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Sedimentary Geology 191 (2006) 3 – 36

Sedimentary Geology

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Sedimentology of a muddy alluvial deposit: Triassic Denwa Formation, India

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Received 25 April 2005; received in revised form 27 December 2005; accepted 5 January 2006

Abstract

Triassic Upper Denwa Formation (~380 m) in the Satpura Gondwana basin, central India is a mudstone-dominated fluvial succession that comprises isolated ribbon-shaped (2–5-m-thick) channel-fill bodies encased within fine-grained extra-channel deposits. Eight architectural elements are recognized, of which five belong to channel-fill deposits and the remaining three to extra-channel deposits. Majority of channel-fill deposits are characterized by sandy or muddy inclined heterolithic strata (IHS) that record limited lateral accretion of point bars or benches (constrained by cohesive banks) in mixed- to suspended-load sinuous channels. A few ribbon bodies are mud rich and attest to nearly stagnant conditions in partly abandoned channels. A few single- or multistorey ribbon bodies that are dominantly sandy and lack inclined strata represent deposits of straight, laterally stable channel. The smallest ribbon bodies (~1 m thick) of calcirudite/calcarenite possibly represent deposits of secondary channels in the interfluves. Coexistence of channel-fill bodies of different dimension, lithology and internal organization in restricted stratigraphic intervals suggests an anabranching system having channels with different fill histories.

The extra-channel deposits mainly comprise red mudstone (1–5 m thick) that indicates pervasive oxidation of overbank sediments in well-aerated and well-drained setting. Sporadically developed calcic vertisols suggest a hot, semi-arid climate during the Upper Denwa period. Sandy to heterolithic sheets (70 cm to 2 m thick) with sharp, planar basal surfaces are replete with features suggestive of unconfined sheet flow. Also at places there are indications of subaqueous emplacement of sands. These bodies with paleocurrent oblique to that of the channel-fills are interpreted as crevasse splay deposits. Tabular heterolithic bodies (3–5 m thick) are characterized by undulating basal surface, complex organization of sandstone lenses interwoven with heteroliths and red mudstone (in decimeter-scale) with desiccation cracks. Such tabular bodies are attributed to repetitive, sheet-like and poorly channelized splaying.

Very thick (10 to 20 m) mudstones intervals are inexplicable in terms of overbank flooding only. Poorly developed pedogenic features in sandy to muddy heterolithic sheets and certain mudstone intervals and well-developed cumulative paleosols in surrounding mudstone highlights the contrast between rapidly emplaced splay deposits and slowly accumulated floodplain deposits.

The Denwa channels are comparable with modern, low-gradient and low-energy anabranching river system in which the sediment load is dominantly fine-grained. The semi-arid climate possibly facilitated enhanced supply of fines to the Upper Denwa system. However, sediment partitioning and distribution in a particular channel was controlled by flow diversion to and from other channels in that anabranching system. Low flow strength with periodic flood events, high bank strength and a rate of sediment

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doi:10.1016/j.sedgeo.2006.01.002

supply that slightly exceeded that of onward transport probably were important factors for the development of the Upper Denwa anabranching system.

Keywords: Fluvial; Mixed-load to suspended-load rivers; Splay; Heteroliths; Mudstone; Semi-arid

1. Introduction

Coarse bedload and suspension-load channels represent end members of a spectrum of possible fluvial channel types (Galloway, 1981). While most of the coarse-grained and/or sandy bedload rivers are braided, majority of the mixed-load and suspended-load rivers are meandering. The traditional depositional model for meandering mixed-load channels is the familiar fining-upward cycle. It arose from the observations in modern streams (Fisk, 1944, 1947; Sundborg, 1956; Bernard and Major, 1963) as well as from the study of ancient sediments (Nanz, 1954; Allen, 1964, 1965, 1970). However, the processes and geomorphology of rivers (Schumm, 1960) that predominantly transport high proportion of their load in suspension have so far received much less attention. To date, only a few detailed descriptions of modern suspended-load rivers and their deposits have been published (Baker, 1978; Taylor and Woodyer, 1978; Woodyer et al., 1979; Jackson, 1978, 1981; Nanson and Page, 1981; Page et al., 2003; Brooks, 2003). Notwithstanding the fact that the deposits of muddy, fine-grained, meandering, low-energy streams are closer in lithology and succession to those of upward-fining facies model than the deposits of less muddy, coarse-grained, meandering streams (such as those of Brazos, Colorado, Endrick, Klaralven and Wabash) the later had received the bulk of attention from sedimentologists (cf. Jackson, 1981).

Schumm (1960, 1968, 1972) and Orton and Reading (1993) recognized that suspended-load streams form morphologically distinct channels with low width-to-depth ratios and very high sinuosities. Recent studies on modern suspended-load streams in Australia and Canada (Gibling et al., 1998; Brooks, 2003, Page et al., 2003) have also revealed important characteristics of their deposits. It has been shown that mud-rich channel-fills of low width: thickness ratio, are generated by a combination of vertical and lateral accretion. The fills of these channels comprise a channel-base deposit mainly composed of sand, mixed with some mud and minor amount of gravel (locally) that occur low in the fills and accretionary bench deposits composed of inclined sand-mud heterolithic strata at higher level. However, in some cases, e.g. in Red River of Canada (cf. Brooks, 2003), the channel-base deposits are absent and the mud deposits extend directly to the base of the channel. In the modern meandering river point bar deposits formed in fluvial and tidally influenced environments, Smith (1987) has shown that there is variability from sand-only to sand with irregularly thick and variably spaced mud beds to rhythmic sand–mud couplets. Jackson (1981) noted the presence of variably thick mud interbeds at irregular intervals while working on the modern, low-energy, fluvial point bars. Though meso-tidally influenced point bar facies have been reported to be characterized by epsilon cross-strata (ECS) with rhythmic sand–mud couplets (Smith, 1987), similar facies have also been reported from muddy fine-grained stream deposits (Jackson, 1978; Gibling et al., 1998; Page et al., 2003; Brooks, 2003) and are common in many ancient meandering river deposits (Stewart, 1981; Mossop and Flach, 1983; Flach and Mossop, 1985). The variation in the lithology and style of the heterolithic strata possibly represents a spectrum of point bar types and are interpreted to represent variations in river-gradients, hydrodynamic regime, climate and sediment supply to the stream channels (Stewart, 1983).

The sedimentologic characteristics of the deposits of low-energy, straight to sinuous, suspended-load meandering streams that are stable or slowly migrating, seem to be inadequately documented from ancient successions (Ori et al., 1981; Stewart, 1983; Smith, 1987). The facies models for such deposits are not yet well constrained. On the other hand, alluvial succession with thick fine-grained deposits has generally been linked with deposition from rivers carrying dominantly suspended-loads and the thick fine-grained deposits has been interpreted mainly as overbank deposits (Stewart, 1981, 1983). A traditional view of the dominant channel in an alluvial floodplain is that it provides the floodplain with suspended sediment during overbank floods and thus is the main supplier of fine-grained sediments in alluvial successions. This view may be incorrect in some settings. Rather it is avulsions, especially progradational avulsions that aggrade floodplains in a relatively short interval of time. Much of the floodplain aggradation may in fact be a relatively rapid product of avulsions rather than the slow vertical aggradations from normal flooding (Slingerland and Smith, 2004). In studies of avulsive deposition where both coarse and fine material comprise the succession, fine sediment clearly dominates the avulsive intervals (Smith et al., 1989; Kraus and Gwinn, 1997; Perez-Arlucea and Smith, 1999; Aslan and Blum, 1999; Kraus and Wells, 1999). Avulsions, not levee-topping floods, are considered as the principal cause of floodplain aggradation (Slingerland and Smith, 2004) and avulsion deposits are reported to make up more than half of the overbank/extra-channel deposits (Kraus and Wells, 1999; Aslan and Blum, 1999). Thus, mudstone-dominated alluvial successions need careful study in view of the fact that splaying related to avulsion can be one of the main processes that builds alluvial stratigraphy.

The present study describes and discusses the morphology and internal architecture of the channel-fill bodies and extra-channel deposits in the mud-dominated Triassic fluvial succession (Denwa Formation, about 500 m thick) from the Satpura Gondwana basin, central India. This fluvial architecture is important because we speculate that the channel-fill bodies represent the deposits of mixed-load to suspended-load river system with the major part of the extra-channel deposits being the product of splays related to channel avulsions. We believe that a comprehensive analysis of this succession, including channel and extra-channel sediments and paleosols developed therein, improves our understanding about the role of splays in creating mudrock-dominated alluvial deposits.

2. Geological background

The Satpura basin is the westernmost of the series of discrete Gondwana basins occurring along the Narmada-Son-Damodar valley. This basin lies at the junction of the Pranhita-Godavari valley and the Narmarda-Son-Damodar valley (Fig. 1). The basin is rhomb-shaped, approx. 200 km long and ~60 km wide. Its longer sides are marked by the ENE–WSW-trending Son-Narmada south fault and Tapti north fault (Chakraborty et al., 2003; Chakraborty and Ghosh, 2005). These faults are subvertical near the surface and show evidence of strike-slip movements. The Satpura basin was created as a pull-apart basin due to the extensions related to the strike-slip movement along the Son-Narmada Lineament (Chakraborty et al., 2003; Chakraborty and Ghosh, 2005).

The Satpura Gondwana basin is filled with about 4-km-thick siliciclastic succession, ranging in age from Permo-Carboniferous to the Late Cretaceous (Crookshank, 1936; Pascoe, 1959; Fig. 1). The regional strike of the basin-fill is ENE–WSW and the regional formation dip (~5°) is northerly.

The Triassic succession in the east-central part of the Satpura basin comprises the Pachmarhi and the overlying Denwa Formations (Figs. 1 and 2). The Pachmarhi Formation overlies the Upper Permian Bijori Formation with an erosional disconformity (Crookshank, 1936, p. 230; Chakraborty and Sarkar, 2005) and gradationally passes upward to the Denwa Formation. The latter is overlain with an angular unconformity by the conglomerate-dominated Jurassic Bagra Formation (Casshyap et al., 1993; Maulik et al., 2000). Pachmarhi–Denwa succession, therefore, constitutes a sedimentary package bounded above and below by unconformity surfaces (Figs 1 and 2). The Pachmarhi Formation occurs as a ~500-m-thick succession comprising numerous vertically stacked, cross-stratified, meter-thick sheet bodies of coarse pebbly sandstone intercalated with minor red mudstone and extends strike-wise for tens of kilometers. Tewari (1995) and Maulik et al. (2000) have interpreted the Pachmarhi succession as braided river deposits. Though the Pachmarhi–Denwa contact is gradational in nature, significant changes occur in lithology, sand/mud ratio, macro- and meso-scale sedimentary architecture vertically upwards across the said contact.

The Denwa Formation, in contrast to the Pachmarhi Formation, is red mudstone-dominated succession. While the Pachmarhi Formation is unfossiliferous, the Denwa Formation is replete with vertebrate fossils. On the basis of faunal content, an Early Middle Triassic age has been assigned to the Denwa Formation (Bandyopadhyay and Sengupta, 1999). Based on contrasting lithofacies, sand/mud ratio, meso- and macroscale architectural element. Maulik et al. (2000) informally subdivided the Denwa Formation (300 to 600 m thick) into a lower and an upper unit with a gradational contact. The "sand–mud" ratio in the lower part (~120 m thick) of the Denwa succession is 9:11 and that decreases to about 1:9 inf its upper part (~380 m, Fig. 3). The lower unit of the Denwa Formation is characterized by an alternation of medium to fine-grained, 3–15 m thick, sheet-like sandstone bodies interleaved with red mudstone intervals (1.5–10 m) having decimeter- to centimeter-scale fine sandstone interlayer. In contrast to the lower unit, the upper unit is muddier and is also characterized by ribbon-shaped channel-fill bodies and sandy to heterolithic sheets encased in red mudstone. Presence of ribbon-shaped, rather than sheet-like, channel-fill bodies of variously organized muddy heteroliths, small ribbon-shaped channel-fill bodies of

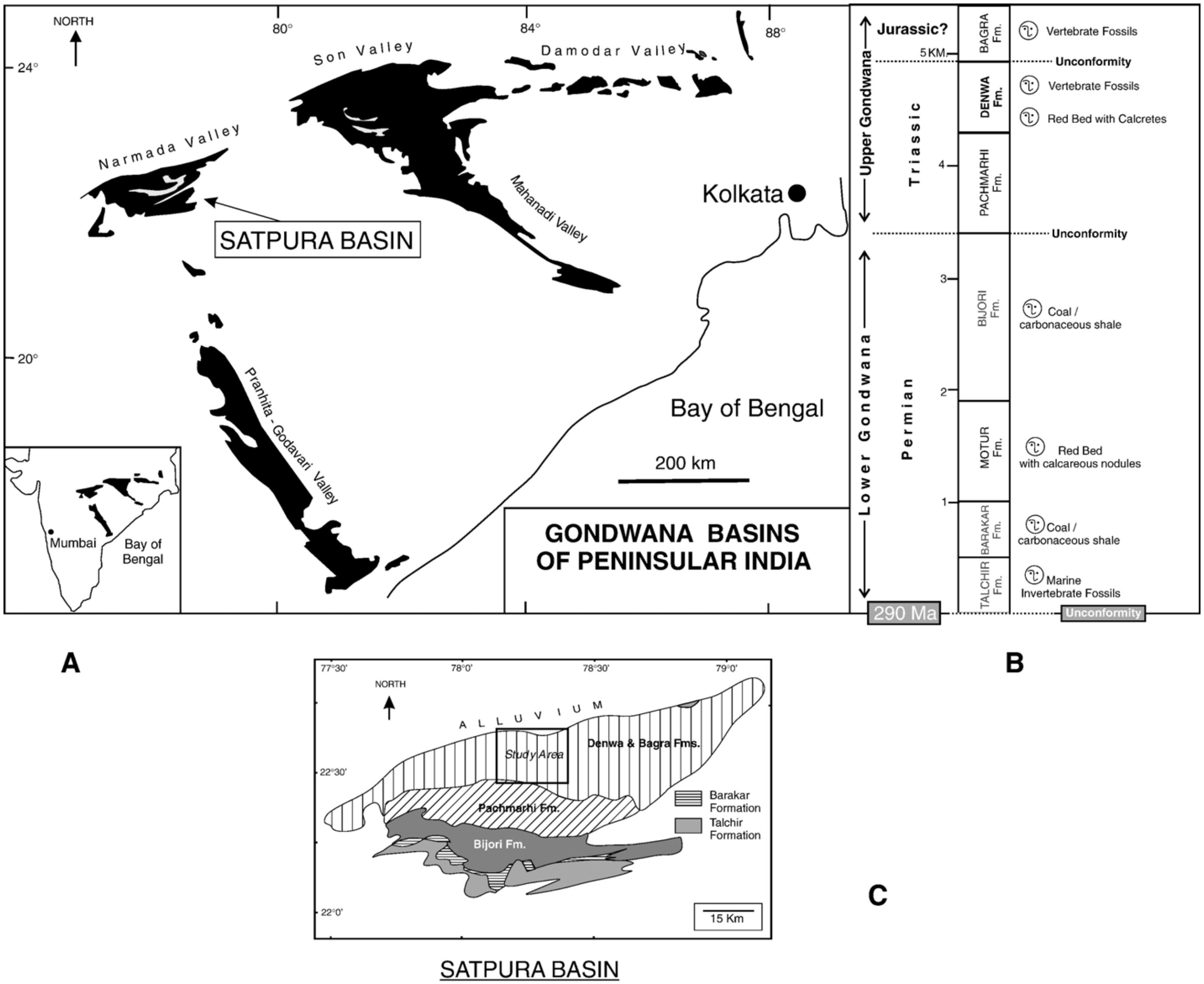


Fig. 1. (A) Location map of the Satpura basin amidst the major Gondwana basins of peninsular India. (B) Stratigraphy of the Satpura basin-fill. (C) The location of the study area within the Satpura Gondwana basin.

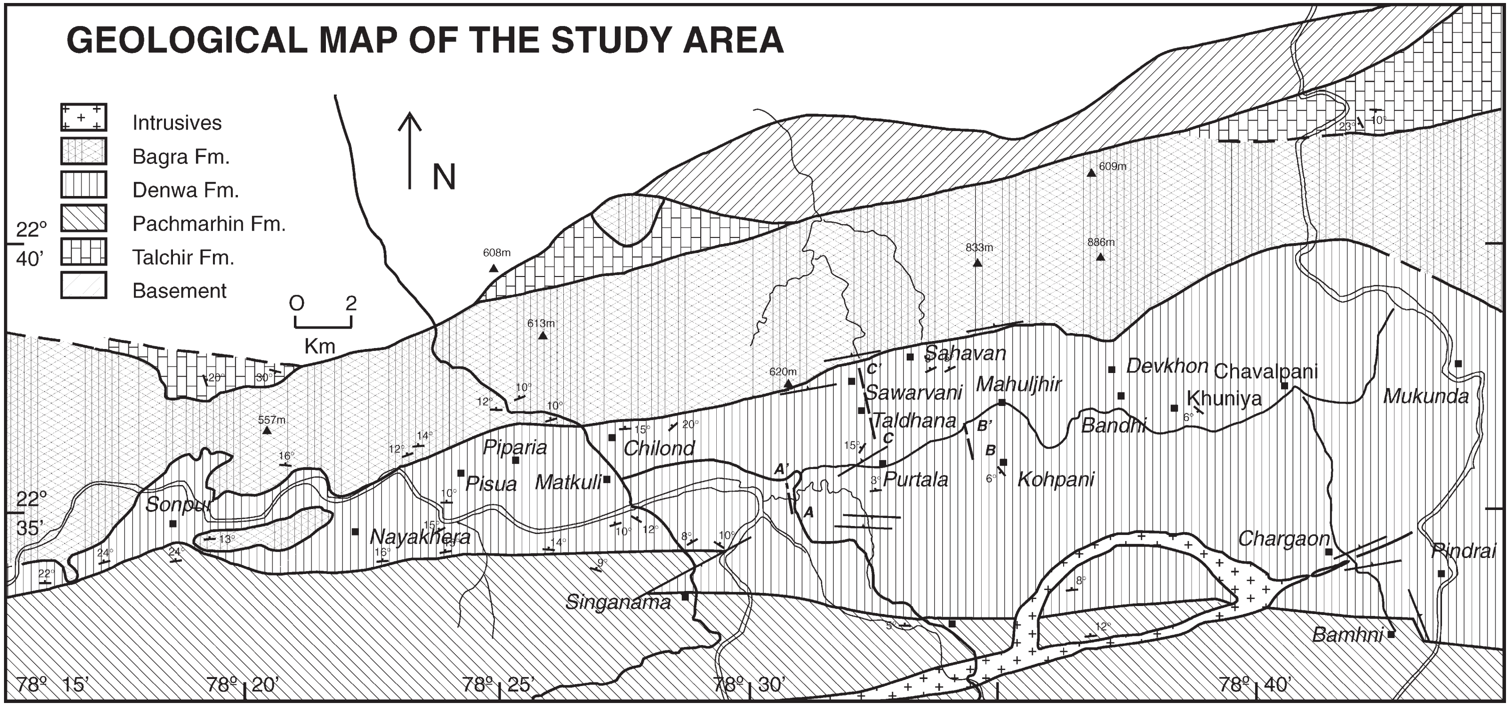
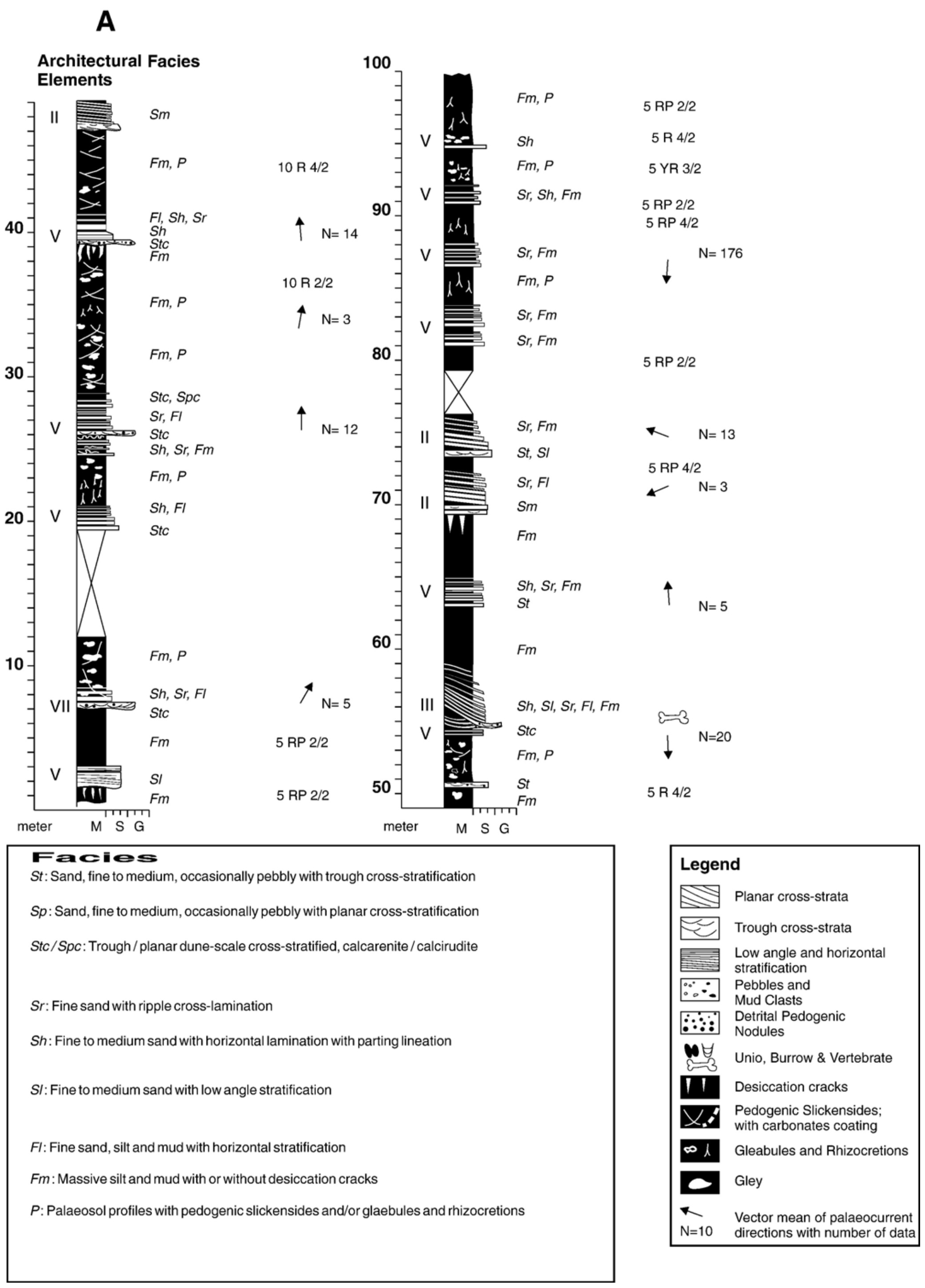


Fig. 2. Geological map of the study area. A–A′, B–B′ and C–C′ represent the section lines for the lithologs (Fig. 3A–C).



Facies

St: Sand, fine to medium, occasionally pebbly with trough cross-stratification

Sp: Sand, fine to medium, occasionally pebbly with planar cross-stratification

Stc/Spc: Trough / planar dune-scale cross-stratified, calcarenite / calcirudite

Sr: Fine sand with ripple cross-lamination

Sh: Fine to medium sand with horizontal lamination with parting lineation

Sl: Fine to medium sand with low angle stratification

Fl: Fine sand, silt and mud with horizontal stratification

Fm: Massive silt and mud with or without desiccation cracks

P: Palaeosol profiles with pedogenic slickensides and/or glaebules and rhizocretions

Fig. 3. Lithologs through the Denwa Formation along section lines A–A′, B–B′ and C–C′ of Fig. 2. I to VII represent the element numbers described in the text. All the unmarked intervals (in black) represent red mudstone of element VIII. The color codes conform to the Geological Society of America, Rock-Color Chart.

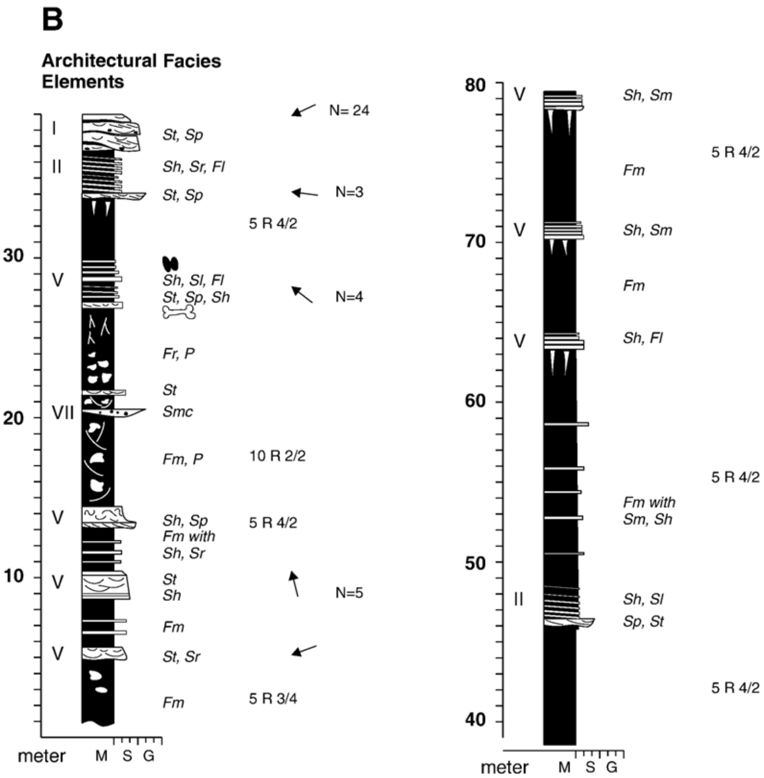


Fig. 3 (*continued*).

calcirudite/calcarenite, occurrence of pedogenically modified red mudstone characterize the upper unit of the Denwa Formation. The majority of the Upper Denwa channel-fill bodies comprise variously organized sand–mud heteroliths whereas, only a few of them are dominated by medium to fine sandstone. Maulik et al. (2000) interpreted the lower and upper part of the Denwa succession as deposits of sandy braided channel belt and network of meandering channel, respectively. The present study restricts itself to the upper mud-dominated unit (sensu Maulik et al., 2000) of the Denwa Formation, informally designated as Upper Denwa.

3. Description and interpretation of architectural elements

The sediment bodies observed within the Upper Denwa Formation show a wide variation in geometry, lithofacies and internal organization. The sediment bodies are mainly ribbon-shaped, short-tabular and sheet-like in geometry. The dominant lithologies in order of decreasing abundance are mudstone, sand–mud heteroliths, quartoze sandstone and intraformational calcirudite/calcarenite. For the convenience of description, we have subdivided these diverse kind of sediment bodies into eight elements (I to VIII; Figs. 3 and 4, Table 1) mainly based upon their overall geometry, dimension, dominant lithology and internal organization. Most of the elements described herein correspond to architectural elements, CH (channel), LA (lateral accretion), LS (laminated sand) and OF (overbank fines), outlined by Miall (1988, 1996). However, in the present situation, there is so much lithological variation and complexity to the internal geometry of the channel-fills, that a detailed classification of channel deposits has been utilized.

3.1. Element IA: single-storey sandy ribbons

3.1.1. Description

These ribbon bodies (3 to 4.5 m thick and 100 to 200 m wide) are dominated by the medium to fine-grained sandstone. They occur vertically separated by mudstones, several meters thick. The basal bounding surface of these bodies is very gently concave upwards. Scours in the scale of tens of centimeters occur along the basal surface.

The internal architecture of these ribbon bodies shows considerable variations. However, two main types of lithosome occurring in varying proportions constitute the fills of these bodies. A lenticular

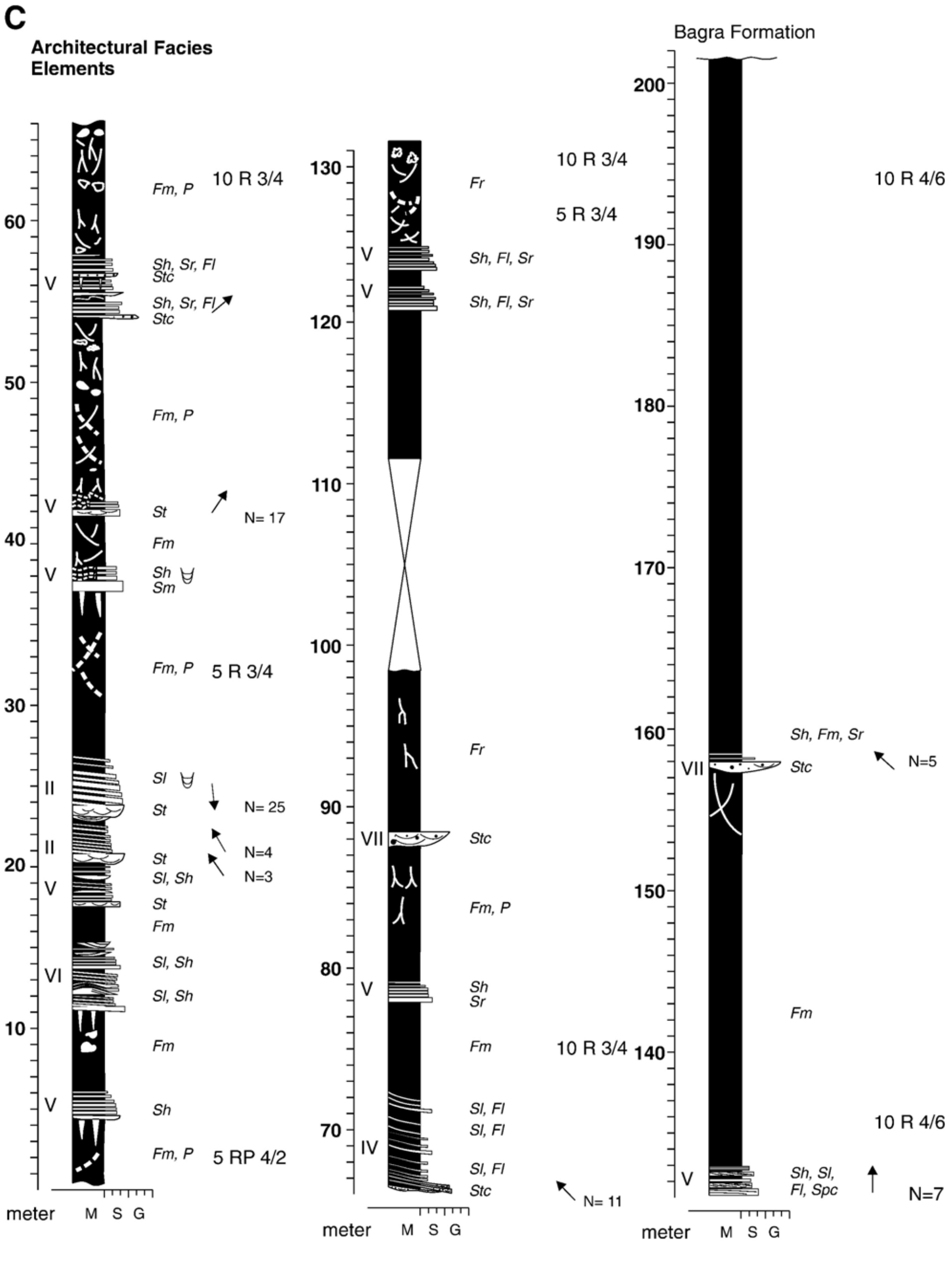


Fig. 3 (*continued*).

lithosome comprising thick cosets of large trough cross-strata is common in many of the bodies. The set thickness decreases towards the top of each coset. The other lithosome is wedge-shaped and planar cross-stratified. The upper and the lower boundaries of the wedges are sharp. The wedges thicken in the direction of accretion of the constituent cross-beds and again the lower bounding surfaces as well as the internal reactivation surfaces are also inclined in the same direction. Vertical burrows and small desiccation cracks are present on the upper bounding surface of the wedges whereas the lower bounding surface is lined with clay chips. Some of the element IA bodies comprise solely the trough cross-stratified lithosome. In other bodies, wedge-shaped and lenticular lithosomes occur together. In such bodies, wedge-shaped lithosomes occur separated by lenticular trough cross-stratified lithosomes. However, the trough cross-stratified lithosome always occurs near the basal part of the body and the trough axes are typically oriented oblique to the migration

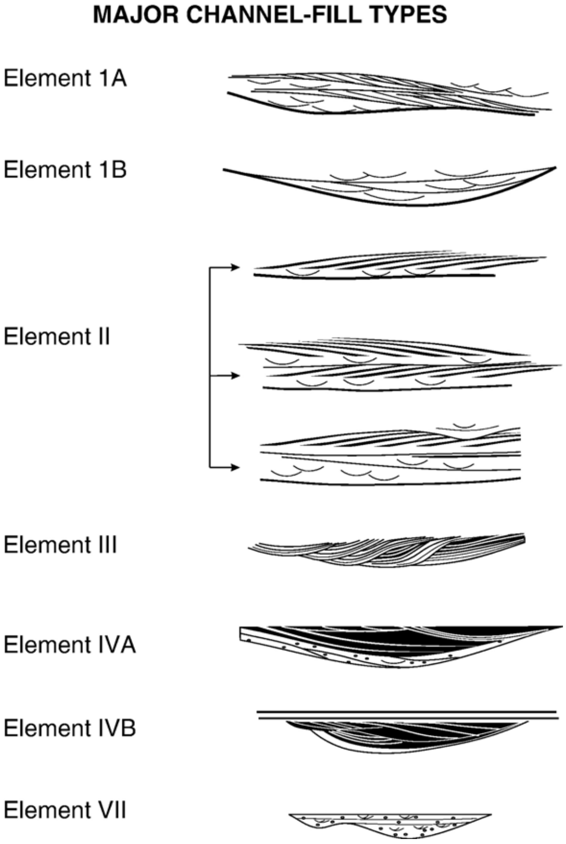


Fig. 4. Idealized internal organizations of the channel-fill bodies of the Upper Denwa Formation.

directions of the planar cross-strata of the wedge-shaped lithosomes.

Single-storey ribbon bodies dominated by sandstone are sparse in the Upper Denwa succession. A partly exposed ribbon-shaped unistorey body (4–5 m thick and ~180 m wide) was studied in a poorly preserved section along a southward closing U-bend of a small creek (Fig. 5). The sandstone-dominated lower half in the thickest part of the body display northward dipping large planar cross-strata overlain by coset of trough cross-strata suggesting a northerly flow (Fig. 5, view I). The sandy lower half is overlain by horizontal heterolith comprising centimeter- to decimeter-scale alternation of sandstone and mudstone that becomes muddier further upwards. In the western part, the body becomes thin and is underlain by thick red mudstone. Three relatively smaller, ribbon- to wedge-shaped sandy to heterolithic bodies are exposed in the western part of the section (Fig. 5, view II). These bodies are laterally connected to the main channel body. The smaller bodies are characterized by the presence of medium to small-scale (set thickness, centimeter- to decimeter-scale) trough cross-strata indicating a westerly paleoflow. Thus, in this section, moving away from the thicker part of the channel body there is a decrease in bedform height, bed thickness, scour depth and an increase in mudstone content. In other locations, however, the field relationships suggest lateral connectedness between element 1A sandstone bodies with sheet bodies (element V).

3.1.2. Interpretation

The element IA sandstone bodies are the only examples of Upper Denwa channel-fills that are characterized by the presence of thick sets of planar cross-strata overlain by cosets of trough cross-strata. The deposits attest to the presence of large straight crested and smaller sinuous crested dunes, respectively. The presence of relatively smaller trough cross-strata in the upper part as well as gradual upward transition to mudstone indicates slow and gradual abandonment of the channel. The absence of lateral accretion surfaces implies that the channels were laterally stable. These sandstone ribbons occurring encased within mudstone are interpreted as the remains of vertically aggrading straight channels. The smaller ribbon- and wedge-shaped bodies displaying paleocurrent at a high angle to that of the thickest part of the channel deposit are interpreted as associated crevasse channels and splay deposits. The apparent lateral connectedness between element 1A sandstone bodies with sheet bodies (element V) also suggests deposition of sheet bodies from splays emanating out of large channels.

3.2. Element 1B: multistorey sandy ribbons

3.2.1. Description

Multistorey sandstone-dominated ribbon bodies are not common in the Upper Denwa Formation. Where they occur, these bodies are about 25 m wide and 2.7 m thick in flow-transverse section. The element IB ribbon bodies are characterized by the presence of a single, major basal erosion surface that shows up to 4 m of relief and internally comprise 3 to 4, slightly laterally shifted, vertically stacked stories (Fig. 6). The sandstone bodies dominantly comprises medium to fine sandstone but large pebble-sized intraformational mudclasts are present in the lower stories. These ribbons are solitary bodies encased in red mudstone. These bodies are characterized by the absence of lateral accretion surfaces. The storey units are bounded by scour surfaces. Thin, discontinuous intervals of red mudstone–sandstone heterolith (in centimeter-scale) are locally preserved between the stories. The element IB bodies show an overall thinning-upwards trend in set thickness of trough cross-strata.

Table 1
Characteristics of the elements of the upper Denwa Formation (*w*: width, *d*: thickness, HS: heterolithic stratification, IHS: inclined heterolithic stratification; for lithofacies codes, see legend of Fig. 3A)

Element	Description	Common lithofacies	Dimensions	Interpretation
I	(A) *Single-storey sandy ribbons*: dominated by cosets of large wedge-shaped planer cross-strata.	Sp,St, Sm, Sr	*w*: 100 to 200 m, *d*: 3 to 4.5 m	Fill of sandy braid-channel with sandy mid-channel bars.
	(B) *Multistorey sandy ribbons*: trough cross-strata dominant. Story thickness 0.25 to 1.2 m.	St, Fl, Sl, Sr, Sm	*w*: 25 m, *d*: 2.7 m Storey: *w*: 15–20 m, *d*: 0.25–1.2 m	Deposits of sandy laterally stable channels of low-sinuosity filled in phases.
II	*Sandy tabular bodies*: IHS overlying basal sandy, trough cross-stratified lithosome. Direction of inclination of HS high-angle to the flow-direction inferred from the basal lithosome.	St, Sp, Sl, Fl, Sr	*w*: ∼100 m, *d*: 7–8 m Storey: *w*: 30–40 m, *d*: 2–3 m	Fill of mixed-load sinuous laterally migrating channel with laterally accreting point bars.
III	*Ribbon bodies of IHS*: dominated by laterally stacked, co-directional lensoid sets of IHS separated by curved discontinuity surfaces.	Stc, St, Sl, Fl,Sr, Fm, Spc	*w*: ∼100 m, *d*: 5 m	Fill of mixed-load to suspended-load sinuous channel. Stable channels filled by obliquely accreting fine-grained point-bar/banks. Channels relocated intermittently.
IV	(A) *Mudstone-dominated ribbon bodies with IHS*: coset of muddy IHS overlying a coarse basal trough cross-stratified lithosome dominated by calcirudite/calcarenite.	Stc, St, Sr, Sh,Sl, Fl, Fm	*w*: ∼150 m, *d*: 5–7 m	Major suspended load channel deposits. Channels dominantly filled by oblique aggradation of muddy banks/benches and by passive plugging.
	(B) *Minor ribbon bodies of mudstone-dominated heterolith*: shallow scours concentrically and asymmetrically filled with muddy HS.	Stc,Sm, Sr, Sl, Fl, Fm	*w*: ∼15 m, *d*: 1.5–3 m	Fills of small short-lived laterally stable, suspended-load channels. Channelized splay (?)
V	*Sandy to heterolithic sheet bodies*: lower bounding surface is sharp and planar. Centimeter- to decimeter-thick flat bedding with or without parting lineation, most common. Alternations of sandy and muddy sheet bodies constitute very thick complexes. Small concavo-planar sandy/heterolithic bodies are encased in such complexes. Plano-convex lenticular beds with wavy stratification occur at the base of complexes.	Sh, Sl, Sr, Fl,Fm, St, Sp	*w*: smaller bodies: tens of meters, larger bodies: hundreds of meters; *d*: smaller bodies: 1–3 m, larger bodies 7–8 m	Proximal (sandy) and distal (muddy) crevasse splay deposits at places emplaced in standing body of water. Sheet-complexes: progradational splays (with small splay channels) at places leading to channel avulsion.
VI	*Tabular bodies of complexly organized heteroliths*: dominantly made up of centimeter- to decimeter-scale heteroliths. Plano-convex and concavo-planar sandstone with gently inclined internal stratification alternate with mudstones that are desiccated in places. The bodies have sharp gently undulating to planar lower contact with VIII. Upper contact with VIII flat and gradational.	Sm,Sl, Fm, Sr	*w*: tens of meters, *d*: 3–5 m	Poorly channelized to non-channelized splay deposits formed under fluctuating and ephemeral flow conditions.
VII	*Minor ribbons of intraformational conglomerate*: concavo-planar ribbon bodies made up of caliche-derived peloidal calcirudite/calcarenite. Crudely bedded and/or trough cross-stratified.	Stc, St	*w*: few meters, *d*: ∼1 m	Small, transient, second order floodplain channels.
VIII	*Mudstone*: grayish red (5R 4/2), dark red brown (10R 3/4) and purple (5RP 2/2) siltstones/mudstones. Mostly massive. Contain very thin sheets of fine sandstone and calcirudite only locally. Pedogenically modified in varying degrees.	Fm	*w*: 1 to 2 km, *d*: (1–5 m) to (7 to 10 m)	Partly suspension settled overbank fines and partly fine-grained splay deposits.

Each story displays a weak fining-upwards trend in grain size and primary structures. Maximum thickness of each storey varies from 0.25 to 1.2 m. The stories (15–20 m wide) are characterized by concavo-planar cross-sectional profile with poorly defined wings. The stories are internally comprised of decimeter-thick trough cross-strata, low-angle plane lamination and ripple cross-lamination.

3.2.2. Interpretation

Absence of lateral accretion surfaces within the individual stories implies that the channels were

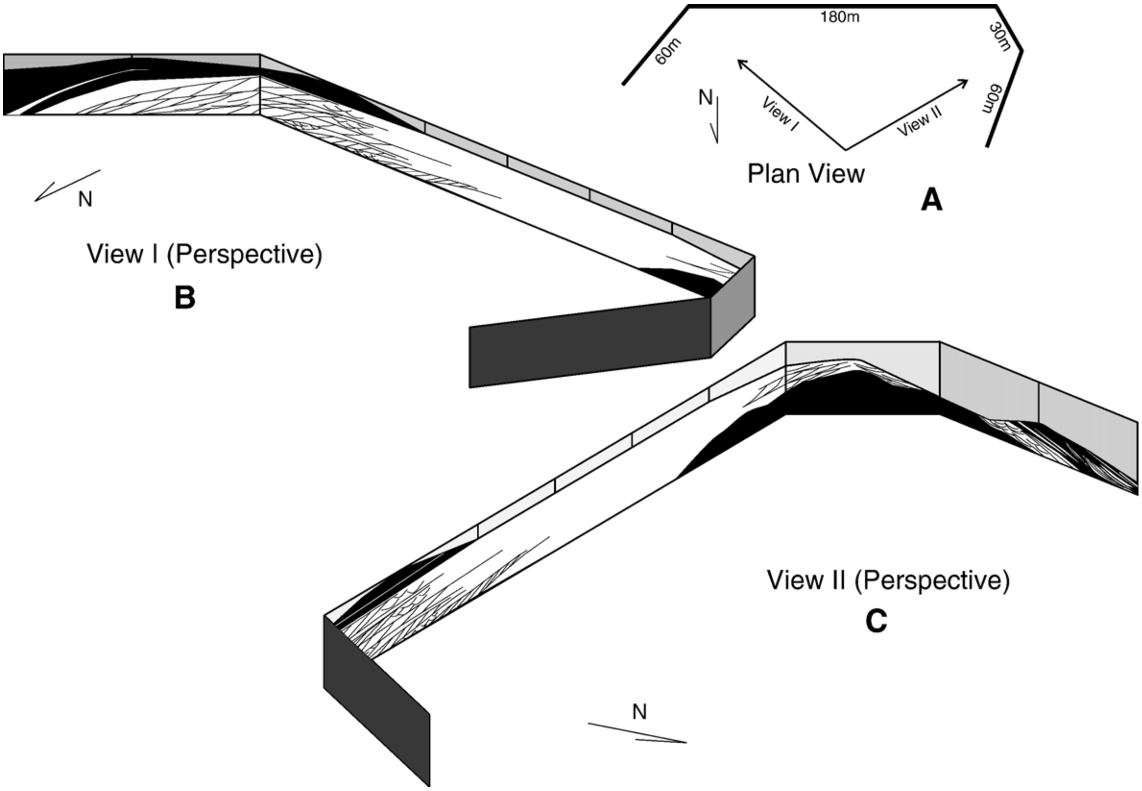


Fig. 5. Line drawings of a northerly dipping single-story, sandy ribbon body (element IA) exposed along a southward closing U-bend of a small creek, just north of Pisua village (see Fig. 2 for location). (A) Planform of the creek. (B) Perspective view of the cross-stratified sandstone body (white), overlain by mudstone (element VIII, shown in black) in the eastern part of the exposure. (C) Perspective view of the same body in the western part of the exposure. Note that the thickness of the body decreases towards west and there are three smaller heterolithic bodies, encased in mudstone of element VIII (shown in black), that are laterally connected with the main sandstone body. Light gray shade in both B and C represents weathered fine-grained sediments.

laterally stable. The occurrence of multistorey ribbon bodies encased in mudstone suggests that channels were laterally stabilized by cohesive mud banks. Partial preservation of fine-grained material between the vertically stacked stories suggests partial scouring of the earlier channel-fill deposits and subsequent plugging in a series of distinct sedimentation events. The grouping of channel-fill deposits giving rise to multistorey sandstone bodies of limited lateral extent implies repetitive reoccupation of the same site by the channels (cf. Stear, 1983; Mohrig et al., 2000).

3.3. Element II: sandy tabular bodies with IHS

3.3.1. Description

Element II channel-fill bodies are short, tabular in flow-transverse profiles. They are mostly multistorey bodies, about 7 to 8 m thick and can be traced laterally

Fig. 6. A multistorey sandstone-dominated ribbon body of element IB, southeast of Chilond village. Two of the stories are marked I and II. Note well-developed desiccation cracks (arrow) in the red mudstone underneath the sandbody. Scale bar 1.5 m.

for about 100 m. There are also single-storey bodies encased in mudstone (element VIII). Individual storeys are 2 to 3 m thick and can be traced laterally for 30 to 40 m. A single storey comprises a basal sandy lithosome overlain by inclined heterolithic strata (IHS, sensu Thomas et al., 1987; Figs. 4 and 7) that passes both vertically upwards and laterally to mudstone. In multistorey bodies, the IHS of a storey either may be preserved or may be truncated by the basal unit of the overlying storey (Fig. 4).

The basal sandy (medium to fine sandstone) lithosome of a storey is sheet-like and varies in thickness from 20 cm to about 1.5 m. The basal lithosome overlies either the massive mudstones (element VIII) or IHS of an underlying storey with a sharp, flat to gently concave-up erosive contact marked by abundant small pebble-sized mud-clasts. The upper bounding surface is flat. This lithosomes is internally trough cross-stratified (10 to 30 cm thick sets) and the trough axes are oriented at high angle to the inclination direction of the inclined heterolithic strata of the overlying lithosome.

The IHS occurs as 1.5 to 2 m thick solitary sets (Fig. 7). The inclination of these heterolithic strata generally varies between 5° and 10°. They are sigmoidal in shape in flow-transverse profiles; topset strata are convex-up in geometry while the toe set strata are concave-up and are tangential to the lower bounding surface. The toe set merges imperceptibly with the underlying sandy lithosome while the top set interdigitate with and passes upward into mudstone. Internally, the IHS comprise “simple” (sensu Thomas et al., 1987) alternation of decimeter- to centimeter-thick layers of fine sandstone and mudstone.

Within the IHS, the sandstone layers are massive or parallel-laminated, whereas the mudstone layers are red and generally massive. The lower bounding surfaces of the coarse-fine couplets of the IHS are sharp and at places are marked with mudstone chips near the toe region of the IHS set. The mutual contact between the coarse and the fine member of a couplet is sharp. The basal sandy lithosome, followed upwards by the IHS set and the topmost mudstone forms a finning upward (F-U) succession. In most exposures, these FU successions are vertically stacked to form thicker multistorey complexes that are 10 to 15 m thick (Figs. 4 and 7). The direction of inclination of the IHS as well as the paleocurrent direction shows considerable variation between the individual FU successions within such complexes (Fig. 7). In places, the upper mudstone/IHS of the FU successions are truncated by the superjacent units resulting in amalgamation and thickening of the basal trough cross-stratified sandstone lithosome. In such cases, however, IHS are preserved in the topmost storey of a multistorey complex (Fig. 4).

3.3.2. Interpretation

The basal trough cross-stratified lithosome records migration of 3D dunes transporting coarse bedload material along the deeper parts of the channel. The overlying IHS indicates the existence of a channel-scale macroform that was accreting across the thalweg. The interdigitation of the accretionary IHS and the overlying fines indicates that the upper part of this macroform remained attached with the muddy overbanks during all stages of accretion. Thus, the internal organization of these bodies resembles the deposits of a mixed-load meandering stream with laterally accreting point bars or bank-attached bars (Thomas et al., 1987; Miall, 1988; Munoz et al., 1992). The occurrence of IHS indicate an autocyclic depositional mechanism which is repetitive in nature and in a fluvial setting maybe ascribed to annual floods (cf. Thomas et al., 1987; Munoz et al., 1992; Brooks, 2003). In some settings, each simple coarse-fine couplet has been correlated with a single flood (Bridge and Diemer, 1983; Mossop and Flach, 1983; Thomas et al., 1987). The sharp contact between the coarse and its immediately overlying fine member of the coarse-fine couplets indicate decelerating flow velocities during prolonged waning flood stage that resulted in efficient differentiation of sediment population

Fig. 7. Stacked tabular channel-fill bodies of element II, northeast of Singanama village. Note strongly divergent dip directions of the inclined heterolithic strata (IHS). One of the trough cross-stratified sandstone bed below IHS is marked *St*.

and prevented gradation between the traction and the suspension populations (Thomas et al., 1987).

The separate storeys in each sandstone body were deposited in a single channel belt and the multistorey bodies are interpreted as deposits of aggrading river channels migrating laterally across the floodplain. However, these tabular bodies having limited lateral extent (width ~ 100 m) suggests that the lateral migration might not been very extensive and a well-developed meander belt was absent.

3.4. Element III: ribbon bodies of IHS

3.4.1. Description

These bodies appear lenticular in flow-transverse sections. These bodies are about 100 m wide and 5 m thick. These are made up of lensoid sets of IHS (Figs. 4 and 8). The IHS sets are muddier as compared to those of element II channel-fill bodies. The IHS sets are laterally superposed to constitute imbricate coset of co-directional sets (cf. Thomas et al., 1987) that are analogous to disconformity-bounded genetic packages of laterally accreted sandstone–mudstone couplets described by Turner and Eriksson (1999). Transverse to flow, an individual IHS set resembles a truncated trough that is bounded by curved and co-directionally inclined erosion surfaces. The toes of the set boundaries merge with the lower bounding surface of the element III bodies (Fig. 8) and are usually marked by the occurrence of calcirudite.

Constituent strata of IHS sets are curved, gently concave upward that approximately conform to the cross-section profile of the lower set boundaries but are asymptotic to the base. However, constituent strata of some of the IHS sets towards the upper part display upward convexity and interdigitate with the overlying mudstone. The maximum inclination of these heterolithic strata and the set bounding surfaces varies between 10° and 20°. In the younger sets the IHS are gently inclined to horizontal. Lateral accretion surfaces in heterolithic strata are steeper than those in sandstone-dominated IHS of element II.

Coarse-fine couplets of the heteroliths comprise alternation of 0.5- to 10-cm-thick fine sandstone and mudstone. The contact between the coarse and the fine member of the couplet is sharp. The coarse member can be massive, parallel- or cross-laminated. The fine member is usually massive, but at places comprises second order alternation of parallel-laminated sandstone and massive mudstone at millimeter-scale.

Within each set of inclined heteroliths, the relative thickness of the coarse and the fine member decreases upwards (Fig. 4) and as a consequence the overall grain-size within an individual set fines upward. The coarse members of the adjacent couplets coalesce in the basal part of the sets to form a ~ 10- to 50-cm-thick coarse-grained lithosome. This lithosome comprises an admixture of coarse sand and granule-sized detrital pedogenic glaebules and is trough cross-stratified. These trough axes are oriented nearly orthogonal to the inclination direction of the IHS. Fragments of limb bones of fossil amphibians and articulated Unio shells are also present within this basal lithosome.

3.4.2. Interpretation

The IHS that mainly comprises these channel-fills developed from lateral accretion and, therefore, may be interpreted as river point bars or bench deposits. The inferred muddy bar/bench deposits of the Upper Denwa Formation closely resemble those described from meandering channels carrying dominantly suspended-load on a low-gradient floodplain (Woodyer et al., 1979; Brooks, 2003). Higher depositional dips of IHS in this kind of channel-fill body may be ascribed either to predominance of suspended–load sediments (Stewart, 1983) or to low width/depth ratios of the precursor channels (Schumm, 1968). The IHS described above differ in some respects from the point bars of mixed-load channel system, which generate lateral accretion units exhibiting a gentle convex-up depositional slope and

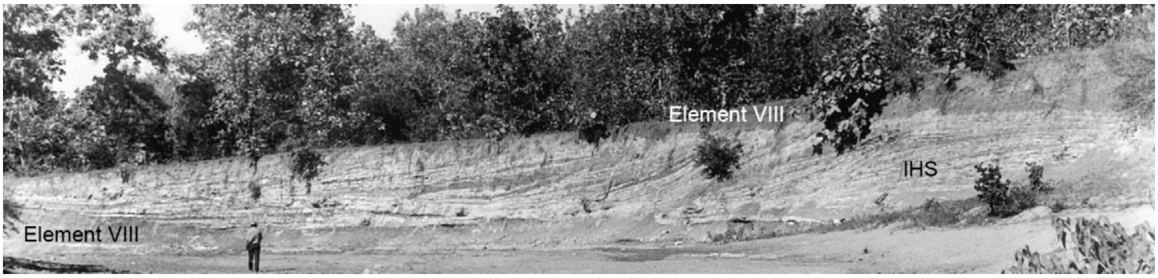


Fig. 8. A ribbon channel-fill body of element III comprising several laterally stacked sets of inclined heterolithic strata (IHS). Note that the element III body is encased in red mudstone (element VIII). Paleoflow is towards the observer. Person for scale.

typically form sand-dominated vertical sequence. Firstly, these channel-fill deposits are muddier and the IHS units are steeper than the typical sandy/mixed-load point bar deposits. Lateral accretion surfaces in heterolithic strata have been noted to be steeper as compared to those in sandy strata (Edwards et al., 1983; Kirschbaum and McCabe, 1992; Turner and Eriksson, 1999) and IHS is generally considered as muddy point bar/bank accretion deposits of mixed-load/suspended-load streams (Piugdefabregas and Van Vliet, 1978; Taylor and Woodyer, 1978; Stewart, 1983; Thomas et al., 1987).

As with element II, IHS, the most dominant constituent of these channel-fill bodies, indicates repetitive and fluctuating discharge related to flood events (Thomas et al., 1987). In somewhat analogous channel-fills of mud-dominated Red River, Canada, Brooks (2003) correlated a single couplet from the accretionary banks as an annual deposit. The major erosion surfaces which subdivide the body into IHS sets, arranged in a coset, probably indicate episodic lateral migration of these channels probably related to meander-loop expansion (cf. Thomas et al., 1987; their Fig. 14 and Turner and Eriksson, 1999). These surfaces indicate that the growth of the accretionary banks/benches was discontinuous.

Similar erosion surfaces separating IHS sets have been ascribed to major flood events by Thomas et al. (1987). In low-gradient settings as in the Upper Denwa Formation, erosion should be very limited even during extreme floods because stream power is generally very low. However, phases of enhanced stream power at least in certain locales are possible even in a low-gradient setting, which gave rise to the discontinuity surfaces separating the IHS sets. The result was the development of wide ribbon body comprising a mosaic of laterally connected point bars/bench deposits in varying states of completeness.

3.5. Element IVA: mudstone-dominated ribbon bodies with IHS

3.5.1. Description

These channel-fill bodies are mudstone-dominated and lenticular in flow-transverse profile (Figs. 4 and 9). These bodies are about 150 m wide and are 5 to 7 m thick. The basal contact with the red mudstone is erosional, gently concave upward and shows up to 3 m relief. The upper contact with the overlying fines is gradational and flat.

A number of discontinuous, lenticular strata of calcirudite (10 to 20 cm thick), interleaved with stratified red mudstone/siltstone occur as the basal unit (20 cm to 80 cm thick) of these bodies (Fig. 10). The calcirudites are made up of coarse sand- to small pebble-sized, reworked, pedogenic calcareous glaebules, medium- to coarse sand-sized siliciclastic grains and rip-up clasts of mudstone. The calcirudite strata are internally trough cross-stratified (set thickness: 5 to 20 cm). The overlying middle lithosome is dominated by red mudstone and contains a few thin, fine sandy/silty layers, which are gently inclined to virtually concordant with the lower bounding surface. In the thickest central part of the body, a small ribbon like body with concentric heterolithic fill occurs in middle level. Further upwards sandy inclined strata alternating with mudstone are organized in lenticular/wedge-shaped sets of inclined heteroliths. Individual sets are 1 to 3 m thick. The inclination varies between 13° and 18° with respect to the basal set boundaries. The heterolithic sets are bounded by planar to gently curved, horizontal to inclined, erosional planes at places marked by the occurrence of intraformational mudclasts. These topmost sets were noted to cut down across the lower sets in the thickest central part of the bodies. The trough axes of the basal calcirudite are oriented at a low angle to the strike of these heterolithic strata. The mudstone members are commonly much thicker (3 to 60 cm) than the sandstone members (5 to 30 cm) of the IHS and consequently IHS sets are mud-dominated. The organization of the coarse-fine couplets within the IHS is simple (cf. Thomas et al., 1987). The coarse members are internally parallel- or ripple cross-laminated and their upper surface is burrowed at places. Even the mudstone-dominated middle parts of the channel-fill are replete with ripple cross-lamination.

3.5.2. Interpretation

The basal cross-bedded calcirudite interbedded with siltstone/mudstone indicate bedload transport by the migrating 3D dunes and intermittent suspension settlement of fines due to flow fluctuations. Predominance of intraformational, caliche-derived material in the basal thalweg deposits implies derivation of material from local sources that were exhausted within a short time after the channel incision and subsequently deposition of the fine-grained sediments prevailed. The centimeter-thick siltstone/fine sandstone beds virtually conformable with the concave-up channel-scale scour suggest passive channel plugging during intermediate stage of channel-filling. The topmost wedge-shaped IHS sets indicate the existence of a swarm of 2D macroforms. Their direction of accretion, being at high angle with the paleocurrent

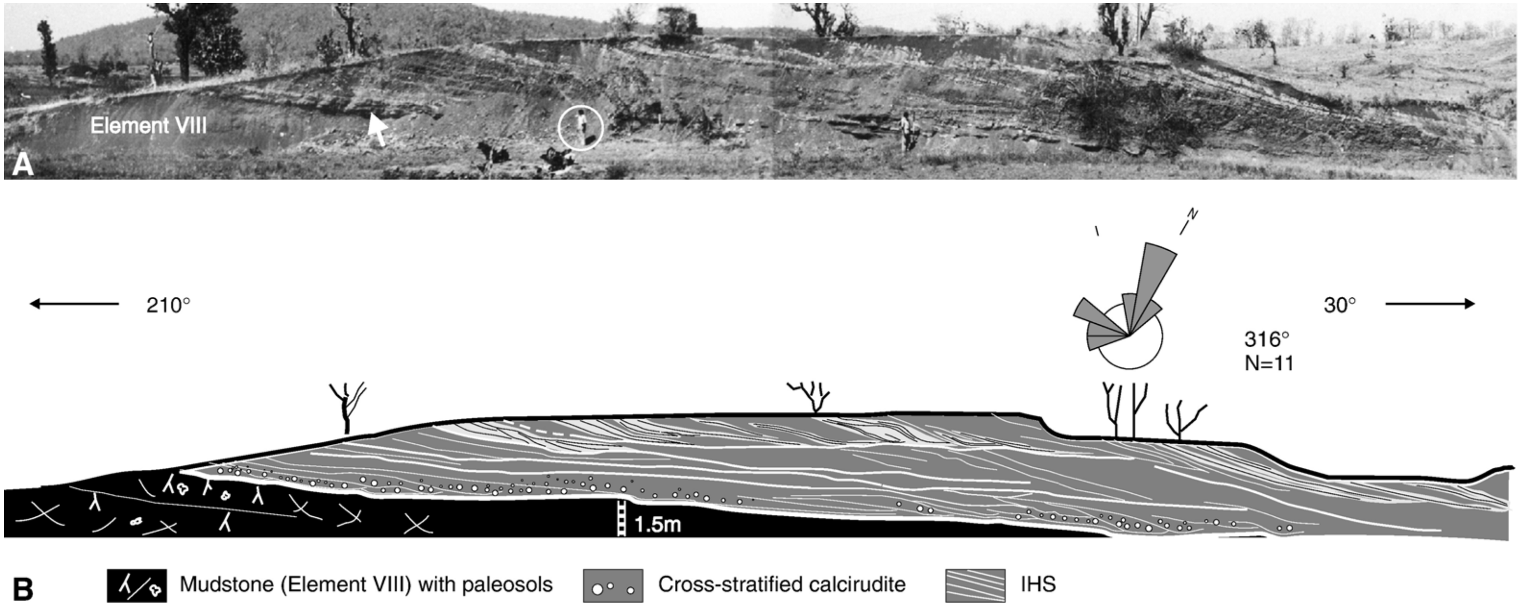


Fig. 9. (A) A partly exposed ribbon-shaped, mudstone-dominated channel-fill body of element IVA, just north of Taldhana village. Note the calcirudite beds (arrow) at the base of the channel-fill. Person within circle for scale. (B) Field sketch showing the internal organization of the same. VM: vector mean of the foreset azimuths. *N*: number of paleocurrent data.

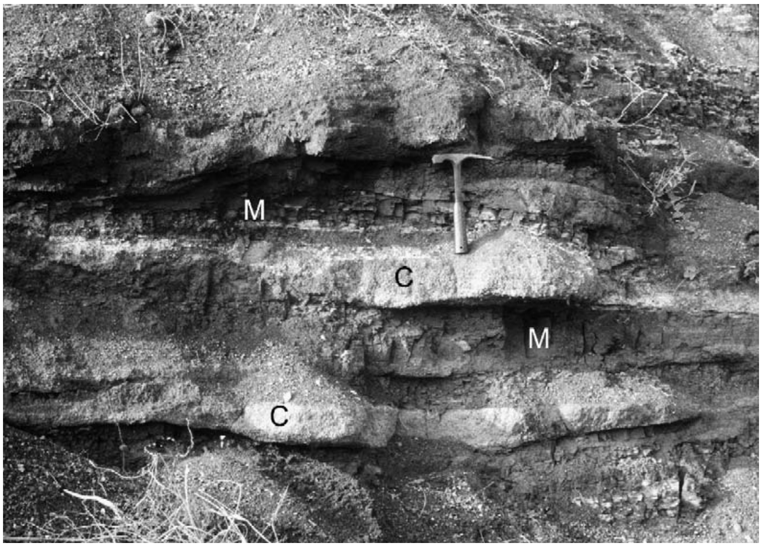


Fig. 10. Calcirudite beds (C) intercalated with mudstone (M) that occur along the basal part of the channel-fills (element IVA) shown in Fig. 9.

direction, suggests that they had migrated laterally across the thalweg.

Limited lateral extent of the element IVA bodies and their isolated occurrence within the fines suggest laterally stable large channels. The occurrence of form-concordant strata in the middle part of these bodies and vertically or laterally stacked sets of IHS in the upper part reflect several distinct episodes of vertical and lateral aggradation. Periodic reoccupation of partially abandoned conduits isolated within the floodplain during major floods is envisaged. The predominance of thick mudstone/siltstone layers in the channel-fill indicates deposition in sluggishly flowing channels overly charged with fines.

3.6. Element IVB: minor ribbon bodies of mudstone-dominated heterolith

3.6.1. Description

These bodies are concavo-planar in flow-transverse profile and relatively smaller in dimension as compared to those of element IVA (Figs. 4 and 11). These bodies on average are more than 15 m wide and are 1.5 to 3 m thick. These bodies represent lithologically complex fills with internal scour surfaces. Basal contact with red mudstone (element VIII) is concave-upward, which is generally lined with 15–20 cm thick veneer of massive to poorly stratified calcirudite that contain pedogenic carbonate peloids, mudstone clasts (granule to small pebble size) and sand-sized siliciclastic. Upper contacts of these bodies are planar and they grade to overlying red mudstone (element VIII) through horizontally stratified sand/mud heteroliths. Many of these bodies are composite and comprise two or more vertically stacked lenticular lithosomes separated by gently undulating to slightly concave-up erosion surfaces. Each of the lenticular lithosome generally comprises sand-dominated to mud-dominated heterolithic fills that may display marked lateral and vertical change in sand: mud ratio (1:2 to 1:7). The heterolithic fills display different styles. There are concentric fills consisting of interbedded sandstone and mudstone. Some are inclined heteroliths that pass laterally towards the deeper part of scour into mudstone and grade upward into horizontal heterolith. Inclined heterolith, at places, comprises pseudo beds formed by climbing ripples. The uppermost lithosome is generally laterally more extensive than the lower one and extends beyond the lateral margins of the ribbon bodies.

3.6.2. Interpretation

Basal conglomeratic material indicate transport and deposition of locally derived intraformational material immediately after channel formation but the source of coarse sediment was either rapidly cut-off or flow strength diminished so that fine-grained sediment dominated in the later period of aggradation. Internal erosion surfaces and small-scale variation in grain size reflect multiple reactivation of these channel-fills. The sandstone interbeds of the heteroliths were deposited as bedload and migration of ripples took place during active flow in the channel and the fine-grained beds were deposited as the current waned. Thus, each couplet

Fig. 11. A ribbon-shaped minor channel-fill body (element IVB), east of Piparia village, mainly comprising nested sets of heterolithic stratification. Note that, in the lower part, heteroliths conformably fill scours, whereas, in the upper part, IHS gradually passes upwards into horizontal heteroliths. Hammer within circle for scale.

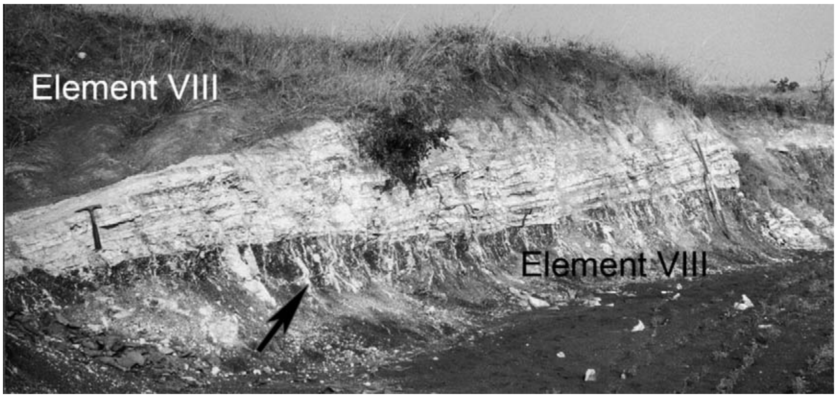


Fig. 12. A sandstone-dominated sheet body of element V. Note slight angular discordance between the sandstone interbeds and the basal bounding surface. Also note profusely developed subvertical desiccation cracks (arrow) in the underlying red mudstone (element VIII). Length of the stick is 1.5 m.

of thin sandstone and mudstone likely records a single pulse of sediment and water supply into the channel. Concentrically and asymmetrically filled small channel bodies similar to those encountered in the Upper Denwa succession have been reported by others (Kirschbaum and McCabe, 1992; Munoz et al., 1992; Newell et al., 1999). The heterolithic strata within channels were likely to be deposited by fluctuating currents. Concentric accretion units require the absence of any significant helical flow within the channel and they probably indicate currents weaker than that implied by asymmetric accretion units (cf. Kirschbaum and McCabe, 1992).

3.7. Element V: sandy to heterolithic sheet bodies

3.7.1. Description

The sheet-like bodies display a wide variation in lithology and dimensions. Individual sheet bodies are generally 1–3 m thick and they extend laterally for tens of meters. However, in exceptional instances, they may attain a thickness of 7–8 m and extend laterally for hundreds of meters. Individual bodies thin out both laterally and distally, either gradually or, in several instances, abruptly. The bodies have sharp and planar basal contacts with red mudstone (element VIII; Fig. 12). Some of them are dominated by medium to fine sandstone with only a minor amount of mud forming millimeter- to centimeter-thick strata (Fig. 12), while others are characterized by the dominance of sandy to muddy heteroliths (Fig. 13).

The upper boundary of the sandstone-dominated sheets with the overlying fines (element VIII) is generally planar and sharp. However, in some of the bodies, the lower sandy part gradationally passes upward into red mudstone (element VIII) through sandy and muddy heterolith. The most dominant

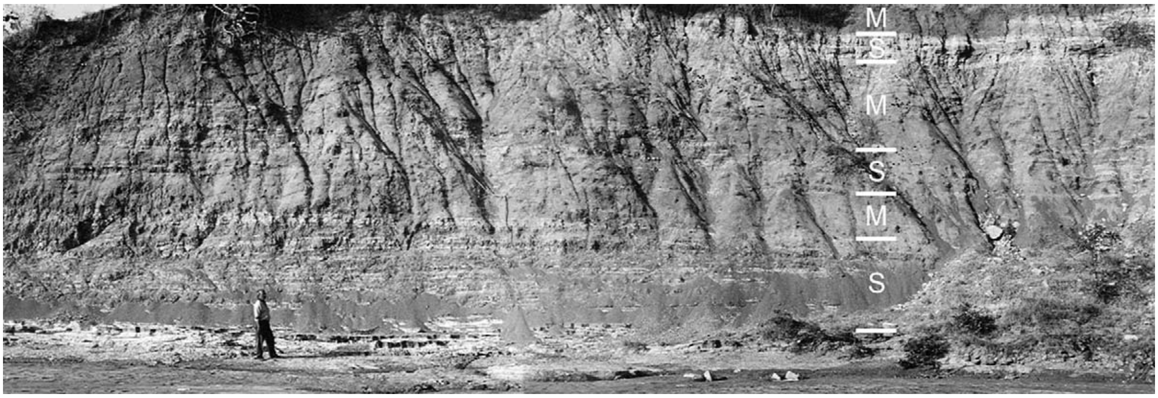


Fig. 13. A thick complex of sheet bodies comprising sand- and mud-dominated heteroliths of element V. Note the basal sandy interval (on which the man stands) overlain by sandy (S) and muddy (M) heteroliths. Also note that the relative thickness of sandy heteroliths decreases and that of muddy heteroliths increases upwards.

sedimentary structures in the sandy sheet bodies are centimeter- to decimeter-scale flat bedding that is either parallel or gently inclined with respect to the basal bounding surface (Fig. 12). In places parallel-lamination with or without parting lineations and a few sets of planar/trough cross-strata, centimeters to decimeters thick, are present in lower sandy parts of the sheets. A few sandy sheet bodies (up to 8 m thick) are massive in nature.

The heterolithic bodies dominantly comprises centimeter- to decimeter-scale alternation of sandstone and mudstone, but many of them are characterized by siliciclastic sandstone or calcirudite/calcarenite-rich basal part and mud-rich upper part (Fig. 13). Thus, a poorly developed F-U succession is discernible. Sand interbeds in the lower part of heteroliths also show parallel-lamination with parting lamination and ripple cross-lamination. At places, the basal sandy units in sheet-like heterolithic body display sharp, planar lower boundaries and undulating to wavy upper boundaries and consequently show large thickness variations within a short distance. These beds are characterized by angle-of-repose trough cross-strata, low-angle planar cross-strata grading into quasi-horizontal parallel laminae, slightly convex-upward draping laminae with form discordant internal strata, low-angle discordance between sets of inclined parallel laminae (Fig. 14). At places ripples are present on the top surface of the sandy units. A wide divergence exists between different sets of cross-strata.

Some of heterolithic sheets are mudstone-dominated. These are characterized by the presence of erosively based, thin (5–10 cm) layers of massive, crudely stratified or even cross-stratified calcirudite/calcarenite (5–10 cm) beds. These sheets dominantly comprise centimeter-thick medium to fine-grained ripple cross-laminated/parallel-laminated sandstone alternating with massive red mudstone of comparable thickness. A number of millimeter-thick sets of sandy ripple cross-lamination are also present within the red mudstone interlayers. At places, wavy lamination are present in the silty/fine sandy interlayers of heterolithic strata (Fig. 15). The frequency of occurrence of sandy layers in heteroliths decreases towards the upper part. Thus, a F-U succession is discernible in muddy heterolithic sheet. At places, the muddy heterolithic strata are characterized by the presence of articulated bivalve shell of unionid. In one instance, an exceptionally rich mixed skeletal assemblage of capitosaurid amphibians, Unio and dipnoan fishes has been reported from the mud interlayers of heterolithic package in the Upper Denwa succession (Bandyopadhyay et al., 2002).

At places, a number of vertically stacked FU units constitute sheet-like heterolithic complexes that are 10 to 13 m thick and a few hundred meters in lateral extent (Fig. 13). Individual heterolithic units display F-U trends that begin either with sharp based sandy or calcirudite/calcarenite layers. The upper part of such complexes generally grades to overlying red mudstone (element VIII). In rare instances, sandy channel deposits occur immediately above the complexes. Apart from a few dispersed large rhizocretions in the upper part of the heterolithic sheet bodies, there is little evidences of pedogenic modification of these bodies. The red mudstones that encase these bodies or complexes show well-developed cumulative paleosols with very well-developed desiccation cracks and pedogenic slickensides and root molds.

3.7.2. Interpretation

The sandy sheet-like bodies of element V with sharp and planar, lower and upper contacts suggest emplacement from poorly confined ephemeral flows. The occurrence of parallel to low-angle stratification also corroborates the sheet flow origin. The presence of

Fig. 14. A part of the basal sandy part of the complex heterolithic sheet body (in Fig. 13). Note lenticularity of the sand body, slight upward convexity of the constituent layers in the upper part and their discordance with the slightly concave up layers in the middle part.

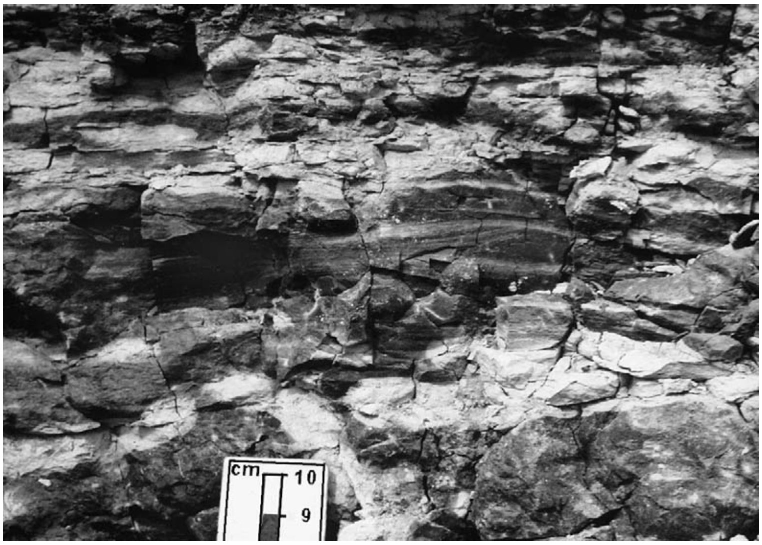


Fig. 15. Ripple-scale wavy lamination within the mudstone-dominated heteroliths of element V.

parting lineations generally in the lower parts of sandy sheets suggests initial deposition under upper plane bed conditions. The thick massive sandstone sheets also indicate very rapid deposition.

In heterolithic sheet complex, the lenticular sandstone beds with solitary set of planar and low-angle trough cross-strata grading upwards into low-angle inclined to horizontal parallel laminae indicate emplacement of sandstone at dune to upper stage plane beds flow condition. Sandstone beds that are in places characterized by undulating to wavy upper boundary and wavy drape of convex-up laminae suggest subaqueous emplacement of sandy splay at places. The complex arrangements of primary structures in these sand beds are reminiscent of crevasse splay sand lobes described by Bristow et al. (1999). Some of the heterolihic sheets in which cross-stratified calcirudite/calcarenite appear in the basal part seem to have been deposited from shallow, low-energy sheet flow that waned to generate only ripple scale bedforms in fine sandstone/siltstone in the upper part of these bodies. In contrast to the sandy sheets, the heterolithic bodies that gradationally pass upward to mudstone through sand–mud alternation in centimeter- to decimeter-scale represent the gradual waning of the flow and suggest slow rather than rapid deposition over a prolonged period. Wavy ripple-lamination in muddy heteroliths indicates wind activity on locally ponded water in the overbank areas (cf. Bridge, 2003).

Though physical connection of these bodies with larger channel-fill deposits could not be established in the field, except in one single instance, these bodies are interpreted as the deposits of crevasse splays. Several workers (Tyler and Ethridge, 1983; Choi, 1986; O'Brien and Wells, 1986; Smith et al., 1989; Mjos et al., 1993; Jorgensen and Fielding, 1996) have described a number of modern and ancient crevasse splay deposits, which are similar to the sheet bodies described herein. Poorly developed pedogenic features in the sheet complexes and the occurrence of well-developed cumulative paleosols in the surrounding red mudstones (element VIII) highlight the contrast between the rapidly emplaced crevasse splay deposits and the slowly accumulated overbank deposits.

The sandy sheets (with minor presence of very thin mud layers) and heterolithic sheets probably constitute the two end members of a continuous spectrum and possibly reflect proximal to distal gradation in a crevasse splay (see also Smith et al., 1989; Mjos et al., 1993). Vertical gradation from sand-dominated to mud-dominated intervals within an individual sheet reflects waning flow through a breached channel. These splays were probably semi-permanent features that were active during high stage and were probably abandoned at low stage when suspension sedimentation dominated in the floodbasin depressions in the distal part. Repeated splaying on a particular site of the floodplain generated the thicker splay complexes. The typical assemblage of fossil amphibians, fishes and articulated shells of unionid in muddy heterolithic sheets along with wavy lamination in the siltstone confirm the presence of floodbasin ponds. However, there is no evidence of large, long-standing bodies of water on the overbank and it is possible that crevasse-splays served as local watering holes for the terrestrial vertebrates.

3.8. Element VI: tabular bodies of complexly organized heteroliths

3.8.1. Description

The bodies of element VI are better described as complex heterolithic zones encased within red mudstone (element VIII). These zones are tabular in flow-transverse section, 3–5 m thick and several tens of meters in lateral extent. Internally, they comprise 25 to 30 cm thick and 1–2 m wide fine sandstone lenses complexly interwoven with heteroliths and mudstones (Fig. 16). The sandstone lenses are either plano-concave, convexo-planar or convexo-concave in profile geometry. Both the upper and the lower boundaries of these lenses are sharp. Internally, the sandstone lenses are characterized by gently inclined stratification that in places is marked by millimeter-thick mud interlayers.

The depressions between adjacent convex-up sandy lenses are partly depositional and partly erosional. These wide, trough-like, shallow depressions are either filled with concordant heteroliths or by red mudstone (element VIII). Horizontally stratified heteroliths and mudstone vertically separate sandy lenses. These heteroliths comprise centimeter-scale alternation of sandstone/mudstone that are in places, overwhelmingly mud-dominated (sand/mud ratio 1:5). A few of the mudstone interlayers show well-developed desiccation features.

All of these lithounits within this element display lateral transition amongst themselves within very short distance (meter-scale). These bodies are characterized by the lack of any major internal erosion surface and also by absence of any distinct vertical trend either in the scale of primary structure or in grain size. Locally, however, a relatively thicker sandy lens (up to 45 cm thick) occurs near the base.

3.8.2. Interpretation

These bodies are characterized by a lack of any discernible vertical trend in grain size and primary structures. Thus the internal organization of these bodies does not match typical patterns of fluvial channel-fills. Sharp, planar to slightly undulating lower bounding surfaces along with absence of large-scale bedforms indicate that these bodies developed by deposition from weakly channelized low-energy flows outside of the major channels. The presence of desiccation within the intervening mudstone confirms that deposition was intermittently interrupted by phases of subaerial exposure. The sand lenses possibly represent small-scale channel/scour fill or low-amplitude bars formed at relatively higher flow stages. This deposition was followed by aggradation in the depression by mud or interbedded mud and sand during subsequent depositional event. Limited lateral migration of the slip faces of the sandy bar or lobe is indicated by the inclined surfaces marked with thin veneers of mudstone. Limited lateral extent or the absence of channel-scale lateral accretion surfaces suggests that these bodies aggraded mainly through intermittent vertical rather than lateral aggradation. Rapid flow fluctuation and ephemerality characterize these deposits (cf. Bridge, 2003) as indicated by the sharp vertical changes from sandstone to mudstone or heteroliths and the presence of desiccations in mudstones. Repetitive fluctuations in flow conditions

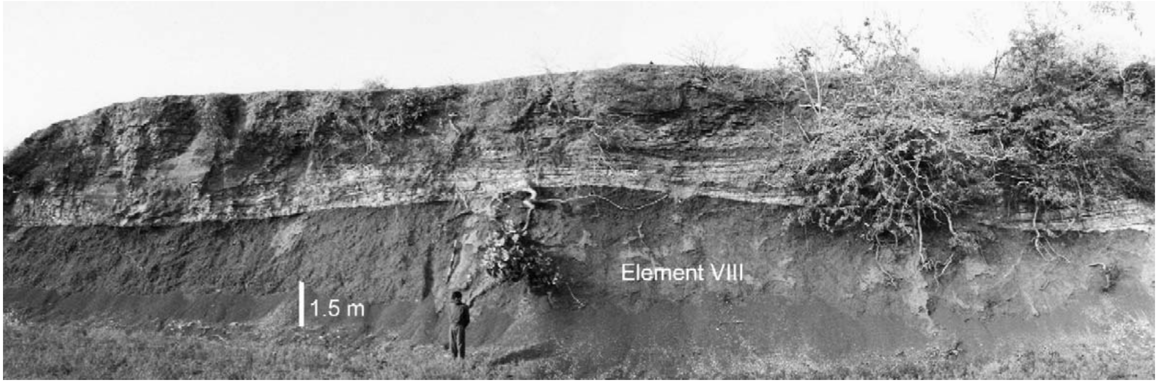


Fig. 16. A tabular heterolithic zone of element VI showing complexly interlayered sandstone and mudstone strata in decimeter- to centimeter-scale (about 2 km south of the Sahavan village). Note slightly wavy, sharp, lower boundary of the heterolithic body with the underlying mudstone (element VIII). Also note lensoid and discontinuous nature of the sandstone–mudstone strata.

also led to repetitive alternation in deposition of bedload sand and mud from suspension.

3.9. Element VII: minor ribbons of intraformational conglomerate

3.9.1. Description

Element VII bodies are minor concavo-planar ribbon bodies, about a meter thick and a few meters wide (Fig. 17). They are made up almost entirely of caliche-derived peloidal calcirudite/calcarenite. Silt to fine sand size siliciclastic grains form a minor lithologic constituent. Interestingly, these small bodies contain the coarsest sediment (granule to small pebble) in the Upper Denwa Formation encountered so far. Element VII bodies occur encased in red mudstones (element VIII) separated by sharp boundaries. Internally, the element VII bodies are crudely bedded and/or trough cross-stratified. The set thickness of cross-strata varies between 10 and 30 cm.

3.9.2. Interpretation

These bodies possibly represent the deposits of short-lived, secondary channels. Occurrence of calcirudite/calcarenite implies that the calcareous peloids were derived from local sources and an influx of siliciclastic was virtually absent. It seems that these minor second-order channels, formed in response to sporadic heavy rainfall on the floodplain and drained local areas stripping away the uppermost, pedogenically modified part of the floodplain sediment. Allen and Williams (1979) interpreted similar deposits (their Type B conglomerates) from the Siuro-Devonian of Wales as representative of an interfluvial drainage system that captured only the precipitation falling locally on the alluvial plain and perhaps the water of the main rivers only during severe floods. Sarkar (1988, his Type II) and Gomez-Gras and Alonso-Zarza (2003, their Type 1) also interpreted similar bodies as small channel-fills in the floodplain.

3.10. Element VIII: mudstone

3.10.1. Description

The mudstones of element VIII constitutes a high proportion of the Upper Denwa Formation and the channel-fill and sheet bodies (elements I to VII) are encased in the mudstones. The channel-fill and the sheet bodies are vertically separated by mudstone intervals that are 1 m to 5 m thick in the lower part of the studied succession and 7 to 10 m in the upper part. In some line traverses through the upper part exceptionally thick (more than 20 m) mudstone intervals are encountered and the mud–sand ratio is as high as 9:1 (Fig. 3). In a particular stratigraphic interval, ribbon and sheet bodies are laterally separated by a vast expanse (about a kilometer or two) of red mudstone (element VIII) that often display lateral transition with sheet-like bodies of heteroliths.

The fine-grained intervals comprises grayish red (5R 4/2), dark red brown (10R 3/4) and purple (5RP 2/2) coloured siltstones/mudstones that are mostly massive. Only locally are the element VIII mudstones stratified. The mudstone intervals display variable degree of development of pedogenic macro-features like pedogenic slickensides (both macro and micro), desiccation cracks, blocky peds, calcareous rhizocretion and glaebules (see Section 4).

However, the apparently monotonous thick red mudstone intervals, at places, can be subdivided into distinct packages on the basis of presence/absence of pedogenic modifications or varying intensity of pedogenesis. There are instances where a mudstone interval with profusely developed slickensides, and rhizocretions is found to be overlain by another package of mudstone that lacks evidence of strong pedogenesis. Such mud–mud contacts are prominent because they are marked by the presence of thin (5–20 cm thick) laterally extensive sheets of fine sandstone and calcirudite (Fig. 18), the latter having sharp lower boundary and

Fig. 17. A small lenticular channel-fill body of calcirudite of element VII near Chilond village.

Fig. 18. A thin sheet of calcirudite (rich in intraformational mudclasts) within a very thick massive red mudstone interval of element VIII. Note sharp, irregular, erosive basal contact and well-developed gradational upper boundary of the calcirudite layer. Also note well-developed pedogenic slickenside surfaces (arrows) and two circular reduction spots in the mudstone below the conglomerate layer. Scale 10 cm long.

gradational upper boundary and are replete with pebble-sized intraformational mudclasts (Fig. 18). Parallel-lamination and ripple cross-lamination are present in these sandstone beds only locally.

The granulometric analysis of the Denwa mudstone show 25% to even 45% of sand, 31–63% silt and 12% to 23% of clay. Under the microscope, Denwa mudstone show microscale network of fractures separating blocky peds. At places, sparsely distributed silt- to fine-sand-sized siliciclastic grains are found floating in the fine groundmass.

3.10.2. Interpretation

As the primary sedimentary features of element VIII are not readily discernible, direct interpretation of their depositional process is difficult. The lack of structures in the red mudstone and the presence of paleosols may reflect the post-depositional bioturbation by plants and animals as well as seasonal wetting and drying. However, as these fines are intimately associated with the fluvial channel-sandstone bodies (at places even the topsets of the stratification of in-channel macroforms of elements II and III pass vertically and laterally into fine-grained clastics), they are interpreted as suspension deposits in overbank areas. The virtual absence of any wave-generated features both in the fines and in the associated sandstone bodies and the presence of thick paleosol profiles and terrestrial fossil remains lend credence to this interpretation (see also Bandyopadhyay and Sengupta, 1999; Maulik et al., 2000). The stable isotopic composition of the pedogenic carbonates of these intervals also suggests deposition under a terrestrial environment (cf. Ghosh et al., 2001). The red mudrock indicates pervasive oxidation of overbank mudstone in well-drained and well-aerated setting. The accumulation of authigenic carbonates in the paleosol profiles suggests a hot, semi-arid climate during Upper Denwa sedimentation (Ghosh et al., 2001).

The fine-grained intervals that lack well-developed paleosols and contain laterally extensive very thin sheets of sandstone and calcirudite are possibly deposited at a higher rate in comparison with the mudstones showing more intense pedogenesis. These intervals possibly represent fine-grained splay deposits may be the distal part of element V.

4. Paleosols

4.1. Description

The paleosol profiles of the Upper Denwa Formation are generally 1 to 5 m thick and can be traced laterally for a few tens of meters and beyond that they become indistinct. Typically, none of the profiles could be recognized as regionally extensive stratigraphic horizon. The profiles comprise a preferential vertical juxtaposition of five pedo-horizons with diffused and overlapping contacts between the horizons (Fig. 3). The generalized sequence of juxtaposition for the pedohorizons is a horizon of desiccation cracks (60 cm to 3 m thick) at the top of the profile, overlying a usually much thicker horizon of pseudo-anticlines (1 to 5 m thick) similar to those reported by Allen (1973), Blodgett et al. (1993) and Driese and Mora (1993). Calcareous glaebules and rhizocretions are well developed only in the basal 30 to 50 cm of the profile.

The desiccation cracks occur as numerous narrow, subvertical wedges (width 2 to 7 cm and maximum length 2 m) that pinch out downward and are filled with fine-grained calcareous sandstones and/or calcirudite.

The pedogenic pseudo-anticlines with inclined (at 5° and 20° and oriented randomly), mutually intersecting, gently curved, centimeters to millimeters thick and up to 2 m long surfaces are the most common and well-developed pedogenic macro features for most of these soil profiles. Their surface appears polished and contains slickensidic lineations (Fig. 19A). The pseudo-anticlines can occur, in two diverse scales within a single horizon.

The glaebules are pebble-sized and subspherical or plate-like calcareous concretions (Fig. 19B) that occur dispersed in the lower part of the profiles. Some of them show honeycomb surface texture and traces of primary stratification. The micro-fabric of the detrital glaebules

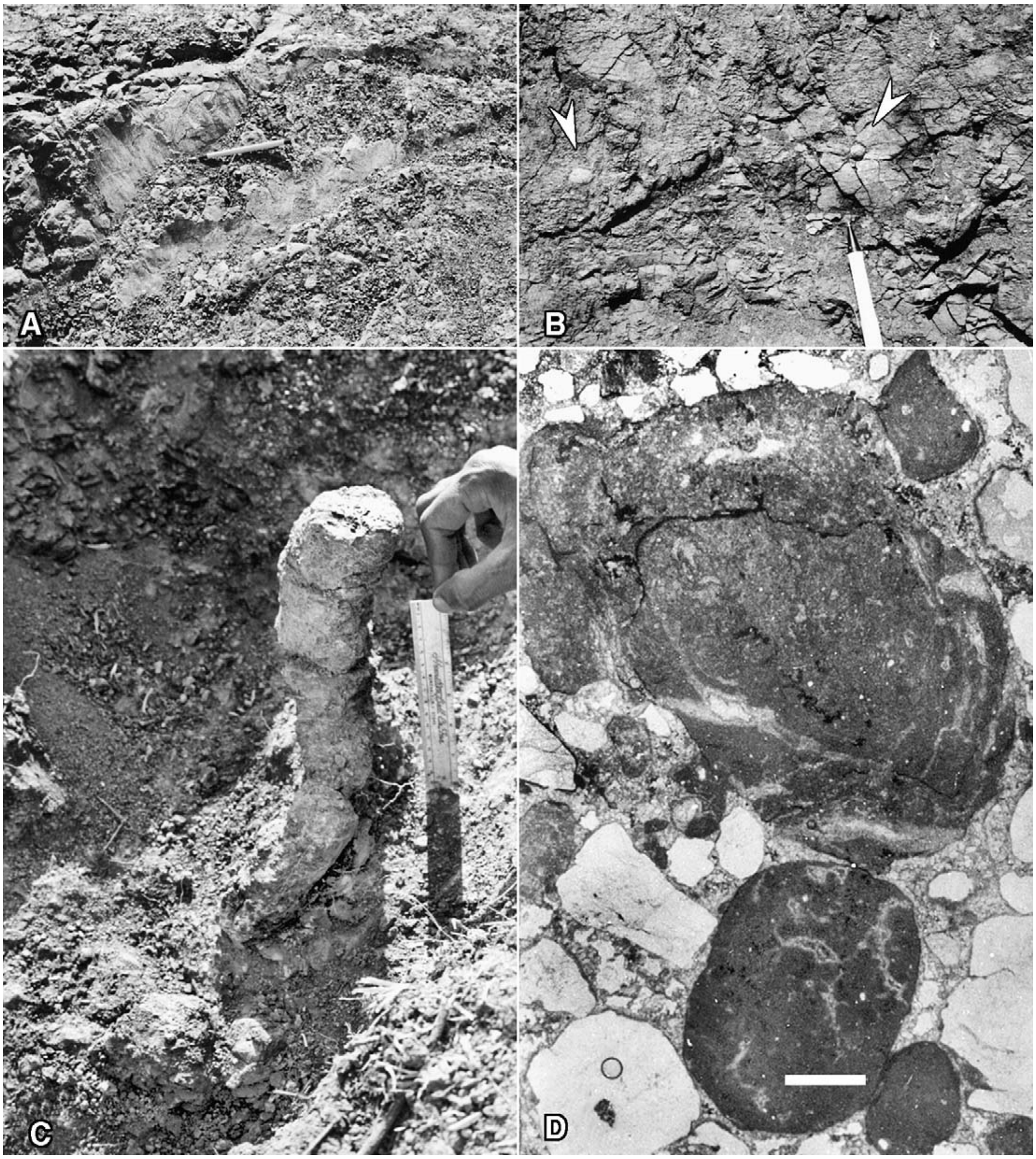


Fig. 19. (A) Pedogenic slickenside surfaces developed in red mudstone of element VIII, in plan view. Pencil for scale. (B) Sparse in-situ calcic glaebules (arrows) within a vertical section of mudstone. Tip of the pencil for scale. (C) A subvertical rhizocretion in mudstone. Scale length 15 cm. (D) Photomicrograph showing detrital glaebules along with detrital quartz grains within calcirudite of element VII. Note the sharp and rounded outline of the glaebules and spar-filled (lighter) circumgranular cracks within a large glaebule. Plane polarized light. Scale bar is 1 mm.

(Fig. 19D) that occur in the channel-fill bodies of elements III, IV and VII are similar to the in situ glaebules of the paleosol profiles. Both the varieties of the glaebules are characterized by pedogenic microfabrics like clotted micrite, corroded detrital quartz, calcite- and barite-filled radial and circumgranular cracks (Fig. 19D).

The rhizocretions (Fig. 19C) occur as vertical or subvertical cylindrical calcareous concretions (2 to 20 cm long, 0.5 to 4 cm in diameter) that taper downward and are characterized by a centrally located axial zone, which is either a void or filled with calcite spars. The host near the rhizocretions display a number of roughly circular (diameter 1–4 cm) gleys in the shades of white and yellow (N8, 5Y 7/2, 10Y 6/2, 5YR 3/2).

Within a single mudstone interval generally two to three paleosol profiles are stacked vertically giving rise to compound paleosol sets (sensu Marriott and Wright, 1993). However, at places, the desiccation cracks and the slickensides of the overlying profiles extend down to the upper part of the underlying profile giving rise to composite sets (sensu Marriott and Wright, 1993).

The paleosol profiles, commonly associated with very thick mudstone intervals, consist either of a solitary set of slickensides (with smaller-scale sets enclosed within them) or stacked sets of slickensides with overlapping boundaries. Numerous and well-developed gleys are typically present along the entire thickness of such profiles.

The upper horizon of desiccation cracks is either poorly developed or absent where the profiles are overlain by channel-fill bodies. On the other hand, the profiles underlying sandstone-dominated sheet bodies display a thick, well-developed horizon of desiccation. The horizon of desiccation is also poorly developed below the sheet bodies of muddy heteroliths and these profiles are typically gleyed.

4.2. Interpretation

The Denwa profiles with ill-differentiated pedo-horizons and with weakly-developed calcareous concretions (Fig. 3) represent immature to at best moderately mature soil profiles, comparable to the Types A and B profiles of Allen (1974, 1986) and stages II to III calcretes of Gile et al. (1966). The inclined surfaces with pedogenic slickensides, which are commonly observed in the upper part of the paleosol profiles, are similar to the pseudo-anticline surfaces of the modern day Vertisols (Bss horizon; Soil Survey Staff, 1975). The lower horizons, characterized by the presence of rhizocretion and glaebules, represent the zone of carbonate accumulation at a deeper part of the soil. They are similar to modern Bk horizons. Thus the soil profiles of the Denwa Formation are similar to the present day calcic-vertisols and their ancient analogues (Driese and Mora, 1993) with an upper pedo-horizon of desiccation and pseudo-anticlines overlying a horizon of carbonate accumulation.

The modern calcic-vertisols commonly form in a fine-grained host under a hot and semi-arid climatic setting. The existence of similar soil-profiles in the Upper Denwa Formation may suggest a similar climatic setting during Denwa sedimentation (cf. Soil Survey Staff, 1975; Reid and Frostick, 1985; Ghosh et al., 2001). The pedogenic slickensides form due to repeated hydration and dehydration which causes repeated shrinking and swelling of the soil matrix and thus may indicate a seasonal rainfall pattern. Occasionally, dry periods must have been prolonged to allow the precipitation carbonates and the development of deep desiccation cracks.

The profiles characterized by large pseudo-anticline sets stacked vertically with overlapping boundaries and associated with thick mudstone intervals (Fig. 3) suggests that the pedogenic process were probably operative side by side with slow but continuous sedimentation to give rise to cumulate paleosols (cf. Marriott and Wright, 1993). The sedimentation was slow enough to permit pedogenesis but sufficiently rapid so that soil development was only weak. On the other hand, absence of regionally extensive soil horizon precludes any regional paleogeomorphologic control on their development. Though the climatic condition remained favorable for the soil formation, as indicated by the presence of calcic-vertisols all throughout the stratigraphic succession of the Upper Denwa succession, localized development of soils possibly indicate that the soil formation was restricted to the areas of low sediment supply within the fluvial system.

The presence of well-developed desiccation below the sandy sheet bodies and their absence below the channel-fills possibly highlights the lack of erosion during the initial phase of emplacement of the sheet bodies. The poorly developed desiccation features below the muddy heterolithic sheet bodies and the presence of gleying possibly indicate the emplacement of these sheets in poorly drained areas.

5. Paleocurrent data

The paleocurrent data of the Upper Denwa Formation mainly constitute the orientations of the medium to large-scale trough axes sampled in the basal part of the

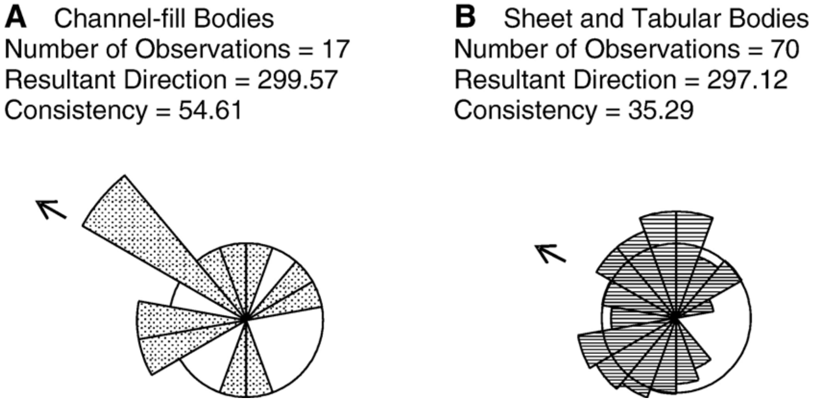


Fig. 20. Rose diagrams showing a comparison of distribution of mean paleoflow vectors for the (A) channel-fill bodies (elements I to IV) and (B) sheet bodies (elements V and VI) of the Upper Denwa Formation.

channel-fill bodies (elements I, II, III, IV and VII). Data from ripple cross-laminations were generally avoided. Orientations of parting lineations, a few trough axes and rib and furrow structures comprise the paleocurrent data for the sandy to heterolithic sheet bodies and the tabular bodies of complexly organized tabular bodies (elements V and VI).

In order to understand the regional flow pattern of the Denwa Formation, the distribution of the local vector means were considered instead of pooling all the individual paleocurrent data together. This approach reduces local weight on the mean arising from inequalities in the number of data collected per sampling point. The rose diagrams (Fig. 20) show that the vector means for the channel-fill bodies show a large dispersion around a mean direction of 300° (NW). However, the orientations of the vector means of the sheet and tabular bodies show a bipolar, bimodal distribution with two prominent modes symmetrically disposed around the mean direction shown by the channel-fill deposits.

6. Discussion

6.1. Nature of the channels

From the foregoing description, it is apparent that the presence of heterolithic strata (excepting in elements I and VII) and wide variation in the geometry, dimension, mesoscale architecture and lithology is a hallmark of the channel-fill bodies of the Upper Denwa Formation. However, the channel-fill bodies of element I, in contrast to this general motif, are rich in siliciclastic sand and lack heterolithic lateral accretion deposits. Again, this is the only channel-fill type that is characterized by the presence of thick planar cross-strata that suggests migration of 2D bedforms under strong northerly current in straight channels (Fig. 21). The F-U succession towards the upper part in some of the element I fill-bodies records gradual infilling of the channels. The multistorey ribbon bodies (element IB) indicate that successive sequences of channel scouring occurred in previously formed channels.

The elements II, III and IV channel-fills are characterized by inclined heterolithic strata (IHS) that record lateral accretion on inclined depositional surfaces with current directions, in general, at high angle to the dip of the inclined surfaces. These structures, therefore, are interpreted to represent lateral accretion of point bars or benches of sinuous channels (Fig. 21). These channel-fills are comparable with those reported from modern mixed-load and suspended-load channel as well as from their ancient analogues. These channel-fill deposits exhibit a gradation from sand-dominated to mud-dominated point bar or point bench deposits. The element II channel-fills contain too much sand to be compared with the deposits of suspended-load rivers like the Barwon, Murrumbidgee of Australia and Red River of Canada (Taylor and Woodyer, 1978; Woodyer et al., 1979; Page et al., 2003; Brooks, 2003). It appears that these are more akin to a mixed–load channel deposits as described by Stewart (1981, 1983). The best available recent analogues of element III channel-fills appear to be the point benches described from the Barwon River and the Murrumbidgee River, Australia and the Red River, Canada (Taylor and Woodyer, 1978; Woodyer et al., 1979; Page et al., 2003; Brooks, 2003) as well as the meandering river point bars of the American middle west (Jackson, 1981). Newell et al. (1999) interpreted similar heterolithic channel-fills as deposits of high–sinuosity channels (indicated by lateral accretion bedding) characterized by low-energy flood events. The Barwon/Murrumbidgee/Red River point

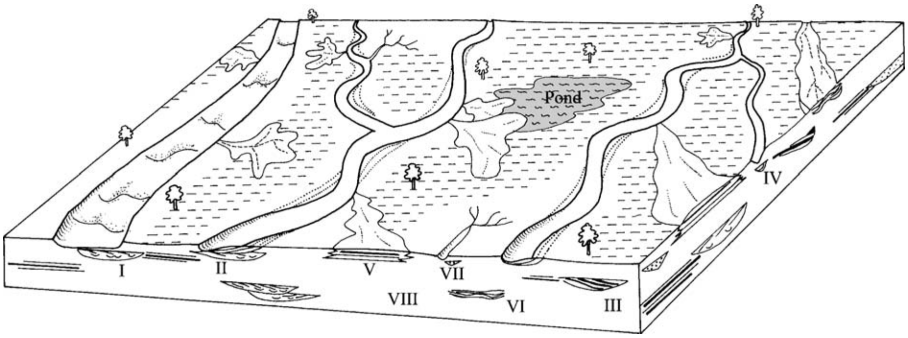


Fig. 21. A cartoon diagram depicting the envisioned Upper Denwa fluvial system. I–VIII correspond to the elements described in the text.

benches and the American middle west point bars are composed of finely interbedded parallel-laminated/cross-laminated sands and massive mud. Along the Barwon River, a major characteristic of the internal bedding as a whole is the inclined bedding dipping at angles of up to 36°. Laterally accreted heterolithic strata in the Cretaceous Dakota Formation exhibit a maximum dip of 23° (Kirschbaum and McCabe, 1992), which is comparable to that of IHS of element III channel-fill bodies of the Upper Denwa Formation.

The element IV channel-fills display a wide variation in dimensions and character of fills, but the deposits are overwhelmingly mud-dominated. Similar channel-fills have been interpreted as abandoned mud-filled channels by Stewart (1983) from the Wesex Formation, Wealden Group, southern England. Small mud-dominated heterolithic channel deposits from the Cretaceous Dakota Formation of southern Utah has been inferred as the fills of abandoned or partly abandoned channels from an anastomosing river system (Kirschbaum and McCabe, 1992). Mudrock-dominated ribbon-shaped channel bodies comprising concentric fills of alternating mudstone and fine-grained sandstone layers has been interpreted as abandoned channel deposits (Munoz et al., 1992). Mudrock-dominated fills formed in 'avulsion splay channels' have also been identified from the Willwood Formation, Wyoming, US (Kraus and Davies-Vollum, 2004). It is suggested that the mudrock-dominated channel-fills in the Upper Denwa Formation represent 'avulsion splay channel' deposits.

Mud-rich lateral accretion structures, occurring in the mud-encased Upper Denwa channel-fills and their lateral interfingering with the overlying massive thick mudstones, indicate a muddy nature of the channel banks and also that the channels carried mainly suspended-loads. However, the presence of subordinate amount of sands and minor intraformational mudstone pebbles suggests that there was a limited supply of sand accessible to the streams.

In comparison with the narrow width of the point benches of the Barwon River, it is suggested that the low width/depth ratio (13 to 30) of the elements II, III and IV channel-fills reflect the cohesive character of the deposits forming the concave bank of the channels. Lateral accretion surfaces are interpreted to represent migration of point bars/benches, but the ribbon shape of the channel-fill bodies indicates that although lateral accretion was initiated in places, a well-developed meander belt was not generated.

The lenticular channel-fill bodies of element VII are smallest in size, but their fill comprises the coarsest material available on the Denwa alluvial system. They lack lateral accretion surfaces and represent the smallest, possibly second order, channels on wide interfluves (Fig. 21). They carried predominantly locally derived intraformational caliche material along with minor siliciclastics sediments.

Wide variation in size of the channels and the lithology of the channel-fills in the Upper Denwa succession may be considered typical of anastomosed systems (cf. Smith, 1983). The Denwa channels that predominantly generated ribbon bodies appear comparable with bank stable anastomosed streams, for example the Saskatchewan River (Smith et al., 1989) or those of the Okavango delta (McCarthy et al., 1991). Limited lateral accretion of the sinuous Denwa channels is also a characteristic feature of an anastomosed system (Smith and Smith, 1980). The predominantly mud-filled ribbon bodies (element IVB) of the Denwa succession are very similar to the U-shaped mixed fills of deep crevasse channels of the anastomosing river system described by Eberth and Miall (1991). Again, Kirschbaum and McCabe (1992), Pelzer et al. (1992) and Hornung and Aigner (1999) interpreted ribbon bodies of heteroliths and mudstone, similar to those of the studied succession (element IV), as representative of partly abandoned or abandoned channels of an anastomosing river system.

6.2. IHS and its implications for the nature of the channels

The superimposition of large numbers of inclined units of simple coarse–fine couplets within an IHS set suggests the repetitive occurrence of a common, autocyclic depositional mechanism. As suggested by many authors, in a fluvial setting the most obvious candidate is some type of recurrent flood event (Bridge and Diemer, 1983; Mossop and Flach, 1983; Thomas et al., 1987). Thus, each "simple" coarse-to-fine couplet can be envisaged as the product of single flood event. The sharp contact between the adjacent coarse–fine couplets was possibly formed due to rapid rise in stage causing an abrupt onset of a traction load. The fine member was, however, deposited on the channel-bench or point bar surfaces during waning flood stage under conditions of much reduced velocity (cf. Bridge and Jarvis, 1976; Thomas et al., 1987; Brooks, 2003). However, the occurrence of higher-order erosion surfaces separating accretionary sets of heteroliths (e.g. in element III) may indicate unusual floods of longer periodicity (see also Thomas et al., 1987; Munoz et al., 1992; Maulik et al., 2000).

In the Upper Denwa Formation, the IHS vary considerably in their regularity, scale, thickness of sand–mud couplet, sand/mud ratio, etc. Additionally, there are, in places, more than one order of sand/mud alternation in the heterolithic strata. Mossop and Flach (1983) had suggested, from their study of McMurray Formation, that a large stream with a high discharge (that is both stable and predictable) tends to produce regular accretion beds, generally due to annual floods. Short-term fluctuations, if any, are dampened because of the large size of the stream (Sternberg, 1975). Presence of sand/mud couplet in varying scales in Upper Denwa Formation suggests the presence of a system of small channels rather than a large, stable river system.

The degree to which water level fluctuated in the Upper Denwa channels remains a matter of speculation. There are no preserved desiccation cracks or root markings in the IHS and except for the local presence of mud clasts (which could have been produced by rip-up of desiccated mud) there is no other evidence to suggest that the point bar/bench slope were exposed during low discharge phase of the annual flood cycle. Continuous mud draping over the entire length of inferred point bar/bench in the Denwa channel-fill bodies may have occurred progressively along the water edge in a low-energy zone that migrated along the bank face as stage dropped.

6.3. Nature of the extra-channel splay deposits and their implications

The commonly occurring sheet bodies (element V), forming thick complexes at places, in the Upper Denwa Formation possibly represent crevasse splay complexes formed by the repeated diversion of flow from channels to the overbank areas (Fig. 21). These sheet bodies, which lack any basal channel-scale scour surface, were emplaced by simple diversion into flood basin (cf. Aslan and Blum, 1999), a style related to progradational avulsion of Morozova and Smith (1999, 2000) and aggradational avulsion of Mohrig et al. (2000).

Internal organization of heterolithic tabular bodies (element VI) displays characteristics that do not match any reported style of channel-fill architecture. Their internal organization is in many ways similar to that of the "Type-4" avulsive channel-fills described by Kraus and Davies-Vollum (2004) from the Eocene Willwood Formation. These heterolithic bodies are characterized by the presence of complexly organized sandstone, mudstone and heterolithic strata which appear to have built up gradually through vertical aggradation from poorly channelized to non-channelized, shallow, fluctuating flow. The complex vertical aggradation of these bodies records a complex history of alternating activity and abandonment due to flow diversions to and from other channels in a complex network of channels (see Section 6.5).

Crevasse splays/splay complexes are known to constitute a significant proportion of progradational avulsion deposits (Morozova and Smith, 1999, 2000; Slingerland and Smith, 2004) and aggradational avulsion deposits (Mohrig et al., 2000). Avulsions in many cases are initiated and develop as crevasse splays in a manner similar to that documented in some anastomosing systems (Ethridge et al., 1999). Colorado River avulsion deposits have been found to comprise crevasse splay sands encased in muds (Aslan and Blum, 1999). The Saskatchewan River avulsion deposits resemble crevasse splay deposits because the avulsion belt is created by a splay system that prograde into low areas of the floodplain (Smith et al., 1989). This is why crevasse splay deposits often become indistinguishable from progradational/aggradational avulsion deposits.

The heterolithic bodies of the Upper Denwa Formation (elements V and VI) are similar to Saskatchewan avulsion deposits in geometry, internal architecture, etc., but the former is much smaller than the latter. On the other hand, the Saskatchewan River progradational avulsion model predicts that, in a fluvial system undergoing avulsion, a major channel sandstone should overlie avulsion deposits. Evidence of minor channelization is present in many of the Denwa heterolithic bodies, but larger channel bodies (elements IB and IV) overlie these bodies only in rare instances. Aslan and Blum (1999) observed that the channel belt incises avulsion deposits locally and a large percentage of avulsion deposits are preserved that may not be incised by channel belt deposits. This may explain why inferred splay deposits of the Denwa succession are not always overlain by channel deposits and are in many cases simply bounded by pedogenically modified floodbasin muds. The rarity of channel-fills occurring on top of the sheet complexes may also suggest that not all the crevassing events led to successful channel avulsion as also noted by Stouthamer (2001) in Rhine-Meuse Delta.

6.4. Dominance of mud and presence of calcisols in the succession and its possible implications

The total thickness of red mudstone intervals in the stratigraphic succession of the Upper Denwa Formation is about nine times that of the coarser-grained deposits. Even many of the individual fine-grained intervals are much thicker than the associated channel-fill bodies. Episodic overbank flooding may provide thin suspended sediment deposits to the floodplain surface, but commonly only faint records of deposition remains after a flood (Gomez et al., 1995). Therefore, the process of suspension settling of fines from overbank floods alone cannot sufficiently account for this huge thickness of fines. It is difficult to envisage a fluvial setting where vertical aggradation at overbank areas grossly exceeds that within the channels for a significant time period. For stable channels, such a situation will lead to progressive deepening of the channel and consequent decrease in flood frequency and eventual cessation of sediment supply to the distal floodplains. Conversely, avulsions provide a longer-term mechanism for continuous supply of fine-sediment to the deeper parts of the floodplain where preservation is enhanced. Thus, as shown by many others, avulsions not levee topping floods are the principle cause of floodplain aggradation (Slingerland and Smith, 2004).

In general, a large accumulation of fines in a fluvial setting requires a climate-induced increase in the production of fines in the source area (Reid and Frostick, 1985) and the existence of a geomorphic setting that traps the fine-grained deposits (Marriott and Wright, 1996). During the mid-Triassic (~230 Ma) the Satpura basin was located between 30°S and 40°S latitudes (Scotese, 2001, 2002). This latitudinal position corresponds to the modern day dry subtropical zone of Strahler and Strahler (1992) and the poleward part of the dry subtropical paleoclimatic zone of Mack and James (1994) that receives dry continental-tropical air mass derived from the subtropical high-pressure cells. This zone is characterized by less than 100 cm/year mean annual precipitation with evapotranspiration exceeding precipitation in all or most of the months. Summer is hot and winter cold. Today, this climatic zone is characterized by the occurrence of calcisols and vertisols that commonly form over a fine-grained substrate under a hot and semi-arid climatic setting (Soil Survey Staff, 1975; Reid and Frostick, 1985; Ghosh et al., 2001). Thus, the climatic interpretation derived form the occurrence of calcic-vertisols in the Upper Denwa Formation is consistent with the inferred paleoposition of the site of deposition. It is interesting to note that the modern river basins of southeastern Australia (e.g. Murrumbidgee, Barwon) are also located within this latitudinal belt (between 30° and 40°) and sediments carried by them is extremely fine-grained. For example, 80% of the sediment load carried by the Barwon River is less than 2 μm in size. Rivers of the Channel Country that cover much of the eastern part of the semi-arid to arid Lake Eyre basin of central Australia (Gibling et al., 1998) have been classified as a distinctive group of mud-dominated anastomosing system by Nanson and Knighton (1996). Thus, by analogy, we speculate that the supply of the fine-grained load in Upper Denwa channels was facilitated by the semi-arid climate prevailing in that particular time period (see also Schumm, 1968; Reid and Frostick, 1985; Marriott and Wright, 1996). Semi-arid climates, as compared to arid and humid ones, enhance the supply of sediment probably through increasing rate of chemical weathering and decreasing vegetation cover (Schumm, 1993). Moreover, a compilation of suspended yields for moderate-sized river basins suggests that semi-arid catchments may export about 20 times more material than humid tropical equivalents (Reid and Frostick, 1987). Thus, a very high proportion of red mudstone in the Denwa Formation along with the calcisols and the inferred semi-arid climate are mutually consistent.

Thick deposits of red mudstone, with pedogenic modifications, intercalated with thin ribbons and sheets of sandstone, sheets and tabular bodies of heterolith and pedogenically unmodified mud suggest variable rates of floodplain aggradation. Repeated episodes of flow diversion into the floodbasin accompanied by rapid floodplain aggradation produced several meter-thick complexes of massive mudstones and heteroliths intercalated/alternating with crevasse-splay sands and heteroliths that remained pedogenically least modified.

On the other hand, mud deposits with strong signatures of pedogenic modifications represent relatively longer periods of floodplain stability that occurred between episodes of crevasse splaying and related avulsive deposition. Vertical change in the degree of pedogenic modification of mud due to variable rate of floodplain aggradation is one of the hallmarks of Denwa mudstone. Similar features have been also reported by Aslan and Blum (1999) from the Colorado River (Pleistocene–Holocene) deposits in which avulsion deposits comprise a significant portion of the fill. Recent work suggests that avulsion deposits forming at least half of the fill is not unreasonable, although this is likely to vary from case to case (Slingerland and Smith, 2004). Much of the floodplain aggradation in Upper Denwa succession may in fact be the product of splaying related to avulsions rather than the product of slower sedimentation from suspension during normal flooding.

6.5. Nature of the Denwa alluvial system

From the foregoing discussion, it is apparent that a hallmark of the Upper Denwa Formation is the presence of isolated ribbon-shaped channel-fills that are in-filled with heterolithic strata, encased in thick extra-channel deposits, and showing wide variation in the dimensions, mesoscale architecture and lithology. Except for the upward increase in mud proportion there is no apparent well-developed pattern in the spatial or vertical distribution of different kinds of channel-fill bodies in the Denwa succession. Coexistence of channel-fill bodies of different dimension, geometry and lithology in a restricted stratigraphic interval indicates the presence of anabranching channels (Fig. 21) of different fill histories although it would be impossible to prove directly that the individual channel-fills were formed by coeval active channels (cf. Nadon, 1994). Thus, a situation where a number of active channels randomly avulse to different parts of an alluvial plain may possibly account for the stratigraphic architecture of the Upper Denwa Formation (Fig. 21).

The sediment grain size in a particular Denwa channel-fill might have been controlled by the proximity of the channel reach to the avulsion node on the relatively larger channel and by whether the splay channel was abandoned or remained active during filling. The ribbon sandstones (element I) represent channels that remained active until they were filled with sand and were abandoned. The newly abandoned channels may remain partly active but, as upstream filling continues in a particular channel reach, downstream flows become weaker, allowing only finer materials to accumulate from suspension in the abandoning reach. This may generate channel-fills with variously organized heteroliths and variable sand/mud ratio as noted in elements II, III and IV. The detritus supplied to the Denwa basin was apparently fine dominated but its partitioning and distribution was controlled by flow diversion to and from other channels in anabranching Denwa river system.

Two modern anabranching river systems are well documented to date. One is Cooper's Creek in SE Australia and the other is the anastomosed reach of Saskatchewan, in Canada. In both the situations, there is little lateral channel migration. In Cooper's Creek, channels avulse (by incision) more frequently to form well-developed anabranches in plan. Whereas, in case of Saskatchewan system, channels are raised and are bound by prominent levees and crevasse-splays breach the levees at many points and form well-developed splay-cum-avulsion deposits that are accommodated in the inter-channel depressions. In Cooper's Creek, inter-channels are virtually positive areas, levees are poorly developed and crevassing is not an important process. The higher residence time of the channels in Saskatchewan system enables generation of thick, multistorey channel-fill bodies separated by overbank fines and splay-avulsion deposits. On the other hand, the rapidly avulsing channels of the Cooper's Creek are likely to generate comparatively thinner isolated uni-storey channel-fills encased in overbank deposits. Occurrence of predominantly uni-storey ribbon to lenticular channel-fill bodies encased within extra-channel deposits suggests that at least some Denwa channels probably relocated by incisional avulsions producing an anabranching pattern similar to that of the Cooper's Creek. However, in variance with Cooper's Creek model, the Denwa overbank deposit is replete with splay deposits suggesting some similarity with the Saskatchewan model. However, Denwa lithofacies are significantly different from that of Saskatchewan deposit. Again in terms of climatic setting the Upper Denwa Formation was more close to the arid central Australian setting (Rust, 1981) rather than the humid Saskatchewan setting (Smith and Smith, 1980).

Many of the present day rivers in southeastern Australia are low-gradient and low-energy rivers and are in general very sluggish in nature. Average valley gradient of the Barwon River plain is 0.00005 (Woodyer et al., 1979), while that of the Murrumbidgee River is 0.0002. In the Channel Country also, the river gradients are very low, generally <0.0002 (Page et al., 2003). Besides these, there are rivers beyond these latitudinal belt, e.g. the meandering Red River, Manitoba, Canada

(Brooks, 2003) in which the suspended sediment load consists of >90% silt and clay, regardless of sediment concentration and river discharge, with an average valley gradient of about 0.0001. In analogy with the modern rivers mentioned above, we speculate that the Denwa river system in general was low-gradient, anabranching and channels were sinuous in nature and thus were conducive to entrapping rather than bypassing of fine sediments.

At any particular stratigraphic level, the Denwa channel-fill bodies are laterally separated by 1 to 2 km of overbank fines (element VIII) and other extra-channel deposits (elements V and VI). Taking into consideration the tectonic strike (ENE–WSW) of the Denwa succession and the mean flow direction (~300°) derived from the channel bodies, it can be suggested that the inter-channel distances were in the order of hundreds of meters (800 m to 1600 m). Localized rather than regionally extensive occurrence of weakly developed paleosol indicate that sites of pedogenesis in the Denwa alluvial plain was probably controlled by the spatial distribution of the channels in the anabranching Upper Denwa river system. Under the prevailing semi-arid climate, soil formation was favored only at places, which were distal to any of the channels of anabranching system and thus subject to low rates of aggradation.

The proposed fluvial style for the Denwa succession is closest to model 8 in the suite of models described by Miall (1985) and very similar to the depositional style proposed for megasequence 2 of the Cutler Formation by Eberth and Miall (1991). We envisage that the Upper Denwa succession was deposited by an anabranching system more akin to that ascribed to a “fixed-channel facies model” by Gibling et al. (1998), rather than to an anastomosing fluvial facies model per se (Smith and Smith, 1980; Smith, 1983, 1986; Nadon, 1994).

7. Conclusions

The Triassic Upper Denwa fluvial succession comprises ribbon-shaped channel-fill deposits and sheet-like splay deposits sparsely dispersed and encased in red mudstone-dominated overbank sediments. The channels show a wide variation from straight, stable, sandy to sinuous, muddy, slightly laterally migrating type. The “Inclined Heterolithic Strata” (IHS), a characteristic component of majority of the ribbon-shaped channel-fills, record limited lateral accretion of point bars/benches in mixed-load to suspended-load, sinuous channels. Sand–mud couplets of IHS owe their origin to repetitive, autocyclic mechanisms, possibly annual flood. Predominance of fines within many of the channel-fills attest to repeated abandonment of channels. The channels were narrow, laterally stabilized by the presence of cohesive mudbanks and were separated by extensive overbank areas.

Coexistence of channel-fill bodies of varying dimension, internal architecture and lithology in a restricted stratigraphic interval suggests the presence of an anabranching system of channels, each having different filling history. The conspicuous reddening of the mudstones suggests deposition in a well-aerated, well-drained setting. Calcic vertisol profiles in mudstones and caliche-derived calcirudite/calcarenite in channel-fills indicate a hot, semi-arid climatic setting during Upper Denwa sedimentation. This climatic setting is consistent with the inferred paleoposition of the Satpura basin during Denwa time (Early Middle Triassic). Such a climate possibly facilitated the supply of fine-dominated load to the Denwa fluvial system.

Sharp based, sandy to heterolithic sheet-like bodies bearing evidence of upper flow regime sheet flow oblique to that of the Denwa channels suggests that the sheets were deposited as prograding crevasse splay. Only a few splays, however, led to channel avulsion. Some of the splay deposits bear evidence of subaqueous emplacement. Some of the sheet to tabular heterolithic bodies with sharp, undulating base and comprising complexly organized heterolith and bearing evidence of intermittent flow fluctuation possibly represent poorly channelized crevasse splay deposits.

The sharp contrast between the poorly developed paleosols in the heterolithic sheets and tabular bodies, in contrast to the well-developed cumulative or compound paleosols in the red mudstone encasing the sheets attests rapid emplacement of these bodies through splaying. Moreover, parts of the mudstone-dominated intervals that are pedogenically least modified could also be products of rapid deposition in the distal part of the splays, rather than the products of slow suspension settlement of fines from normal flooding. It can be suggested that the splaying, in combination with overbank flooding, may explain the occurrence of overwhelming proportion of fines in fluvial successions like Upper Denwa Formation.

In analogy with present day river systems, we envision that the Upper Denwa river system was in general low-gradient and low-energy one, in which majority of channels were sinuous and conducive to entrapping rather than bypassing of fine sediments. Low flow strength with periodic flood events, high bank strength and a rate of sediment supply higher than that of onward transport were the important factors for the development of anabranching Upper Denwa system.

Acknowledgements

This study is a part of an integrated research program of the Geological Studies Unit, in the Satupra Gondwana basin, central India. The Indian Statistical Institute, Kolkata, provided the financial support and infrastructure for this study. Thanks are due to Drs. Chandan Chakraborty, D.P. Sengupta, Tapan Chakraborty and Mr. S. Ghosh of the Geological Studies Unit for help rendered during the fieldwork and for innumerable useful comments and suggestions. Constructive suggestions from Dr. Gregory R. Brooks, Dr. K. Sian Davies-Vollum, two journal reviewers and from the Journal Editor, Prof. A.D. Miall led to substantial improvement of this manuscript. We also thank Mr. A. Das for drafting maps and diagrams for this work.

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