CHAPTER-7

SEQUENCE STRATIGRAPHIC ANALYSIS:
TRANSgressive-REGressive SEquences

7.1 BACKGROUND

Sequence stratigraphy addresses the strata stacking patterns and changes thereof in a chronological framework and lay stress on cyclicity, temporal framework, genetically related strata and the interplay of accommodation and sedimentation (Catuneanu et al, 2009). The stratal stacking patterns respond to the interplay of changes in rates of sedimentation and base level, and reflect combinations of depositional trends that include progradation, retrogradation, aggradation and downcutting. From the environmental perspective, each stratal stacking pattern defines a particular genetic type of deposit which may include tracts of several age-equivalent depositional systems.

7.1.1 SEQUENCES:

Sloss et al (1949) defined the concept of “sequence” in the context of stratigraphy as a large-scale unconformity-bounded unit and later on redefined by Mitchum (1977) in the context of the seismic stratigraphy as “a relatively conformable succession of the genetically related strata bounded by unconformities or their correlative conformities”. In other words, the “stratigraphic sequence” represents the product of sedimentation during a full stratigraphic cycle of change in accommodation or sediment supply, irrespective of whether all parts of the cycle are formed or preserved and the sequence boundaries may be unconformable or conformable portion of the bounding surface. As a result, the stratigraphic sequence, commonly known as the depositional sequences, have a predictable internal structure of surfaces and systems tracts (suites of coexisting depositional systems, such as coastal plains, continental shelves, and submarine fans).

There are several models of systems tracts within depositional sequences for example, the four system tract model, wherein all the depositional sequences contain the following systems tract in the order: Lowstand Systems Tract (LST), Transgressive Systems Tract (TST), Highstand Systems Tract (HST), and falling-stage systems tract (Regressive System
Tract- RST). Here, a sequence accordingly, begins with the slow rise following a fall in sea level, and continues through the next fall in sea level. These system tracts are bounded by important named surfaces: the lowstand and transgressive system tracts are separated by the transgressive surface; the transgressive and highstand system tracts are separated by the maximum flooding surface; and the highstand and falling-stage systems tract are separated by the basal surface of forced regression.

Therefore, a sequence may be subdivided into component system tracts (Brown and Fischer, 1977) which consist of packages of strata that correspond to the specific genetic type of deposits and interpreted based on the stratal stacking pattern in the position of the sequence and type of the bounding surfaces. The sequence boundary of a sequence depends on the scale of sequence, depositional setting, and the mechanisms driving stratigraphic cyclicity.

7.1.2 PARASEQUENCES:

“Parasequences” is defined as “a stratigraphic unit composed of a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative conformities” (Mitchum, 1977) and is geographically restricted to the coastal to shallow water settings, where marine flooding surfaces may form (Catuneanu et al, 2010). Parasequences may be stacked to form progradational, aggradational and retrogradational parasequence sets, which typify the systems tracts (Van Wagoner et al., 1990). The mapability of the parasequences depends on the development of their bounding surface and it marks a difference between the concept of sequence within the coastal and shallow water systems (Catuneanu et al, 2009)

The flooding surfaces that define the top and bottom of the parasequence display abrupt contacts of relatively deeper-water facies lying directly on top of relatively shallow-water facies. Therefore, the Walther’s Law cannot be applied across the flooding surfaces. Moreover, the limited usage of the parasequence term, by authors, to shallow-marine cycles developed without intervening relative sea-level falls, while others extending the term to successions recording full cycles of relative sea level change or even in deep-water and alluvial settings, has increased confusion in its meaning.
Parasequences and sequences are also considered to be objects of the same rank that differs only in their bounding surfaces and internal architectures and which may also pass laterally each other (Nummedal et al, 1993; Zecchin, 2010). Thus, instead of a term like “parasequence” which is tied to a specific architecture and depositional environment, a generic and descriptive terminology is used by several authors (Walker, 1992; Zecchin, 2007). The present study follows the concept of “facies” are used instead of “parasequence”

7.1.3 STACKING PATTERNS:

The method of sequence stratigraphy emphasizes changes in depositional trends (i.e., progradation, retrogradation, aggradation, erosion) and the resulting stratal stacking patterns through time, which are controlled by shifts in the balance between accommodation (space available for sediments to fill) and sediment supply (Weimer and Posamentier, 1993; Emery and Myrow, 1996; Posamentier and Allen, 1999; Catuneanu, 2002, 2006; Catuneanu et al., 2009; Martins-Neto and Catuneanu, 2010). This balance between the accommodation space and the sediment supply controls the manifestation of transgressions and regressions. In vertical stacking patterns, progradation implies a facies succession where proximal facies gradually replaces the distal facies with time and generates a coarsening upward succession in a shallow water setting. Retrogradation displays the proximal facies at the base that grade upwards to the distal facies at the top and generates a fining upward trend in a shallow water setting (Fig. 7.1).

7.1.4 GENETIC TYPES OF DEPOSITS: SYSTEMS TRACTS:

A sequence may be subdivided into component systems tracts, which consist of packages of strata that correspond to specific genetic types of deposits (“Forced regression”, “Normal Regressive” and “Transgressive”) with a distinct geometry and facies preservation style (Catuneanu et al., 2009). The original definition of systems tract as stated by Brown and Fisher (1977) is “Systems tract is a linkage of contemporaneous depositional systems, forming the subdivision of as sequence”. It is interpreted based on the stratal stacking patterns, its position within the sequence, and the types of bounding surfaces. The changes in stratal stacking patterns are driven by corresponding changes in shoreline trajectory that then defines the “conventional” systems tracts.
Figure-7.1 Responses of the depositional trends to the interplay of accommodation and the sediment supply (Martins-Neto and Catuneanu, 2010).

The systems that prograde with time and record a basinward decrease in the elevation of the coastline are the product of the base level fall and represent the “forced regression” deposits. It displays progradational and downstepping stacking patterns. The systems tract nomenclatures applicable to these deposits are “early low stand”, “late highstand”, “forced-regressive wedge” and “falling stage”.

The systems that prograde with time during stages of base level rise or stillstand are the “normal regressive” deposits. In a normal scenario, two normal regressions may be expected during a full cycle of base level change: a lowstand normal regression that follows that onset of base level rise after a period of base level fall and a highstand normal regression
<table>
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<tr>
<td>Subaerial unconformity (Stoss et al., 1949)</td>
<td>Unconformity that forms under subaerial conditions, mainly as a result of fluvial or wind degradation</td>
<td><em>Lowstand unconformity</em> (Schlager, 1992); <em>Regressive surface of fluvial erosion</em> (Plint &amp; Nummedal, 2000); <em>Fluvial entrenchment/incision surface</em> (Galloway, 2004)</td>
<td>Fluvial erosion or bypass, pedogenesis, wind degradation, dissolution or karstification</td>
<td>During base level fall; during periods of transgression accompanied by coastal erosion; during periods of climate driven increased fluvial discharge, or tectonic driven isostatic rebound and increased topographic gradients</td>
</tr>
<tr>
<td>Correlative conformity (Posamentier et al., 1988)</td>
<td>Surface that marks a change in shoreline trajectory from highstand normal regression to forced regression</td>
<td><em>Basal surface of forced regression</em> (Hunt &amp; Tucker, 1992)</td>
<td>Paleoseafloor at the onset of base level fall at the shoreline</td>
<td>Onset of forced regression</td>
</tr>
<tr>
<td>Correlative conformity (Hunt &amp; Tucker, 1992)</td>
<td>Surface that marks a change in shoreline trajectory from forced regression to lowstand normal regression.</td>
<td>-</td>
<td>Paleoseafloor at the end of the base level fall at the shoreline</td>
<td>End of forced regression</td>
</tr>
<tr>
<td>Maximum flooding surface (Frazier, 1974; Posamentier et al., 1988; Van Wagoner et al., 1988; Galloway, 1989)</td>
<td>Surface that marks a change in shoreline trajectory from transgression to highstand normal regression.</td>
<td><em>Final transgressive surface</em> (Nummedal et al., 1993); <em>Surface of maximum transgression</em> (Helland-Hansen &amp; Gjelberg 1994); <em>Maximum transgressive surface</em> (Helland-Hansen &amp; Martinsen 1996)</td>
<td>Change in depositional trends (coastal retrogradation to progradation) during base level rise</td>
<td>End of transgression</td>
</tr>
<tr>
<td>Maximum regressive surface (Helland-Hansen &amp; Martinsen, 1996)</td>
<td>Surface that marks a change in shoreline trajectory from lowstand normal regression to transgression.</td>
<td><em>Transgressive surface</em> (Posamentier and Vail, 1988); <em>Top of lowstand surface</em> (Vail et al., 1991); <em>Initial transgressive surface</em> (Nummedal et al., 1993); <em>Conformable transgressive surface</em> (Embry, 1995); <em>Surface of maximum Regression</em> (Helland-Hansen &amp; Gjelberg, 1994; Mellere and Steel, 1995) &amp; <em>maximum progradation surface</em> (Emery &amp; Myers, 1996)</td>
<td>Change in depositional trends (coastal progradation to retrogradation) during base level rise</td>
<td>End of regression</td>
</tr>
<tr>
<td>Transgressive ravinement surface (Galloway, 2001)</td>
<td>Proxional surface that forms during transgression in wave- or tide-dominated settings</td>
<td><em>Transgressive surface of erosion</em> (Posamentier and Vail, 1988)</td>
<td>Wave or tidal-current scouring in the coastal to upper shoreface settings.</td>
<td>During transgression.</td>
</tr>
<tr>
<td>Regressive surface of marine erosion (Plint, 1988)</td>
<td>Subaqueous erosional surface that forms during base level fall in wave dominated settings</td>
<td><em>Regressive ravinement surface</em> (Galloway, 2001) &amp; <em>regressive wave ravinement</em> (Galloway, 2004)</td>
<td>Wave scouring in the lower shoreface to inner shelf settings</td>
<td>During forced regression</td>
</tr>
</tbody>
</table>

**Table-7.1** Definition, origin, and timing of sequence stratigraphic surfaces.
during the late stage of base level rise. These normal regression deposits display a combination of progradational and aggradational depositional trends. The systems tract nomenclatures applicable to lowstand normal regressive deposits are “late lowstand” and “lowstand” while to highstand normal regressive deposits are “highstand” or “early highstand” systems tract.

The landward shift or marine or lacustrine systems, triggered by a rise in base-level at rates higher than the rates of sedimentations at the shoreline is termed as the “transgressive” deposits. It is thus driven by the base level rise and includes characteristic retrogradational geometries. These deposits belong to the transgressive systems tract. All the systems tracts are not necessarily found in each sequence, either because of the shape of the base-level curve did not allow one or more systems tracts to form, or because subsequent erosion. Similarly, not all the sequences need to be divided into “conventional” systems tracts defined above.

7.1.5 SEQUENCE STRATIGRAPHIC SURFACES:

Sequence stratigraphic surfaces are the surfaces that can serve, at least, in part, as boundaries between different genetic types of deposit (Catuneanu et al, 2009). There are seven sequence stratigraphic surfaces; namely, subaerial unconformity, correlative conformity (in the sense of Posamentier et al, 1988), correlative conformity (in the sense of Hunt and Tucker, 1992), maximum flooding surface, maximum regressive surface, transgressive ravinement surface, and regressive surface of marine erosion (Table.1); among which four corresponds to event of the base level cycle and three others form during stages between such events.

The criteria that can be used to identify each sequence stratigraphic surface include: the conformable versus unconformable nature of the contact, the depositional systems below and above the contact, the depositional trends below and above the contact, the types of substrate-controlled ichnofacies associated with the contact, and stratigraphic terminations associated with the contact (Catuneanu et al., 2009). All the type of data does not contain the recognition of all sequence stratigraphic surfaces, and not all the sequence stratigraphic surfaces are present in every depositional setting.
7.1.6 SEQUENCE BOUNDARY:

Across the existing sequence stratigraphic models, the sequence stratigraphic surfaces may be considered a sequence boundary, as systems tract boundary, or even a within-systems tract contact. A generic definition of a sequence that satisfies all approaches, while leaving the selection of sequence boundaries to the discretion of the individual, provide the flexibility that allows one to adapt to the particularities of each case study (Catuneanu et al., 2009). Accordingly, the stratigraphic patterns have to be analysed on a case-by-case basis to decide which set of surfaces represented in that particular succession can provide the best boundaries for correlating and mapping “relatively conformable successions of genetically related strata.”

In the case of drowning, the contact between carbonates and the overlying fine-grained hemipelagic facies has been termed the “drowning unconformity” (Schlager, 1989), and has been designated as a special type of sequence boundary in mixed carbonate-siliciclastic successions (Schlager, 1999). The selection of stratigraphic surfaces considered by the “depositional,” “genetic stratigraphic” and “transgressive-regressive” sequence models for the nonmarine and marine portions of the sequence boundary is listed with its merits and pitfalls in Table.2.

7.2. SEQUENCE STRATIGRAPHIC ANALYSIS OF PATCHAM ISLAND

The elevation of the stratigraphic surface to sequence boundary is attempted for the relatively conformable succession of the Patcham Island, and hence, a model dependent workflow is considered for sequence stratigraphic analysis (Catuneanu et al, 2009). The exposed sequence of the Kaladongar and Goradongar Formation is represented into four parts: (1) composite litholog of Kuar bet, (2) Dingy Hill, (3) Chappar Bet and (4) composite litholog comprising the Kuran, Babia Cliff, Raimalro and Sadhara Hill; and Dhorawar, Paiya, Tuga, and Juna villages; which are further detailed and analysed below to interpret the rock records.

Transgressive-regressive (T-R) sequences, proposed by Embry and Johannessen (1992) and Catuneanu et al (2009) are used to define the sequential filling of this part of the
<table>
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<tr>
<th>SEQUENCE</th>
<th>SEQUENCE BOUNDARY</th>
<th>PITFALLS</th>
<th>MERITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depositional Sequence</td>
<td>Subaerial Unconformities</td>
<td>1. Its potentially cryptic expression when represented by paleosols; 2. It, fully or portions thereof, may be eroded during subsequent transgression; and 3. The dependency on base-level falls to define sequences.</td>
<td>1. Subaerial unconformities commonly mark significant hiatuses in the stratigraphic record. 2. Recognizes the importance of separating forced regressive, normal regressive and transgressive deposits as distinct genetic units.</td>
</tr>
<tr>
<td>Genetic Stratigraphic</td>
<td>Maximum Flooding Surfaces</td>
<td>1. Inclusion within the individual sequence where subaerial unconformities are present, leads to the placement of genetically unrelated strata (from below and above the subaerial unconformity) within the same “sequence.” 2. The timing of formation of maximum flooding surfaces depends on sedimentation, and hence they may be more diachronous, especially along strike.</td>
<td>1. Maximum flooding surfaces are among the easiest distinguishable sequence stratigraphic surfaces in all marine depositional systems, and with any type of data set. 2. The definition of this stratigraphic sequences is independent of subaerial unconformities, and, implicitly, of base-level fall. 3. This model can be applied to all types of cycles, including those that develop during continuous base-level rise</td>
</tr>
<tr>
<td>Transgressive-regressive</td>
<td>Composite sequence boundary which includes the subaerial unconformity and the marine portion of the maximum regressive surface</td>
<td>1. Maximum regressive surfaces may be cryptic in deep-water systems, where they may occur within an undifferentiated succession of leveed channel low-density turbidites 2. The formation of maximum regressive surfaces depends on sedimentation, and hence they may be highly diachronous along strike 3. The fluvial and marine segments of the sequence boundary are of different ages, and so they may only connect physically where the intervening lowstand normal regressive deposits are missing and 4. All “normal” and “forced” regressive deposits are included within one “regressive systems tract,” which may be considered an over-generalization</td>
<td>1. This model emphasizes the importance of subaerial unconformities and 2. The ease of recognition of maximum regressive surfaces in shallow-water systems.</td>
</tr>
</tbody>
</table>

Table-7.2 Selections of stratigraphic surfaces considered by different stratigraphic models for non-marine and marine portions of sequence boundaries with it merits and pitfalls.
Kachchh basin. The T-R sequence stratigraphy subdivides the stratigraphic successions into
the transgressive-regressive couplets with the top of the regressive systems tracts as the
sequence boundary (Embry and Johannessen, 1992; Embry 1993; Catuneanu 2006;
Catuneanu et al., 2009). This concept suggests the fact that the frequently corresponding
intervals of increasing and decreasing influence from land in deep water deposits correspond to subdivide the shallow water deposits into shoaling and deepening intervals. A
hierarchy of cycles has been proposed for T-R sequences by Embry (1993) and Catuneanu
(2006). The range of base-level fall and the degree of change in sedimentary regime at the
R/T sequence boundaries as well as the degree of deformation that occurred during the
formation of the boundary distinguishes the sequence ranks. This hierarchy does not change
the internal architecture of the T-R sequences. Accordingly, this principle holds for a wide
range of scales in time and space; and could serve as the basis of a scale invariant model of
stratigraphic sequences (Schlager, 2010).

These middle Jurassic sediments, ranging in age from Bajocian to Callovian, can be
explained in terms of one large scale transgressive sequence (+ 462 m), composed of four
mid-scale or T-R sequences (mean thickness 115 m), with several small scale cycles or T-R
cycles (average thickness: 33m). The portion of the Middle Jurassic sediments present in the
Kalandongar and Goradongar Formations represents Bajocian to Callovian age (Fürsich et al.,
2001) which suggests a time interval as an average of 6.9 My and therefore suggest that the
large scale sequence is a 2nd order sequence and the mid-scale sequences are of 3rd order
sequences (mean duration of 1.1 My). The T-R cycles fall within the ranges of 4th order units,
with an average duration of ~0.5 My. Each cycle comprises of two parts; 1. Transgressive
system tract (TST), characterized by low terrigenous influx and high carbonate productivity
that marked an increase in the accommodation space and 2. Regressive system tract (RST)
characterized by high terrigenous influx and low-carbonate productivity marked decrease in
the accommodation space; separated by the flooding surfaces. The material based
stratigraphic surfaces identified in the sequence are regressive surface (RS), flooding surface
(FS), and drowning unconformity (DU).

7.2.1 TRANSGRESSIVE-REGRESSIVE SEQUENCES OF KUAR BET SECTION:

The composite lithog of Kuar bet represents total thickness of the Mesozoic rocks in
the column is +248 m; the lower +41.80 m fining (thinning) upward succession, the middle
179.9 m siliciclastic dominant coarsening (thickening) upward sequence and the upper 26.40 m carbonate dominant fining (thinning) upward succession in foreshore to shoreface environment. The sequence represents three regressive surface (RS), two flooding surface (FS), and one transgressive lag deposits (TLD) (Fig. 2).

An asymmetric cycle of deepening-shallowing phase is apparently observed from the arrangement of the facies. The deepening phase is represented by comparatively little sediment compared to the sediments recording the shallowing phase. Thus, the sedimentary cycle represents major Transgressive system tract (TST) and Regressive system tract (RST) deposits. Each system tract is described below with the stratigraphic surfaces and is coupled with facies analysis to interpret the depositional trends.

7.2.1.1 4th Order Transgressive-Regressive Cycles (TRC)

This transgressive-regressive cycle constitutes the fundamental units of the Kuar bet member of the Kaladongar Formation. They show a significant variation in thickness and mark a deepening and a shallowing upward trend representing retrogradational, aggradational and progradational stacking pattern. These help in identifying the fundamental T-R sequences. Each cycle is bounded by flooding surfaces indicated by vertical and abrupt facies variations.

7.2.1.2 3rd Order Transgressive-Regressive Sequence (TRS)

Two T-R cycles have been identified in the 3rd order of hierarchy of the sequence with a mean thickness of about 96 m. Each of these cycles of the sequence is bounded by the regressive surfaces which also mark the sequence boundary bounding them.

7.2.1.2.1 Transgressive-regressive cycle (TRC) - I

The lower +41.80 m fining (thinning) upward succession and the middle ~179.9 m coarsening upward succession of Kuar Bet represents the Transgressive-Regressive cycle (TRC)- I. The TRC-I show presence of stratigraphic surfaces such as Flooding surface (FS), Transgressive lag deposit (TLD) and Regressive surfaces (RS). In the Transgressive-Regressive Cycle-I of the Kuar Bet sequence, the flooding surface is observed in the
allochonic sandstone overlying the shale facies. It shows non bioturbation in the underlying strata and increasing bioturbation in the overlying strata. Transgressive lag usually record the time intervals and are thin, relatively coarse grained beds that contain pebbles, shell fragments, intraclasts and bivalve shells, suggesting the storm influenced deposition above fair weather wave base. Quartz pebble conglomerate is interpreted as a transgressive lag deposit; all the finer material winnowed away leaving only the coarsest and most resistant grains to form the bedforms. The conglomerate consisting of bivalves and fossil wood overlying the sandy allochem limestone represents the transgressive lag deposits in the Kuar Bet member exposed at Kuar Bet. The regressive surface is observed at the quartz arenite and mark the top of the Regressive System Tract – I

7.2.1.2.1 Transgressive System Tract (TST) - I

This system tract is dominated by 41.80 m thick sequence of mixed siliciclastic carbonate and shale facies. These mixed siliciclastic-carbonate deposits are characterized by upward increase in the carbonate content. Body fossils such as bivalves, corals and fossil wood are observed. It also consists of trace fossils such as Arenicolites, Diplocraterion, Palaeophycus, Rhizocorallium and Thalassinoides are present in this system tract. Accordingly, the shales facies consisting of gypsum suggest that the sediments were deposited in quiet water, protected, lagoon environment, with low wave and current energy, sudden appearance of massive limestone bed over the shale may be indicative of precipitation of calcareous materials in normal marine environment.

The overlying graded sandstone showing ripple marks, sharp erosional base associated with the flute cast, and trace fossils Diplocraterion and Rhizocorallium underlain by the cross bedded sandstone suggest a high energy condition or may be post-storm event indicator. The trace fossil content in the TST-I represents Rhizocorallium assemblage representing the mixed Skolithos-Cruziana ichnofacies which suggest a stressed environmental conditions. The presence of conglomerate facies embedded with the fossil wood and the concavo-convexo bivalve fossils also indicate some high energy event that reworked the fossils and redeposited in the basin. This set of facies association is thus indicative of being formed during the late transgression or the early sea level regression (Fursich and Pandey, 2003).
Figure-7.2 Composite lithog showing siliciclastic-carbonate curve, ichnoassemblages and sequences of 4th, 3rd, and 2nd order Transgressive-regressive cycles in Kuar Bet.

7.2.1.2.1.2 Regressive System Tract (RST) - I

This system tract is dominated by ~179.9 m thick sequence of intercalated mixed siliciclastic-carbonate sediments and shale facies. Body fossils contain disarticulated and broken fragments of bivalves. The trace fossils present are *Arenicolites*, *Monocraterion*, *Palaeophycus*, *Planolites*, and *Thalassinoides*. The lower part of this regressive phase of the cycle represents moderate to low bioturbation, and shows thick shale intercalated with the mixed siliciclastic-carbonate sediments and presence of ripple marks while the upper part of
the phase represents massive sediments showing thin shale facies intercalated with the mixed siliciclastic-carbonate sediments.

The upper part of the sequence shows lack of the sedimentary structures and presence of some lenses of conglomerate. The start of the Regressive System Tract (RST) shows presence of *Arenicolites*, *Planolites* and *Thalassinoides* assemblages representing the *Skolithos* ichnofacies which indicate the high energy conditions in the soft substrate condition. The analysis of the facies association and the trace fossil content represent the coarsening upward succession showing the progradational and aggradational trend of deposition suggesting the deposition during the regressive phase of sea level.

### 7.2.1.2.2 Transgressive-regressive cycle (TRC) – II

Transgressive Regressive Cycle II comprises of ~26.40 m thick intercalated sequence of mixed siliciclastic-carbonate and shale facies. This T-R cycle represents shallowing and deepening phase of the sequence and shows presence of one *Regressive surface* (RS) and two flooding surfaces (FS). The top of the cross bedded micritic sandstone represents minor regression within the transgressive system tract-II. The flooding surfaces are observed in the allochemic sandstone within the transgressive phase and in sandy allochem limestone at the top of the sequence. These flooding surfaces are developed on a high energy transgressive surface within the Transgressive system tract (TST) – II. The regressive deposits of Regressive System Tract (RST) – I is not observed in the Kuar Bet sequence either due to the erosion or may be concealed below the overlying Miocene beds (Fig. 2a).

#### 7.2.1.2.2.1 Transgressive System Tract (TST) - II

This system tract is 26.40 m thick sequence of mixed siliciclastic-carbonate sediments intercalated with the shale facies. The TST-II is characterized by upward increase in carbonate content and is fossiliferous and bioturbated in nature. The sandy allochem limestone represents a relatively quiet marine condition of the later stage of transgressive highstand and possibly the minor regressive phases of the sea level cycle. It is overlain by the intercalated fossiliferous cross bedded mixed siliciclastic carbonate sediments and shale facies representing the minor regression in a tidally influenced environment.
The association of the bioturbated, fossiliferous thin sandy allochem limestone intercalated with the shale represents a low energy marine environment deposited with low supply of sediments or low accommodation space. This transgressive system tract shows presence of *Arenicolites* and *Ichhalassinoïdes* assemblages representing the *Skolithos* ichnofacies which is indicative of the high energy conditions within the transgressive phase. Thus, these sediments mark the minor regression in the early TST while the fossiliferous, bioturbated unit at the top represent the dominant retrogradational deposit of the TST-II.

### 7.2.2 Transgressive-Regressive Sequences of Chhappar Bet Section:

The sequence exposed at the Chhappar Bet comprises ~120 m thick mixed siliciclastic-carbonate sediments intercalated with shale facies. The sequence represents two transgressive regressive cycles (TRC I and II. It represents the lower +66.3 m thick coarsening upward sequence, the middle ~37.8 m thick fining upward sequence and the upper ~15.5 m thick coarsening upward sequence in the shoreface region. The sequence represents two major regressive surfaces and one flooding surface; and the sedimentary cycle represents two major Regressive system tract and one Transgressive system tract.

#### 7.2.2.1 4th Order Transgressive-Regressive Cycles (TRC)

The sediments exposed at Chhappar Bet represent transgressive-regressive cycle which constitutes the fundamental units of the Dingy Hill member of the Kaladongar Formation. They show a significant variation in thickness with a mean thickness of 14 m. These TRC mark a deepening and a shallowing upward trend representing retrogradational, aggradational and progradational stacking pattern; bounded by flooding surfaces which further helped in identifying the fundamental T-R sequences.

#### 7.2.2.2 3rd Order Transgressive-Regressive Sequence (TRS)

Two TR cycles have been identified in the 3rd order of hierarchy of T-R sequence with a mean thickness of about 52 m. Each cycle of this sequence is bounded by the regressive surfaces which also mark the sequence boundary bounding them.
Figure-7.3 Litholog showing siliciclastic-carbonate curve, associated ichnoassemblages and 4th, 3rd, and 2nd order Transgressive-Regressive sequences of Dingy Hill member of Chhappar Bet.
7.2.2.2.1 Transgressive-regressive cycle (TRC) - I

The transgressive-regressive cycle – I represents ~66.28 m thick sequence of mixed siliciclastic-carbonate sediments intercalated with the shale facies. This cycle represents shallowing phase and consist of Regressive system tract (RST) – I. The Transgressive system tract (TST) – I of the 3rd order is not exposed in the study area.

7.2.2.2.1.1 Regressive System Tract (RST) – I

The regressive system tract – I represents ~66.28 m thick deposits of intercalation of allochemic sandstone, micritic sandstone and sandy allochem limestone with micritic mudrock and shale facies; and sandy micrite occasionally. The regressive system tract is separated from the transgressive system tract by the regressive surface present above the micritic sandstone. The admixture sediments of carbonate and siliciclastics alternating with the shale facies generate a fluctuating siliciclastic-carbonate curve during the regressive phase.

The trace fossil assemblage represents the presence of *Thalassinoides* and *Gyrocrorte* assemblage representing a mixed *Skolithos-Cruziana* ichnofacies which grade into the *Ophiomorpha* and *Skolithos* assemblage representing the *Skolithos* ichnofacies which then grade into *Planolites-Palaeophycus* assemblage representing *Cruziana* ichnofacies at the top. Overall trace fossil analysis of these sediments suggest that the *Skolithos* ichnofacies were dominant conditions during this phase with some intermittent *Cruziana* ichnofacies and mixed *Skolithos-Cruziana* ichnofacies indicative of change in energy conditions, substrate and bathymetry.

7.2.2.2.2 Transgressive-regressive cycle (TRC) – II

The Transgressive-Regressive cycle – II represents ~ 53.3 m thick deposits of intercalated mixed siliciclastic-carbonate and shale facies. This T-R cycle represents the second cycle of the Transgressive-Regressive sequence of the Chhappar bet and shows the transgressive and regressive phase of the cycle i.e., Transgressive System Tract (TST)-II and Regressive System Tract (RST) - II respectively.
7.2.2.2.1 Transgressive System Tract (TST) – II

The Transgressive System Tract-II represents ~37.8 m thick deepening upward sequence. The lower part of this system tract is represented by the retrogradational deposits of shale and micritic mudrock intercalated with micritic sandstone grading into allochremic sandstone. The siliciclastic proportions decreases and the non-bioturbated sequence grade to presence of Gyrochorte assemblage which represents the Cruziana ichnofacies suggesting a moderate to low energy conditions of the shoreface. These deposits then aggrade but becomes fossiliferous in nature which further grade into the sandy allochem limestone overlain by the conglomerate facies indicating a depositional hiatus (i.e. a period of non-deposition).

These facies association represented a phase of retrogradational and aggradation representing the transgression phase within the Transgressive system tract-II. The next phase of deposition started with the allochneic sandstone which graded into the succession of intercalated micritic mudrock and shale facies. The presence of micritic mudrock and shale facies suggests very low energy conditions. The top of these facies association represents the Flooding Surface (FS) separating TST-II from the RST-II of the T-R sequence.

7.2.2.2.2 Regressive System Tract (RST) – II

The Regressive System Tract- II represents ~ 15.5 m thick deposits of intercalated allochneic sandstone-shale grading to micritic-sandstone shale facies. These facies association represents the progradational and aggradational depositional trend defining the Regressive system tract of this T-R Cycle. These facies association do not show presence of any biological or biogenic evidences. The shale facies above the micritic sandstone facies indicate the end of the regressive which may be continuing further with this pause (cannot be judged because of the absence of the overlying sediments). This is termed as the Regressive Surface (RS) of this system tract.

7.2.3 TRANSGRESSIVE-REGRESSIVE SEQUENCE OF DINGY HILL:

The sequence exposed at the Dingy Hill member comprises ~173 m thick mixed siliciclastic-carbonate sediments intercalated with shale facies. The sequence represents a single transgressive-regressive cycles (TRC) - I. It represents the lower +150.3 m thick fining
upward sequence, and the upper ~22.4 m thick coarsening upward sequence developed in shoreface region.

7.2.3.1 4th Order Transgressive-Regressive Cycles (TRC)

The sediments exposed at Dingy Hill represent the fundamental units of the Dingy Hill member of the Kaladongar Formation which comprises of transgressive-regressive cycle showing a significant variation in thickness with a mean thickness of 21 m. These TRC mark a deepening and a shallowing upward trend representing retrogradational, aggradational and progradational stacking pattern; bounded by flooding surfaces which further helped in identifying the fundamental 3rd order T-R sequences.

7.2.3.2 3rd Order Transgressive-Regressive Sequence (TRS)

One Transgressive-Regressive Cycle has been identified in the 3rd order of hierarchy of transgressive-regressive sequence with a mean thickness of about 86 m. The sequence is bounded by the regressive surface which also marks the sequence boundary bounding them.

7.2.3.2.1 Transgressive-regressive cycle (TRC) - I

The Transgressive-Regressive cycle – I comprises ~172.7 m thick deposit of mixed siliciclastic-carbonate sediments intercalated with shale facies. These deposits represent the sediments of the transgressive phase and the regressive phase of the cycle. This T-R cycle represents Transgressive System Tract and Regressive System Tract. It represents aggradation, progradation and retrogradational depositional trend and shows presence of one Flooding Surface (FS) separating the Transgressive System Tract (TST) and Regressive System Tract (RST).

7.2.3.2.1.1 Transgressive System Tract (TST) – I

The Transgressive System Tract comprises ~150.3 m thick deposit of mixed siliciclastic-carbonate sediments intercalated with shale facies. The lowermost exposed bed shows a retrogradation represented by cross-bedded micritic sandstone grading to the sandy
allochonic limestone which then show aggradation. These beds are overlain by the conglomerate facies which suggest a break in the deposition.

The lower grading admixture also shows a gradation in the trace fossil contents; the lower beds shows presence of *Arenicolites*, *Gyrochortes* and *Planolites-Palaeophycus* assemblage while the sandy allochonic limestone facies presence of *Planolites-Palaeophycus*, *Rhizocorallium* and *Skolithos* assemblage which represents the representing a mixed *Skolithos-Cruziana* ichnofacies showing gradation from the dominance of vertical structures to horizontal structures. These sediments and the trace fossil content represents a transgressive phase within the TST-I.

The micritic sandstone-shale facies overlies the conglomerate facies which is again underlaid by the allochonic sandstone-shale facies consisting *Planolites-Palaeophycus* assemblage and shows a retrogradational depositional trend. The succession again is overlain by the micritic sandstone-shale facies grading into allochonic sandstone-shale facies consisting *Thalassinoides* assemblage which also shows the retrogradational depositional trend and the overall succession represents the retrogradation within the aggradational depositional trend. This succession is overlain by the sandy micrite that shows presence of *Gyrochorte* and *Rhizocorallium* assemblages representing the *Cruziana* ichnofacies; capped by the conglomerate facies indicating the stormy condition. These successions represent the second phase of transgression within the transgressive phase TST-I, in the exposed part of the sequence of the Dingy Hill.

These sediments are further overlain by the mixed siliciclastic-carbonate sediments, micritic sandstone, allochonic sandstone and sandy allochonic limestone representing retrogradations and presence of *Rhizocorallium* assemblage representing *Cruziana* ichnofacies. This succession shows presence of allochonic limestone on the top which marks flooding surface; the peak of the 3rd order transgression, i.e., the end of the Transgressive System Tract-I of the TRC-I and the onset of the Regressive System Tract-I of TRC-II.
Figure-7.4 Litholog showing siliciclastic-carbonate curve, associated ichnoassemblages and 4th, 3rd, and 2nd order Transgressive-Regressive sequences of Dingy Hill member of Dingy Hill of Kaladongar Range.
7.2.3.2.1.2 Regressive System Tract (RST) – I

The Transgressive-Regressive cycle comprises ~22.4 m thick coarsening upward sequence of micritic sandstone facies with shale and conglomerate facies. The allochemic limestone facies grades to the micritic sandstone facies which represents the aggradation within the progradational trend. This micritic sandstone however shows presence of conglomerate facies within the deposit which indicate a minor re depositional or erosional phase (a phase of depositional hiatus); the micritic sandstone facies is massive in nature which dykes intruded in them and some embedded corals are also observed.

7.2.4 TRANSGRESSIVE-REGRESSIVE SEQUENCE OF COMPOSITE SECTION OF KALADONGAR AND GORADONGAR RANGES:

The litho sections exposed at Babia Cliff; Raimarlo and Modar Hill; Sadhara dome; and exposures near Kuran, Paiya, Dhorawar, Tuga villages were studied and analysed to prepare a composite litho log for the Kaladongar and Goradongar Range. This composite litho log exposes Kaladongar as well as Goradongar Formation and attain a thickness of 462 m and mainly consists of relatively conformable succession of mixed silici clastic-carbonate sediments.

It also displays cyclic patterns of shallow marine deposits which formed in the shoreface to offshore region. The sediments and the trace fossil content of the sequence of the Island represent many shallowing and deepening events of 4\textsuperscript{th} order and four 3\textsuperscript{rd} order T-R cycles.

7.2.4.1 4\textsuperscript{th} Order Transgressive-Regressive Cycles (TRC)

The 4\textsuperscript{th} order transgressive-regressive cycle constitutes the fundamental units of the Kaladongar and Goradongar formation and show a significant variation in thickness with a mean thickness of 14 m. These T-R cycles mark a deepening and a shallowing upward trend representing retrogradational, aggradational and progradational stacking patterns that identify the fundamental 3\textsuperscript{rd} order T-R sequences.
7.2.4.2 3rd Order Transgressive-Regressive Sequence (TRS)

Four TRC have been identified in the 3rd order of hierarchy with a mean thickness of about 131.69 m. Each cycle of the sequence is bounded by the regressive surfaces which also mark the sequence boundary bounding them.

7.2.4.2.1 Transgressive regressive cycle (TRC) – I

The Transgressive Regressive Cycle -I comprises ~80.95 m thick deposits of mixed siliciclastic-carbonate sediments intercalated with shale facies. This cycle shows presence of aggradation, retrogradation and progradation depositional trends within the sediments which recognizes shallowing phase of the cycle. The transgressive deposits of the cycle are not observed in the sequence which may be due to either erosion of the thin transgressive bed or may be present in the subsurface. The regressive phase are represented by the Regressive system tract (RST) – I.

7.2.4.2.1.1 Regressive System Tract (RST) – I

The Regressive system tract- I is characterized by the +80.95 m thick coarsening and shallowing upward sedimentary cycles consisting of mixed siliciclastic-carbonate sequence of Dingy Hill member (Fig. 2) of the Kaladongar Formation. These sediments consist of trace fossils like Arenicolites, Chondrites, Daedalus, Didymulichmus, Gyrochorte, Lockeia, Monocraterion, Ophiomorpha, Planolites, Palaeophycus, Phoebichmus, Protovirgularia, Rhizocorallium, Skolithos, and Thalassinoides. The lower part of the RST-I consist of intercalated micritic sandstone-shale sequence is characterized by mainly horizontal traces like Chondrites and Planolites, Palaeophycus, Rhizocorallium in the lower part and vertical structures like Arenicolites, Monocraterion, Skolithos, and Thalassinoides in the upper part.

While the upper of the RST-I is consists of massive thick micritic sandstones are consisting of abundant burrows of Skolithos and Ophiomorpha with few horizontal structures like Planolites and Protovirgularia. The sediment characteristics and trace fossils of the RST-I marked gradual shallowing upward of the sequence from middle to upper shoreface environments. Late regressive conditions are represented by the amalgamated micritic
sandstone bed which records aggradational condition in the regressive phase. These regressive deposits are separated from the transgressive deposits by regressive surface (RS).

7.2.4.2.2 Transgressive - regressive cycle (TRC) - II

The transgressive-regressive cycle (TRC) - II comprised ~ 322.43 m thick sequence of mixed siliciclastic-carbonate sediments of Dingy Hill member, Kaladongar Sandstone member and Babia Cliff Sandstone member of Kaladongar Formation. It consists of Transgressive system tract and Regressive system tract representing deepening and shallowing phases in the cycle.

7.2.4.2.2.1 Transgressive System Tract (TST) – II

The transgressive system tract II is characterized by ~ 63 m thick deepening and fining upward sequence of mixed siliciclastic carbonate sediments of Dingy Hill member of Kaladongar Formation. The sediments consist of trace fossils like Nerettes, Rhizocorallium and Scolicia.

TST-II consists of micritic mudrock and sandy allochonic limestone, percentage of carbonate; including allochems are increases in upward direction. Sandy allochamic limestone of the TST-II is bioturbated and consists of horizontal crawling traces with few isolated feeding burrow. The litho units of the TST-II display major transgression in the retrograde deposits. The sedimentary features and trace fossils suggest a significant change in bathymetry and indicate the deepening of the basin. Transgressive conditions are represented by retrogradational deposits above the regressive phase and the top of the TST-II is represented by the flooding surface (FS).

7.2.4.2.2.2 Regressive System Tract (RST) – II

Regressive system tract-II is represented by ~259.43 m thick coarsening and shallowing upward sequence of the mixed siliciclastic carbonate sediments of the Dingy Hill member, Kaladongar member and Babia cliff sandstone member of Kaladongar Formation. It consist of trace fossils like Arenicolites carbonarius, Asterosoma radiciforme, Beaconites, Berguaria, Cochlichnus, Dactylophycus, Didymaulichnus lyelli, Diplocraterion parallellum,
Gordia arcuata, Gyrochorte comosa, Halopoa isp, Lockeia siliquaria, Ophiomorpha nodosa, Planolites beverleyensis, Palaeophycus tubularis, Phycodes palmatum, Phoebichmus trochoides, Pilichmus dichotoma, Rhizocorallium irregulare, Rhizocorallium jenense, Skolithos linearis, Taenidium, Teichichmus, Thalassinoidea horizontalis and Thalassinoidea suevicus.

Sedimentary structures like cross bedding and ripple marks is observed in dingy hill member and Babia cliff sandstone member. Bivalve and gastropods shells, and echinoids tests and their spines are observed in the Babia cliff sandstone member whereas only bivalve shells are observed in dingy hill and Kaladongar sandstone members.

The start of the regressive phase is indicated by the flooding surface (FS) marked on sandy allochemic limestone. The initial phase of the RST-II consists of micritic mudrock (silt size qtz - 60%) which progressively change to allochemic sandstone to thick micritic sandstones. Latter rock type shows textural variations with presence of physical structures (X-bedding and wave ripples) indicate the shallowing upward. RST-II also comprises of relatively thin beds of sandy allochemic limestone, micritic mudrock and muddy micrite with ethologically diverse groups of trace fossils that marked the minor transgressions. The micritic sandstone indicates shoal deposits in the prograding environment of upper offshore-transitional to middle shoreface zone.

7.2.4.2.3 Transgressive-regressive cycle (TRC) – III

The Transgressive-Regressive cycle – III comprises ~111.3 m thick sequence of Babia cliff sandstone member, Goradongar flagstone member, Gadaputa sandstone member, Raimalro limestone member and Modar Hill member. It shows aggradation, progradation and retrogradation depositional trend and represents deepening and shallowing phase of Transgressive System tract and Regressive System tract respectively.

7.2.4.2.3.1 Transgressive System Tract (TST) – III

This is characterized by ~31.1m thick fining and deepening upward sequence of Babia cliff sandstone member, Goradongar flagstone member, Gadaputa sandstone member and Raimalro limestone member. These sediments show presence of bivalve shells, echinoide
spines and the trace fossils like *Arenicolites carbonarius, Arenicolites statheri, Asterosoma radiciforme, Beaconites coronus, Bifungites, Chondrites intricatus, Circulichnus montanus, Cochlichnus isp, Diplocraterion parallelum, Diplocraterion isp, Gyrochorte, Hartsella sumsumaramosa, Laevicyclus, Locketa amygdalooides, Locketa situquaria, Oldhamia radiate, Ophiomorpha nodosa, Palaeophycus alternatus, Palaeophycus striatus, Palaeophycus tubularis, Phoebichnus trochoides, Phycodes palmatum, Pilichnus dichotoma, Planolites beverleyensis, Protovirgularia dichotoma, Rhabdoglyphus, Rizocorallium irregularre, Rizocorallium jenense, Skolithos linearis, Taenidium serpentinum, Thalassinoides horizontalis, Thalassinoides isp, Thalassinoides suevicus, Treptichnus pedum* and *Walcottia devilsdingli*.

The regressive surface delineates the transgressive deposits TST-III from the regressive deposits of RST-II. The geometry of the beds sediments characteristics and presence of trace fossils suggest lower shoreface to offshore region. The later phase of TST III show major retrogradation in the retrogradation-aggradational sequence and top allochomous (oolitic) limestone (Raimalro limestone member) mark the drowning unconformity/flooding surface (DU/FS).

7.2.4.2.3.2 Regressive System Tract (RST) – III

This system tract is characterized by ~80.23 m thick coarsening and shallowing upward sequence of mixed siliciclastic-carbonate rocks with thin bands of ferruginous sandstone and allochomous limestone. The mixed siliciclastic-carbonate sediments are moderately bioturbated and consist of trace fossils like *Rizocorallium irregularre, Quebecichnus, Arenicolites carbonarius, Diplocraterion parallelum, Planolites beverleyensis, Taenidium serpentinum, Gyrochorte comosa* and *Palaeophycus tubularis*.

The maximum sediment flux or the regressive part is represented by the siliciclastic sediments (sandstone) at the lower part of the sequence of the modar hill member, which may indicative sudden drop of base level due to tectonism or eustatic changes. The rise of the base level or decreased in elastic influx is suggestive by the limestone near the top of the regressive sequence of the RST-III.
These sediments show retrogradation and aggradation in the major prograding sediments which suggests the environmental influence in the stacking pattern (Potma et al., 2001). The aggradational micritic sandstone sediments indicate the intervening stand still condition of the sea and continual sediment supply resulting to attain a thickness of ~20 m. The top of the prograding RST-III is marked by the regressive surface (RS).

7.2.4.2.4 Transgressive-regressive cycle (TRC) - IV

The Transgressive-Regressive Cycle – IV comprises of ~12.1 m thick sequence of coarsening and shallowing upward sequence. The cycle shows presence of aggradation, progradation and retrogradation depositional trends and represents the Transgressive System Tract and Regressive System Tract.

7.2.4.2.4.1 Transgressive System Tract (TST) – IV

This system tract deposits are comprises of ~ 9.9 m fining upward sequence of intercalated sandy allochonic limestone-shale to limestone-shale sequence. The TST-IV records the increasing of carbonate rich sediments and their thickness in upward direction represent aggradational pattern within the retrogradation deposits. The allochonic limestones are devoid of oolites but dominated by bioclastic mudstone/wackestone mark the maximum flooding surface (MFS/FS) of the sediments of the Patcham Island.

7.2.4.2.4.2 Regressive System Tract (RST) – IV

It is characterized by ~2.2 m thin sequence of coarsening and shallowing upward sequence of mixed siliciclastic-carbonate sediments. The base of the deposit of this system tract represents micritic mudrock above the maximum flooding surface. The presence of ripple marks and the cross-beddings in overlying micritic sandstone suggest tidally influence lower shoreface condition. Top of the RST-IV represent sandy micrite, capped by muddy micrite - a transgressive deposit may indicate an end of the regressive phase and an onset of the transgressive phase which is not observed in the sediments of the Patcham Island due to the stratigraphic gap.
Figure-7.5 Composite Lithclog showing siliciclastic-carbonate curve, associated ichnoassemblages and 4th, 3rd, and 2nd order Transgressive-Regressive sequences of Kaladongar Formation and Goradongar Formation exposed at Kaladongar and Goradongar Ranges.
7.2.5 2\textsuperscript{nd} ORDER TRANSGRESSIVE-REGRESSIVE SEQUENCE:

The 2\textsuperscript{nd} order transgressive-regressive cycle constitute the major unit of the Patcham Island constituting the 3\textsuperscript{rd} order transgressive-regressive sequences. The overall pattern of the depositional trend represents a major sequence of transgression during the deposition of the sediments of the Patcham Island.

A noteworthy aspect of the 2\textsuperscript{nd} order sequence of the Patcham Island is the common aggradational or even progradational deposition in the major transgressive deposits showing the retrogradation. Such depositional trend reflects the influence of the environmental factors on the stratigraphic stacking patterns (Potma et al, 2001). The sequence shows an asymmetrical change throughout but an overall depicts the slowly transgressive sea over the Patcham Island, Kachchh Basin.

7.3 TRANSGRESSIVE-REGRESSIVE SEQUENCE STRATIGRAPHIC MODEL

Trace fossils are analyses in context of sequence stratigraphic analysis, for e.g., Diplocraterion parallellum has been linked to transgressive and marine flooding surfaces (Dam, 1990; Taylor and Gawthorpe, 1993; Goldring et al., 1998) as well as to sequence boundaries (Olo’riz and Rodri’uez-Tover, 2000) and Rhizocorallium jenense is generally related to transgressive surface, produced during a period of non-deposition, before and at the beginning of the subsequent deposition (Uchman et al 2000). The absence or non-preservation of hardground Glossifungites ichnofacies in the sequence makes the identification of the boundaries difficult on the basis of trace fossils (Pemberton and MacEachern, 1992). However, the present study incorporated the possibility of the sedimentary deposits coupled with ichnoassemblages as useful in identifying the sequence stratigraphic surfaces and sequence boundaries.

The trace fossils of the Patcham Island is represents recurring ichnoassemblages namely; Arenicolites, Asterosoma, Gyrochorte, Rhizocorallium, Thalassinoides, Planolites-Palaeophycus, Phycodes, Ophiomorpha and Skolithos assemblages are studied in order to unravel the relationship with the sedimentary packages and stratigraphic surfaces (Fig. 7.6). The studied sections of Kuwar Bet, Chhappar Bet, Dingy Hill, and Kaladongar and Goradongar ranges display depositional trends of progradation, retrogradation and
aggradation which represents four 3rd order transgressive-regressive cycle (RST-I, II, III, IV & TST-II, III, IV) bounded by three regressive surfaces (Fig. 7.2, 7.3, 7.4 and 7.5).

The geomorphic, tectonic and dynamic settings have a strong influence on the way in which the changes in accommodation are expressed or preserved (Catuneanu et al 2009). According to them sequence may be preserved in multiple combinations in the terms of component systems tracts and every sequence whose framework is linked to changes in shoreline trajectory consists of one or more of the same genetic types of deposits (i.e., normal regressive and transgressive). The sedimentological and the ichnological characteristics display a wide range of depositional facies belts including (a) foreshore, (b) shoreface, (c) transitional, and (d) offshore facies (Fig. 7.6).

(a) The foreshore facies comprises of micritic sandstone, allochhemic sandstone (Fig. 4.5a), sandy allochem limestone and argillaceous shale. It is characterized by planar laminations, cross-bedding and ripple marks. It shows presence of trace fossils such as Arenicolites, Monocraterion, Ophiomorpha, Planolites, Palaeophycus, Skolithos and Thalassinoides which are related to the Seilacher’s (1967) Skolithos ichnofacies. It is observed in the Kuar Bet member of the Kuar Bet. This depositional facies comprises the transgressive TST-I and the regressive RST-I deposits of Transgressive-regressive cycle-I of the sequence (Fig. 7.6).

(b) The shoreface facies consists of the upper, middle and the lower shoreface sub-facies.

The upper shoreface sub-facies comprises of thick allochhemic sandstone (Fig. 4.5a) and micritic sandstone intercalated with the argillaceous shale facies. It is observed in the Kuar Bet and its equivalent Dingy Hill member of Kaladongar Formation. It is characterized by the low angle cross-beddings and ripple marks (Fig. 4.4 c; Fig. 4.6 b) and also shows presence of trace fossils such as Arenicolites, Monocraterion Ophiomorpha, Planolites/Palaeophycus, Skolithos and Thalassinoides which are related to the Seilacher’s (1967) Skolithos ichnofacies and Proximal Cruziana ichnofacies (MacEachern and Pemberton 1992). The presence of cross-bedding and wave rippled structures indicate wave dominated environment in regressive setting. Thick allochhemic sandstone (20m) and micritic sandstone (45m) suggests the deposits of the barrier bar and also reflect a continued supply of the clastic sands but the sub-angular to sub-rounded,
moderately sorted grains (Fig. 4.5 a, b, d and f) reflect winnowing and grain attrition by wave action. Thus, the physical and biogenic structures and the nature of the sediments indicate moderate to relatively lower energy conditions in upper shoreface facies and geometry and contact of the beds represent a barrier bar deposits.

The middle shoreface lies between the lower and upper shoreface intervals and consists of non-bioturbated micritic mudrock, highly-bioturbated allochemic sandstone, micritic sandstone (Fig. 4.7 a) and argillaceous-rich shale facies. It is characterised by planar lamination, cross-bedding and asymmetrical-linguoidal ripples marks (Fig. 4.4 b, Fig. 4.6 c). The rate of bioturbation varies widely showing non-bioturbated to highly-bioturbated layers of *Arenicolites, Chondrites, Didymaulichmus, Laevicyclus, Lockeia, Ichnocumulus, Margaritichmus, Ophiomorpha, Plug shaped form, Walcottia Palaeophycus Planolites, and Rhizocorallium*. It also shows presence of body fossils such as bivalves, corals and fossil wood (Fig. 4.4 g and h). The middle shoreface sub-facies is observed in the Kuar Bet and the Dingy Hill members.

The lower shoreface consists of sandy allochem limestone and micritic mudrock. This sub-facies is characterized by thin laminations, cross-bedding and ripple marks. It is intensely bioturbated and consists of diverse groups of trace fossils represented by both vertical (*Skolithos, Arenicolites and Daedalus*) and horizontal (*Gyrochorte, Planolites, Palaeophycus, Didymaulichmus, Rhizocorallium and Thalassinoides*) traces. This facies characteristically intercalate with the argillaceous-rich shale layers and locally with the intraformational conglomerate. It is observed in the Kuar Bet/Dingy Hill, Babia Cliff Sandstone and Modar Hill members. The shoreface (Upper to Lower) depositional facies is observed in the TST-II and RST-I, RST-II, and RST-IV of the transgressive-regressive cycle of the sequence.

(c) Transitional facies comprises of micritic mudrock, sandy allochem limestone, allochemic sandstone and micritic sandstone. It shows presence of planar laminations, low angle cross-laminations, and ripple marks and trace fossils such as *Arenicolites, Asterosoma, Beaonites, Cochlichmus, Dactylophycus, Diplocraterion, Gyrochorte, Halopoa, Lockeia, Ophiomorpha, Palaeophycus, Planolites, Phycodes Protovirgualaria, Rhizocorallium, Skolithos, Thalassinoides* which represents diverse
assemblages (Asterosoma, Gyrochorte, Planolites-Palaeophycus Ophiomorpha, Skolithos, Thalassinoides, Rhizocorallium and Phycodes) which represents the mixed Skolithos-Cruziana and Cruziana ichnofacies. It is observed in the Dingy Hill, Babia Cliff sandstone, Kaladongar Sandstone, Goradongar Flagstone and Modar Hill members representing the TST-III and TST-IV and RST-II, and RST-III of the Patcham Island sequence.

(d) The offshore facies consists of muddy micrite, sandy micrite, micritic mudrock, sandy allochm limestone and allochemic limestone which are variably intercalated with thin calcareous rich shale layers. It is characterised by planar laminations, cross-bedding and ripple marks and trace fossils such as Areniculites, Didymaulichnus, Diplocraterion, Gyrochortes, Lockeia, Planolites, Palaeophycus, Rhizocorallium and Teichichnus which represents Rhizocorallium, Planolites/Palaeophycus and Gyrochorte assemblages and also represent the distal part of the Cruziana ichnofacies (MacEachern and Pemberton 1992). It is observed in the Kaladongar Sandstone, Babia Cliff Sandstone, Goradongar Flagstone, Gadaputa Sandstone, Raimarlo Limestone and Modar Hill members which represents the TST-II, RST-II, and TST-III of the sequence.

The relationship of the trace fossils and the depositional trends shows frequent and abundant recurrence of Planolites-Palaeophycus, Skolithos, Areniculites and Rhizocorallium assemblages in the regressive deposits while Rhizocorallium, Planolites-Palaeophycus, and Gyrochorte assemblages in the transgressive deposits (Fig. 7.6). Ophiomorpha and Thalassinoides assemblages are representing the intermittent high energy conditions and/or opportunistic conditions in the regressive as well as in transgressive deposits. The Rhizocorallium ichnoassemblage (Cruziana ichnofacies) recur conspicuously in the sequence and mark the flooding surface (TST-II and TST-III) while Areniculites, Skolithos and Ophiomorpha ichnoassemblages (Skolithos ichnofacies) associated with Gyrochorte assemblage (Cruziana ichnofacies) seem to mark the regressive surface (RST-II and RST-III). Ichnoassemblages reveals the transgressive-regressive cycles and helped in distinguishing the various system tracts developed in the sequence of Mesozoic of Patcham Island.
7.4 REGIONAL AND GLOBAL CORRELATION

The sediment of the Patcham Island and their associated trace fossils are significant evidence of slowly transgressing sea over low energy coastlines of initially rifting Kachchh basin. The Jaisalmer sedimentary basin is a shelf basin neighbouring the Kachchh basin, a rift basin in the south. During Jurassic, both the basin was at a distance of about 2° latitude and was situated in the subtropical belt (Ziegler et al, 2003; Wang et al, 2005).

The Late Bajocian transgression of Kachchh Basin of Gujarat resulted into the inundation of sea which started the first marine transgression covering the western Rajasthan shelf (Narayanan et al, 1961; Singh et al., 1982). The depositional trends of both the basin show comparatively gradual deepening of basin and an increase in marine sediments during the late Bajocian time (Pandey and Choudhary, 2007). Moreover, based on faunal studies, Bajocian to Bathonian sediments of Jaisalmer Basin can be broadly correlated with those of the Kachchh Basin (Pandey et al., 2006). The present investigation of comparable time slice of Patcham Island sediments of Kachchh basin also shows similar depositional trend. Moreover, the Callovian deposits of Jaisalmer shows transgression at the lower part which then shows regressive shallow marine deposits in the upper part (Pandey et al., 2010); sedimentological and ichnological data of the of the Callovian of the Patcham island also shows similar trend in the Kachchh basin.

On comparison with the global sea level changes during the Callovian stages, and their 3rd order sequences given by Haq et al (1987), Hallam (2001), and Hardenbol et al (1998), the overall transgression seems to be correlative to the Bajocian-segment representing the world-wide transgression of Toarcian to the Bathonian time. However the sedimentary record of the Callovian sediments of the studied section of the Kachchh Basin seems to be incomplete like the neighbouring Jaisalmer Basin (Krishna, 1987) and the trend is also different from the eustatic curve.

These long-term changes may be therefore indicative of some local factors such as tectonics during the Callovian times. The transgressive event is similar to the Tethyan/Boreal scheme of Hardenbol et al (1998) and the T-R facies cycle of Jacquin et al (1998), indicating that the sedimentation pattern was majorly influenced by the the regional as well as the global factors.
Figure 7.6 Sequence stratigraphic model of Patcham Island showing change in shoreline trajectory with associated ichnoassemblages and depositional trends in the strata stacking pattern and relative short-term and long-term changes compared to the eustatic sea level. (1) Arenicolites, (2) Asterosoma, (3) Gyrochorte, (4) Ophiomorpha (5) Phycodes, (6) Planolites/Palaeophycus, (7) Rhizocorallium, (8) Skolithos and (9) Thalassinoidea ichnoassemblages.
CHAPTER 8
DISCUSSION AND CONCLUSIONS

The Middle Jurassic sequence of Patcham Island represent total nine sedimentary facies: a) six mixed siliciclastic-carbonate facies namely, micritic sandstone, allochem sandstone, sandy allochem limestone, micritic mudrock and sandy micrite facies; and b) pure sedimentary facies namely, ferruginous sandstone, allochemic limestone, shale and conglomerate facies. These sedimentary facies also show variations in the proportion of clastics and nonclastics components. The nonclastic compositional variations are well documented in allochemic limestone facies, which is consisting of varying proportion of allochems like mollusks (bivalves and gastropods), coralline algae, echinoderms, foraminifers, with oolites and carbonate grains. The variation in carbonate constituents represented by allochemic limestone facies is indicative of changes in bathymetry, salinity, and energy conditions. Likewise, the facies analysis of the overall sediments of the Patcham Island suggests change in the depositional factors such as energy conditions, salinity levels, and agitation conditions etc in the depositional regime of foreshore to offshore.

These sediments show presence of abundant and ethologically diverse trace fossils. Total 67 ichnospecies of 43 ichnogenera were identified which demonstrated nine trace fossils assemblages namely, Arenicolites, Asterosoma, Gyrochorte, Rhizocorallium, Thalassinoides, Planolites/Palaephycus, Phycodes, Ophiomorpha and Skolithos assemblages. The assemblages characterized by a particular association of trace fossils indicate hydrodynamic condition, mode of food supply, oxygenation conditions, substrate conditions and bathymetry. The shallow sea floor marked the foreshore-upper shoreface by the presence of the Skolithos and Ophiomorpha assemblages, members of the Skolithos ichnofacies whereas the deepest sea floor position as the offshore marked by the presence of Planolites-Palaephycus, Rhizocorallium and Gyrochorte assemblages, the members of the distal Cruziana ichnofacies (MacEachern and Pemberton, 1992). The gradual deepening in the shoreface is marked by Asterosoma, Gyrochorte, Rhizocorallium, Thalassinoides, Planolites-Palaephycus and Phycodes assemblages; the members of the proximal Cruziana ichnofacies (MacEachern and Pemberton, 1992) and typically marked the middle/lower shoreface to transitional environment.
The data of sedimentary facies coupled with ichnoassemblage/ichnofacies revealed that the Middle Jurassic sequence of the Patcham island comprises of aggradation, progradation and retrogradation deposits of shallow marine environments; which displayed four 3rd order transgressive-regressive asymmetrical sedimentary cycles (KST-I, II, III, IV & TST-II, III, IV) bounded by three regressive surfaces. The aggradational sequence represents the standstill conditions of the sea while the other progradational and retrogradational sequence represents the regressive and transgressive condition of the sea respectively (refernce). The shallowing upward and symmetrical cycles occur in protected lagoon-shoreface areas (Dingy Hill member of Chlappar bet) and in open-marine, high energy domain (upper part of the Ding Hill member; Kaladongar Sandstone; Babia Cliff Sandstone; and Modar Hill members). While the deepening upward and aggradational cycles are generated in low energy, sub wave-base in open marine areas (Dingy Hill member of Dingy hill and Kaladongar range; Goradongar Flagstone; Gadaputa sandstone; and Raimalro Limestone members).

These sedimentary cycles reflect similarity with the typical rift sequence suggested by Martins-Neto and Catuneanu (2010). Accordingly the absence of the Lowstand systems tract (LST) in the sediments of Patcham Island may be considered due to the strong asymmetrical shape of the base level curve, with fast rise followed by prolonged still stand. The transgressive deposits does not show any ravinement surface which indicates that it is characteristically of low energy coastlines and are typically developed in the mud dominated successions (Cattaneo and Steel, 2003). Moreover, the common aggradational or even retrogradational deposition in the highstand systems tract reflects the influence of environmental factors on stratigraphic stacking patterns (Potma et al, 2001).

The first 3rd order transgressive-regressive cycle (TRC-I) suggests that the transgressive deposits (TST-I) are deposited in the foreshore to shoreface environment whereas the regressive deposits (RST-I) are deposited in the high energy shoreface condition. The second 3rd order cycle of transgression-regression (TRC-II) suggests the transgressive deposits (TST-II) in the lower shoreface to transition environment while the regressive deposits of RST-II can be interpreted as those deposited in the shoreface to transition zone. The third 3rd order transgressive-regressive cycle (TRC-III) formed the transgressive deposits (TST-III) in the transitional to offshore zone whereas the regressive deposits (RST-III) in the offshore to transitional zone. The fourth 3rd order transgressive-regressive cycle (TRC-IV)
formed the transgressive deposits (TST-IV) in the transitional zone whereas the regressive deposits (RST-IV) in the lower shoreface zone. The sedimentation pattern and the varying proportion of clastic/nonclastic grains in the sequence/composition suggest fluctuations of sea levels and sediment influx; carbonate productivity is increased with increasing depth and decreasing energy, which also halted the deposition of clastic grains. Therefore, this sequence represents number of cycles of transgression and regression but overall indicates a slowly transgressive sea during the deposition of the mixed siliciclastic-carbonate sediments in siliciclastic platform to carbonate ramp conditions during the Bajocian to Callovian time.

Most carbonates are biogenic in origin and therefore the siliciclastic and carbonate sediments are found to be mutually exclusive within modern environments; the fine-grained siliciclastics frequently dilute carbonate sediments and negatively affect carbonate production by reducing the light available to autotrophs and/or covering filter-feeding organisms (Flugel, 2010). Coeval carbonate and siliciclastic sedimentation thus requires specific conditions: terrigenous influx has to be low enough to allow the growth of carbonate-producing organisms, which can be achieved by a temporary shift of the siliciclastic depocenter (e.g. abandonment of delta lobes), the winnowing of fine-grained material by currents, or spatial separation of siliciclastic and carbonate depocenters. The mixed siliciclastic-carbonate deposits of the Patcham island characterised by land-derived siliciclastic sediments are trapped in foreshore and shoreface environments and contemporaneous deposition of carbonate sedimentation takes place in offshore settings; similar type of deposits are observed in modern environment at eastern Nicaragua coast and Great Barrier Reef (Mount, 1984).

The formation of carbonate platforms (Goradongar Flagstone, Gadaputa Sandstone and Raimalro Limestone member) during the Bathonian times within siliciclastic settings (Kaladongar Formations) require combinations of adaptive strategies by carbonate-producing organisms and sheltering mechanisms that protect the organisms from unfavorable influences where the sheltering mechanisms include an elevated position (e.g. basement uplift) within areas dominated by siliciclastic sedimentation; longshore currents that screen off suspended siliciclastic grains; local subsidence traps; or sea-level rise resulting in the reduction of siliciclastic influx; and favoring carbonate deposition (Blair 1988; Brachert 1992; Philip 1993; Leinfelder 1994; Okhravi and Amini 1998; Sanders and Höfling 2000; Khetani and Read 2002).
The transgressive phase of TRC-III and IV shows presence of limestone with mixed siliciclastic-carbonate sequence which may be developed during an offshore siliciclastic sediment starvation (Brett, 1995) or due to the development of the conditions responsible for the increase in carbonate production (Lukasik and James, 2003; Pomar and Kendall, 2007). The Allochemic carbonates represents the keep up margin formed at the platform while the micrite rich carbonate sequences suggest the catch up carbonate highstand representing a relatively slow rate of accumulation (Sarg, 1988). This change in the depositional system (depositional bias) as well as environmental changes strongly influenced the sequence patterns (Tucker et al, 1990). This also explains the aggradational or even retrogradational deposition in the regressive system tracts of TRC-II and III (Potma et al, 2001) and the drastic reduction in the carbonate productivity indicated by the drowning unconformities (Schlager, 1992).

The mixed siliciclastic carbonate sediment of the Patcham Island and their associated trace fossils are significant evidence of slowly transgressing sea over low energy coastlines of initially rifting Kachchh basin during Bajocian to Callovian time. These sequences are compared and studied with the equivalent Jaisalmer basin for regional constraints and the global sequences of the Bathonian to Callovian time for the global constraints. The Bajocian sediments of the Kadalongar Formation show similar depositional system in the equivalent Jaisalmer basin (Pandey and Choudhary, 2007). Both the depositional trends show comparatively gradual deepening of basin and an increase in marine sediments during the late Bajocian time. Moreover, the overall transgressive trend of the Formation seems to be correlative to the segment representing the world-wide transgression of Toarcian to the Bathonian time (Haq et al, 1987, Hallam, 2001) and is seen precisely correlated with the eustatic sea level of Haq et al., 1987 (Fig. 7.6). This transgressive event is similar to the Tethyan/Boreal scheme of Hardenbol et al 1998 and the T-R facies cycle of Jacquin et al, 1998. The sequence stratigraphic analysis of the sedimentary sequence of Middle Jurassic of Patcham Island revealed that the depositions of sediments were influenced by both regional and global factors.

The present study on sequence stratigraphic analysis based on sedimentological and ichnological aspects provide important conclusions as the following:
The Middle Jurassic sequence of Patcham Island is exposed at Kaladongar and Goradongar hill ranges, as well as at Kuar bet, Chappar Bet and Ding Hill and attain composite thickness of +462 meter.

This sequence comprises of two Formations: the lower Kaladongar Formation and the upper Goradongar Formation which are further divided into three (Dingy Hill/Kuar Bet, Kaladongar Sandstone and Babia Cliff Sandstone) and four (Goradongar Flagstone, Gadaputa Sandstone, Raimalro Limestone, and Modar Hill) members respectively.

The stratigraphic sequence comprises mixed siliciclastic-carbonate sediments with subordinate shale, limestone, sandstone and shale which are further divided into nine sedimentary facies, namely, allochemic sandstone, micritic sandstone, micritic mudrock, sandy allochem limestone, sandy micrite, allochemic limestone, ferruginous sandstone, shale and conglomerate facies.

Presence of intraformational conglomerates facies indicates typical characteristic of storm generated deposits.

The whole sequence is highly fossiliferous and contains mainly bivalves, gastropods, cephalopods, echinoderms, corals, foraminifers, fossil wood etc. Sequence is also highly bioturbated and consisting of total 67 ichnospecies of 43 ichnogenera which recur throughout the sequence and can be classified under five ethological groups Cubichnia, Repichnia, Pascichnia, Fodinichnia and Domichnia.

A new ichnogenus *Virgoglyphus* and its type ichnospecies *Virgoglyphus modari* has been reported from the study area.

Nine trace fossil assemblages namely, *Arenicolites*, *Asterosoma*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Planolites/Palaeophycus*, *Phycodes*, *Ophiomorpha* and *Skolithos* assemblages were observed to represent the recurring ecologically related group of trace fossils.

These association of trace fossils that recurred in time and space directly reflected environmental conditions such as bathymetry, salinity and substrate characters and represented three ichnofacies namely, *Skolithos* ichnofacies, *Cruziana* ichnofacies and mixed *Skolithos-Cruziana* ichnofacies.
The sedimentological and ichnological characteristics indicate a wide range of depositional facies belts including foreshore, shoreface, transitional and offshore; and comprised of sedimentary facies and depositional trend within the sequence.

The sedimentary layers coupled with the ichnoassemblages were used in identifying the sequence stratigraphic surfaces and sequence boundaries which identified the large scale transgressive-regressive (T-R) sequence of 2\(^{nd}\) order and four mid-scale sequence of 3\(^{rd}\) order with several small scale cycles or 4\(^{th}\) order unit of Transgressive-Regressive (T-R) cycles.

The material based stratigraphic surfaces identified in the Patcham Island sequence are regressive surface (RS), flooding surface (FS), and drowning unconformity (DU) and every framework of sequence is linked to changes in the shoreline trajectory and consisted of two genetic types of deposits: normal regressive and transgressive.

The 3\(^{rd}\) order cycles (TRC-I, TRC-II, TRC-III, TRC-IV) are bounded by three regressive surfaces and are comprised of two parts; the transgressive system tract and the regressive system tract separated by the flooding surfaces.

The first 3\(^{rd}\) order transgressive-regressive cycle (TRC-I) represents deposition in the foreshore to shoreface environment; the second 3\(^{rd}\) order cycle of transgression-regression (TRC-II) represents in the lower shoreface to transition environment; The third 3\(^{rd}\) order transgressive-regressive cycle (TRC-III) was formed in the transitional to offshore zone; and the fourth 3\(^{rd}\) order transgressive-regressive cycle (TRC-IV) formed in the transitional zone to lower shoreface zone.

The stratigraphic sequence of the Patcham Island is corelatable with the equivalent Jaisalmer Basin and other world-wide Bajocian-Callovian deposits which also suggest that the deposition was influenced by the regional as well as the global factors.

The sequence stratigraphic analysis of the Middle Jurassic rocks of the Patcham Island with the sedimentological and ichnological aspects revealed development of asymmetrical cycles of transgression and regression in an overall slowly transgressive sea during the deposition in the siliciclastic platform to carbonate ramp conditions during the Bajocian to Callovian time.