CHAPTER -7

SIGNIFICANCE OF TRACE-FOSSILS AND SEDIMENTARY CYCLES TO SEQUENCE STRATIGRAPHY

7.1 SEQUENCE STRATIGRAPHY: BACKGROUND INFORMATION

Sequence stratigraphy was generally observed as a branch of the seismic stratigraphy in the 1970s with the work of Vail (1975) and Vail et al. (1977). In fact, however, major studies investigating the relationship between sedimentation, unconformities, and changes in base level, which are directly relevant to sequence stratigraphy, were published prior to the birth of seismic stratigraphy (e.g., Grabau, 1913; Barrell, 1917; Sloss et al., 1949; Wheeler and Murray, 1957; Wheeler, 1958, 1959, 1964; Sloss, 1962, 1963; Curray, 1964; Frazier, 1974). Sequence stratigraphy marks the third and most recent revolution in sedimentary geology, starting in the late 1970s with the publication of AAPG Memoir 26 (Payton, 1977). The first revolution provided a combined theory to clarify, from a hydrodynamic perspective, the genesis of sedimentary structures and their predictable associations within the context of depositional systems. Beginning in the 1960s, the incorporation of plate tectonics and geodynamic concepts into the analysis of sedimentary processes at regional scales, marked the second revolution in sedimentary geology (Catuneanu, 2006). Sequence stratigraphy analyzes the sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of accommodation (space available for sediments to fill) and sedimentation (Catuneanu, 2006). Sequence stratigraphy is one of the most active areas of research in the industry as well as in the academics because it serves vital information regarding geological record of local to global changes and improves economic exploration and production aspect. 'Principles' of sequence stratigraphy are to a large extent independent of the type of depositional environments established within a sedimentary basin (e.g., siliciclastic vs. carbonate), and clastic systems are generally used by default to explain and exemplify the concepts (Catuneanu, 2006).

Sloss et al. (1949) introduced the term 'sequence' to define a stratigraphic unit bounded by subaerial unconformities. In addition, Sloss (1963) highlighted the importance of tectonism in the generation of sequences and bounding unconformities, which is now widely accepted but was largely unnoticed in the early days of seismic stratigraphy. Mitchum (1977) included 'relatively conformable succession of genetically related strata' to the meaning of a stratigraphic sequence. Further in 1970s, Pettijohn (1975), Reading (1978) and Selley (1978) redefined the term 'sequence' and included a 'vertical succession of facies' reflecting the natural evolution of a depositional environment. The unconformity-bounded sequence was promoted by Sloss (1963) and Wheeler (1964) where as the concept of unconformity-bounded unit was formalized by the European international stratigraphic guide in 1994. 'Correlative conformities,' which are extensions towards the basin center of basin margin unconformities, gives confinement of seismic and sequence stratigraphy (Mitchum, 1977). Vail et al. (1977) published seismic stratigraphy together with a global sea-level cycle chart which opened up the sequence formation and cyclic-stratigraphic concept. Following this, from outcrop and subsurface, it became very clear that global sea-level changes (global eustasy model) and sequence stratigraphy are dissociated because outcrop can given more objective analysis on empirical evidence. In this regard, Van Wagoner et al. (1990) stated that 'Each stratal unit is defined and identified only by physical relationships of the strata, including lateral continuity and geometry of the surfaces bounding the units, vertical stacking patterns, and lateral geometry of the strata within the units. Thickness, time for formation, and interpretation of regional or global origin are not used to define stratal units, which are regardless of their interpreted relationship to change in eustasy'.

Different authors have defined the term 'sequence stratigraphy' in different ways.

"The study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities".

Posamentier et al. (1988) and Van Wagoner (1995)

"The analysis of repetitive genetically related depositional units bounded in part by surfaces of nondeposition or erosion".

Galloway (1989)

"The analysis of cyclic sedimentation patterns that are present in stratigraphic successions, as they develop in response to variations in sediment supply and space available for sediment to accumulate".

Posamentier and Allen (1999)

"The recognition and correlation of stratigraphic surfaces which is represent changes in depositional trends in sedimentary rocks. Such changes were generated by the interplay of sedimentation, erosion and oscillating base level and are now determined by sedimentological analysis and geometric relationships".

Embry (2001)

The analysis of the sedimentary response to changes in base level, and the depositional trends that emerge form the interplay of accommodation (space available for sediments to fill) and sedimentation.

Catuneanu (2006)

Sequence stratigraphy can be an effective tool for correlation on both local and regional scales. However, it remains the only stratigraphic method that has no standardized stratigraphic code. Different models with respect to how the sequence stratigraphic method should be applied to the rock record are illustrated in the Fig. 7.1 and Fig. 7.2.

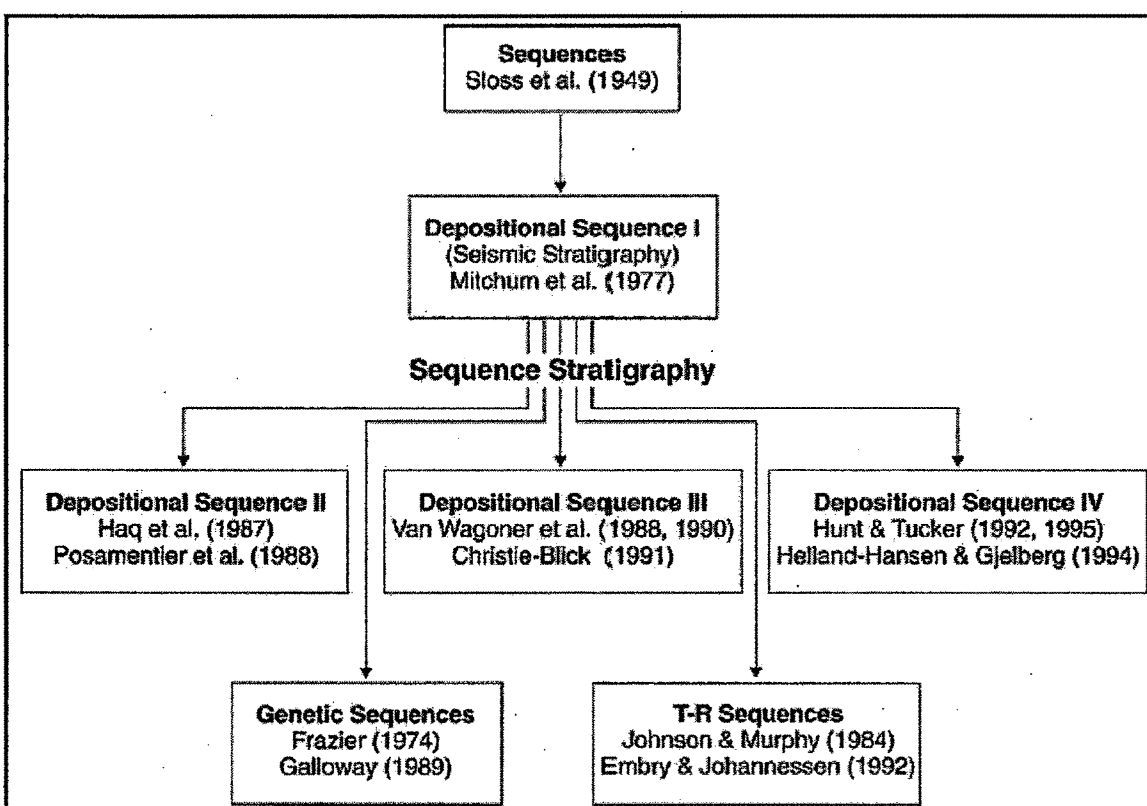

Fig. 7.1 Sequence stratigraphic models (from Catuneanu, 2006)

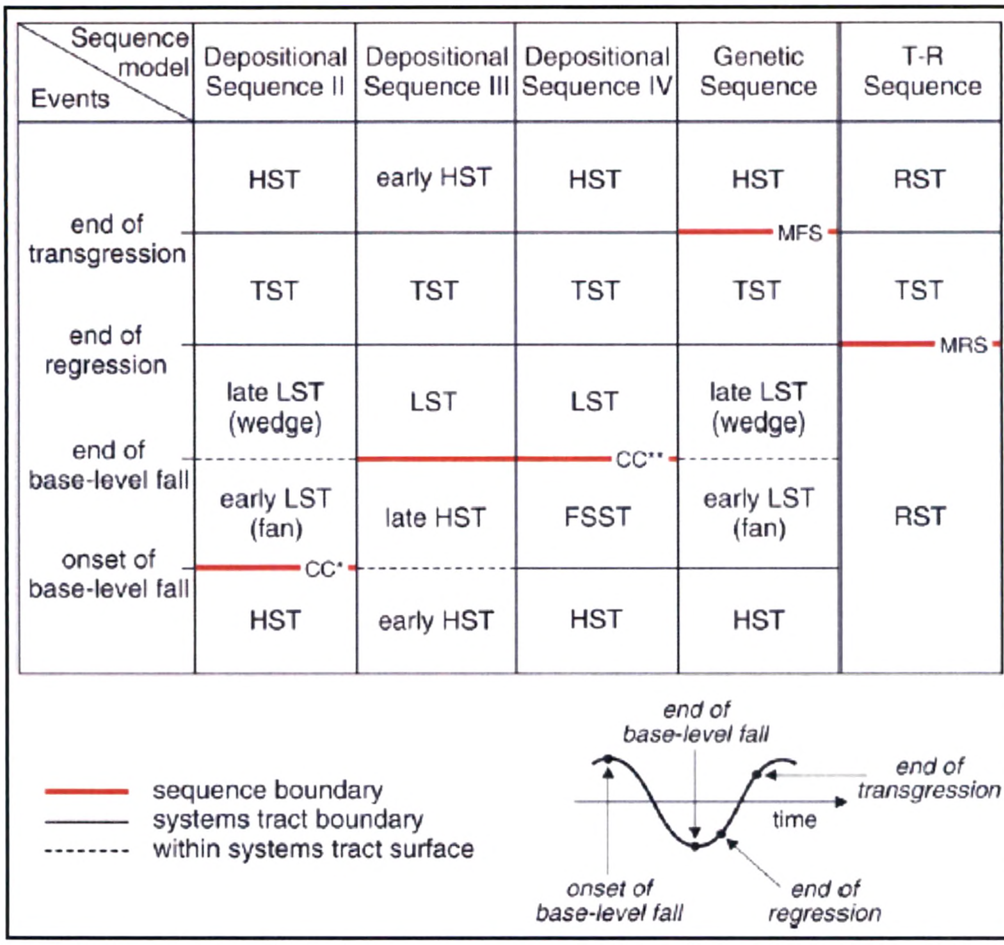

Fig. 7.2 Nomenclature of system tracts and timing of sequence boundaries for the existing sequence stratigraphic models of Fig. 7.1 (from Catuneanu, 2006). Abbreviations: LST - lowstand system tract; TST - transgressive system tract; HST – highstand system tract; FSST – falling stage system tract; RST – regressive system tract; T-R – transgressive-regressive; CC* - correlative conformity; MFS – maximum flooding surface; MRS – maximum regressive surface.

There has been no general acceptance of any single approach or model for sequence stratigraphic analysis. The study area consist of both siliciclastic and carbonates, hence, author has adopt model-independent workflow of sequence stratigraphic analysis as mentioned below.

Model-independent aspects of sequence stratigraphy (Catuneanu et al., 2009) have four major components. 1) Basic concept (i.e. stratal stacking patterns, stratal terminations, accommodation, base-level changes, shoreline trajectories); 2) Genetic units (forced regressive, normal regressive for lowstand and highstand, transgressive and system tracts); 3) Sequence stratigraphic surfaces (that bound different genetic type of deposits) and 4) workflow (subdivision of the stratigraphic section into a succession of genetic units / system tracts / parasequence). Sequences, system tracts and sequence stratigraphic surfaces in relation to base-level are illustrated in the Fig. 7.3.

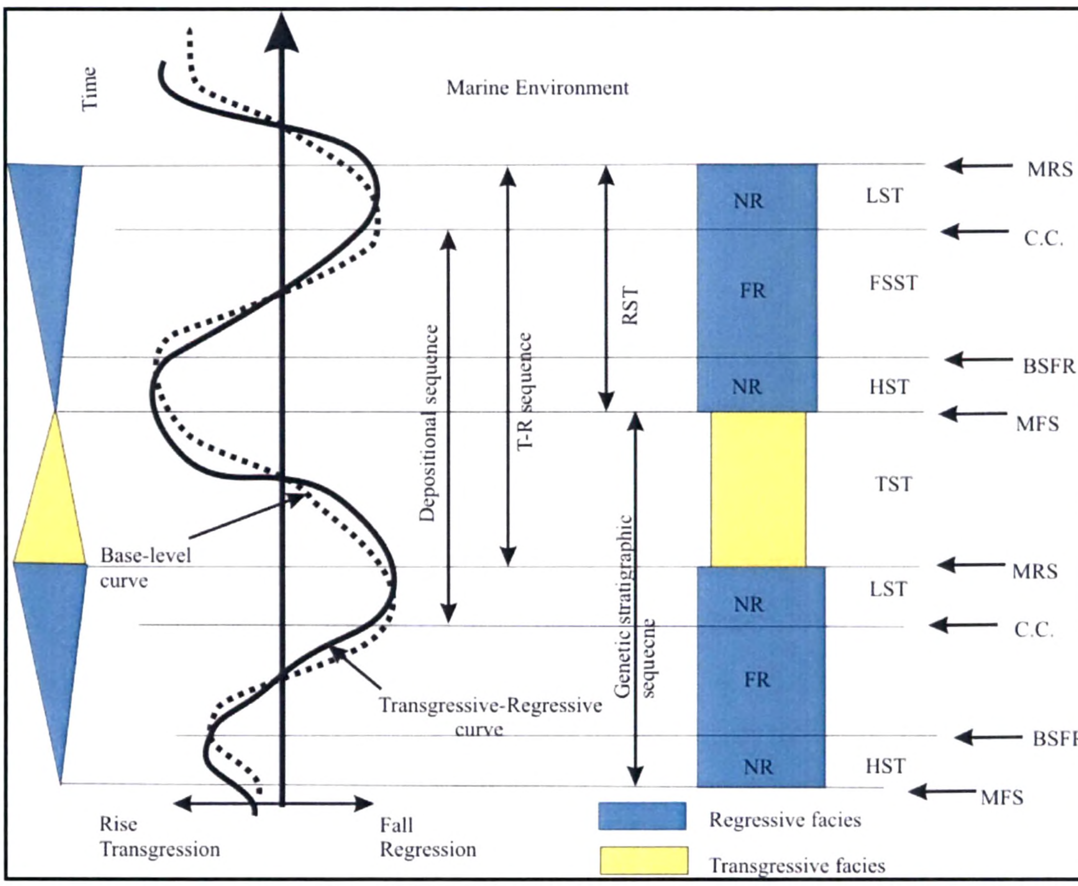

Fig. 7.3 Sequences, systems tracts, and stratigraphic surfaces defined in relation to the base level. abbreviations: C.C. - Correlative conformity; BSFR - basal surface of forced regression; MRS - maximum regressive surface; MFS - maximum flooding surface; NR - normal regression; FR - forced regression; LST - lowstand systems tract; TST - transgressive systems tract; HST highstand systems tract; FSST - falling stage systems tract; RST - regressive systems tract

7.1.1 Definition of 'Sequence' and 'Sequence Stratigraphy'

The sequence means a representation or product of sedimentation during a full stratigraphic cycle, irrespective of whether all parts of the cycle are formed or preserved. The start and the end of the full cycle called 'event'. The term 'sequence', as applied in sequence stratigraphy, was also defined by Mitchum (1977) as: A stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded as its top and base by unconformities or their correlative conformities. Stratigraphic sequence means a succession of strata deposited during a full cycle of change in accommodation or sediment supply (Catuneanu et al. 2009) where the boundaries may be unconformable and conformable. It is independent of temporal and spatial scales. Sequence corresponds to a full stratigraphic cycle with bounding surfaces the same as the sequence stratigraphic surfaces.

All the above mentioned definitions of Sequence stratigraphy emphasize on 1) cyclicity; 2) temporal framework; 3) genetically related strata and 4) the interplay of accommodation and sedimentation. Basically, sequence stratigraphy studies address stratal stacking patterns and changes in chronological framework.

7.1.2 Parasequences

A parasequence is a relative conformable succession of genetically related beds or bedsets bounded by flooding surfaces (Catuneanu et al. 2009). Flooding surface indicates a surface across which there is an abrupt shift of facies that may indicate an increase in water depth or a decrease in sediment supply (modified after Van Wagoner et al., 1990). Sediment starvation – condensed sections can give the appearance of abrupt increase in water depth even though water depth has not risen suddenly. Parasequence is geographically restricted to the coastal and shallow-water portion of a sedimentary basin since for fully fluvial as well as deep-water systems, the concept of flooding surfaces becomes meaningless.

7.1.3 Genetic types of deposits (system tracts)

A sequence may be subdivided into component system tracts, which consists of packages of strata that correspond to specific genetic types of deposit (i.e. forced regressive, lowstand and highstand normal regressive) (Catuneanu et al., 2009). The term system tract was first defined by Brown and Fisher (1977) as a linkage of contemporaneous depositional systems, where a depositional system is three dimensional assemblage of lithofacies, genetically linked by modern or ancient processes and environments. System tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces (Van Wagoner et al., 1990; Van Wagoner, 1995). The following types of genetic deposits define conventional system tracts (Catuneanu et al., 2009).

7.1.3.1 Normal regression (NR): Progradation driven by sediment supply. Sedimentation rates outpace the rates of base-level rise at the coastline. Depositional trend is progradational with aggradational. It applies to late lowstand, lowstand, highstand and early highstand.

7.1.3.2 Forced regression (FR): Progradation driven by base-level fall. The coastline is forced to regress, irrespective of sediment supply. Depositional trend is progradation with dwonstepping. This type of genetic deposits is present at early lowstand, late highstand, forced regressive wedge and falling-stage (Catuneanu et al., 2009).

7.1.3.3 Transgression: Retrogradation (backsteeping) driven by base-level rise. The rates of base-level rise outpace the sedimentation rates at the coastline. The transgressive deposits belong to transgressive system tract.

Author has referred to Van Wagoner et al. (1988), Posamentier and Vail (1988), Galloway (1989), Hunt and Tucker (1992); Emery and Myers (1996); Vail et al. (1977); Mitchum (1977); Mitchum et al. (1977); Posamentier and Allen (1999); Miall (1997); Miall and Miall (2001); Catuneanu (2002, 2006) and Catuneanu et al. (2009) to define all three system tracts and sequence stratigraphic surfaces as mentioned below:

7.1.3.4 Lowstand System Tract (LST): The basal (stratigraphically oldest) system tract in a type 1 depositional sequence. The system tract is deposited during an interval of relative sea-level fall at the offlap break, and subsequent slow relative sea-level rise. This is also known as downward shift in coastal onlap below the level of the offlap break and is indicative of type 1 sequence boundary. Basin floor fan deposition, canyon, incised valley erosion, canyon formation commonly occur during lowstand system tract. Lowstand submarine fans and lowstand prograding wedges are the most striking features of the system tract. Type 1 sequence boundaries record subaerial exposure and subaerial erosion related to stream rejuvenation and are characterized by a basinward shift in facies, a downward shift in coastal onlap and onlap of overlying strata.

7.1.3.5 Transgressive System Tract (TST): This is the middle system tract of both type 1 and type 2 sequences. It is deposited while the relative sea-level rise cycle when topset accommodation volume is increasing faster than the rate of sediment supply. It has topsets, few clinoforms and entirely retrogradational stacking pattern. This system tract may pass into a condensed section characterized by extreme low rates of deposition and glauconitic, organic rich, phosphatic shales or pelagic carbonates. The marine portion of the transgressive systems tract develops primarily in shallow areas adjacent to the shoreline, with correlative condensed sections, unconformities and onlapping gravity flow and pelagic offshore deposits (Galloway, 1989). The shallow marine facies are represented by onlapping healing-phase deposits that accumulate in the lower shoreface (Dominguez and Wanless, 1991; Posamentier and Chamberlain, 1993), plus a transgressive lag that blankets the ravinement surface in the upper shoreface. The maximum flooding surface is the end of the system tract and occurs when the rate of topset accommodation volume decreases to a point where it just matches sediment supply, and progradation begins again. The active depositional systems are topset systems, alluvial, paralic, coastal plain and shelf (i.e. foreshore to shelf).

7.1.3.6 Highstand System Tract (HST): It is the youngest system tract in either a type 1 or type 2 sequence. It is of relative sea-level rise through time, resulting in initial aggradational and later progradational architecture. It represents progradational topset-clinoform system deposited after maximum transgression and before a sequence boundary, when the rate of sediment supply is higher than the rate of aeration of accommodation. Posamentier and Vail (1988) have characterized fluvial deposition in the late highstand system. The infill of shelf areas by progradation is characteristic element of the system tract which decrease in tidal influence and rate of relative sea-level rise.

7.1.3.7 Type 2 sequences: Relative sea-level may fall over the proximal area of the highstand topsets, without falling at the offlap break. A sequence boundary results but not one characterized by fluvial incision or submarine fan deposition. The only difference in the type1 and type 2 is lack of subaerial erosion and the basinward shift in facies in type 2 (Savrda, 1991).

7.1.4 Sequence stratigraphic surfaces

Genetic types of deposits and corresponding system tracts were defined and bounded by above and below surfaces. Sequence stratigraphic surfaces are boundaries between different genetic types of deposit. There are four major sequence stratigraphic surfaces corresponding to events of the base-level cycle and three other sequence stratigraphic surfaces during stages between such events (Fig. 7.4). Following is a brief definition of the seven surfaces of sequence stratigraphy.

7.1.4.1 Subaerial unconformity (SU): Sloss et al. (1949) have defined the term as an unconformity that forms under subaerial conditions. It is a function of fluvial erosion, karstification, wind degradation and dissolution. Many stratigraphers have given some alternative terms like regressive surface of fluvial erosion (Plint and Nummedal, 2000), fluvial entrenchment / incision surface (Galloway, 2004) and lowstand unconformity (Schlager, 1992). Subaerial unconformities continue to form after the end of base-level fall that are beyond the extent of the lowstand and transgressive fluvial deposits where lowstand relative to the point of fluvial onlap.

7.1.4.2 Correlative conformity (CC): Posamentier and Allen (1999) and Hunt and Tucker (1992) have defined the term in two different ways. From Posamentier and Allen (1999) point of view, it is a stratigraphic surface that marks the changes in stratal stacking patterns from highstand normal regression to forced regression where the oldest marine clinoforms are associated with offlap.At the same time in deep water setting, correlative conformity is placed at the base of basin floor sub marine complex. In general, the surface marks the change from an increase to decrease in the elevation of coastal facies. The analysis of Hunt and Tucker (1992), suggested that it is a surface that marks the change in stratal stacking patterns from forced regression to lowstand normal regression where the youngest marine clinoforms are associated with offlap and it marks the change from decrease to increase in elevation of coastal facies. The alternative term basal surface of forced regression is given by Hunt and Tucker (1992).

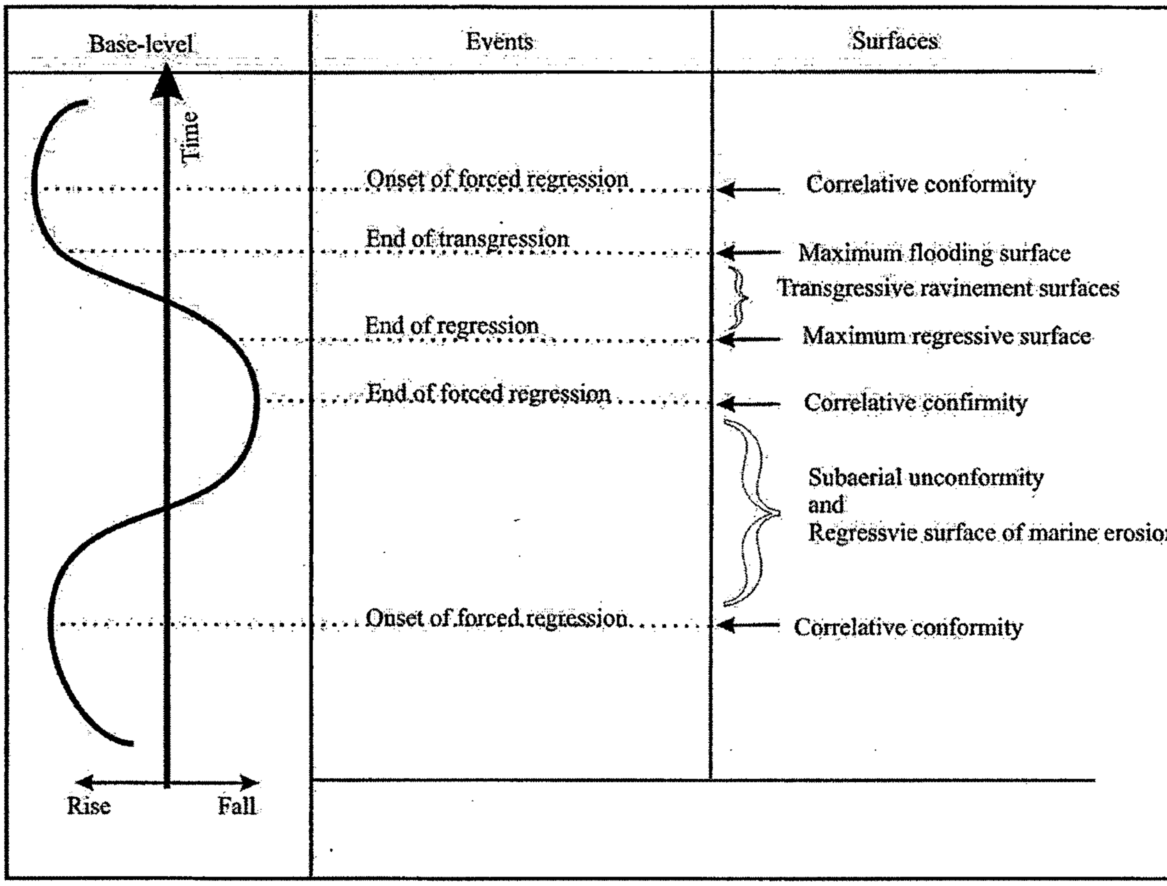

Fig. 7.4 Timing of the seven surfaces of sequence stratigraphy related to the four events of the base-level cycle (form Catuneanu, 2006).

7.1.4.3 Regressive surface of marine erosion: A subaqueous erosional surface that forms by wave scouring in regressive wave-dominated lower shoreface to inner shelf settings (Plint, 1988). Generally the surface is associated with forced regression and high energy normal regression where the shoreline trajectory at a low angle. Regressive ravinement surface and regressive wave ravinement are the different terms recommended by Galloway (2001, 2004).

7.1.4.4 Maximum regressive surface (MRS): It is a surface that marks a change in shoreline trajectory from lowstand normal regression to transgression. The surface encompasses youngest marine clinoforms onlapped by transgressive strata and corresponding correlative surfaces develops in non-marine and deep-water settings. It forms during base-level rise when depositional trend change from coastal progradation to retrogradation. It appears as surface the end of regressive phase along depositional-dip line. Alternative terms are: transgressive surface (Posamentier and Vail, 1988), surface of maximum regression (Helland-Hansen and Gjelberg, 1994), conformable transgressive surface (Emery, 1995), top of lowstand surface (Vail et al., 1991) and maximum progradation surface (Emery and Myers, 1996). For the present study, author has also use the term **regressive surface**; not maximum regressive surface, which represents highstand regression to transgression for shoreface marine sequences.

7.1.4.5 Maximum flooding surface (MFS): Transgression to highstand normal regression change marked by a surface called Maximum flooding surface (Posamentier et al., 1988; Van Wagoner et al., 1988; Galloway, 1989). It is commonly downlap surface in shallow-water settings, where highstand coastlines prograde on top of transgressive condensed sections. Along depositional dip line, this surface corresponds to end-of-transgression event. This surface can call as: final transgressive surface (Nummedal et al., 1993); maximum transgressive surface (Hellan-Hansen and Martinsen, 1996) and surface of maximum transgression (Helland-Hansen and Gielberg, 1994). As mentioned in the maximum regressive surface, here also, author has applying **transgressive surface** term for the present study which demonstrates transgression to highstand regression.

7.1.4.6 Transgressive ravinement surfaces: This is an erosive surface formed by either tidal or wave scouring activity during transgression. The surface is confined to coastal to upper shoreface settings. Usually, these surfaces are called as **flooding surfaces**. Basinward extinction of such surfaces joins with the maximum regressive surface and landward termination joins with the maximum flooding surface (Catuneanu et al., 2009). Wave and tidal ravinement surfaces are the two basic types of transgressive ravinement surfaces.

7.2 TRACE-FOSSILS AND SEDIMENTARY CYCLES IN SEQUENCE STRATIGRAPHY

A number of studies indicate that ichnofacies along with ichnoguild and ichnoassemblages analysis may significantly contribute in characterizing and differentiating system tracts within depositional sequence and in recognizing major sequence stratigraphic surfaces (e.g. Frey and Pemberton, 1984; Frey and Pemberton, 1985; Ghibaudo et.al., 1996; Frey and Howard, 1990; Savrda, 1991). Trace-fossils are proving to be one of the most important groups of fossils in delineating stratigraphically important boundaries related to sequence stratigraphy (Pemberton and MacEachern, 1995; Pemberton and MacEachern, 2005; MacEachern et al., 1991a, b, 1992a, b), allostratigraphy (Pemberton et al., 1992a), and event stratigraphy (Frey and Goldring, 1992; Pemberton et al., 1992b). Use of trace-fossils along with sedimentary structures to document the anatomy of a depositional sequence and to define boundaries and internal organization of parasequences in relatively mix siliciclastic - carbonate setting at shallow marine to shelf conditions. Fursich et. al., (2001); Fursich and Pandey (2003); Mishra and Biswas (2009) have worked on the line of sequence stratigraphy using sedimentary cycles and shell concentrations in the Jurassic - Cretaceous sequence of Kachchh, western India.

7.3 SEQUENCE STRATIGRAPHIC SURFACES OF THE STUDY AREA

The third order sequence of Bathonian to Oxfordian in the Jhura dome is composed of a Transgressive system tract, comprising NWWLs; CSSL; DOs deposits along with one Transgressive Surface (TS); two Flooding Surface (FS); Transgressive Lag Deposits (TLD); Maximum flooding surface (MFS) and Highstand system tract mainly consisting of five Regressive Surfaces (RS); five Correlative Conformities (CC) and one Maximum Regressive Surface (MRS). In shallow marine sequences, the classical types of system tracts, i.e. TST, HST and LST (e.g. Van Wagoner et al., 1988), are commonly represented only by the former two because, due to lack of accommodation space, lowstand deposits are generally absent (Embry 1993, 1995; Holland 1993; Brett 1995; Fursich et al., 2001).

Mixed siliciclastic-carbonate sedimentation occurs primarily within arid settings characterized by low influx of clastic sediments to the shoreface (Gostin et al., 1984; Flessa and Ekdale, 1987; Belperio et al., 1988). Low clastic input may be due to low relief and thus low sediment availability in the source area, or to minimal fluvial input to the shoreline. In arid setting, particularly those with a gently sloping shoreface, bioclastic accumulation may outpace siliciclastic deposition. The sequence of the Jhurio and Jumara formations of Jhura dome is characterized by a unique mixture of siliciclastic and oolitic limestone (=clastic limestone) as well as bedded limestone.

7.3.1 Drowning unconformity

The study area have both carbonate and siliciclastic sequences, mixed system alternate in time and conforming to the concept of reciprocal sedimentation (Wilson, 1967). The termination of carbonate production and the shift to a siliciclastic system may be attributed to various controls, like 1) subaerial exposure triggered by base-level fall; 2) rapid base-level rise and consequent drowning of the carbonate system; 3) progradation of siliciclastic systems under normal regressive conditions and 4) change in climate and ecological conditions (Catuneanu et al., 2009). The sudden increase in terrigenous run-off, including both siliciclastic sediment and nutrients, may eventually shut down carbonate factory. Here in the study area due to rapid base-level rise and subsequently, drowns carbonate production provide an opening to siliciclastic deposits under regressive phase. Normally, Drowning unconformities wrap by progradation of siliciclastic system and develop under normal regression of HST.

Drowning unconformity has been observed twice in the entire sequence of Jhura dome (Fig. 7.5), where BLs comes in contact with overlying clastic facies like CSSL and NWWLs overlain by CSSL of Jumara Formation. Trace fossils of significance with the drowning unconformity are *Zoophycos, Thalassinoides, Rhizocorallium, Urohelminthoida, Ophiomorpha, Protovirgularia, Lockeia, Phoebichnus, Palaeophycus, Keckia, Cosmorhaphe, Cochlichnus, Chondrites, Beaconites* and *Ancorichnus* representing SWWB to shelf depositional environment.

7.3.2 Correlative Conformity

As mentioned in the introductory part of sequence stratigraphy as well as in the Fig. 7.4, a surface develops either at the onset or at the end of forced regression. Five times onset of forced regression has developed within entire sequence of the Jhurio and Jumara Formations contained by two Highstand System Tracts. The coastline is forced to regress, irrespective of sediment supply giving rise to a coarsening upward-shallowing upward prograding sequence of GOs and calcareous coarse grain sandstone of RMCSSL, overlain by Transgressive CSSL and shale of RMCSSL respectively. A coastline forced to regress in forced regression is due to rifting that took place in early stages by series of sub-parallel latitudinal faulting along primordial tectonic trends (Biswas, 1987). A sudden decrease in bathymetry is indicated by many opportunistic dwelling and feeding burrows like *Ophiomorpha, Skolithos, Diplocraterion, Arenicolites, Rhizocorallium, Calycraterion, Palaeophycus, Planolite* and *Margaritichnus*.

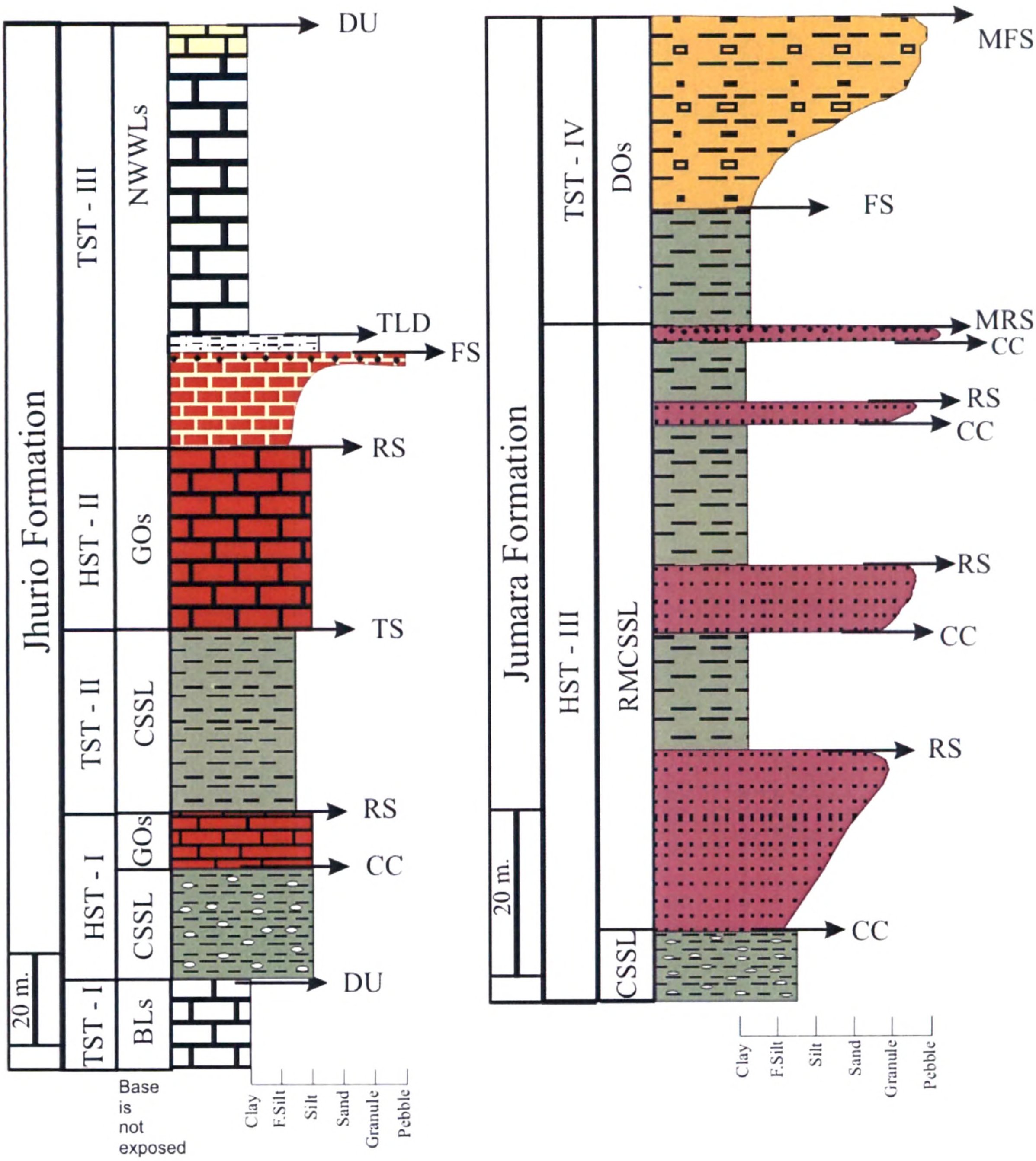

Fig. 7.5 A composite stratigraphic section of Jhura dome showing identified sequence stratigraphic surfaces and corresponding system tracts. FS = Flooding Surface; MRS = Maximum Regressive Surface; CC = Correlative Conformity; RS = Regressive Surface; DU = Drowning Unconformity; TLD = Transgressive Lag Deposits; TS = Transgressive Surface.

7.3.3 Transgressive Surface

The surface reveals transgression to highstand regression; change in depositional environment from deep to shallow. Transgressive surfaces are manifest by largely non-erosive low-energy marine FS. The transgressive surface occurs once at the top of CSSL of Jhurio Formation of Transgressive System Tract (Fig. 7.5).

This surface may coincide with the Maximum Flooding Surface (MFS) at foreshore environment. Along the strike, the surface records a higher degree of diachroneity, reflecting by high density and high diversity of ichnofossils. Presence of densely crowded *Rhizocorallium uraliense* feeding burrows along with *Diplocraterion, Pilichnus, Chondrites, Palaeophycus* and *Planolites* indicates a distinct break in offshore deposition and vertical shift in facies.

The surface is typically characterized by the abrupt juxtaposition of offshore facies (CSSL) with shoreface facies (GOs). The ichnology associated with transgressive surface is dense. The facies immediately overlying the surface is thick GOs showing shoreface environment. The suite consists of deposit-feeding structures, dwelling as well as grazing structures. The foremost trace-fossils are *Rhizocorallium, Chondrites, Diplocraterion, Palaeophycus, Pilichnus, Planolite, Scolicia, Thalassinoides, and Urohelminthoida* modest are *Arenicolites, Calycraterion* and *Laevicyclus* propose mixture of *Cruziana* and *Skolithos* Ichnofacies. The trace-fossil suites show abundant burrowing, characterized by a high diversity of forms, a lack of dominance of a few forms, presence of significant numbers of specialized feeding/grazing structures, and uniform distribution of individual elements, supportive of an equilibrium, unstressed community within fully marine environments. Sedimentation is interpreted to have been relatively slow and generally continuous.

7.3.4 Regressive Surface

A surface which represents the end of Highstand system tract in comparatively intermediate lower shoreface environment (GOs), where as in shoreface shallow marine environment (RMCSSL), it signifies end of forced regression and back to normal regression on the top of calcareous coarse grain sandstone of RMCSSL. In the second case, it may be called Correlative Conformity. Hunt and Tucker (1992) have described CC surface that marks the change in stratal stacking patterns from forced regression to lowstand normal regression, in absence of Lowstand system tract however, the author has not used the term CC for Regressive surface. It forms two times at the end of Highstand system tract and thrice within Highstand system tract (Fig. 7.5). For the lower shoreface facies, it signifies *Cruziana* ichnofacies and shoreface shallow marine environment be evidence for *Skolithos* to proximal *Cruziana* ichnofacies. A surface at the end of Highstand system tract is associated with trace-fossils like *Margaritichnus, Monocraterion, Arenicolites, Ophiomorpha, Chondrites, Keckia, Palaeophycus, Phycodes, Sabularia, Taenidium* and *Thalassinoides*. The high diversity and abundance of *Arenicolites, Ophiomorpha, Skolithos, Taenidium, Keckia, Phycodes* and *Chondrites* suggest lower shoreface to transition depositional environments. In context with regressive surface of shallow shoreface deposits, they typically contain, *Arenicolites, Bergaueria, Diplocraterion, Ophiomorpha, Palaeophycus, Thalassinoides* and *Parahentzscheliana*.

7.3.5 Flooding Surface or Transgressive ravinement surface

A Flooding surface is a high energy Transgressive surface within Transgressive system tract and has transgressive facies above as well as below. To some extent it shows erosive nature due to scouring activity of either wave or tide. Striking features like reworked concretions, pebbles and fossils are seen in the intraformational conglomerate towards the top of GOs where as there is no bioturbation in the relatively deeper environment of thick shale of Dos. It occurs twice in the present study area, on the top of thick gypseous shale of DOs and top of GOs; both represent different depositional environments. In the shoreface it is developed on the Bottom of Transgressive lag deposits and top of GOs of Jhurio Formation while non-bioturbated transgressive thick shale is developed on the top of Jumara Formation. As such, there is no establishment of any biogenic activity at the surface or within the facies. As it is found within Transgressive system tract, it has been described under flooding surface.

7.3.6 Maximum Regressive Surface

A surface that is marks a change in shoreline trajectory from transgression to Lowstand normal regression. A surface found only once in the entire Mesozoic sequence of the Jhura dome at the end of Highstand system tract, top of RMCSSL. This surface is underlain by thick transgressive shale of Highstand system tract of DOs and overlain by intercalated shale of RMCSSL. At Kamaguna, the coarsening-upward sequence of the upper most sandstone is topped by poorly sorted, gravelly to coarse-grained, trough cross-bedded sandstone with sandstone pebbles. Typical sedimentary structures associated with this surface are ripple marks and cross-stratification, extremely rich in bivalve, brachiopods and gastropods; conglomeratic nature towards the top suggests maximum regression over the period of time recommend shoreface environment of deposition. It shows end of regression and startup of transgression of Transgressive system tract. The same has been recommended on the basis of associated ichnofossils. The resident ichnofauna consists of a moderately high-diversity and high-density trace fossil assemblage. Trace fossils include *Ophiomorpha*, *Arenicolites*, *Diplocraterion*, *Planolite*, *Parahentzscheliana*, *Calycraterion* and *Palaeophycus*.

7.3.7 Transgressive Lag Deposits

Transgressive lags usually record time intervals and, as a result, bear the imprint of various taphonomic processes (Fursich and Oschmann, 1993). Simple transgressive lags are thin, relatively coarse grained beds that contain pebbles, shell fragments, intraclasts or other clasts. Due to long residence time on the sea floor, reworking, transport, bored and encrusted concretions were found along with abundant skeletal concentrations and shells of molluscan-brachiopods; suggesting storm influenced deposition above fair weather wave base. Transgressive lag deposit formed once during Transgressive system tract in the Jhurio Formation; a transgressive lag that blankets the ravinement surface (flooding surface) in the shoreface environment overlying GOs (Fig. 7.5).

7.3.8 Maximum Flooding Surface

The typical Oxfordian Dhosa Oolite member represents slow and low rate of pelagic sedimentation (Singh, 1989; Fursich at al., 1992), a lithologically very variable unit which extended across much of the Kachchh sub-basin and contained several ammonite zones (Fursich et al. 1992), in usually less than 20 m thickness. Hard-grounds, shell-rich (ammonites-belemnites), reworked concretions with cemented fill concentration, shell pockets and shell layers consist of entire 'Dhosa Oolite' at the end of Transgression. Top most bed of Dhosa oolite is exposed as hard, resistant, ridge-forming, highly fossiliferous (ammonoids-belemnites), olive brown weathered, conglomeratic in nature (pebbles, crinoid debris, Fe-oncoid), ferruginous oolite. The typical 'Dhosa Oolite' band is about 1 – 1.5 m.

thick and forms a distinct Maximum flooding surface towards the top. The trace-fossils in this part of the conglomeratic section are eventually absent. Finally, at Kamaguna and Jhura village, trace fossils are represented by abundant species of *Chondrites; Palaeophycus, Thalassinoides, Gyrochorte Rhizocorallium* and *Zoophycos* suggesting *Cruziana* ichnofacies according to the classic bathymetric ichnofacies model of Seilacher (1967) and Frey and Seilacher (1980). Furthermore, presence of abundant species *Zoophycos* in the *Cruziana* type of setting, indicate that the animals temporarily accommodated themselves in the transgressive sequence. Trace fossil distribution and degree of bioturbation proves transition to upper offshore depositional environment.

7.4 POTENTIAL SEQUENCE BOUNDARIES

There is as such no potential sequence boundary formed in the studied section of the Jhura dome. The entire sequence of the Jhurio and Jumara Formations were deposited in the near shore marine shoreface to offshore depositional environment indicating absence of Lowstand system tract where subaerial exposure has been observed. Top of the DOs may be considered as correlative surface of MFS in the transition to offshore environment. The Drowning unconformity at the top of NWWLs is may be considered as a potential sequence boundary which divides the entire sequence into two major tectno-sedimentary events.

7.5 SYSTEM TRACKS

The sequence of the Jhura dome comprises only two system tracks i.e. Transgressive system tract (TST) and Highstand system tract (HST) that conformably overly each other like T-R sequence. In general, transgression corresponds to TST and regression is resultant of HST. There are four TSTs and three HSTs identified on the basis of 1) depositional system-trend below and above the contact; 2) type of ichnofacies; 3) ichnoassemblages and ichnoguilds and 4) conformable versus unconformable nature of contact within the sequence of study area.

TST – I has bedded limestone along with *Zoophycos* ichnofacies indicating a shelf, below storm weather wave base (SWWB) depositional environment. TST – II contains thick CSSL facies with *Cruziana* ichnofacies suggestive of upper offshore to lower offshore environment. TST – III comprise of transgressive lag; flooding surface and thick bedded parallel laminated limestone intercalated with oolites in the lower part indicating lower offshore to shelf environment of deposition above SWWB. TST – IV includes one flooding surface which divides thick shale of DOs and Dhosa oolite beds where Dhosa oolite conglomeratic section conformably overlies thick shale containing *Cruziana* ichnofacies suggesting an offshore depositional environment.

HST – I deposits unconformably underlain by TST – I and overlain by TST – II deposits comprise of CSSL facies in the lower part and GOs facies in the upper part, with correlative conformity (CC) as a dividing surface. It has both distal *Skolithos* and *Cruziana* ichnofacies indicating transition to lower shoreface environment of deposition. HST – II deposits have thick mega rippled GOs facies showing *Skolithos* ichnofacies and indicating lower shoreface above FWWB environment. HST – III has RMCSSL facies, MRS on the top as well as forced regressive coarsening upward parasequence along with *Skolithos* ichnofacies designated as lower and middle shoreface environment of deposition.

7.5.1 Transgressive System Tracts

TST – I (Shelfal): Thick Badi Limestone subfacies (BLs), where the base is not exposed, is the oldest rock exposed in the study area as well as in the Mainland Kachchh. It establishes unconformable contact with siliciclastic facies of CSSL and marks the drowning unconformity where the carbonate production drowns due to subsequent rise in base-level. Transgression was very slow and it has been understood as still stand condition of base level prevailing at the time of deposition of BLs. The dominant trace fossil is *Zoophycos* associated with *Thalassinoides*, *Rhizocorallium* and rarely *Ophiomorpha*. The low diversity trace fossil assemblage is characteristic of *Zoophycos* ichnofacies of Seilacher (1967), although it certainly does not correspond to greater depth (i.e. continental slop) as implied by Seilacher's original scheme. In the presence of above mentioned ichnofossils and lack of sedimentary structures these have been identified as shelf environment of deposition below SWWB.

TST – II (Upper to Lower Offshore): About 40 to 45 m. thick calcareous silty shale lithofacies of Jhurio Formation was deposited under the transgression of TST – II deposits comprising of thin parallel laminations. It unconformably overlies GOs of HST where lower shoreface deposit comes in contact with offshore deposits. The presence of *Diplocraterion habichi* along with *Rhizocorallium* clearly suggests a transgressive surface on the top and a regressive surface at bottom confining the entire deposits to the Transgressive system tract. As mentioned above in the transgressive surface, it has high diversity and density among the trace fossils suite. Degree of bioturbation of feeding and grazing traces decreases with the depth indicating relatively deepening upward trend and enormous feeding burrows observed on the top of TS. The ichnologic record of TST – II comprising *Rhizocorallium, Pilichnus, Planolites, Chondrites, Palaeophycus, Scolicia, Thalassinoides, Phymatoderma and Urohelminthoida* assemblage suggest *Cruziana* ichnofacies along with sporadic development of an opportunistic distal or outer *Skolithos* ichnofacies suggests upper offshore to lower offshore depositional environment.

TST – III (Lower Offshore to Shelf): These deposits are characterized by upward increase in carbonate content from oolitic facies to well bedded limestone of Jhurio Formation. It has been interrupted twice through a flooding surface and a transgressive lag. There are two 4th order parasequences identified on the basis of flooding surface. The lower parasequence is consisting of intercalations of GOs and NWWLs where as the upper parasequence is of well bedded limestones. Both the parasequences show different ichno-suites corresponding to the depositional environment. During this TST-III, again transgression was very slow and it has been considered as still stand condition of base level prevailing at the time of deposition of NWWWLs. GOs has developed within lower offshore environment with bedded limestone as suggested by the associated ichnoassemblage of abundant *Taenidium, Keckia, Thalassinoides, Gordia, Phycodes, Palaeophycus, Didymaulichnus, Asterosoma* and *Sabularia*. The upper parasequence consists of about 60 to 65 m. thick Nodular White Well Bedded Limestone subfacies with parallel lamination, the ichnoassemblage associated with the parasequence is *Protovirgularia, Lockeia, Thalassinoides, Cosmorhaphe, Phoebichnus, Cochlichnus, Beaconites* and *Scolicia* representing shelfal deposition environment. In summary, the TST – III have shown the lower offshore to shelf environment of deposition.

TST- IV (Lower to Upper Offshore): A typical 20 m. thick DOs as cap facies of these Transgressive system tracts and forms a Maximum flooding surface. It has one flooding surface which divides the thick, monotonous, soft, very fine-grained, transgressive gypseous shale from upper Dhosa oolitic bands. No biogenic activity is found associated with the gypseous shale as well as flooding surface. A 4th order Parasequence gypseous shale unit can be recognized on the basis of a flooding surface at top and a MRS at bottom. The TST - IV is an unconformable contact with underlain HST of RMCSSL. The DOs is coarse-grained, siltysandy, variably oolitic with copious concentration of ammonoid - belemnites and subsequently it forms conglomeratic nature towards top. Numerous *Zoophycos* beds along with *Chondrites, Thalassinoides, Palaeophycus, Rhizocorallium* and *Gyrochorte* suggest *Cruziana* ichnofacies developed in upper offshore depositional environment.

7.5.2 Highstand System Tracts

HST – I (Transition to Lower Shoreface): Followed by drowning unconformity of TST – I, it shows coarsening upward (shallowing upward-regressive) sequence consisting of calcareous silty shale to oolitic GOs. This system tract is dominated by lower Calcareous Silty Shale Facies in thickness from 25 to 30 meter and upper 10 to 12 meter thick oolitic facies. The upper oolitic facies contain well bedded, rubbly, Fe-oolitic bioclastic grain to rudstone showing coarsening upward sedimentation. A correlative conformity divides the lower silty shale facies from upper oolitic facies. It demonstrates the *Diplocraterion, Arenicolites, Calycraterion, Rhizocorallium, Palaeophycus, Planolite* and *Margaritichnus* ichnoassemblage. The top surface concludes as regressive surface, with ichno-suits of *Arenicolites, Ophiomorpha, Skolithos, Margaritichnus, Monocraterion, Chondrites, Palaeophycus, Phycodes, Sabularia,* and *Thalassinoides*. Overall, ichnoassemblages of both the facies indicates transition to lower shoreface environment of deposition.

HST – II (Lower Shoreface above FWWB): This system tract is dominated by 40 meter thick oolitic facies rich in Fe giving golden color to the facies called 'Golden-oolite'. Towards the top, it becomes more massive and cross-bedded and terminates with a meagripple surface. The trace-fossils are abundant and uniformly distributed throughout the facies. *Ophiomorpha, Diplocraterion, Skolithos, Arenicolites, Planolites, Pilichnus, Palaeophycus, Phycodes, Gordia* and *Thalassinoides,* comprise the dominant elements of the suite, and are present in moderate numbers in the facies. Based on lithology, sedimentary structures, and trace-fossils data, the HST – II can be clearly interpreted as sediments deposited in fully marine, high energy, lower shoreface environment.

HST – III (Lower to Middle Shoreface): A characteristic 80 meter thick fully siliciclastic sequence (CSSL - RMCSSL) of Jumara Formation is regarded as Highstand system tract – III. The sequence contains four shallowing upward-regressive 4^{th} order cycles by means of three regressive; four correlative conformities and a maximum regressive surface at the end of system tract. The entire siliciclastic sequence has been introduced informally by Biswas (1980) as 'Ridge Sandstone Member'. The system tract has established contact with overlying gypseous shale of TST – III and underlying drowning unconformity of TST – II (NWWLs) of Jhurio Formation. All four shallowing upward-regressive cycles have shown medium to coarse-grained sandstone with trough-crossbedding scattered pebbly ripple surfaces towards the top (Fig. 7.5). Subsequently, four, intercalated argillaceous silty shale facies were deposited after regressive surface within the HST – III system tract. The ichnofossils associated with the coarse-grained sandstone facies are *Ophiomorpha, Arenicolites, Monocraterion, Margaritichnus, Diplocraterion, Laevicyclus, Gordia* and *Calycraterion* and those with the silty shale are *Thalassinoides, Planolites, Pilichnus, Phycodes, Parahentzscheliana, Palaeophycus, Gyrolithes, Gyrochorte, Bergaueria, Biformites, Ancorichnus, Rhizocorallium* and *Chondrites*. Hence, the overall sedimentary environment of the system tract is shallow marine high energy lower shoreface to middle shoreface based on lithologic character, sedimentary structures and ichnoassemblages.