CHAPTER 7
SEQUENCE STRATIGRAPHY

7.1 CONCEPTS OF SEQUENCE STRATIGRAPHY

The concept is defined as a succession of strata deposited during a complete cycle of change in accommodation and sedimentation; it encompasses all types of sequence and has the option of application of any model of choice (Catuneanu et al., 2009). It was introduced three decades ago (Payton, 1977) and is still undergoing refinement. The method could not be standardized as code in the International Subcommission on Stratigraphic Classification (ISSC) due to a lack of consensus amongst different schools of thought on its methodology and models (Catuneanu et al., 2009).

7.1.1 SEQUENCE

It is defined as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum, 1977). However, the latest study of Catuneanu et al. (2011) removes the criterion of unconformities at its boundaries and identifies sequence as "*A stratigraphic cycle defined by the recurrence of the same type of sequence stratigraphic surface in the rock record.*" Later studies defined various sequences viz. depositional, genetic stratigraphic, and transgressive-regressive, which are also referred to as models.

7.1.2 PARASEQUENCE

A parasequence like sequence is a relatively conformable succession of genetically related beds, but they are bounded by flooding surfaces and are progradational; they may be stacked to produce progradational, retrogradational, and aggradational parasequence sets which resemble the systems tract of a sequence (Van Wagoner et al., 1987, 1988, 1990; Catuneanu et al., 2009). Several authors have considered the concept of parasequence and sequence equivalent and objects of the same rank that differ in the internal architecture and are bounded by surfaces of deepening and shallowing, respectively (Zecchin, 2010). The usage of this term is dropped considering inconsistencies in its definition and limited applicability (coastal and shallow water settings) compared to a sequence that encompasses all depositional systems across the sedimentary basin. Its applications are limited to shallow marine cycles without intervening relative sea-level falls. Others extended the term in succession, recording the full cycle of relative sea level change or alluvial settings and even deep water (Walker, 1992; Catuneanu, 2006; Zechhin, 2007, 2010). Since the concept is limited to a specific architecture and depositional setting and cannot effectively describe cyclic succession, the author has also observed limited usage in sequence stratigraphic analysis in the present study.

7.1.3 SEQUENCE STRATIGRAPHY

The Sequence stratigraphy is the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition or their correlative conformities (Posamentier et al., 1988; Van Wagoner, 1995) as they develop in response to variations in sediment supply and space available for sediment to accumulate (Posamentier and Allen, 1999). The relatively conformable sequence always includes the genetically related strata, but genetically related strata do not always consist of a conformable sequence because the presence of the subaerial unconformity (which lies as internal unconformity) within the genetically related sequence would break the continuity in paleogeographic evolution, leaving the succession not relatively unconformable and can no longer be considered negligible. Therefore recently, the concept of relatively conformable succession was removed from the definition of a sequence by Catuneanu (2019). It focuses on analyzing the variation in facies and the geometric of strata and recognizing the major surfaces to understand the chronology of basin fill and erosional events.

The concept of base-level changes and the rate of base-level changes is explained in Figure 7.1. No. 0-3 marks the positive base level; however, the base-level within it varies from rising (0-2) and falling (2-3). Similarly, no. 3-6 marks the negative base-level, but its base-level varies from falling (3-4) to rising (4-6). The trends of falling base-level during positive and negative base-level changes when combined give the base-level fall/ negative rate of base-level change (c-d), while the trends of rising base-level during positive and negative base-level changes when combined give a rise in base-level/ positive rate of base-level change (a-c; d-g). When combined with sedimentation, the rate of the base-level change gives rise to transgression or regression. The transgression occurs when the rate of base-level change curve is positive and above the sedimentation line. Normal regression occurs when the rate of base-level change curve is positive (either at the start of base-level fall or rise) but is less than the rate of sedimentation line (Fig. 7.1). Forced regression occurs when the rate of base-level change curve is negative and below the rate of sedimentation line.

7.1.3.1 Systems tract/Genetic units

It is defined as the linkage of contemporaneous depositional systems that forms the sequence's subdivision (Brown and Fisher, 1977), which is interpreted based on stratal stacking patterns at bounding surfaces and positions within the sequence (Van Wagoner et al., 1987, 1990; Van Wagoner, 1995). It includes all strata accumulated across the basin during a particular stage of shoreline shifts. The nomenclature for systems tract differs based on models viz. the systems tract nomenclature used for transgression is transgressive systems tract; early lowstand, late highstand, forced regressive wedge, and falling stage are used for forced regression; late lowstand, and lowstand are used for lowstand normal regressive deposits whereas highstand or early highstand are used for highstand normal regressive deposits.

7.1.3.2 Base level

Base-level is generally referred as the sea level, and lies below it (due to waves and currents and because rivers meeting sea erode below the sea level, which is the base level) and is considered as a dynamic surface moving with respect to changes in eustatic sea-level changes to which continental denudation and marine aggradation take place (Jervey, 1988; Schumm, 1993; Posamentier and Allen, 1999; Catuneanu, 2002). Its projection into the continent defines the level up to which continental denudation can take place (Plummer and McGeary, 1996). It is variably defined as the surface of balance between erosion and deposition (Cross, 1991), above which particles cannot come to rest and below which deposition and burial are possible (Sloss, 1962), placed at the lowest level of continental erosion or lowest point on a fluvial profile and is the highest level up to which a sedimentary succession can be built (Twenhofel, 1939). Sequence stratigraphy uses the base level

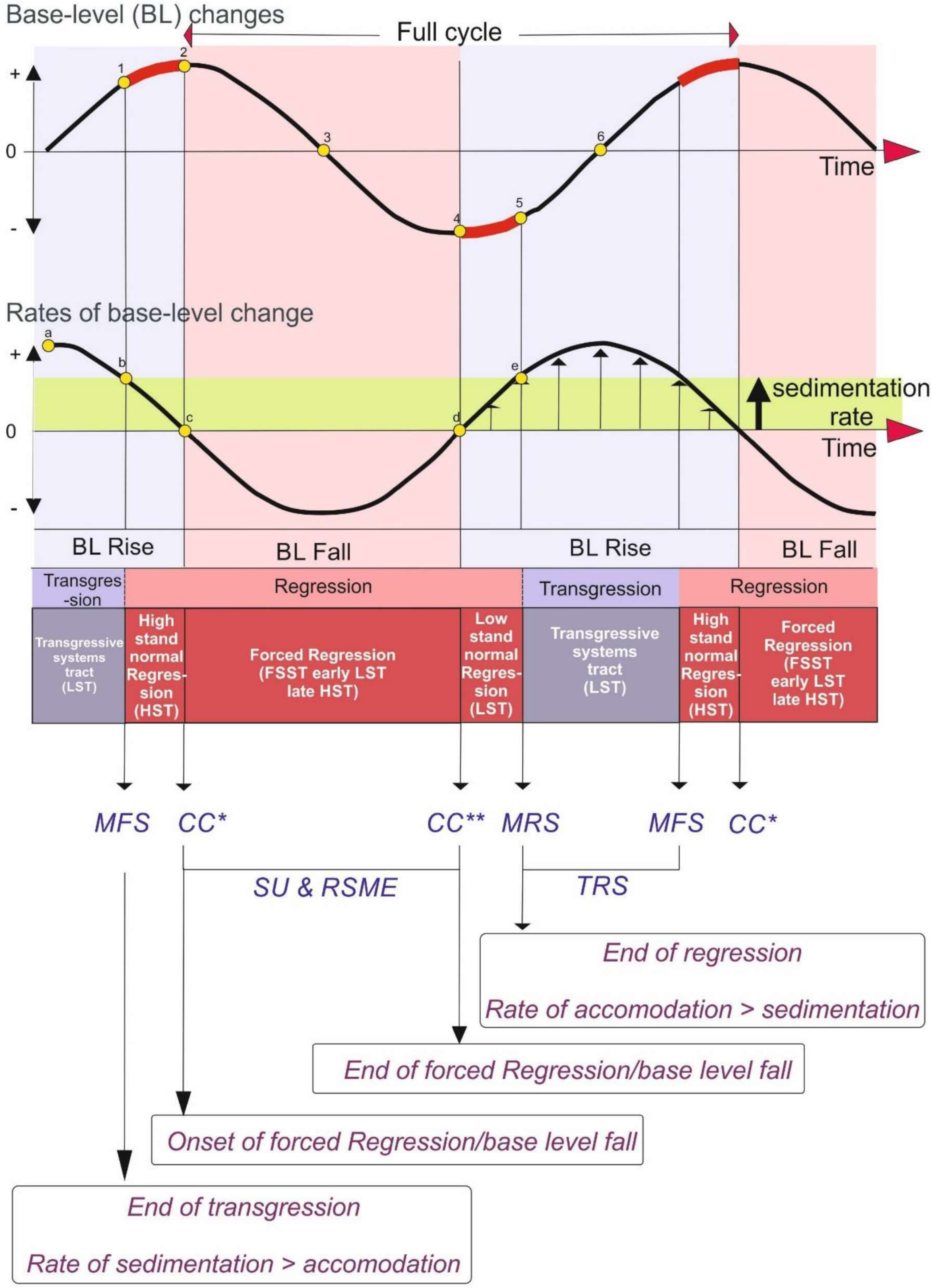
Base-level (BL) changes
Full cycle
Time
Rates of base-level change
sedimentation rate
Time
BL Rise
BL Fall
BL Rise
BL Fall
Transgres -sion
Regression
Transgression
Regression
Transgressive systems tract (LST)
High stand normal Regres-sion (HST)
Forced Regression (FSST early LST late HST)
Low stand normal Regres-sion (LST)
Transgressive systems tract (LST)
High stand normal Regres-sion (HST)
Forced Regression (FSST early LST late HST)
MFS
CC*
CC**
MRS
MFS
CC*
SU & RSME
TRS
End of regression
Rate of accomodation > sedimentation
End of forced Regression/base level fall
Onset of forced Regression/base level fall
End of transgression
Rate of sedimentation > accomodation

Figure 7.1 Transgression, regression, and forced regression defined by the interplay of base-level changes and sedimentation at the shoreline (Catuneanu, 2002, 2006; Catuneanu et al., (2009). LST marked by thick red lines represent the initial stage of base-level rise when the rates of base-level rise increase from zero and HST represent the late stages of base-level rise when the rates of base-level rise decrease to zero. CC* and CC** stand for correlative conformity in the sense of Posamentier and Allen (1999) and Hunt and Tucker (1992), respectively. Abbreviations: MFS – maximum flooding surface, CC – correlative conformity, MRS – maximum regressive surface, SU – subaerial unconformity, RSME – regressive surface of marine erosion, TRS- transgressive ravinement surface.

concept as a curve of base-level fluctuations, which describes changes in accommodation at the shoreline when consumed by sedimentation, giving rise to transgressive or regressive shifts in the shoreline (Catuneanu, 2002). In other words, the ratio between the rate of base-level changes and sedimentation gives rise to transgression and the two types of regression (Plint, 1988; Posamentier et al., 1992). The base-level fluctuations are affected by eustatic, tectonic, climatic, diagenetic, wave, and current energy changes and are independent of sedimentation (Catuneanu, 2002). The concept of base level is used for marine and lacustrine settings, whereas the concept of graded fluvial profile for alluvial settings.

7.1.3.3 Accommodation

The available space to be filled up to the base level for sediments is defined as accommodation (Jervey, 1988); this space can be either created or destroyed by the rise and fall of the base-level, respectively. The accommodation space is measured by the vertical distance between the seafloor and base level, and its consumption at higher and lower sedimentation rates results in shallowing and deepening of water, respectively (Catuneanu, 2002). Forced regression represents the negative accommodation, whereas progradation and retrogradation are represented by positive accommodation i.e., water deepening or shallowing can occur at the time of base-level rise depending on the balance between the rate of accommodation and sedimentation.

7.1.3.4 Transgression

The landward shift of shoreline results in the landward shift of facies and deepening of marine water close to shoreline due to a rise in base-level at a rate higher than sedimentation. Transgression in a fluvial sequence is indicated by tidal evidence, oyster beds, and brackish to marine trace fossils (Shanley et al., 1992; Miall, 1997; Catuneanu, 2002).

7.1.3.5 Regression

The seaward shifts of shoreline and facies result in the shallowing of the marine water close to shoreline driven by either high rates of sediment supply during base-level rise (normal regression) or base-level fall (forced regression). Marine facies overlain by nonmarine facies indicate regression in a marine sequence. Normal regression occurs in the early and late stages of base-level rise, whereas forced regression is due to base-level fall irrespective of the sedimentation rate (Catuneanu, 2002).

7.1.3.6 Stacking patterns (depositional trend)

The stratal stacking patterns changes in response to the base-level and rate of sedimentation changes. Each defines a genetic deposit/systems tract (transgressive, lowstand, and highstand normal regressive and forced regressive). The stratal stacking patterns reflect a combination of depositional trends (progradation, aggradation, retrogradation, and downcutting). Transgression gives rise to a retrogradational stacking pattern where the accommodation space/rate of base-level rise outpaces the sedimentation rate. Forced regression produces the progradation with downstepping pattern irrespective of the sediment supply, whereas Normal regression (HST and LST) also produces the diagnostic progradational stacking pattern accompanied by aggradation (in delta plain systems), wherein the rate of sedimentation outpaces the accommodation space/rate of base-level rise (Catuneanu, 2002). The progradational and downstepping pattern is formed in forced regression due to the successive drops in sea level forming a subaerial unconformity.

7.2 SEQUENCE STRATIGRAPHIC MODELS, SURFACES, AND BOUNDARIES

According to Catuneanu et al. (2009), an interplay between accommodation and sedimentation generates transgressive and regressive shifts in the shoreline, giving rise to genetic units/systems tracts (transgressive, forced regressive, highstand, and lowstand normal regressive). Each of these genetic units is defined by a stratal stacking pattern (retrogradational, progradational, and aggradational), bounding surfaces consisting of systems tracts/genetic units (LST, TST, HST, FSST). The depositional models have systems tracts, and their order of occurrence is the stratal stacking pattern. In the different sequence stratigraphic models, the sequence stratigraphic surface can be considered the sequence boundary, a systems tract boundary, or a within systems tract contact (Fig. 7.2). There is no general agreement on which surface should be treated as a sequence boundary. The maximum flooding surface, correlative conformity, and the maximum regressive surface form the sequence boundary for the genetic sequence stratigraphic surface, depositional sequences, and the transgressive-regressive sequence, respectively (Fig. 7.2). The fining-upward and coarsening-upward texture in siliciclastic shallow water settings is used to demarcate the MFS and MRS, respectively, whereas in carbonate platforms, dirtier and cleaner limestone are used to demarcate transgression and regression, respectively. However, the timings of these surfaces depend completely on the sediment supply, which varies along the coastline resulting in highly diachronous surfaces. Still, the boundaries like correlative conformities whose formation is based on base-level shift are independent of sediment supply, synchronous over a large area, and the criterion for recognizing them is based on changes in the stratal stacking pattern irrespective of the sediment supply. Therefore, the criterion of stratal stacking pattern rather than grain size variation is used to recognize the correlative conformities since the correlative conformities form based on changes in the direction of base-level shift. Accordingly, the correlative conformity *sensu* Posamentier and Allen (1999), which occurs at the onset of relative sea-level fall, forms the sequence boundary in the Depositional Sequence I and II. It marks the change in stratal stacking pattern from highstand normal regression to forced regression. It is placed at the base of the basin-floor submarine fan complex in deepwater settings. It occurs at the onset of forced regression due to a decrease in the accommodation space; it is marked by an increase in the average grain size, also known as the basal surface of forced regression.

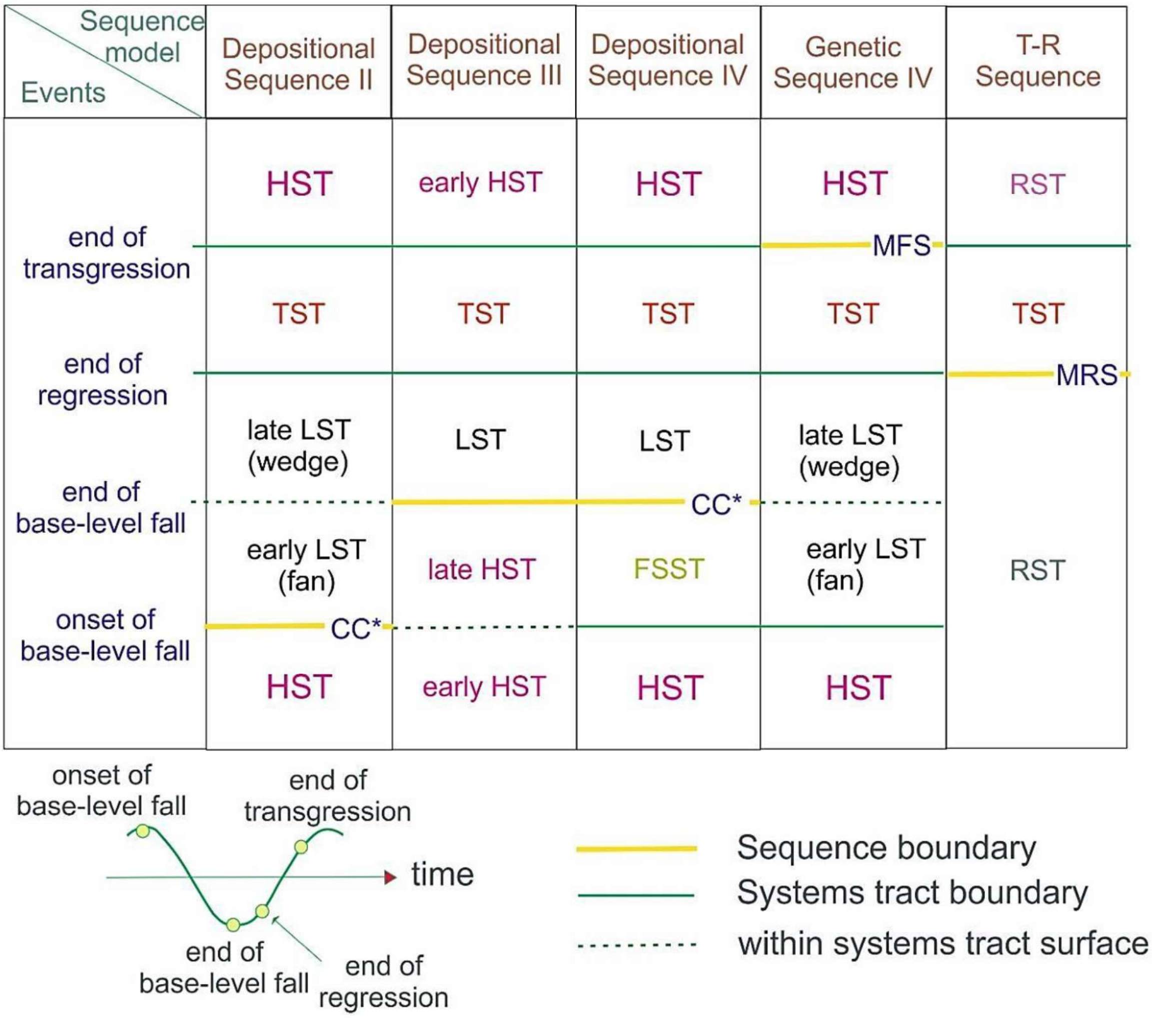

Figure 7.2 Position of sequence boundaries and the subdivision into systems tracts (Catuneanu et al. 2009). Abbreviations LST- Lowstand Systems Tract; HST- Highstand Systems Tract; TST- Transgressive Systems Tract; FSST- Falling-Stage Systems Tract; RST- Regressive Systems Tract; T-R- Transgressive-Regressive; CC*- Correlative Conformity; MFS-Maximum Flooding Surface; MRS- Maximum Regressive Surface.

Correlative conformity *sensu* Hunt and Tucker (1992) which occurs at the end of relative sea-level fall, forms the sequence boundary in Depositional Sequence III and IV (Fig. 7.2). It marks the stratal stacking pattern change from forced to lowstand normal regression. It is placed at the top of the coarsest sediments within the submarine fan complex in deepwater settings. An increase in the fluvial accommodation at the end of forced regression is represented by a decrease in the average grain size. The grain size variation observed at the top and bottom can be used to delineate the correlative conformities. The period between these two correlative conformities has no fluvial accommodation, and in the non-marine environment, it is marked by a subaerial unconformity, whereas in the marine environment, it is characterized by falling stage systems tract. Due to lack of fluvial accommodation, the sediment supplied to the coastline has coarser sediments than the normal regression; therefore, the base and top of the FSST are marked by the increase and decrease in the grain size, respectively. The correlative conformity *sensu* Posamentier and Allen (1999) and the correlative conformity *sensu* Hunt and Tucker (1992) can be distinguished based on the presence and absence of fluvial incision, respectively.

7.3 METHODOLOGY

The methodology of sequence stratigraphy constitutes model-independent workflow and model-dependent choices. The succession is divided into genetic units (systems tracts) separated by the sequence stratigraphic surfaces in the model-independent workflow. Then a model-dependent choice is made by selecting and thus elevating a particular surface to sequence boundary based on the model chosen. Names of constituent systems tracts and surfaces are model-dependent; however, specific terms based on shoreline trajectories viz. transgressive, normal regressive (lowstand and highstand), and forced regression are used as standard terms independent of the model adopted. Thus, the terminology used for the systems tracts and sequence stratigraphic surfaces for genetic units and the surface selected as sequence boundary in the model-dependent aspects does not affect the end result achieved in the analysis. Based on the difficulty encountered in identifying certain stratigraphic surfaces, it is now established that no single model can be generalized for all the case studies, and the interpreter is free to choose any of the models which would serve best to select surfaces and boundaries present in succession for correlating the relatively conformable sequence of genetically related strata. The maximum flooding surface in the genetic stratigraphic model is considered the sequence boundary (Fig. 7.1-7.2.) owing to their easier delineation in succession. The subaerial unconformities or the marine correlative conformities bound the depositional sequences; however, it poses certain problems in their usage as sequence boundaries, viz. their possible erosion during the subsequent transgressive event, identification based on recognition of base-level fall, making their identification difficult in base-level rise. The genetic stratigraphic surfaces are defined based on the base-level fall. They are independent of subaerial unconformities but, wherever available, are included within the sequence. This makes the model easier to apply to all types of cycles and those developed during constant base-level rise (Catuneanu et al., 2009).

The seven surfaces defined in Table 1 are the proper sequence stratigraphic surfaces, which can be used in part as sequence boundaries; apart from them, two other surfaces represent within trend facies contacts, namely, within trend normal regressive surface (normal regression) and within trend flooding surface (during transgression other than MRS, MFS or RS) which are highly diachronous (i.e., varies in age from place to place) with the rate of normal regression and shoreline transgression respectively. They mark lithological variation and have application more commonly in lithostratigraphy and allostratigraphy (Catuneanu, 2002). Within Trend Normal Regressive Surface has a conformable nature which does not rework the below lying deposits or systems tract boundaries and develops within LST or HST. Within Trend Flooding Surface, mark contact between shoreface sands and overlying shelf shales and develop within TST.

7.4 HIERARCHY

The different orders of cyclicity in the sequence are explained in terms of hierarchical order. The hierarchical level can also be explained as the scale of observation. The eustatic fluctuations of the global sea level are controlled by tectonics and climate. The lower orders can be recognized within a sequence with higher resolution data acquisition.

According to Catuneanu (2019), the concept of sedimentological and stratigraphical cycles are related because, at each hierarchical level or scale of observation, depositional systems (units of sedimentology) form the building blocks of systems tracts, which in turn are building blocks of sequence (both are units of sequence stratigraphy). A sequence stratigraphic unit is not controlled by age or scale; the smallest and largest scale of the systems tract and component depositional system is defined by beds and sequences, respectively. Thus, the depositional systems, although sedimentological, are related to the sequence stratigraphy (indirectly form the small element of sequence) and are a three-dimensional assemblage of lithofacies linked by genetically related processes and environments. The scale of depositional systems is not defined (varying from 10^0 to10^3 m). It depends on the purpose of the study and/or availability of data. Still, it requires minimum 10^2 years to form architectural elements (Miall, 2015). At each scale of observation/hierarchical level, they have paleogeographic significance and can be attributed to environments of deposition (Catuneanu, 2019). Thus, the systems tract can also be defined at different scales based on the purpose of the study and data availability; its lowest rank is defined by the stacking pattern of sedimentological units (beds, bedsets).

Hierarchical order	Duration (MY)	Cause
1st order	200-400	Formation and breakup of supercontinents
2nd order	10-100	Volume changes in mid-oceanic spreading centres
3rd order	1-10	Regional plate kinematics
4th and 5th order	0.01-1	Orbital forcing

Table 7.1 Hierarchical orders based on duration.

A sequence should not be regarded as 1st or 2nd order simply based on the duration (Table- 7.1), but each stage is considered as a 1st order sequence defined by a specific tectonic setting (accommodation controlled by subsidence); sequences of equal hierarchical rank in different basins may differ in terms of timing and scales. The sequence stratigraphic frameworks are basin specific, and the 1st order sequence is the fill of sedimentary basins deposited within a tectonic setting. Therefore, the limits of tectonic settings are defined by the 1st order sequence boundary. According to Catuneanu (2019), the depositional systems consisting of only sedimentological cycles are generally incorporated in the lowest rank and consist of only processes related to facies deposited in a specific environment; referred to as depositional systems *sensu stricto*. However, the higher rank depositional systems consist of lower rank stratigraphic cycles that incorporate the changes in systems tract, and the depositional systems are referred to as depositional systems *sensu lato*. The systems tract based on the stratal stacking pattern can exist at each scale except the lowest rank, consisting of only sedimentological cycles. There is no physical standard for the scale of any sequence stratigraphic unit.

7.5 SEQUENCE STRATIGRAPHIC ANALYSIS OF THE BAGH GROUP ROCKS

The composite lithologs of the Bagh Group of the WLNV revealed more or less complete development of the Cretaceous succession. It is Berriasian? (Neococmian) to Coniacian in age, whereby four different composite lithologs of (1) Navagam, (2) Men River Valley, (3) Mohanfort-Vajepur, and (4) Songir are used for sequence stratigraphic analysis. Four different models are suggested for sequence characterization (Catuneanu et al., 2009).

The choice of model in sequence stratigraphy is independent; however, the genetic type of deposits and the surfaces remain the same. For the sequence stratigraphic analysis of the WLNV basin, the interplay of base-level changes and sedimentation can be explained in the second-order Genetic Sequence model proposed by Fraizer (1974) and Galloway (1989) is used to define the sequential fillings. The integration of data on facies, conformable or unconformable stratigraphic contacts, pattern of stacking (depositional trends such as progradation, retrogradation, aggradation, and downcutting), variation of facies along the strike, stratal terminations, and geometries are used to identify the sequence stratigraphic surfaces and systems tracts. The stacking pattern helps to delineate sequence stratigraphic surfaces. Together with-it, systems tracts can be identified. Finally, the surfaces and systems tract help define the stratigraphic sequences. According to the genetic sequence model, the sedimentary succession of the Bagh Group deposits of the WLNV represents two different stratal stacking patterns, downstream controlled and upstream controlled (Catuneanu et al., 2019). Downstream controlled comprises conventional systems tracts, Transgressive Systems Tract (TST) and Highstand Systems Tract (HST) based on shoreline trajectory separated by the Maximum Flooding Surface (MFS). Upstream controlled stacking pattern characterized by channel dominated sequence comprises High Amalgamation System Tract (HAST).

The Bagh Group of the WLNV represents an intracratonic rift system characterized by continuous deposition of sediments from Berriasian? to Coniacian, which comprises the fluvio-marine genetic sequence of the 1st order. The 1st order sequence is further divided into five 2nd orders of depositional events, including HAST, LST, TST-I, HST-I, and TST-II. Based on the evidence of sedimentological and ichnological data in the Cretaceous Bagh Group, a 2nd order sequence separated by three sequence stratigraphic surfaces and one sequence boundary, Maximum Flooding Surface. These depositional events are further subdivided into fourteen 3rd order events based on stacking patterns.

7.5.1 1ST ORDER GENETIC SEQUENCE

As discussed earlier, the hierarchy of sequence is defined based on tectonic settings, and the limits of tectonic settings are defined by 1st order sequence boundary. The 1st order sequence is related to the formation and breakup of continents affecting the evolution of basins and global eustatic changes (Catuneanu, 2006). Accordingly, the 1st order sequences are applied to the entire sedimentary basin irrespective of their origin and the time span

(Catuneanu, 2019). The sequence stratigraphic analysis of the Cretaceous Bagh Group deposits ranging in age from Berriasian? (Neocomian) to Coniacian reveals a complete cycle of base-level changes (transgressive and regressive), which can be explained based on the Genetic sequence model. The genetic sequence is composed of one large-scale 1st order sequence (~56 MY). The genetic sequence model of the Bagh rocks exposed in the WLNV comprises the early syn-rift continental deposits followed by marine deposits, which marked the deepening and shallowing trend representing retrogradation, progradation, and aggradation stacking patterns.

7.5.2 2ND ORDER GENETIC SEQUENCE

The 2nd order sequences are related to the volumetric changes in the mid-oceanic ridge, relative sea-level, and accommodation caused by tectonism of scale affecting the basin and sedimentation, which would affect the basin; 3rd order with the regional plate kinematics affecting the base-level changes (Vail et al., 1991; Gale et al., 2002; Haq 2014). Accordingly, the 2nd order basin-fill within these packages corresponds to the shifts in the balance between accommodation and sedimentation (Catuneanu, 2006). The 2nd order sequence comprises HAST, LST, TST-I, TST-II, and HST-I (Fig. 7.3-7.4), and seventeen 3rd order events have been identified. These systems tract, sequences, and events are bounded by maximum flooding surface and systems tracts surfaces, including the transgressive surface of ravinement and flooding surfaces. To delineate the systems tract and sequence stratigraphic surfaces, sedimentologic characteristics in conjunction with ichnofacies such as *Glossifungites*, *Skolithos* and *Cruziana* are used, which are discussed below.

7.5.2.1 High Amalgamated Systems Tract (HAST)

The High Amalgamated Systems Tract is not related to the base-level changes; accommodation space created by tectonics and sediment supply are the main controls on the sedimentation. The stacking pattern in HAST is dominated by channel facies, low rates of floodplain aggradation, channel avulsion, and unconfined fluvial channels (Catuneanu, 2017). The high amalgamation systems tract is identified based on the progradation-aggradation stacking pattern observed in the WLNV above the Precambrian rocks. The HAST accumulated the initial continental coarse deposits in the fluvial channels, and the fan environment depicts two third-order events characterized by the deposition of conglomerates and sandstones. It is dominated by coarse-grained gravelly sandstones and conglomerates exposed around Agar, Naswadi, Chosalpura, Mohanfort, and Songir villages. This systems tract comprises a 130 m thick succession of the Berriasian? to Aptian deposited in the early rift phase. The gravelly and sandy sediments are characteristic of the alluvial fans and braided channels in fluvial systems, which gave rise to different facies like conglomerate (Plate 5.1-5.3), planar and trough-stratified sandstone (Plate 5.4), horizontal thinly-bedded sandstone, and massive sandstone (Plate 5.5-5.6). The conglomerates at the base of the Songir Formation overlie the Precambrian rocks, represents the hiatus which indicates prolonged erosion, non-deposition, and subaerial exposure. Thereafter, the deposition of thick siliciclastics suggests progradation and increasing accommodation with the advancement of rift opening. The initial coarse-grained gravelly sedimentation took place in the active channel and due to progradation and aggradation of the sediments, which occurs in the proximal portion of an alluvial fan. The advancement of fan is reflected in sedimentary characteristics giving rise to different facies like clast supported conglomerate with sandstone and planar stratified gravels. The further advancement of the fan aggrades relatively fine sediments shows amalgamation with clast-dominated conglomerates, matrix-dominated conglomerates, and planar stratified sandstone of the channel that are well developed in the Songir-Chosalpura and Mohanfort area. The horizontal stratified sandstone indicates the sheet flood over the alluvial fan. The stratified sandstone is poorly bioturbated and shows the presence of *Apectoichnus* trace fossil. The trace is interpreted to be produced by *Teredinidae* bivalves reported from freshwater fluvial settings (Shipway et al., 2019). The presence of dwelling traces produced by freshwater bivalves suggests high energy conditions and sedimentation rate. The Songir Formation is mainly characterized by high-density debris flow deposits with planar stratified sandstone of the channel, and the absence of flood plain deposits suggests a high amalgamation systems tract.

7.5.2.2 Lowstand Systems Tract (LST)

The opening of the Narmada rift in the early Cretaceous gave rise to coastal deposits above the alluvial fan sediments of the Songir Formation. The LST forms during the initial stage of the base-level rise and is characterized by aggradational and progradational deposits of the coastal beach-bar complexes and tidal flat deposits. Lowstand Systems Tract is developed during the Aptian, lower part of the Vajepur Formation, and represents three 3rd

order events. It is dominated by the deposition of intercalated sandstone-carbonaceous shale, intercalated sandstone shale, and thickly-bedded sandstone.

The basal part of the LST comprises thick 60 m quartz arenite facies deposited over the Songir Formation. The large-scale planar cross-stratification of sandstones indicates the high-energy foreshore environment. The lower part of the quartz arenite is non-bioturbated, but few identifiable trace fossils like *Helminthoidichnites* and *Gordia* are observed in the upper part. The absence of bioturbation in the lower part can be attributed to the high sedimentation rate. The clastic deposits suggest increased accommodation due to the prograding shoreline. The analysis of facies association and the trace fossils suggests that the initial phase of sea-level rise was outpaced by sedimentation, which gave rise to lowstand systems tract and, thus, a progradational and aggradation depositional trend during rising sea-level.

The overlying Quartz arenite of LST comprises two contemporaneous deposits; intercalated sandstone-carbonaceous shale and intercalated sandstone-purple shale (Plate 5.9 c-d). The sandstone-carbonaceous shale sequence is developed in the Navagam area, and the base comprises thick carbonaceous shale that grades above in intercalated sandstone-shale. This deposit was developed in slowly rising sea-level, which encroached the land and expanded the tidal flat area. The succession in the basal part characterized by thick carbonaceous shale suggests tidally influenced sediments filled restricted circulation and accommodation space in slowly prograding coastline, whereas the overlying intercalated sandstone with shale suggests accommodation space was filled in the foreshore environment by prograding coastline with repetition of carbonaceous shale suggest a renewal of tidal flat environmental condition.

The intercalated thick sandstone-purple shale succession is well developed in the Kara River (Vajepur) and Men River (Devaliya) sections at the base are attributed to autocyclic pauses in the deposition. The sandstones in the lower part show the presence of cross-beds formed by superimposed barrier-bar complex, and intercalated purple shale suggests a tidally-influenced shoreline. The amalgamated beach-bar complex is characterized by cross-bedded sandstones that dip in the same direction, suggesting increased accommodation space filled by prograding coastline. The large-scale cross-stratification and mud balls observed in the

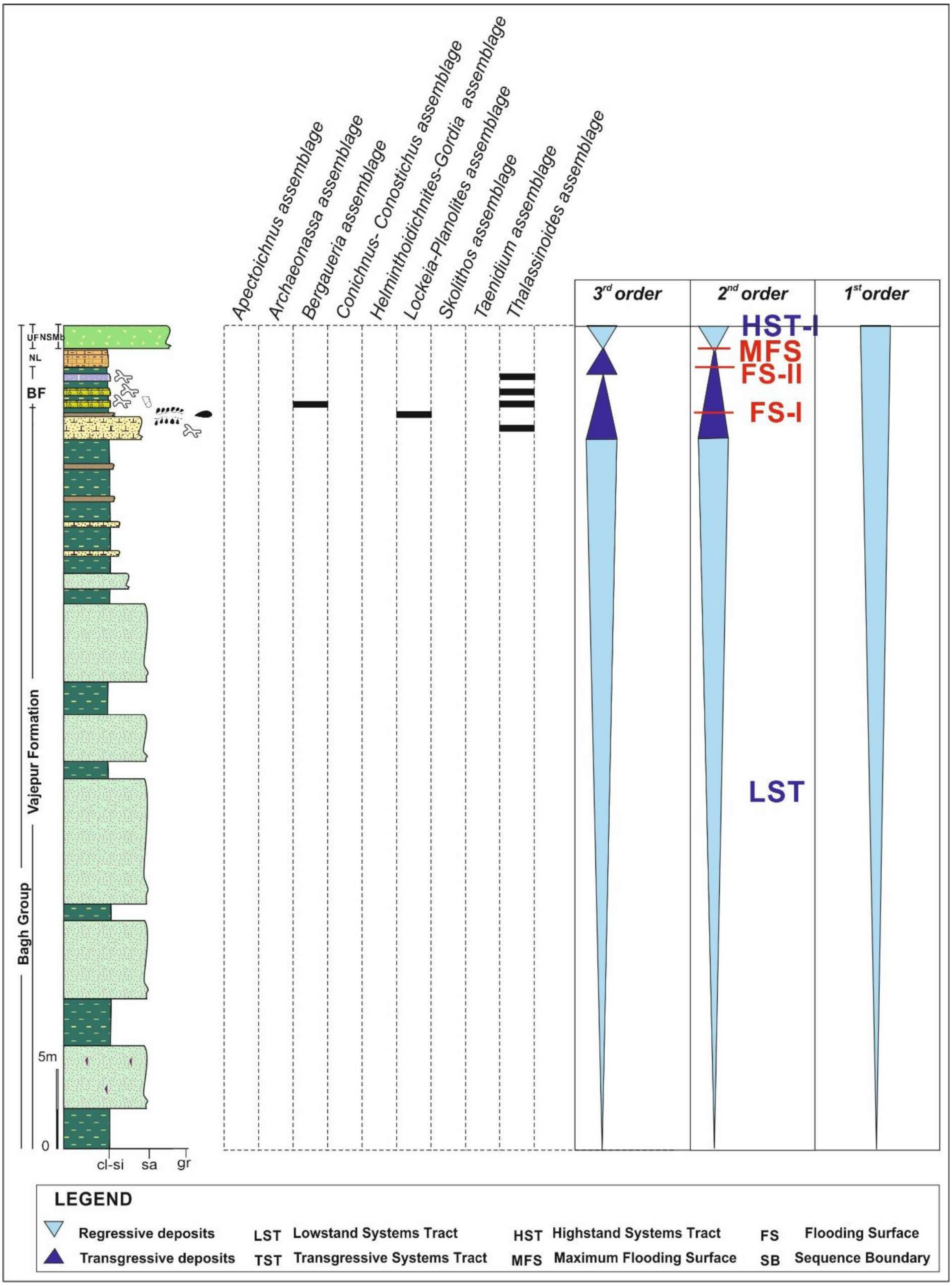

Figure 7.3 Bagh Group succession of the Mohanfort-Vajepur section showing distribution of the ichnoassemblages and genetic sequence of 1st, 2nd and 3rd order.

bedded quartz arenite and the calcareous sandstone facies are regarded to be migration of bars by tidal currents. These sandstones are characterized by sedimentary structures like combined -flow ripples, undulatory to linguoid and sharp-crested wave ripple, and trace fossils like *Planolites* and *Taenidium* (Plate 6.2b-c) suggest tidally-influenced sandy shoreline. The presence of shale indicates tidal current lost the energy in the higher reaches of the intertidal zone and allowed the deposition of the fine-grain sediments, which compensate with accommodation space.

The thick sandstones above the intercalated sandstone-carbonaceous in the Vajepur, Navagam, and Men River Valley are fine to coarse-grained, laminated, or cross-bedded. The laminated nature and lack of bioturbation indicate the sandstones were deposited in the swash zone. Overlying cross-bedded sandstones suggest the beach bar complex developed in the foreshore environment. The amalgamation of the laminated sandstone with cross-bedded sandstone suggests accommodation space was filled due to aggradation and progradation of the coastline.

7.5.2.3 Transgressive Systems Tract (TST) – I

This systems tract is dominated by carbonates, mixed siliciclastics-carbonates, and siliciclastics rocks of the marine environments. It consists of five 3rd order events that characterize rippled calcareous sandstone, micritic sandstones, sandstone-siltstone, intercalated oyster limestone (fossiliferous limestone and sandy/silty allochemic limestone)-shale and limestone (mudstone) deposits. TST sequence consists of abundant body fossils (oysters and ammonites) and trace fossils (*Archaeonassa, ?Arenicolites, Bergaueria, Conichnus, Conostichus, Lockeia, Oniscoidichnus, Planolites, Palaeophycus, Ptychoplasma, Skolithos, and Thalassinoides*).

The calcareous sandstone facies at the base of TST are flaggy and characterized by ripples on each bed and consist of invertebrate fossils (oyster and echinoderms), trace fossils towards the top. The absence of bioturbation in the lower part can be attributed to the high sedimentation rate. *Archaeonassa* isp. in the rippled calcareous sandstone facies is suggests the presence of invertebrate grazers like gastropods. The presence of body fossils and trace fossils in the calcareous sandstone above the cross-bedded sandstone of LST marks the

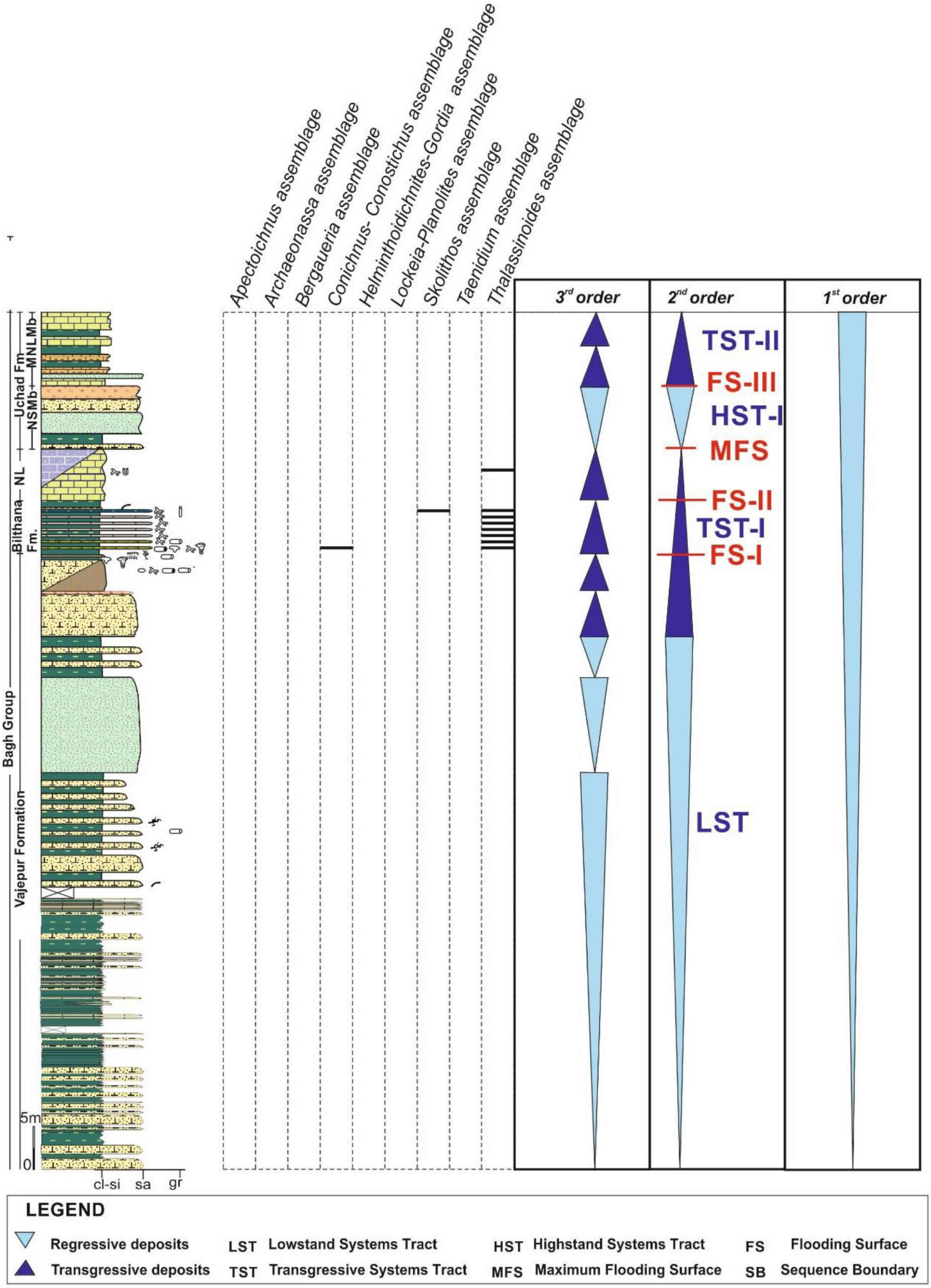

Figure 7.4 Bagh Group succession of the Men River Valley showing the distribution of ichnoassemblages and genetic sequence of 1st, 2nd, and 3rd order.

deepening of the sea. Overlying thinly bedded fine-grained micritic sandstone suggests deposition took place in the moderately agitated shoreface environment. The thinly bedded sandstone-siltstone unit is characterized by sinuous crested ripples consisting of abundant plug-shaped burrows such as *Conichnus, Conostichus* with *Oniscoidichnus, Planolites, Palaeophycus, Thalassinoides,* and *Ptychoplasma.* The calcareous sandstone-siltstone of Vajepur Formation marks the Flooding Surface-I (FS-I) overlying shales of Bilthana Formation, and Flooding Surface-II (FS-II) is marked between the oyster-shale and mudstone facies of the Nodular Limestone (Fig. 7.3-7.4). These stratigraphic surfaces marked the abrupt increase in water depth (Catuneanu, 2002) and allowed the deposition of the fine-grain clastic and carbonate sediments.

The intercalated oyster limestone-shale facies is characterized by abundant oysters and plug-shaped burrows, *Bergaueria, Conichnus, Conostichus* with *Planolites, Palaeophycus, Skolithos,* and *Thalassinoides*. The development of *Cruziana* ichnofacies in the sandstone-siltstone facies and substrate-controlled *Glossifungites* ichnofacies in cohesive mud represents FS-I. The time gap characterized by *Glossifungites* ichnofacies is indicated by the firmground substrate colonized by the sea anemones and crustaceans, which was initially dewatered due to burial, and the firmer the substrate greater is the temporal break generally of allocyclic nature (Gingras et al., 2001). The *Cruziana* and *Glossifungites* ichnofacies observed in the TST-I suggest deposition in the lower shoreface to the offshore environment below FWWB and above SWWB. Flooding surface- II (FS-II) marked at the top of shales of Bilthana Formation too represents an abrupt increase in the water depth characterized by deposition of ammonite-bearing mudstones of Nodular Limestone. The deposits of the fine clastics are replaced by the carbonates owing to the increase in water depth and accommodation space.

This is further overlain by poorly fossiliferous mudstones facies of Nodular Limestone containing the *Placenticeras*ammonite of the Turonian age. A thick and basin-wide occurrence of the Nodular Limestone suggests the deposition of thick carbonates in deeper water below the SWWB due to base level rise and increasing accommodation space. Mudstone facies of Nodular Limestone has marked the maximum transgression in the WLNV coinciding with worldwide Cenomanian-Turonian eustatic sea-level rise. The Vajepur Formation, Bilthana Formation, and Nodular Limestone represent a transgressive systems tract evident from the retrogradational stacking pattern of landward shifting facies and a fining-upward succession characterized by an increase in the carbonate content towards the top.

7.5.2.4 Highstand Systems Tract (HST) – I

The Highstand Systems Tract developed during the late stage of base-level rise characterized by sandy micrite facies deposited over the mudstone facies of the Nodular Limestone exposed around Uchad village (Fig. 7.4). It consists of five 3rd order cycles comprising sandy micrite, micritic sandstone, quartz arenite, calcareous sandstone, and gravelly sandstone. HST-I is dominated by mixed siliciclastic-carbonates and siliciclastic rocks well-developed at Navagam and Men River Valleys sections. The sudden increase in fine sand influx above the mudstone with their variable proportions at different places has given rise to the different types of mixed siliciclastic-carbonate rocks. The accommodation space filled with mixed clastic- nonclastic sediments resulted in the progradation of the coastline. The sandy micrite is devoid of body, and trace fossils marked the early stage of HST-I, lateral increase in clastic proportion is represented by micritic sandstone. The intensely bioturbated micritic sandstone consists of abundant *Skolithos* burrows belonging to *Skolithos* ichnofacies observed at Navagam village. This sequence further grades upward with the interbedded calcareous sandstone and quartz arenite facies of the Narmada Sandstone Member characterized by herringbone cross-stratification (Plate 5.8a) and ripple marks. Lithological and ichnological evidence suggests high wave and current energy, shifting substrate of the shoreface environment. The HST-I is represented by gravelly sandstone at the top, suggesting a high wave energy coastline. This gravelly sandstone comprises a number of gravel lag deposits of the high-energy beach environment indicating the maximum base-level drop in the WLNV. The sedimentary structures, ichnological and lithological evidence suggest shifting substrate and a high-energy shoreface environment where the rates of sedimentation exceeded the rate of base-level rise, giving rise to normal regression with an aggradational and progradational stacking pattern. It is bounded by the maximum flooding surface (MFS) at the base. A coarsening upward sequence of the HST-I shows the gradation in the facies where the lower part corresponds to the progradation of the shoreface facies over the offshore facies and the upper part corresponds to high energy upper shoreface-foreshore facies.

The development of HST-I over TST is observed throughout the Western Lower Narmada Valley basin, which suggests a low rate of base-level rise due to an increase in the rate of sedimentation. Sedimentary structures such as planar, trough and herringbone cross-stratification, and the *Skolithos* ichnofacies observed in the HST-I suggest deposition mainly above the FWWB in the regressive coastline. The Coniacian sequence aggraded and prograded over the Turonian transgressive deposits and correlates with global eustatic sea-level drop.

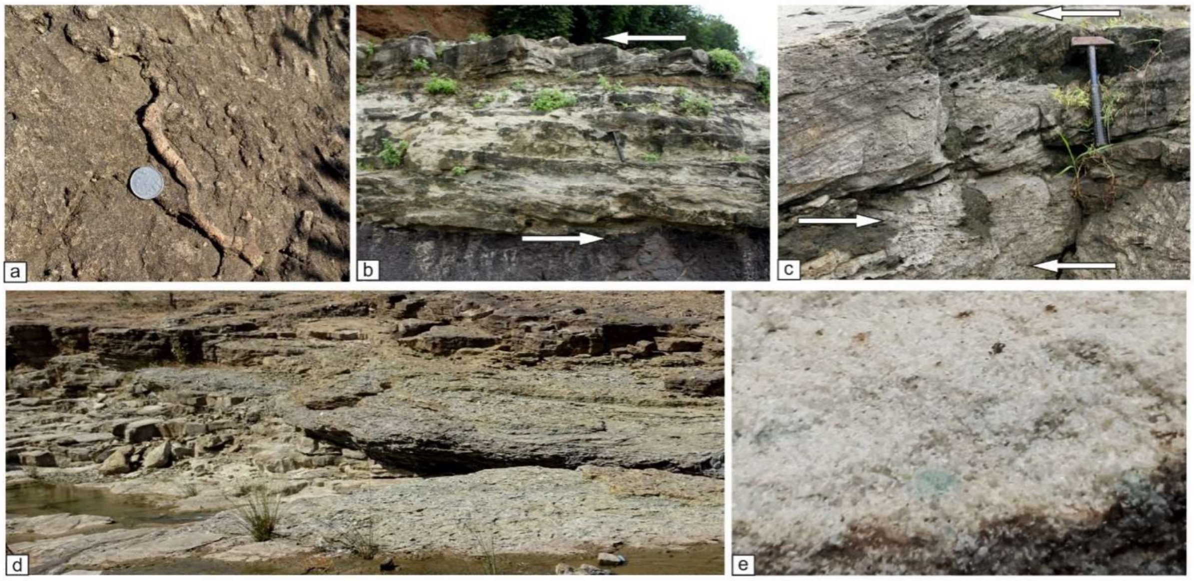

Plate 7.1 Field photographs showing primary and biogenic sedimentary structures and compositional variation. a. *Thalassinoides* with collapsed branches represented as circular scars on the burrow, Narmada Sandstone Member, Navagam section. b-c. Bidirectional cross-stratified sandstones, Vajepur Formation, Men River valley. d. Coarse-grained sandstone of the Vajepur Formation demarcating the Transgressive Ravinement Surface, Men River Valley. e. Glauconitic grains in the calcareous sandstones of Vajepur Formation, Men River valley.

7.5.2.5 Transgressive Systems Tract (TST) – II

The Transgressive Systems Tract–II was developed during the Coniacian age and observed in the succession of the Men Nadi Limestone Member of the Uchad Formation. It comprises four 3rd order events and mainly consists of carbonates (mudstone) with quartz arenite, muddy micrite, and shale. The micritic sandstone of the underlying HST-I grades to mudstone and marks the base-level increase immediately followed by progradation and gave rise to quartz arenite facies in TST-II. This event marked the temporary withdrawal of carbonate sedimentation that further renewed upward, giving rise to mixed siliciclastics-carbonates (muddy micrite) with fine-grained clastics, suggesting increasing base-level and accommodation place in the shoreface environment. Further increase in the base-level resulted in the deposition of carbonates and fine-grained clastics. The gradual change from siliciclastics to mudstones suggests deposition took place in a calm environment below the SWWB. Overall, TST-II shows the increasing proportion of carbonate sediments with delicate bivalve shell fragments upward, marking the second flooding episode in the WLNV.

The Flooding Surface-III (FS-III) is identified at the contact of sandstone of the Narmada Sandstone Member and carbonate of the Men Nadi Limestone Member (Fig. 7.4), which suggests minor submarine erosion or non-deposition across which there is an abrupt increase in water depth developed during transgression (Catuneanu, 2006). This facies contact is not a part of a systems tract boundary or of a sequence boundary but serves to demarcate the internal facies detail as Within Trend Flooding Surface (Catuneanu, 2002). The development of Flooding Surface-III (a minor unconformity) suggests a rapidly rising sea level. TST-II indicates the rate of sea-level rise exceeded the sedimentation rate giving rise to a retrogradational stacking pattern.

7.5.3 MAXIMUM FLOODING SURFACE (MFS) / SEQUENCE BOUNDARY

The Sequence Boundary integrated with the transgressive surfaces at the top of mudstone facies of Nodular Limestone represents a Maximum Flooding Surface (MFS). It separates the retrograding strata (TST-I) of Nodular Limestone from the prograding deposits (HST-I) of Narmada Sandstone Member of Uchad Formation. The Maximum Flooding Surface is characterized by either sharp or gradational contact in the WLNV Basin. The contact between TST-I and the overlying HST-I is gradational at Navagam, marked by an increasing proportion of fine clastics in carbonate, characterized by sandy micrite/micritic sandstone to bioturbated, *Skolithos* and *Thalassinoides* (Plate 7.1a) bearing fine gravelly calcareous sandstone.

The TST-I is characterized by thick nonclastic (carbonate) deposits that suggest a diminishing in terrigenous supply to the basin, marking the Maximum Transgressive Surface. It has sharp contact with overlying Narmada Sandstone Member, clastic facies of shoreface deposits (HST-I), and thus high preservation potential (Catuneanu et al., 2006). The Sequence Boundary MFS in the WLNV marks the beginning of normal regression represented as gradational or sharp contact and suggests minor erosion in HST-I.

7.5.4 SYSTEMS TRACT BOUNDARIES

The genetic sequence Bagh Group succession of the WLNV is represented by the HAST, LST, TST-I, HST-I, and TST-II. Apart from the Sequence Boundary, Maximum Flooding Surface (MFS), Sequence Stratigraphic Surface (Transgressive Ravinement Surface), and Systems Tract Boundary are identified (Catuneanu, 2019). The Transgressive Ravinement Surface separates the TST-I from the LST, while the Systems Tract Boundary separates the HAST and LST.

The surface between the alluvial fan facies of the HAST and the overlying tidal flat facies of the LST is observed between Songir Formation and Vajepur Formation at Vajepur, marked by an abrupt change in bed geometry and lithology. The gravelly sandstones of the HAST are overlain by the intercalated sandstone-shale succession of the foreshore-tidal flat environment. During the base-level rise, the higher sediment supply developed the aggradation and progradational stacking pattern of a beach-bar complex in the Vajepur Formation. Systems Tract Boundary consists of bi-directional cross stratified (Plate 7.1b-c) calcareous sandstone and intercalated with purple shales; glauconitic grains (Plate 7.1e) indicate the onset of base-level rise.

Transgressive Ravinement Surface marks the contact between LST and the overlying TST-I. The ravinement surface concept was first introduced by Stamp (1921) to demarcate the first stage in the landward movement of a transgressing sea characterized by a wave-deposited coarse conglomerate of coastal origin. The coarse-grained sandstone with oyster-lag deposits (Plate 7.1d) of the Vajepur Formation marks the ravinement surface and separates the LST from the above fine-grained shoreface deposits of the TST-I. This change shown by the stacking pattern from progradation to retrogradational suggests the increased rate of base-level rise. The preservation of thick normal regressive coastal deposits of the Vajepur Formation suggests prolonged stages of lowstand normal regression and high rates of sediment aggradation (Catuneanu, 2006).

7.6. DISCUSSION

The eustatic sea-level changes are brought by either change in the volumes of ocean water (glacio-eustatic changes) or change in the volume of spreading of oceanic ridges (Plint et al., 1992). A global greenhouse was reported in several studies during the Cretaceous, which raised the average temperatures, and major plate-reorganization events changed the volumes of oceanic ridge basalts. All such factors probably induced the Cretaceous global transgression; the transgressive Tethys Sea encroached in the LNV and deposited thick calcareous sandstone with mixed siliciclastics – carbonate sediments and limestone during Cenomanian-Coniacian. These transgressive deposits are represented as Vajepur Formation, Bilthana Formation, Nodular Limestone, and Uchad Formation in the WLNV (Shitole et al., 2021) and coincide with the high global sea level. The eustatic sea-level rise during the Cenomanian-Turonian can be caused by the fast rate of spreading, which generated large volumes of oceanic lithosphere, thereby increasing the ridge volume and raising the sea level (Ramkumar, 2015). The high rates of seafloor spreading are attributed to the major plate reorganization event, which generated intra-plate stresses and reactivated the Narmada rift along the pre-existing crustal weakness.

The sequence stratigraphic analysis of the Bagh Group rocks based on sedimentology and ichnology revealed slowly transgressing Tethys Sea over the fluvial rift sediments. Unconventional High Amalgamation Systems Tract characterizes the Pre-Albian succession; this early developed rift precludes correlation of the pre-Albian succession with the eustatic curve (Fig. 7.5). The post-Aptian succession is characterized by the transgressive deposits representing the encroachment of the Tethys Sea, whereby the trend of the eustatic and WLNV curves indicates the eustatic changes mainly influenced the sedimentation. The global Cretaceous sea-level changes of Haq (2014), averaging the highstands and the lowstands by Ruban (2014), is correlatable with the Albian-Coniacian transgressive deposits of the Western Lower Narmada Valley, with a minor Early-Coniacian regression (Fig. 7.5) which is observed worldwide (Haq, 2014) and attributed to the uplifts or tectonic events.

An integrated data of sedimentology and ichnology of the Cretaceous Bagh Group sequence of the Western Lower Narmada valley revealed the Genetic Sequence up to 3rd order (Galloway, 1989). The intracratonic WLNV rift basin comprises a well-developed fluvio-marine genetic sequence resulting from the interaction of tectonics and sea-level changes. The Genetic Sequence model (Fig. 7.6) shows the development of the Systems Tracts including, HAST, LST, TST-I, HST-I, and TST-II, Sequence Boundary (MFS), Sequence Stratigraphic Surface, and Systems Tract Boundary.

The initial phase of the rifting received continental sediments of the braided channel and alluvial fan during the Early Cretaceous, represented by the HAST before the Albian.

The sequence of HAST unconformably overlies the Precambrian and marks a long hiatus indicating prolonged subaerial exposure and erosion. The conglomerate and sandstone facies of the Songir Formation consist of sediments derived from the Precambrian basement. The Thick fluvial

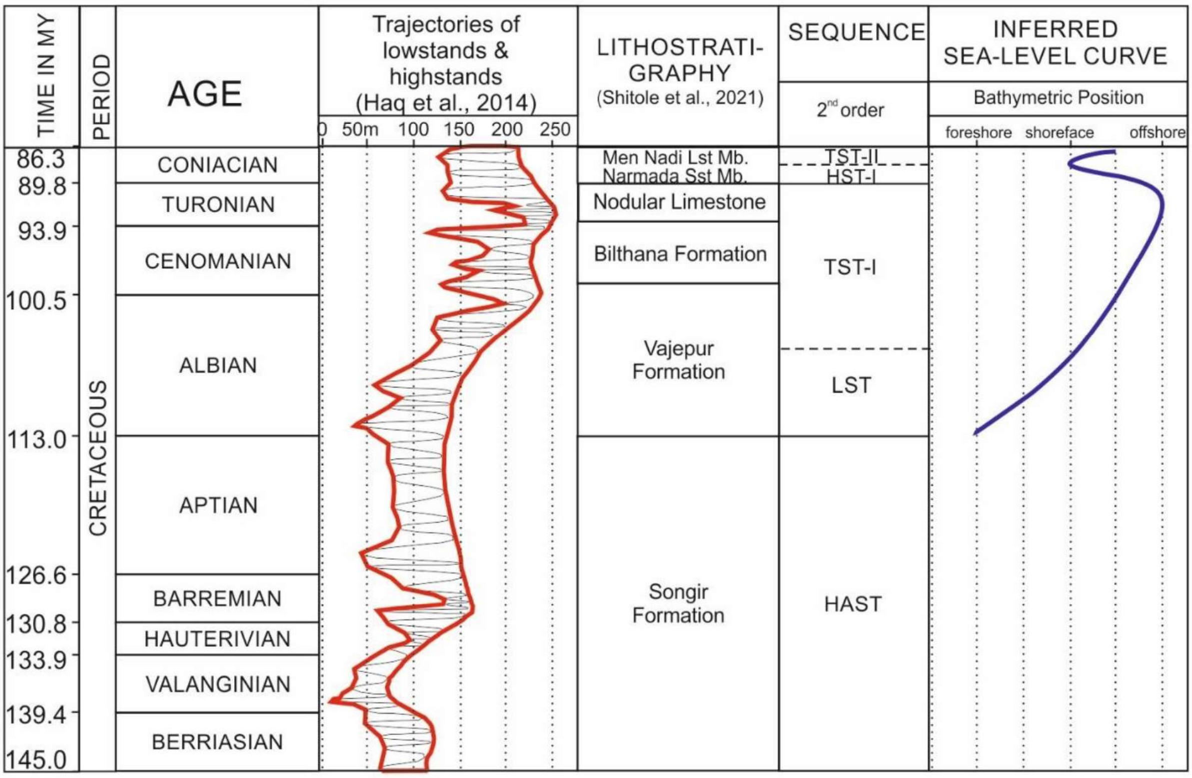

Figure 7.5 Comparison of Cretaceous shoreline trajectory of the WLNV with the eustatic curve (Haq, 2014) based on systems tracts, sequence boundary, sequence stratigraphy surfaces, and systems tract boundary (Ruban, 2014). The Pre-Albian succession is characterized by unconventional High Amalgamation Systems Tract, while conventional systems tracts characterize Post-Aptian succession.

sedimentary sequence of the Songir Formation suggests advancement of the alluvial fan with increased accommodation space giving rise to prograding and aggrading of HAST. Further advancement of the rift and increased base-level during the Albian gave rise to deposition of the LST over the HAST. The Vajepur Formation depicts the change in lithology and bed geometry compared to the lower Songir Formation, which marked the shifting of unconventional HAST to conventional LST (Fig. 7.6). The LST conformably overlies the HAST and is characterized by intercalated sandstone-shale succession deposited in a tidally-influenced beach/foreshore environment. It is interpreted as prograding and aggrading deposits consuming the accommodation space created during the rising base-level.

The upper part of the Vajepur Formation is characterized by Cenomanian transgressive deposits of TST-I, which conformably overlies the sandstone–shale sequence of the LST. Initially, TST-I is characterized by fine-grained rippled calcareous sandstone facies and, in an upward direction, shows the development of carbonate-rich sediments, including the fossiliferous limestone, sandy allochemic limestone, and shale facies of the Bilthana Formation; sandy micrite and mudstone facies of the Nodular Limestone of Turonian. The oyster bearing limestone consists of *Thalassinoides* and plug-shaped structures, indicating omission surfaces developed in the shoreface environment. Further rise in base level gave rise to mudstone of Nodular Limestone, which formed in the offshore environments.

The abrupt change in facies during the Coniacian over the Turonian TST-I marked a change in base level due to aggradation of the sediments or local tectonics. Sediments of the Narmada Sandstone Member characterize HST-I deposited during the high stands of sea level, which consumed the accommodation space and resulted in progradation and aggradation. The fine-grained pebbles were observed in the calcareous sandstone at the base of the HST-I, suggesting they were less transported and moved rapidly with the regressing sea.

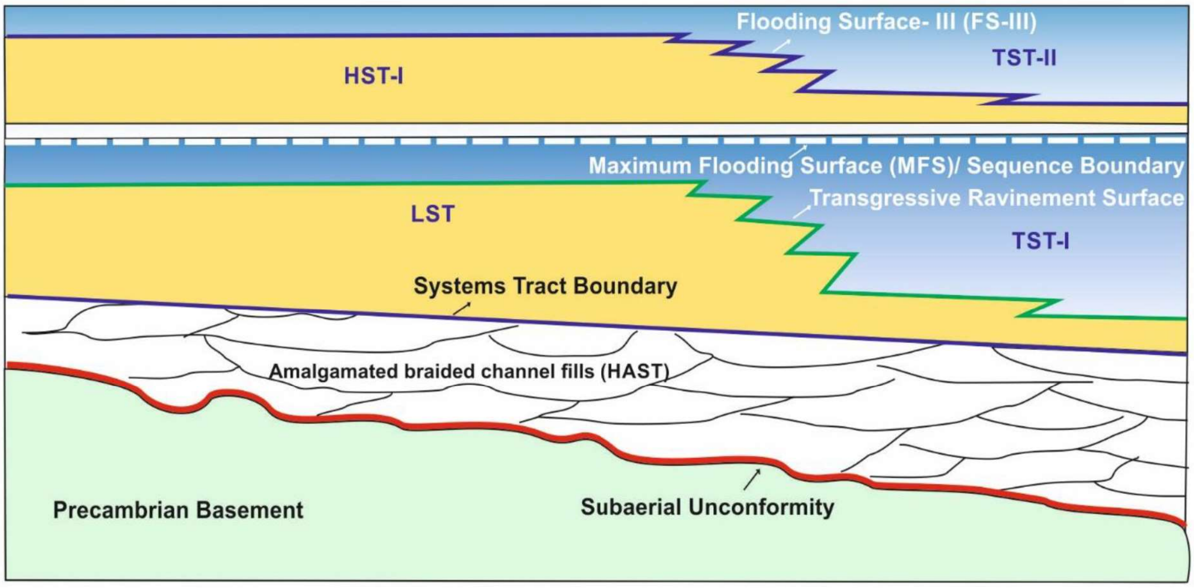

Figure 7.6 Conceptual sequence stratigraphic model of the Cretaceous Bagh Group rocks, WLNV showing stratal stacking pattern.

The second transgressive event occurred in the Coniacian, which gave rise to the conformable succession of TST-II over the HST-I (Fig.7.6). The TST-II is observed in the Men Nadi Limestone Member, characterized by muddy micrite, shale, and mudstone facies with delicate shell fragments suggesting low energy distal shoreface environments.

A sudden change or passing the threshold in an environmental parameter leads to the formation of discontinuity in the sedimentation process marked by a sharp change in facies or a surface in a stratigraphic section and is independent of scale (Hillgartner, 1998). Moreover, lithology and trace fossils help demarcate sequence stratigraphic surfaces, which correspond to changes in sea level in the WLNV Basin. One major unconformity and three major types of discontinuities are identified in the Bagh Group sequence (Fig. 7.4): 1. erosional discontinuities observed in the Vajepur Formation characteristic of Transgressive Ravinement Surface (TRS) and Maximum Flooding Surface (MFS) observed at the top of mudstone facies of TST-I. 2. depositional discontinuity i.e., Marine Flooding Surface, which represents abrupt deepening observed between calcareous sandstone-siltstone facies of Vajepur Formation and shale facies of Bilthana Formation (FS-I), between the fossiliferous limestone-shale facies of Bilthana Formation and mudstone facies of the Nodular Limestone (FS-II) and at the top of Narmada Sandstone Member (FS-III). 3. non-depositional hiatus in the Bilthana Formation indicated by the presence of firmgrounds.

Moreover, the minor discontinuities are also identified in the study area based on the presence of trace fossils that largely coincide with the minor flooding surfaces (Fig.7.4). It is observed at the top of the bioturbated rippled calcareous sandstone characterized by the trace fossils of *Cruzian*a Ichnofacies of the Vajepur Formation in contact with shales of the Bilthana Formation within the TST-I. The abundant occurrence of *Thalassinoides* in the shale towards the top of Bilthana Formation and *Bergaueria*, *Conichnus,* and *Conostichus* at its bottom represent submarine erosion by short-term high-energy events, where the semi-consolidated micrite offered resistance to erosion. This shale bed was a stable substrate colonized by firmground trace makers, indicated by the presence of sharp-walled and unlined burrows of suspension feeders, which were later passively filled. *Glossifungites* Ichnofacies at the sharp-based contact between the shale and oyster beds of Bilthana Formation and in the middle-level of the Nodular Limestone marks a hiatus (short-lived discontinuity) in the deposition.

Based on sedimentological and ichnological data, the sequence stratigraphic analysis of the Cretaceous succession of the WLNV Basin revealed that it was evolved due to intra-cratonic rifting, initially filled by fluvial deposits and later by eustatic sea-level rise.