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Sedimentary Record of Forced Regression Along The Margin of Kutch Basin: Terminal Cenozoic Succession (Sandhan Formation), Western India

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Abstract: The sedimentation of Cenozoic successions of Kutch took place in passive margin sag-basin over the stable continental shelf, primarily controlled by relative sea-level fluctuations vis-à-vis siliciclastic supply/carbonate production. The basin-wide two-tier unconformity bounded clastic dominated Sandhan Formation is deposited in shallow marine (~135m, lower part) to fluvial environment (~157m, upper part). The discontinuous exposures along cliff/banks of Kankawati River (type section) and Kharod River provided an excellent opportunity for detailed sedimentological and sequence stratigraphic analysis. The fluvial forced regressive sediments are very rare in rock records because of subsequent transgression and erosion. The total 11 facies were identified (Miall, 1985 classification) viz. **Gm, Gmm, Gp, Gt, Sh, Sp, St, Sm, Fsm, Fl,** and **P** are grouped into three Facies Association (FA): 1. **Channel and Channel Fill FA;** occurs at the base, characterized by **Gm, Sh** and **Sp** facies with vertically and laterally amalgamated stacked tabular sheet sandstone bodies with concave upward erosional base, individual sandstone sheet shows the fining upward trend with channel-lag. 2. **Sandy and Gravel Bar FA;** characterized by fining upward tabular sandstone bodies (**Sh** and **Sp**) overlain by the cycle of coarse poorly sorted massive gravel fining upward to trough cross-stratified sandstone. Towards downstream section multistoried stacked sheet of trough cross-stratified gravel beds are overlain by the planar stratified gravel bed (**Gm, Gt** and **Gp**). 3. **Overbank Fines and Floodplain FA;** characterized by **Fl, Fsc,** and **P** elements and by 5-6m thick massive deposit of lithofacies **P** in the upper part of the succession, dominated by abundant root penetration structures and extensive pedogenic features with calcrete/ferricrete layers, indicates a major break in sedimentation and sequence boundary. The Sandhan Formation is characterized by the wave-dominated TST overlain by normal regression/progradation of HST followed by the forced regressive deposit of FSST. The FSST is bounded at the base by a basal surface of forced regression, characterized by cobble/pebble horizons followed by abundant fluvial channel lags occurring at the top of HST. The low dipping shelves are very sensitive to sea-level changes and subjected to inundate/expose a large part of the shelf in small fluctuations. The abrupt fall in the sea-level exposed a large part of the continental shelf and older HST prism provided the sufficient slope for the braided fluvial system to develop. The relative sea-level never reached to its previous extent which leads the preservation of forced regressive deposits. The final withdrawal of shoreline shifted the depositional milieu westward and sedimentation/basin closed at the onland part of Kutch.

Keywords: Sandhan Formation, Falling Stage Systems Tract, Channel and Channel Fill, Sandy and Gravel bar, Overbank Fines and Floodplain.

Introduction

The falling stage systems tract develops during falling limb of sea level curve is characterized by shoreface wedge or fluvial sediments having distinct offlap strata of partially attached or detached lobes (Bera et al. 2008; Hunt, 1992; Hunt and Tucker, 1992). Initially, it was assumed that due to the overall erosive regime during base-level fall there was no sedimentation on the exposed part of the shelf (Van Wagoner et al. 1987; Vail, 1987: Mitchum, et al. 1977). The deposits of forced regression driven by fall in sea level was recorded by many (Plint (1988, 1991; Plint and Norris, 1991; Ainsworth, 1994; Hunt, 1992; Hunt and Tucker, 1992; Nummedal, 1992 etc). This systems tract was introduced by Hunt and Tucker (1995) as Forced Regressive Wedge Systems Tract (FRWST), later renamed as Falling Stage Systems Tract (FSST) and comprehensive explanation was given by Plint and Nummedal (2000) and introduced to the original tripartite classification of depositional sequences (Vail, 1987; Posamentier and Vail, 1988). This is the only systems tract in the depositional sequence which has no direct correlation of sediment supply and relative sea-level fluctuations, however, systems tract develop due to the high rate of sea-level fall irrespective of rate of sediment supply. Its development is controlled by shelf geometry, slope, tectonics, climate, magnitude of relative sea-level fall characterized by general high rate of sedimentation. The preservation potential of this systems tract is very low because of extensive erosion along the depositional profile to lowest sea level (Coe et al., 2005) or erosion from the subsequent transgressive event, therefore, in rock record FSST are rare. The FSST can experience the marine or fluvial influences depending upon the rate of base-level fall.

This study aims at process based sedimentological and stratigraphic analysis of the upper part of the Sandhan Formation for its depositional and sequence stratigraphic interpretation. The basin-wide two-tier unconformity bounded terminal Cenozoic Sandhan Formation is clastic dominated succession deposited in shallow marine (~135m) followed by the fluvial environment (~157m) is considered as 'sequence', comprised of wave-dominated TST overlain by HST and followed by fluvial deposits of forced regressive FSST. The distinctive location and subsequent sea-level cycle provided an opportunity to develop FSST in the upper part of Sandhan Formation.

Geological Setting

The Kutch basin evolved as a passive margin sag-basin during Cenozoic, exposed along the western margin of Kutch, India. The sedimentation initiated after Deccan volcanism is exposed along narrow coastal plain trending NNW-SSE separated by various magnitude of unconformity, non-conformity or paraconformity. The sedimentation took place on the tectonically undisturbed continental shelf so the beds are almost flat to low dipping at 1-3° towards SSW to NW (Fig: 1). Because of almost flat topography, Cenozoic successions are mainly exposed along cliffs and banks of rivers. The sedimentation in the passive margin setting is controlled by relative sea-level fluctuations vs. the rate of siliciclastic supply/carbonate production without large-scale tectonic hindrance is divided into various formations (Table: 1). The terminal Cenozoic formation of Kutch is designated as Sandhan Formation is siliciclastic dominated. The age of the Sandhan Formation is not clear because of the absence of age-diagnostic fauna, instinctively, the Pliocene age is assigned to it because of a prominent break in sedimentation above Lower-Middle Miocene and according to the order of superposition (Biswas, 1992). Nearly 292m thick Sandhan Formation is exposed along cliffs and banks of Kankawati (type section) and Kharod River with several exposure gaps towards upper part. The Sandhan Formation is bounded by basin-scale unconformity, the lower unconformity above Chhasra Formation is characterized by the conglomerate bed and upper contact with Sub-recent sediments is identified by regional and laterally persistent paleosol horizon. According to Biswas (1992), the depositional environment of Sandhan Formation is interpreted to be supra littoral to deltaic or foreshore environment.

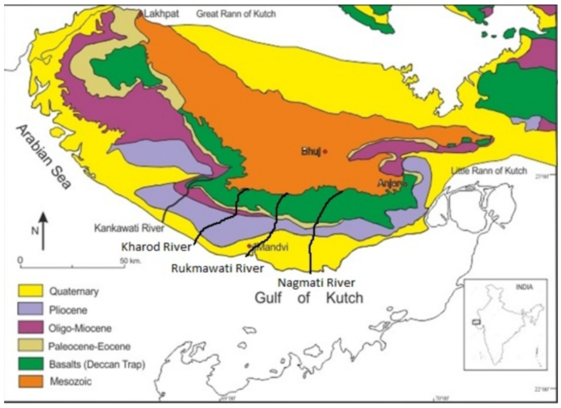

Figure: 1. Geological map of the Kutch basin (After Biswas, 1992).

Methodology

The mainstay of the present study is outcrop process based sedimentology, stratigraphic observation for the purpose of depositional environment and sequence stratigraphic analysis of upper part of

Sandhan Formation. The detailed fieldwork was carried out along Kankawati River (type section) and Kharod River sections to document lithology, grain size, colour, sedimentary structures, bed geometry and nature of contact. Wherever possible, the beds were traced along strike and down dip to understand the geometry and lateral continuity. The standard procedure was applied to stratigraphic and sedimentological observations and information was used to prepare graphic-log of the two river sections. The identified facies are clubbed into facies association for depositional environment interpretation. The samples were collected for petrographic analysis.

SERISES		STAGES	Base (Ma)	LITHOSTRATIGRAPHY FORMATIONS	MEMBERS	FORAMINIFERAL ZONES	W.COAST/ KUTCH STAGES
PLIOCENE			5.33				
MIOCENE	UPPER	MESSINIAN		SANDHAN		To be Zoned	KANKAWATIAN SUPER STAGE
MIOCENE	UPPER	TORTONIAN	11.60	SANDHAN		To be Zoned	KANKAWATIAN SUPER STAGE
MIOCENE	MIDDLE	SERRAVALLIAN	13.82	SANDHAN		To be Zoned	KANKAWATIAN SUPER STAGE
MIOCENE	MIDDLE	LANGHIAN	15.97	SANDHAN		To be Zoned	KANKAWATIAN SUPER STAGE
MIOCENE	LOWER	BURDIGAIAN	20.43	CHHASRA	SILTSTONE CLAYSTONE	*A. papillosus* *M. (L.) excentrica* *M. (L.) droogeri* *M. globulina-thecideaformis*	VINJHA-NIAN
MIOCENE	LOWER	AQUITANIAN	23.03	KHARI NADI		*M. (M.) tani* Poorly Fossiliferous	AIDAIAN
OLIGOCENE	UPPER	CHATTIAN	28.4	MANIYARA FORT	BERMOTI	*M.(M.) complanta-formosensis* *M. (L.) excentrica* *M.(M.) bermudezi* *P. freudenthali*	WAIORIAN
OLIGOCENE	LOWER	RUPELIAN	33.9	MANIYARA FORT	CORAL LIMESTONE LUMPY CLAY BASAL MEMBER	*N. fichteli / E. dialata* *N. fichteli*	LR UPPER RAMANIAN
EOCENE	UPPER	PRIABONIAN	37.2				
EOCENE	MIDDLE	BARTONIAN	40.4	FULRA LIMESTONE		*T. rohri* *O. beckmanni*	BABIAN
EOCENE	MIDDLE	LUTETIAN	48.6	FULRA LIMESTONE HARUDI		*T. topilensis* *N. obtusus*	BABIAN
EOCENE	LOWER	YPRESIAN	55.8	NAREDI	FERR.CLAYSTONE ASSILINA LIMESTONE GYPSEOUS SHALE	Poorly Fossiliferous *A. granulosa* *A. spinosa* Ostracod Zone	KAKDIAN
PALEOCENE	UPPER	THANETIAN	61.7	NAREDI MATANOMADH			KHASIAN MADHIAN
PALEOCENE	LOWER	DANIAN	65.5	DECCAN TRAP			DECCAN TRAPS
CRET.	UPPER	MAASTRICHTIAN		DECCAN TRAP			DECCAN TRAPS

Table: 1. Cenozoic stratigraphy of Kutch Basin (after Biswas, 1992).

Facies Analysis

The introduction of facies in sedimentology has changed the way of looking at the sedimentary rocks. The process-based sedimentological analysis of sedimentary succession is now exclusively conducted through the facies analysis. The facies are distinctive lithounits deposited under the particular depositional condition and reflect process operated at the time of its deposition and modification later on. The facies can be identified through their distinct lithology, texture, grading, sedimentary structures, bed geometry and biogenic contents etc. The process operated during the deposition of particular lithounits can suggest depositional environment through the genetically related facies (follows Walther's Law) into facies association (Walker, 1979). However; facies association can have a very progressive and dynamic shift through time (Walker, 1984; Reading, 1986; 1996; Posamentier and Walker, 2006). The process-based sedimentological and stratigraphic analysis is carried out in the upper part of the Sandhan Formation (~157m) to identify facies, facies association for the interpretation of depositional environment. Studied stratigraphic interval is dominated by granular/pebbly to coarse-grained sandstone and occasional gravel beds. The coarse sandstone bodies are overlain by the fine siltstone or mudstone at places. The sandstones are arkosic to sub-arkosic in nature and comprises of angular to sub-angular grains with a dominant proportion of orthoclase feldspar. The lithofacies name were assigned according to the scheme provided by facies classification of Miall (1985, 1996). Total 11 lithofacies were identified in the field (Table: 2).

Facies Association: 1
Channel and Channel Fill Facies Association

This facies association occurs at the base of the studied section are characterized by the stacked tabular sheet sandstone bodies with distinct concave upward erosional base. The thickness of individual sheet ranges from 2-3m, fining upward trend with coarse channel lag at the base. Sandstone sheets are vertically and laterally amalgamated. Disorganized coarse channel lag (**Sm)** facies (Fig. 2.A), is overlain by the **St, Sp** and **Sh** Facies. At places, **Fsm** is encased between sheet sandstone indicating frequent channel shift.

Facies Code	Lithofacies	Description	Interpretation
Gravel Facies			
Gmm	Coarse grained poorly sorted matrix supported gravel facies	This facies consist of poorly sorted gravels and pebbles supported by the poorly sorted sandy matrix. Massive to crudely bedded. Elongate lobate geometry. Thickness of the lobes is ~75 cm. Imbrication is absent. (Fig. 3.B).	This facies suggests deposition by the non-cohesive sediment gravity flow. High viscosity lead to the lobate geometry.(Miall , 1996).
Gt	Trough cross-stratified gravel facies	Shallow scoop shaped trough cross-stratified gravel bodies having erosional base filled with the lag deposit of coarse granule to pebble size grains which fines upward.Erosional troughs are overlain by diffused multistoried gravel sheet (Fig.3.A).	Trough cross stratification indicate the migration of transvers dunes with curved crest (Miall, 1985).
Gp	Planar cross-stratified gravel facies	Poorly sorted planar cross stratified gravels typically overlie the Gmm and Gt facies in the section. Cross set thickness are less than 1m.(Fig. 2.E).	Transverse bedform, deltaic growth from older bar remnants (Miall, 1996).
Gm	Massive to crudely planer-stratified gravel facies	This facies is characterized by the stacked sheet of the poorly sorted gravels bodies, often overlain by the Gp and Gt facies (Fig. 2.E).	Deposition by longitudinal bar in relatively shallow flow, high stage of flow. Diffused sheet (Hein & Walker, 1977). Grow upward and downstream during episodes of high water and sediment discharge to form longitudinal bar (Rust, 1972).
Sand Facies			
Facies Code	**Lithofacies**	**Description**	**Interpretation**
Sh	Medium grained horizontally laminated sandstone facies	Tabular medium to coarse grained poorly sorted planar laminated sandstone. Each unit of the sandstone bodies are 2-3m thick. (Fig. 2.B).	Represent the upper plane bed condition at the transition from subcritical to supercritical flow (Miall, 1996).
Sp	Planar cross stratified sandstone	Coarse to medium grained tabular cross stratified sandstone. Grain size and set thickness reduces upward. (Fig. 2.C).	Form by the migration of 2D dunes (Miall,1996)), migration of ripples in upper flow regime. Sand waves generate planar cross-bedding (Smith, 1970, 1971).
St	Trough cross stratified coarse grained sandstone, often pebbly facies	Characterized by large scale cross strata in poorly sorted sandstone. Grain size and set thickness reduces upward. Thickness of large set is up to 3o cm which reduces upward to 1o cm. cross strata are oriented in the same direction. (Fig. 2.D)	Migration of the curved crested transverse and longitudinal dunes on the channel floor.
Sm	Massive, pebbly sandstone	Very coarse grained poorly sorted pebbly sandstone. Pebbles are present in the matrix of poorly sorted sand and have rounded to angular shape. Measured thickness of this facies is 40-50 cm (Fig. 2.A).	It has been envisaged as a channel lag deposit. It can also be a product of rapid deposition from heavily loaded flow, possibly a flash flood scenario (Pflüger and Seilacher, 1991).
Fine Grained Clastic Facies			
Facies Code	**Lithofacies**	**Description**	**Interpretation**
Fsm	Mud, Silt	Massive silty mudstone bed above the poorly sorted sandstone body. Thickness is around 2-3m (Fig. 3.D).	Overbank fines, abandoned channel (Miall, 1996).
Fl	Mudstone interbedded with fine silt and sand.	Tabular bodies of laminated mud interbedded with rippled fine silt and sand. Overall thickness of the facies is about 4-5m with individual mud and silt layers being 50-75cm thick (Fig. 3.C).	Ovebank fines, back swamp deposit, bar top deposits (Bridge, 2006).
P	Paleosol associate with calcrete nodules	Fine mud deposits marked by the pedogenic features with distinct root penetration structure indicative of soil formation. Occurs at uppermost part of the section (Fig. 2.E-F).	Floodplain deposits exposed for considerable period of time. Soil with chemical precipitation (Miall, 1996).

Table: 2. The facies description of Sandhan Formation and its interpretation

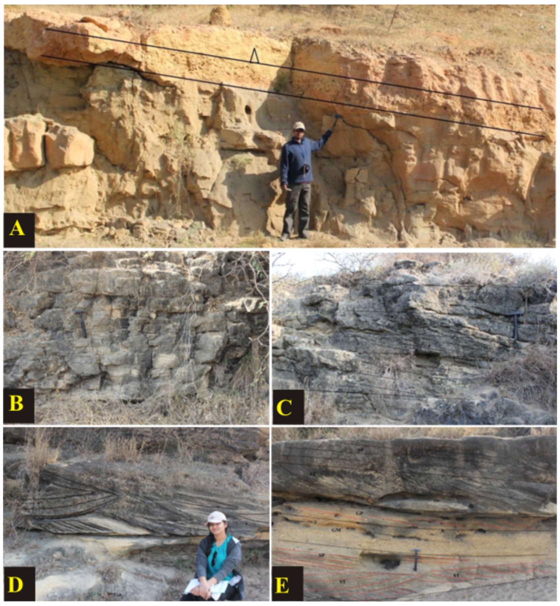

Figure: 2. Outcrop photographs of fluvial facies identified in the field. **(A.)** Massive pebbly sandstone with channel lag (**Sm**) **(B.)** Planar Laminated sandstone (**Sh**). **(C.)** Tabular cross stratified sandstone (Sp). **(D.)** Trough cross stratified sandstone, Curved bounding surfaces and trough sets have been marked (**St**). **(E.)** Gravel Bed characterized by lithofacies **Gm** and **Gp**.

Interpretation

The sediments deposited in the channels are left behind as river migrate laterally across their floodplain. This lateral migration continues till the river avulses. After the avulsion river abandons their old channel and follows a new pathway across the floodplain. As the aggradation rate increases, these isolated lenses of the abandoned channel sediments will amalgamate into sheet-like bodies due to lateral migration of the channel. Lateral migration of the channels is represented by the vertically and laterally amalgamated sheet sandstone bodies in the rock record (Church and Rood, 1983; Crowley, 1983). Mudstone Facies above the sheet sandstone body mark the channel fill succession deposited by the vertical aggradation. The fining-upward trend with a related decrease in cross set thickness clearly shows the temporal decrease in flow strength.

Facies Association: 2

Sandy and Gravel Bar Facies Association

The 3-4m thick tabular bodies of fining-upward planar to crudely cross-stratified sandstone occur above channel element. The vertical stacking of a number of lithofacies **St, Sp, Sh, and Sr** is present (Fig. 2.B-D). The fining-upward succession with a reduction in set thickness upward and change in structure from cross set to ripples was observed. The facies association is repetitive in nature and individual cycle is overlain by another cycle of pebbly to coarse sandstone with large trough cross-stratification with reduction in set thickness and grain size in up section. This facies association is most common in middle part and share major part of stratigraphic section. In the upstream section, it occurs stratigraphically above the multistoried stacked sheet sandstone whereas, in the downstream section it occurs stratigraphically above the gravel sheet facies.

In the downstream part trough cross-stratified sandstones are overlain by the crudely bedded massive gravel. The lithofacies gives way to facies **Gp** and **Gm** (Fig. 2.E) with clast imbrications. This gravel layer is overlain by **St→Sp→Sh→Sr** facies shows a cyclic deposition of lithofacies each consisting of **Gm, Gp, Gt, Sp, Sh** and capped by **Sr**. The trough set thickness varies from 15-25 cm. In downstream part above facies are overlain by the medium to large scale low angle trough cross-stratified sandstone bed capped by the tabular cross-stratified to planar bedded sandstone. The troughs are characterized by the coarse granule to pebble size grains at the base of the foresets, with fining upward trend as well as a decrease in the size of the trough set thickness. These planar beds are overlain by another cycle characterized by coarse gravel-rich large scale trough beds, which shows a fining upward trend and have a lateral extent of ~10m.

Further downstream two major outcrops were identified. The lower one is characterized by trough cross-stratified gravel, **Gt** (Fig. 3.A), overlain by the massive gravel bed, **Gm**, overlain by the facies sequence as described above. Trough set thickness is ~30cm which reduces to 15cm in upward section. The upper bar is characterized by the gravel sheet. Each sheet consists of facies **Gm→Gt→Gp**. The gravel sheet are occasionally capped by the thin layer of fine sandstone. The layer of sediment gravity flows is also associated with these facies and occur as an elongate lobe dominated by the lithofacies **Gmm** (Fig. 3.B).

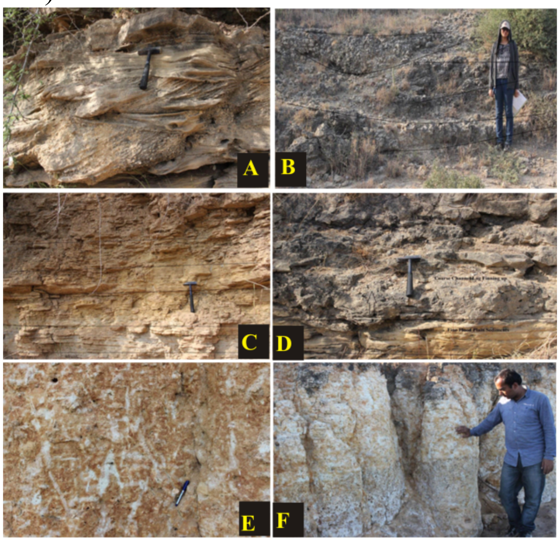

Figure: 3. Outcrop photographs of fluvial facies identified in the field. (A.) Trough cross stratified gravel forming gravel bar (Gt). (B.) Sediment gravity flow showing an elongated lobe geometry (Lithofacies Gmm). (C.) Inter-laminated mud, sit and sandstone (Fl). (D.) Floodplain sediment above channel characterized by mud, silt (Fsm). (E.) Paleosol with root penetration structures (P). (F.) Calcrete layers associated with the paleosol.

Interpretation

The lower part of the facies association is characterized by dune scale planer cross bedding may have formed by the migration of transverse bar. Transverse bars and sand waves are known to produce planar cross bedding (Smith, 1970, 1972; Levey, 1978; Blodgett and Stanley, 1980). The middle part of the section dominated by the trough-cross bedding has been showing the result of migration of dunes in the deeper part of the channel which is overlain by planar-cross strata. Vertical stacking of different bedform type indicates frequent changes in the flow regime. Longer term changes reflect aggradation and reduction in water depth (Miall, 1985). It is supported by the field evidence of fining-upward succession associated with a reduction in set thickness. Each repeating cycle shows a reduction in flow strength with fine rippled sand overlying the trough-cross bed.

In the downstream part trough-cross stratified sandstone overlain by the crudely bedded massive gravel and the cyclic succession of the facies, **St→Sp→Sh→Sr** were identified as the product of the growth, migration and lateral and downstream accretion of lobate unit bars. The bar head regions are deposited as a result of accretion of fronts of unit bars and bar tails by accretion of sides of lobate unit bars (Hein and Walker, 1977; Bridge, 2006). Individual unit bars showing a temporal reduction in flow strength. In the downstream section, flow strength decreases further as fine sediments begin to appear as interpreted as bar top facies possibly deposition in very shallow water on top of the bars.

The outcrops of gravel beds are identified as the gravel longitudinal bars. During the episode of high water and sediment discharge gravel sheet grow upward and downstream to form gravel longitudinal bars (Rust, 1972). Sheet and clast accumulation tend to result in fining up succession as observed in the field. The repeated cycle of the bed indicates the bar migration downstream (Gustavson, 1978). The geometry of the gravel bar bedform has been modeled as multistoried sheet of 10's of meter thick flat/erosional surface between each set (Miall, 1986). Deposits of gravity flows occur as narrow, elongate lobes and typically associated with the gravel bars (Miall, 1996).

Facies Association: 3

Overbank fines and Floodplain Facies Association

In the upstream section, 5-6m thick silty mudstone deposit are incased in the sheet sandstone bodies. In the downstream section the outcrop of sheet/tabular fine silt interbedded with mud (lithofacies **Fl** and **Fsm**) overlain the trough-cross stratified sandstones (Fig. 3.C-D). The silt layer is represented by the horizontal laminations due to deposition through suspension settling. The silt layers are characterized by the ripple lamination and ripple scale cross stratification. Occasional ferruginous layers and desiccation cracks observed in the mudstone.

Uppermost part of the succession is marked by the 4-5m thick massive mudstone deposit. It is dominated by the abundant root penetration structure and marked by the extensive pedogenic features which indicate the soil formation (Fig.3.E). It also shows the succession of calcrete/ferricrete layers towards the top (Fig.3.F). This facies is the uppermost deposition facies of the Sandhan Formation and is directly overlain by the recent Quaternary sediments.

Interpretation

It is inferred that deposition took place away from the channels by the vertical accretion of the fine clastic sediments. The most active vertical accretion environments occur along high-energy channels with sandy floodplains that can be destroyed catastrophically by large floods and subsequently reconstructed by overbank deposition (Schumm and Lichty, 1963; Burkham, 1972; Nanson, 1986). Fine silt and sand layer suggest that deposition took place under low energy condition from suspension settling of fine-grained sediments. Small-scale ripples and cross stratification present in the silt layer suggest traction transport process during occasional high energy condition. Paleosol succession preserved at the uppermost part of the succession suggests the seasonal/longer term drying out of the floodplain.

Depositional Environment

The three facies associations were identified through outcrop based facies analysis along the Sandhan Formation viz. Channel and Channel Fill Facies Association, Sandy and Gravel Bar Facies Association, and Overbank fines and Floodplain Facies Association. Channel and Channel Fill Facies Association characterized by a stacked sheet of poorly sorted medium to coarse-grained sandstone with fining upward character represented by **Gm, Sh** and **Sp** facies. The Sandy and Gravel bar Facies Association is characterized by fining upward tabular sand bodies comprised of **Sh** and **Sp** facies. The fining-upward cycles of gravel culminate at the top by **Sp** or **St** Facies. Mid-channel bar is formed by the accretion of unit bars **St** and **Sp**, which are capped by the overbank fines facies **Fl** in the downstream sections. Gravel bar Facies Association are characterized by multi-storied stacks of trough cross stratified gravel overlain by the planar stratified gravel of **Gm, Gt** or **Gp** facies. Gravel bar facies interspersed with sediment gravity flow deposits. The Overbank fines and Floodplain Facies Association represent the minor fraction and are characterized by the lithofacies **Fl, Fsm** and paleosol **P** facies in the upper part of the succession. The coarse-grained sandstone, gravels, abundant trough-cross stratification, very rare preservation of the current ripples and erosive bounding surface indicate the high energy condition of the flow. Many basin margins are characterized by the wedges of gravel deposit, commonly these are deposited by the distributary fluvial system (Miall, 1996). Associated sediment gravity flow deposit and minor thickness of fine-grained deposit (low water and overbank sedimentation) also indicate the high energy stream flow (Miall, 1996). Multi-storied channels, multi-storied gravel sheets, the absence of floodplain levee complex and lateral accretion character indicate the braided character of fluvial deposits. The absence of complete open marine and estuarine sediment inter-tonguing with fluvial sediments and high energy condition inferred from the above sedimentological evidence suggests that the deposition of the upper part of the Sandhan Formation took place in unincised, unconfined gravel-bed braided river system. Sufficient slope for the braided river system to develop is provided by the abrupt fall in relative sea-level led to the exposure of large part of the continental shelf and highstand prism of previous deposits.

Sequence Stratigraphic Framework

Sequence stratigraphy is a novel concept of sedimentary record that provides a predictive model of basin fill architecture. The paradigm uses unconformities or their correlative conformities to split sedimentary succession into unconformity-bounded sequences at different scales. The concept was first developed for the siliciclastic environment for passive margin basins where evidence of sea-level fluctuation and sedimentary fill can be better preserved and documented in the stratigraphic record. Being an association of genetically related strata bounded by unconformity or their correlative conformity; the process based sedimentology and facies analysis is a backbone for sequence stratigraphic analysis. Identification of sequence boundary is the first step in sequence analysis. The two-tier unconformity-bounded succession of Sandhan Formation is considered as a sequence. The lower sequence boundary with Chhasra Formation is clearly observed in river sections under study as an undulating erosional surface with a conglomerate bed, can be traced at basinal-scale. The contact implies a fall in relative sea-level, exposure of the depositional substrate and the development of a subaerial unconformity. The unconformity between the two formations defines a plane across which depositional pattern changed and a large shift in depositional environment noticed at basin-wide scale and thus marks a sequence boundary. The upper sequence boundary with overlying sub-recent sediments is characterized by the thick and regional occurrence of paleosol horizon with abundant root penetration and calcretes. The thick formation of paleosol requires landscape stability associated with the physical, chemical and biological transformation of exposed sediments (Kraus, 1999) thus indicates an episode of non-deposition/unconformity. The development of paleosol in marginal marine to shallow marine environments is controlled by base-level fall and subaerial exposure of shelf (Lander et al., 1991; Webb 1994; Wright 1994; Van Wagoner, 1995). The fall reaches its maximum extent at the end of the forced regression (Helland et al., 1992), however, the type of paleosol developed at sequence boundary is dependent on fluctuating base-level and prevailing climate (Write and Marriott, 1993; Tandon and Gibling, 1994). The unconformity-bounded Sandhan Formation is divided into transgressive systems tract (TST), highstand systems tract (HST) and falling stage systems tract (FSST) separated by standard sequence stratigraphic surfaces (Fig.4). The study section lies at the shallow shelf where lowstand systems tract (LST) are typically absent and TST directly overly on sequence boundary/transgressive surface (Baum and Vail, 1988). The base of FSST is demarcated by the basal surface of forced regression, characterize the base of all the deposit that accumulates during the forced regression of the shoreline (Hunt and Tucker, 1992). This surface marks the boundary between the normal regressive strata below and the forced regressive strata above. This surface is very prominent if the rate of relative sea-level fall is high and shelf slope is very gentle. The distinct and extensive fluvial deposits

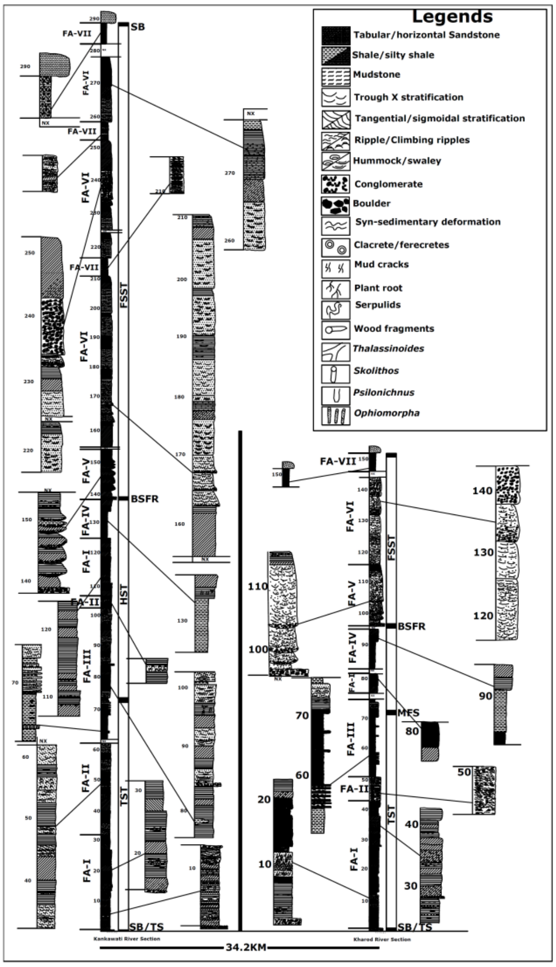

Figure: 4. Sedimentary log of Sandhan formation along Kankawati and Kharod River, showing Facies Associations and Sequence stratigraphic elements

above HST is separated through the basal surface of forced regression is characterized by multiple channel stacking and channel fill sediments (Fig: 5. A). The immediate incision of the fluvial channel above highstand deposits led to abrupt facies break which argues for relative sea level fall. The fluvial erosion due to relative sea-level fall eventually truncates earlier highstand strata (Plint and Nummedal, 2000). Whereas FSST is bounded at the top by composite surface may include subaerial unconformity or its correlative conformity (Hunt and Tucker, 1992). The distinct 11 facies of fluvial environment is clubbed into three facies associations are designated as forced regressive deposits of FSST (Fig. 6). The FSST is overall coarsening and shallowing upward strata of an offlap pattern. The occurrence of distinct overbank and floodplain sediments with abundant channels and bars indicates unconfined braided fluvial system. The abundance of large grain size and gravity deposits suggests intermittent high energy during occasional flash flood condition (Fluger and Seilacher, 1991; Wright and Marriott, 1993).

The continental shelf of western India around Kutch is wide (~375km) which tapers down southwards. The slope of the shelf is around 1-3° towards SSW. This geometry of shelf generates very low slope due to which minor fluctuation in base level can inundate or expose the wide area of the shelf. The preservation potential of shallow marine falling stage systems tract is inversely proportional to the magnitude of base level fall (Catuneanu, 2006). In the case of low magnitude fall in base level when the shoreline does not reach the shelf edge the forced regressive shelf sediments get preserved between the basal surface of forced regression and subaerial unconformity (Catuneanu, 2006). The fluvial system also common in the upper part of HST, however, HST fluvial system is characterized by lowest energy fluvial system of stratigraphic sequence. It is commonly sluggish, meandering type, characterized by a channel of moderate to high sinuosity (Catuneanu, 2006). In the absence of topographic relief, HST fluvial system does not form braided pattern until affected by tectonics or climate-driven high discharge of clastic supply. The LST sediments are coarse grain deposits and can develop a braided pattern. The occurrence of the regional unconformity at the upper part of Sandhan Formation (Fig. 5. B) exclude the possibility of LST sediments as it is bounded by correlative conformity at the base, not by the basal surface of forced regression and topped by the transgressive surface of marine erosion, not by the subaerial unconformity. The argument for fluvial sediments of Sandhan Formation to assign lowstand

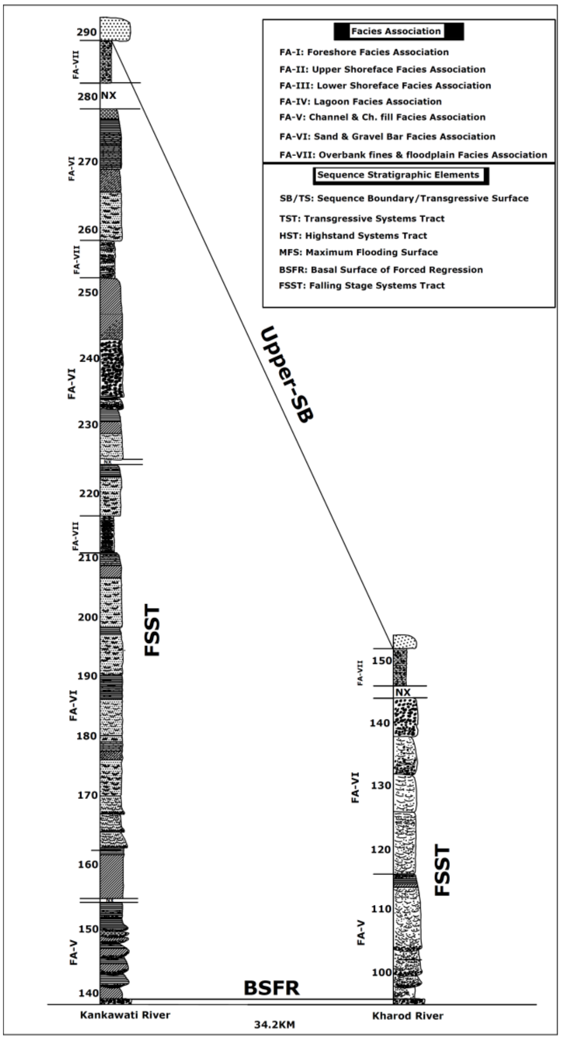

Figure: 6. Sedimentary logs showing the correlation of FSST of Sandhan Formation between Kankawati and Kharod River sections.

deposits is not valid in this situation. Moreover, the development of LST is restricted at shelf slope or shelf edge area. The unincised fluvial system of the falling stage is now documented as having a more common occurrence in the rock record than originally inferred by early standard sequence stratigraphic models. There are specific conditions in the shallow marine basin with a gently sloping ramp or margin of continental shelf setting where the forced regressive shoreline does not fall below the elevation of shelf edge (Posamentier, 2001). The fluvial deposits of upper part of Sandhan Formation are characterized by unincised braided pattern, deposited on the gentle sloping shelf of Kutch is affected by relative sea-level fall, however, fall does nor exceeded beyond shelf edge provided opportunity to preserve FSST sediments. The subsequent sea level rise after Sandhan Formation does not raise up to an extent to rework/erode the FSST sediments.

Conclusions

1. The sedimentary succession of the upper part of Sandhan Formation deposited in unincised, an unconfined braided system characterized by three Facies Associations: Channel and Channel Fill, Sandy and Gravel Bar and Overbank fines and Floodplain, affected by episodic high energy environment.
2. The combined effect of HST prism and shelf provided the sufficient slope for the deposition of braided fluvial sediments.
3. The thick accumulation of paleosol at the uppermost part of succession formed due to end of base level fall, geomorphic stability and extensive pedogenic processes, indicates a large break in sedimentation.
4. The specific location of FSST in the base provided the opportunity to preserve the forced regressive sediments. The sea-level not increased afterward, depositional milieu shifted basin-ward and sedimentation stopped/closed in the onland part of Kutch.

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