale-dominated with intermittent fine to coarse sandstone. The Hadibhadang Sandstone Member is characterized by thinly bedded micritic sandstone at the base, transitioning from shale-dominated to sandstone-dominated succession. During this period, the basin witnesses abundant sediment supply during the rise in the accommodation space thereby creating aggradation and progradation in the pro-delta-delta front environment. This distinctive shallowing upwards sequence where the shallow water deposits build laterally over the deeper deposits indicates a progradational shoreline (Harms et al., 1975). This aggradation is then outpaced by the accommodation space where a thick succession of non-clastic sediment gets deposited in offshore conditions. This marks the maximum flooding surface on Khadir Island. The progradational shoreline formed during Early Bathonian coincides with the sea-level curves of Haq et al., (1987) but tends to deviate towards the Late Bathonian where non-clastic carbonate gets deposited during MFS. The global sea-level curve of Hallam, (1988) shows the continuous rise in the sea level till Callovian, however, this does not coincide with the Khadir succession as progradational shoreline resumes during Early Callovian.

7.3.1.3 Highstand Systems Tract (HST -II)

The HST is bounded by the MFS at the base, and by a composite surface at the top that includes the subaerial unconformity, the regressive surface of marine erosion, and the basal surface of forced regression (Catuneanu, 2002). The HST-II was developed in Khadir Island during the Callovian age and is observed in Ratanpur Sandstone and Bambhanka members of the Gadhada Formation. The HST-II is developed on top of the MFS and is characterized by ~385 m thick succession of micritic sandstone dominated at the base and a shale dominated succession on the top. In Ratanpur Sandstone Member, the succession (190 m) is characterized by thick micritic sandstone above the maximum flooding surface which in turn is overlain by shale intercalated with thin bands of bioclastic packstone/grainstone along with mixed siliciclastic sediments. The micritic sandstone is yellowish to brown in color with occasional cross-bedding and contains pockets/lenses of the reworked conglomerate. This facies is bioturbated by *Hillichnus, Chondrites, Arenicolites, Diplocraterion, Planolites* and *Skolithos* of *Hillichnus* assemblage belonging to *Skolithos-Cruziana* Ichnofacies. The rejuvenation of high sediment influx on top of carbonate displaying coarsening upward profile suggests retardation of sea-level rise. The high rate of sediment supply indicated by the presence of *Skolithos* Ichnofacies (Tonkin, 2012) and the occurrence of pockets of reworked sediments suggest with the deposit indicates filling up of accommodation space thereby forming a progradational shoreline or normal regression. This progradational shoreline deviates from the global sea-level curves of Hallam (1988) and Haq et al., (1987) who show a continuous rise in sea level throughout the Callovian age, the succession shows a dissimilar pattern due to local tectonic activity and abundant sediment supply. The shale-dominated succession is characterized by intercalation of thinly bedded micritic sandstone, bioclastic packstone/grainstone, bioclastic grainstone, and peloidal wackestone/packstone along with sandy allochemic limestone. It is also bioturbated at varying intensity levels by an ethologically related group of trace fossils forming *Lockeia, Planolites-Palaeophycus, Rhizocorallium,* and *Protovirgularia* assemblages belonging to

Cruziana Ichnofacies. The occurrences of *Cruziana* Ichnofacies in a shale-dominated succession indicate aggradation in low – moderate energy shoreface conditions.

7.3.2 Sequence stratigraphy of Bela Island

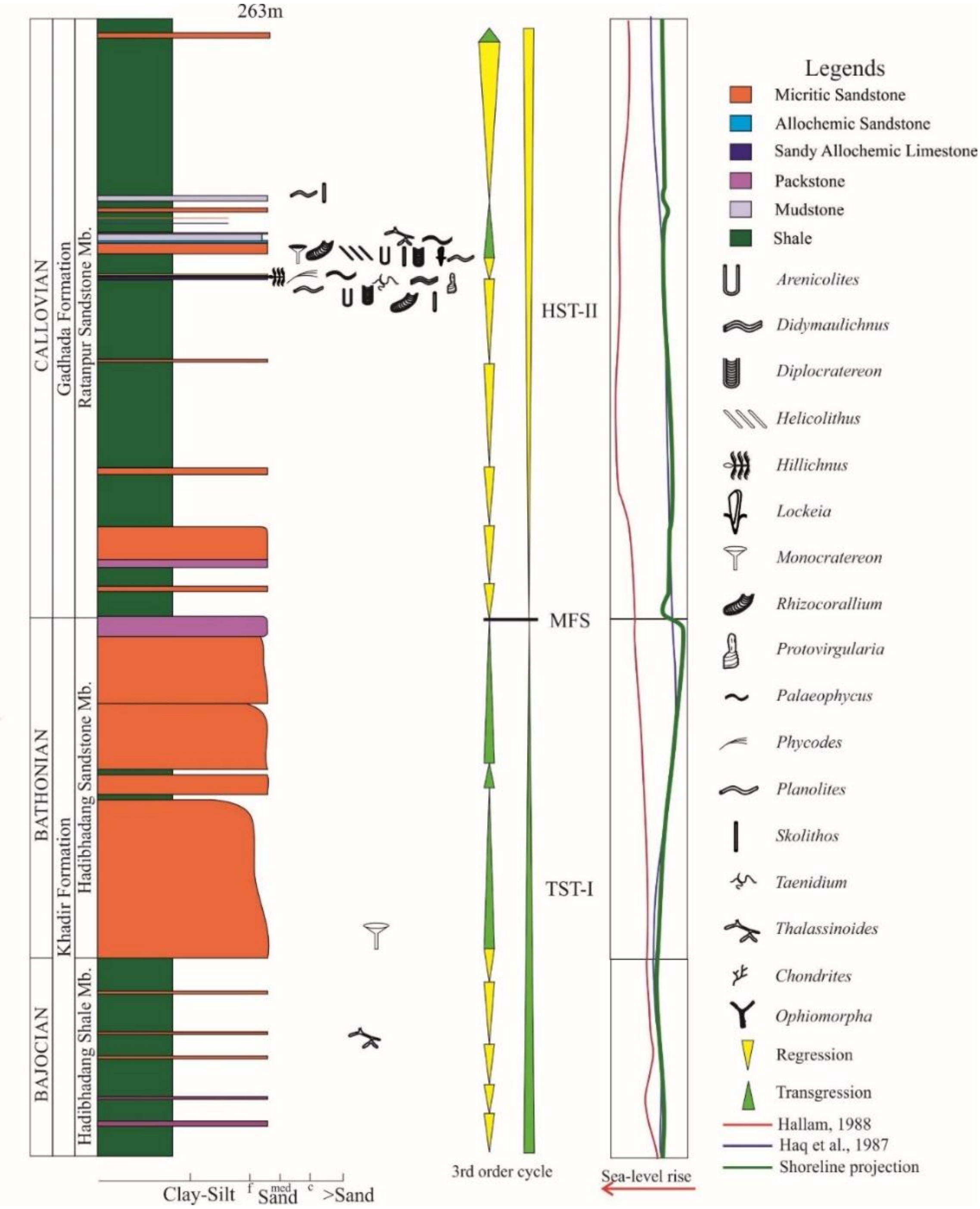

Fig. 7.2 The composite litholog of the Bela Island showing the distributions of lithofacies, trace fossils, stacking pattern of the sequence and comparison with the global eustatic sea-level curves.

The Jurassic succession in Bela Island comprises 263 m of clastic, non-clastic and mixed siliciclastic-carbonate rocks. The vertical succession is mostly exposed along the north-facing vertical cliff and the back slop of the Bela uplift. It is characterized by allochemic sandstone facies, bioclastic packstone facies, micritic sandstone facies, mudstone facies, sandy allochemic limestone facies and shale facies. The succession is intermittently bioturbated and mostly barren in terms of fossil content and bioturbation. The trace fossils comprise 23 ichnospecies belonging to 17 ichnogenera forming three ichnoassemblages including *Monocraterion, Thalassinoides,* and *Hillichnus* belonging to *Skolithos, Cruziana* and *Skolithos-Cruziana* Ichnofacies. The bioturbations are mostly concentrated in micritic sandstone and sandy allochemic limestone facies of Ratanpur Sandstone Member although few trace fossils are observed in micritic sandstone facies of Hadibhadang Shale and Hadibhadang Sandstone members.

7.3.2.1 Transgressive Systems Tract I (TST-I)

In Bela Island, the TST-I is observed in Hadibhadang Shale and Hadibhadang Sandstone members. The Hadibhadang Shale Member (46 m) is characterized by thick shale with thin beds of packstone and micritic sandstone belonging to Bajocian in age The thinly bedded micritic sandstone often contains abundant *Thalassinoides* burrows. The shale-dominated succession suggests a continuous rise in the accommodation space which coincides with the global sea-level rise while the thinly bedded packstone and micritic sandstone suggest a temporal change in energy condition below the fair-weather wave base in the pro-delta setting. The Hadibhadang Sandstones Member (78m) is characterized by pale yellow to grayish colors which are generally friable in nature and shows sedimentary structures such as cross-bedding, parallel lamination, and trough cross-stratification with soft substrate deformational structures and biogenic structure such as *Skolithos* and *Monocraterion.* The sandstone-dominated succession with negligible carbonate influx suggests a sudden increase in sediment supply with the continuous creation of accommodation space during the Aalenian?/Bajocian age. The occurrences of *Skolithos* Ichnofacies also support a rapid rate of sedimentation. The sudden increase in the sediment supplies possibly with temporal tectonic uplift outpaces the gradual increase in the accommodation space during Bathonian sea-level rise (Haq et al., 1987) leading to a prograding pro-delta/delta front environment. The occurrences of minor shales suggest temporal fluctuation in energy conditions. The top of Hadibhadang Sandstone Member is marked by bedded bioclastic packstone facies characterized by chaotic and abundant carbonate shell fragments, ooids, intraclasts and dolomite grains suggesting low sediment supply in agitating conditions marking the Maximum Flooding Surface (MFS). The succession of Bela Island during Bajocian-Bathonian shows a continuous transgression with a progradational shoreline during Early Bathonian overlain by MFS at the end of Bathonian. This progradational shoreline is due to active delta building where the sediment supply is outpacing the accommodation space. The progradational shoreline or temporal regression conforms with the regressive events of Haq et al., (1987) during the Bathonian age.

7.3.2.2 Highstand Systems Tract I (HST-II)

In Bela Island, HST - II is developed on top of the MFS and is observed in Ratanpur Sandstone Member of Gadhada Formation. It is characterized by 138 m thick shale-dominated succession intercalated with thin bands of micritic sandstone, packstone, sandy allochemic limestone, allochemic sandstone and mudstone facies. The thick argillaceous succession suggests low energy conditions which allow settling of fine sediments which are interrupted by trough cross-bedded micritic sandstone suggesting a sudden increase in energy condition/storm condition. The succession is bioturbated by an ethologically related group of trace fossils forming *Monocraterion* and *Hillichnus* assemblages. The dominance of feeding burrows in the *Hillichnus* assemblage overlain by the *Monocraterion* assemblage also reflects a sudden change in the energy condition in the shoreface environment. The thick shale-dominated succession suggests a continuous creation of accommodation space in a rift basin in fluctuating energy conditions. Thus, the HST-II in Bela Island shows initial progradation followed by aggradation which conforms/is identical with the global sea-level curve of Haq et al., (1987).

7.3.3 Sequence stratigraphy of Chorar Island

In Chorar Island, the Jurassic succession comprises of 109 m clastic, non-clastic, and mixed siliciclastic-carbonate succession which is classified into nine lithofacies. These facies include allochemic sandstone facies, coralline limestone facies, cross-bedded white sandstone, ferruginous sandstone, micritic sandstone, mudstone, sandy micrite, sandy allochemic limestone and shale facies. The whole succession is bioturbated at a varying intensity which includes sixteen ichnogenera (*Arenicolites*, *Asterosoma*, *Curvolithus*, *Didymaulichnus*, *Diplocraterion*, *Gyrochorte*, *Halopoa*, *Hillichnus*, *Lockeia*, *Megagrapton*, *Palaeophycus*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Skolithos* and *Thalassinoides*) of five assemblages, *Hillichnus, Rhizocorallium, Gyrochorte*, *Thalassinoides* and *Skolithos* belonging to *Skolithos* and *Cruziania* Ichnofacies.

7.3.3.1 Transgressive Systems Tract I (TST-I)

In Chorar Island, TST-I is also observed in Hadibhadang Shale and Hadibhadang Sandstone members of the Khadir Formation. The succession is characterized by 23 m thick argillaceous shale with micritic sandstone. The succession shows a gradual base-level rise with a minor fluctuation at the end of Bajocian (Darngawn et al., 2019). In Hadibhadang Sandstone Member, the succession is characterized by ~31m thick intercalated sequence of mixed siliciclastic-carbonate sediments which include sandy allochemic limestone, micritic sandstone and sandy micrite with shales and coralline limestone at the top. The gradual increase in the carbonate content suggests a reduction in the energy condition in a transgressing sea and an increase in the accommodation space. The rise in the eustatic sea level is also reflected in the bioturbation pattern where the succession shows *Hillichnus*, *Rhizocorallium*, *Gyrochorte* and *Thalassinoides* assemblages. The occurrence of *Hillichnus* assemblage in sandy allochemic limestone facies suggests a deposit-feeding tellinacean bivalve in shallow marine conditions. *Rhizocorallium* is observed in a range of environments from shallow marine to deeper marine (Worsley and Mørk, 2001). The occurrences of recurring *Rhizocorallium, Gyrochorte* and *Thalassinoides* assemblages belonging to *Cruziana* Ichnofacies represent well below fair-weather wave base conditions in shallow marine environments. The Hadibhadang Sandstone Member is capped by coralline limestone facies containing abundant large-size coral up to 1 m in diameter with the negligible siliciclastic component. The occurrence of well-developed corals in association with algae and shell fragments with negligible sediment influx suggest well-oxygenated offshore conditions and marks the maximum flooding surface. This flooding surface also coincides with the global sea-level rise during the Bathonian age (Haq et al., 1988; Haq and Al-Qahtani, 2005). Thus, the TST-I represents aggradation deposits in a middle shoreface to an offshore environment (Darngawn et al., 2019). Haq et al. (1987) states a temporal regression during Bathonian, however, the succession of Chorar Island shows a continuous rise in sea level with MFS at the end of the Bathonian which coincides with the sea-level curve of Hallam (1988).

7.3.3.2 Highstand Systems Tract I (HST-II)

In Chorar Island, the HST-II is represented by a 55-m-thick succession characterized by intercalated mudstone and argillaceous shale facies, allochemic sandstone, cross-bedded white

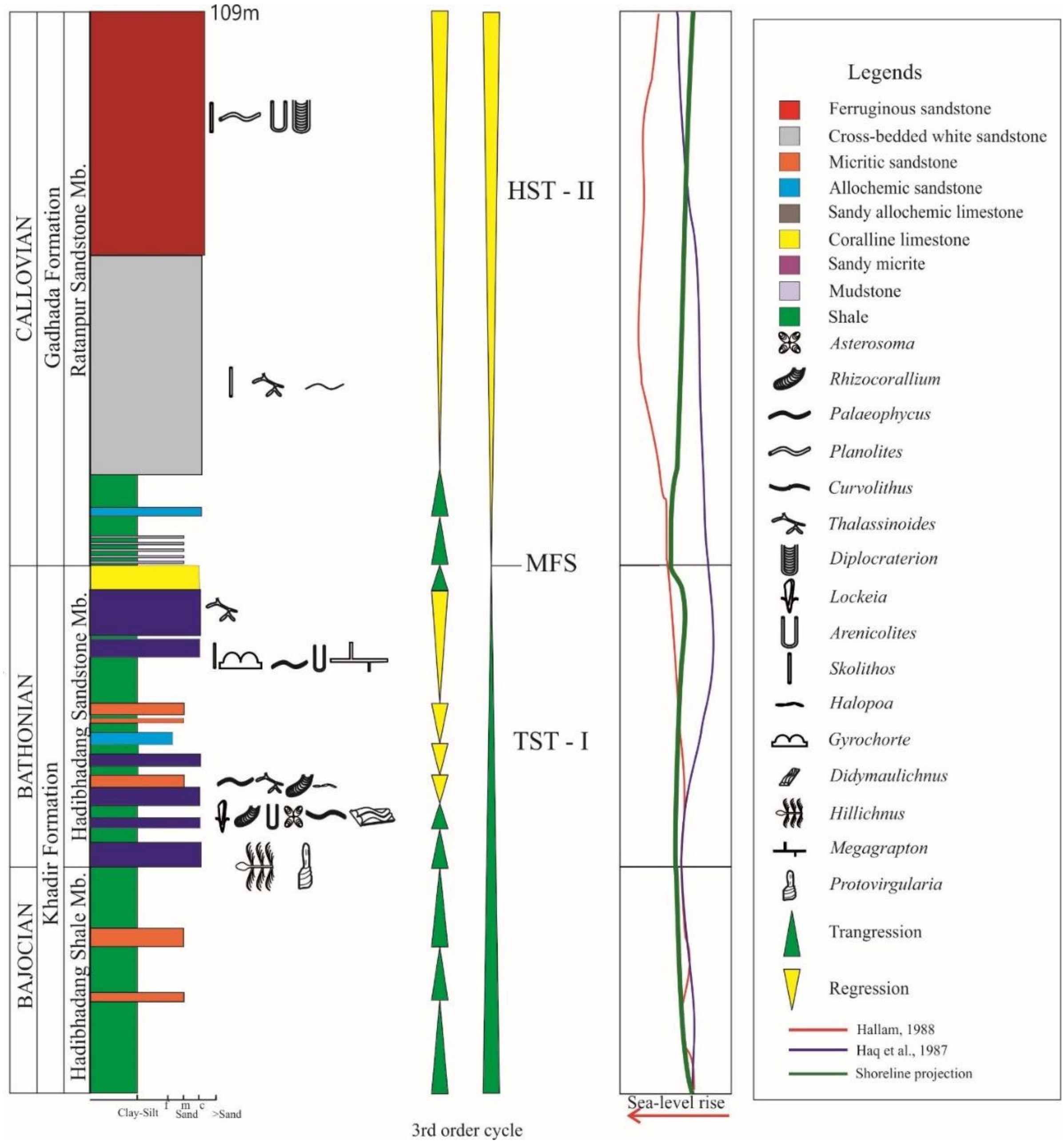

Fig. 7.3 The composite litholog of the Chorar Island showing the distributions of the lithofacies, trace fossils and stacking pattern of the sequence are compared with global eustatic sea-level curves.

sandstone and ferruginous sandstone facies of Ratanpur Sandstone Member of Gadhada Formation. The intercalated mudstone and shale facies that overlies the flooding surface marks the onset of siliciclastic sediments supply in calm conditions of lower shoreface-offshore environments indicating the onset of a progradational coastline. The allochemic sandstone that overlain the mudstone-shale intercalation contains ~60 percent of siliciclastic component with abundant pellets, suggesting an increase in clastic sediment supply in a tidally influenced shoreface zone and a reduction of accommodation space during the early Callovian marking the beginning of HST-II (Darngawn et al., 2019). The allochemic sandstone facies is overlain by thickly bedded, friable, poorly sorted and bioturbated, cross-bedded white sandstone facies and cross-bedded ferruginous sandstone facies containing body fossils such as bivalves, gastropods, as well as driftwood. These facies are predominantly bioturbated by vertical burrows including *Skolithos, Diplocraterion* and *Arenicolites* which are member of *Skolithos* Ichnofacies suggesting moderate to high-energy conditions in the middle shoreface (Pemberton et al., 2001).

The HST-II in Chorar Island displays coarsening upward profile in relation to the basinward facies shift, and includes low-rate of prograding and aggrading normal regressive sequence. This suggests that the deposits of HST-II show a shallowing-upward sequence of lower- and middle shoreface environments, indicating a base-level fall during the Callovian age. Thus, the HST-II represents a major progradation of the shoreline in the Chorar Island area during the Callovian, which does not coincide with the global sea-level curve (Haq et al., 1988; Haq and Al-Qahtani, 2005). However, in a typical rift sequence, the HST that overlies the maximum flooding surface display a progradational coarsening-upward succession (Martin-Neto and Catuneanu, 2010) which is exactly similar to the sequence of the Ratanpur Sandstone Member of Gadhada Formation of the Chorar Island.

7.7 BASIN MARGIN CONDENSED SEQUENCE STRATIGRAPHY

The concept of the condensed section is very old and mainly applicable to beds (Catuneanu, 2017; Loutit et al., 1988) that show the equivalent time span of the deposits with relatively lesser thicknesses. These sequences are thin marine stratigraphic units consisting of pelagic and hemipelagic sediments characterized by very slow sedimentation (Loutit et al., 1988). They are thin, extensive and usually associated with maximum flooding surface as they are mostly deposited during transgression. The rapid creation of accommodation space during transgression led to the rapid creation of accommodation space which leads to the lowest rates of siliciclastic sediment supply to the marine environment which results in the sediment starvation of the seafloor and the formation of marine condensed sections (Catuneanu, 2017; Loutit et al., 1988). The condensed section also serves as a reliable marker for correlation across the basin. In the present study, the author has tried to describe the condensed sequence stratigraphic units, this concept differs from the condensed section which marks the major flooding event in the basin. The condensed sequence stratigraphic concept is erected in the present study to facilitate the comparison and correlation of the sequence of the particular stratigraphic unit that is presented across the basin or sub-basins. The author has made an attempt to describe the basin margin condensed stratigraphic units that are exposed in the three small sub-basins of the Eastern Kachchh Basin.

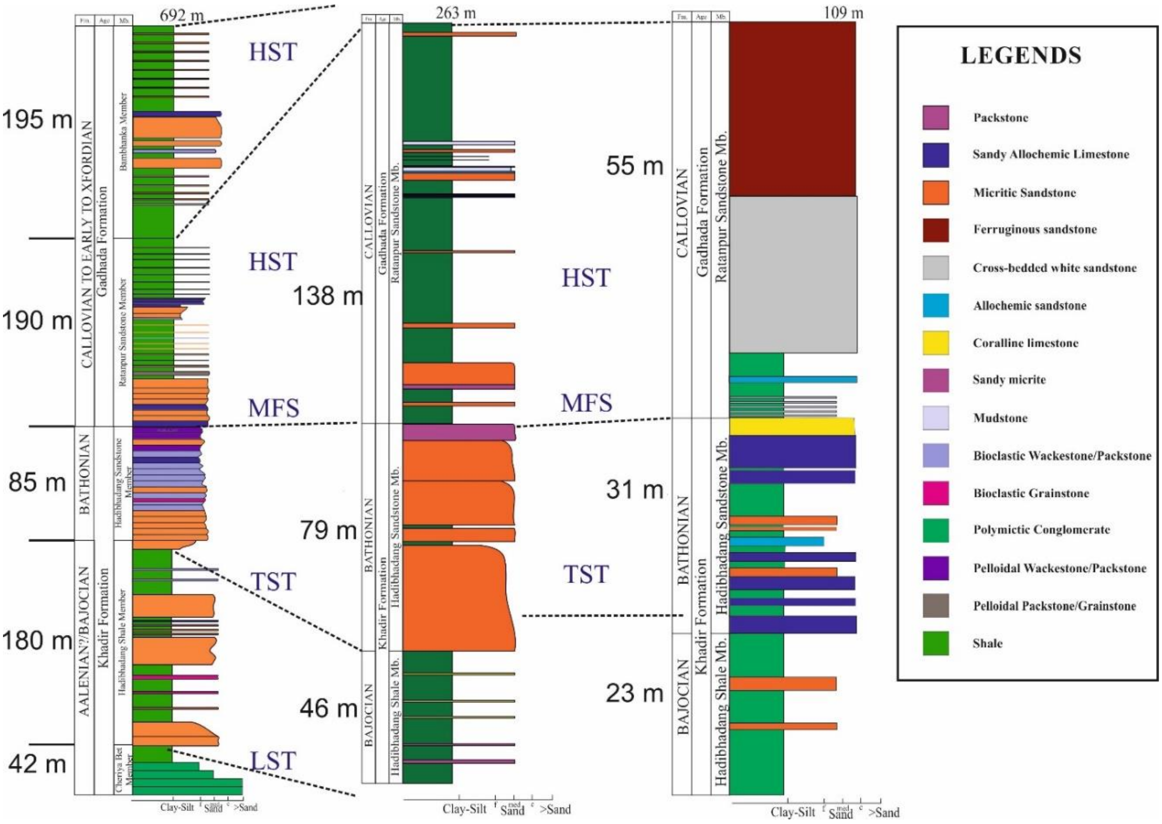

Fig. 7.4 Litholog of Khadir, Bela and Chorar Island show the developed and exposed sequence of the Jurassic which are correlated amongst each other depicting the condensed stratigraphic units.

All the three sub-basin, Khadir, Bela and Chorar Islands show identical systems tract in the exposed lithostratigraphic units, where Khadir Island represents the maximum development of the units with a longer geological time span (Fig. 7.4). The northern boundary of the Jurassic sedimentary deposits of the Khadir and Bela Islands is not known beyond the Island Belt Fault (Fig.1.4) but the huge thickness of the exposed northern fault scarps of these islands suggests that both the sub-basins are extended further north and their sedimentary units are concealed beneath the Quaternary sediments of the Great Rann. While on the easternmost side of the Kachchh basin, Chorar Island limits the basin as well as Mesozoic deposits. The comparison and correlation of the stratigraphic units are only possible from west to east, i.e., from Khadir

Island through Bela Island and to the easternmost basin margin, Chorar Island. The basement is not exposed in the study area and the oldest deposit is observed only at the northern tip of Khadir Island at the Cheriya Bet, which is 42 m thick and marks the beginning of the sedimentation of the sub-basin in a fan delta environment and represents as the sequence, Lowstand System Tract (LST). This LST deposit is unique in the whole Kachchh basin and consists of mainly bouldery and pebbly clasts of the Precambrian igneous (Plate 4.5) and metamorphic rocks. Due to the absence of these deposits in the Bela and Chorar Islands, the correlation would not be possible even though it gives insight into the development of the particular environmental condition during the initial phase of the rifting; the lower contact is not exposed that controlled/restricted the further exploration of the oldest sequence as well as the relationship with the basement.

Above the LST, TST is well-developed across all three sub-basins and is represented in the Hadibhadang Shale Member and Hadibhadang Sandstone Member of the Khadir Formation which are Bajocian and Bathonian in age respectively. These lithostratigraphic units show high variation in the lithofacies, bioturbation structures and their density and diversity, and more importantly their exposed thickness. The Hadibhadang Shale Member is 180, 46 and 23 meters thick and Hadibhadang Sandstone Member is 85, 79 and 32 meters thick in Khadir, Bela and Chorar Islands respectively. These units are developed during the onset of transgression and the top of the sequence is marked by the MFS. Both the lithostratigraphic units become condensed toward the east even though they are penecontemporaneous deposits. The condensation of the units in the TST suggests a change in bathymetry due to tectonics or regional paleo-slope of the ocean floor. The TST of the Khadir and Bela Island developed in the pro-delta-delta front environment while the Chorar Island, it is developed in the shoreface environment. The deepening of these sub-basins conditions was observed during the Bathonian where the Units have become thick and comprise more non-clastic material suggesting the deposition of the sediments took place away from the coastline. The carbonate sequence of the Hadibhadang Sandstone Member is pervasive in all three sub-basins marking the condense section/bed. The TST in Khadir Island is characterized by thinly bedded non-clastic carbonate which includes bioclastic wackestone/packstone, sandy allochemic limestone with thinly bedded micritic sandstone. In Bela Island, it is characterized by thinly bedded packstone while it is characterized by thinly bedded coralline limestone with negligible siliciclastic components in Chorar Island. These facies are equivalent to the Raimalro Limestone of the neighboring Patcham Island (Joseph et al., 2016). This condense section/bed is developed during the maximum transgression and deposited in the offshore environment above the delta front sequences of the Khadir and Bela Islands and shoreface deposit of the Chorar Island; and hence marks the MFS in these sub-basins.

The rocks of the Gadhada Formation are exposed in all three sub-basins, and maximum development is observed in Khadir Island, where it is represented as Ratanpur Sandstone and Bambhanka members. The rocks of Bambhanka Member are not exposed in the Bela and Chorar Islands. All the three sub-basins represent the sequence that developed in HST with variable lithofacies. In Khadir Island, the total thickness of the Gadhada Formation is 385 m, where Ratanpur Sandstone Member is 190 m thick and Bambhanka Member is 195 m thick. These units are Callovian- Oxfordian in age and characterized by coarse clastics in lower parts while the upper part is mainly characterized by fine clastic which are mainly observed in the Kakinda Bet. The succession of the Ratanpur Sandstone Member is Callovian in age and is observed in all three sub-basins and attained a thickness of 190 m, 138 m and 55 m in Khadir, Bela and Chorar Islands respectively. This sequence is developed in the shoreface environment, above the MFS, with textural variation in clastic sediments observed from Khadir to Chorar Islands. The high variation in the thickness of the HST across the sub-basins is depicted as condensed stratigraphic units (Ratanpur Sandstone Member) that suggest a change in bathymetry, sediment supply and local tectonics which played a crucial role in accommodation space which is reflected in the stratigraphic unit. The youngest stratigraphic unit, Bambhanka Member is only exposed in Khadir Island, developed during the HST, in the absence of this unit in the other two sub-basins, indicates either erosion of the sediments, non-deposition of the sediments due to change in base level or local tectonics, in either of these cases, the sub-basins have witnesses of starved sedimentation condition in the eastern part of the basin margin.

7.8 GLOBAL SEA LEVEL CORRELATION

After the Gondwana breakup in the Late Triassic (Biswas, 1982), the Indian continent suffered many local and regional tectonic movements, which preserved varied environmental facies; among's one, a pericratonic rift basin evolved in the Kachchh and Tethyan sea was encroached, giving rise to the thick pile of marine sediments. This sequence is controlled by both, eustasy and local tectonics; the sea level curves are redrawn based on the integration of the sedimentological, paleontological and ichnological information for the Khadir, Bela and Chorar Islands (Fig. 7.1, 7.2 and 7.3). These curves are further compared with the global sea-level curves of Haq et al., (1987) and Hallam, (1988), and their results are discussed in detail as follows.

The occurrence of polymictic conglomerate as distal fan deposits, exposed in Cheriya Bet marks the beginning of marine influx into the Island Belt of Kachchh basin during the Aalenian?/Bajocian age. This oldest deposit is exposed only at the northern tip of Khadir Island and is overlain by pro-delta deposits of Hadibhadang Shale Member of the Bajocian age. The sea encroachment into the sub-basins is penecontemporaneous with the Early Bajocian transgressive/deepening event and can be recognized widely across the world (Hallam, 1978, 1988). The deepening of the basement floor and gradual rise in the sea level is represented by a shale-dominated succession which is exposed at the foothill of the north-facing scarp of Khadir and Bela Island and in the core of Chorar dome in Chorar Island.

These sub-basins are witnesses of a continuous rise in the sea level throughout the Bathonian age with maximum flooding surface at the end of Bathonian. A prograding delta is developed in Khadir and Bela Islands during the Early Bajocian age due to high sediment supply outpacing the accommodation space. Hallam, (1988) shows a continuous rise in the sea level without any regression during Bajocian-Bathonian. However, Haq et al., (1987) describe a minor short-term regression during early Bathonian and pulses of transgression at the end of Bathonian with an overall transgression. This sea-level curve coincides with the prograding pro-delta/delta front deposits of the Bela and Khadir Islands overlain by offshore deposits. The short-term regression favours the development of prograding delta, characterized by thick micritic sandstone facies which are well-sorted fine to medium quartz grains having point to floating contact with sedimentary structures such as planar cross-stratification and cross-bedding in Khadir Island. This delta extends up to Bela Island where the prograding delta is represented by coarsening upward succession of thinly to thick-bedded micritic sandstone facies with negligible shale. The micritic sandstones are pale yellow to grayish colors which are generally friable in nature and show sedimentary structures such as cross-bedding, and parallel lamination with soft sediment deformational structures. However, in Chorar Island, the Bathonian succession is represented by an intercalated sequence of mixed siliciclastic carbonate rocks with thin bands of shales and indicates the overall transgression which coincides with Hallam, (1998). The contrasting shoreline projection between Khadir-Bela and Chorar Islands during Bajocian to Bathonian is due to different tectonic activities and rate of sediments supply which favours the active delta formation in Khadir and Bela Islands. Surlyk, (1991), Li and Grant-Mackie, 1993 and Hallam (1988) also described a major transgression at the end of Bathonian. This major transgression is represented by offshore deposits of non-clastic thinly bedded bioclastic wackestone/packstone and grainstone facies interrupted by thin bands of sandy allochemic limestone and micritic sandstone facies in Khadir Island and packstone in Bela Island. This major transgression is represented by thickly bedded coralline limestone in Chorar Island where well-developed large size of the corals has been preserved (Plate. 3.3g). The ichnological evidence of these three sub-basins remarkably follows the deepening of the basin marked by a change in ichnofacies, from *Skolithos* to *Cruziana* Ichnofacies Thus, the major transgression at the end of the Bathonian age is observed in all three islands as offshore deposits.

Hallam, (1988) and Haq et al., (1987) show global transgression during the Callovian age. However, Khadir, Bela and Chorar Islands show a progradational shoreline. The progradational shoreline in Khadir is developed during HST and is represented by thickly bedded micritic sandstone with thin bands of sandy allochemic limestone facies overlain by shale-dominated succession. In Bela Island, the succession is represented by shale-dominated succession intercalated with well-developed bioclastic packstone, sandy allochemic limestone, allochemic sandstone, and mudstone facies. The Callovian succession of Chorar Island is characterized by thinly bedded mudstone and allochemic limestone intercalated with shale at the base, overlain by thick cross-bedded white sandstone and ferruginous sandstone. The Ratanpur Sandstone Member of these three sub-basins is characterized by mainly large size vertical burros of the *Skolithos* Ichnofacies marked by shallowing of the bathymetry as well as substrate conditions. The progradational shoreline at the beginning of HST is due to sediment supply outpacing the accommodation space and followed aggradation of thick shale dominated succession.

In the genetic sequence stratigraphic analysis of the Jurassic sub-basins of the Khadir, Bela and Chorar Islands of the Kachchh Basin, the integrated sedimentological and ichnological data revealed that the eustacy and tectonics have played significant roles in the deposition of the sediments. Moreover, a comparison of the local sea-level curves with global sea-level curves remarkably shows marine inundation during the development of the Jurassic sequence and the accommodation space filled by these sub-basins margin sequences and is reflected by the condensation of the stratigraphic units towards the eastern side which also supports the view.