Lithofacies palaeogeography and sedimentology

A new ‘superassemblage’ model explaining proximal-to-distal and lateral facies changes in fluvial environments, based on the Proterozoic Sanjauli Formation (Lesser Himalaya, India)

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Abstract Facies analysis of fluvial deposits of the Proterozoic Sanjauli Formation in the Lesser Himalaya was combined with an architectural analysis. On this basis, a model was developed that may be applied to other fluvial systems as well, whether old or recent. The new model, which might be considered as an assemblage of previous models, explains lateral variations in architecture and facies but is not in all respects consistent with the standard fluvial models. The Sanjauli fluvial model is unique in that it deals with lateral facies variations due to shifts of the base-level along with fluctuations in accommodation space owing to changes in palaeoclimate.

Keywords Fluvial model, Braided river, Sanjauli Formation, Simla Basin, Proterozoic, Lesser Himalaya, India

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1. Introduction

Fluvial systems show significant differences. It appears nevertheless that lateral facies associations can commonly well be recognized and the geometry of sand bodies can commonly well be explained. The differences in characteristics of fluvial systems require, however, different models for fluvial environments and fluvial sedimentation. It is commonly difficult to attribute a specific fluvial system to one of the specific vertical facies models that were proposed by Miall (1978). Therefore, we combined a number of his suggested vertical profile models into a new braided river system, and applied it to the Proterozoic Sanjauli Formation (which belongs to the Simla Group) instead of trying to fit the Sanjauli characteristics in one of the existing models. The facies of the Sanjauli Formation can be understood best if they are fit in what has been called a ‘superassemblage’ (Miall, 1994, 1996), showing an evolution from the Scott-type (G11) to the Trollheim-type to the Platte-type (see Miall, 1977, 1978). The formation incises the shallow-marine shales and siltstones of the underlying Chaossa Formation as a result of a changing base-level due to a regression.

1.1. Standard models vs. a new ‘superassemblage’ model

Case histories from all over the world have made clear that facies analysis of fluvial successions based solely on the study of vertical profiles can severely limit the characterization of these depositional systems, as similar types of bedform can develop in rivers of different type (Allen, 1983; Bridge, 1985; Jackson II, 1978; Jo and Chough, 2001; Miall, 1988, 1996).

To overcome these limitations, the main focus of our study was an architectural analysis, with special attention to large-scale sedimentary structures (cf. Allen, 1983; Miall, 1985, 1988, 1996). This fluvial architectural analysis led to the recognition of six standard vertical profile models, namely the Trollheim-type (G1), the Scott-type (G11), the Donjek-type (G111), the South Saskatchewan-type (S11), the Platte-type (S11), and the Bijou Creek-type (S1) of Miall (1977, 1978). Miall (1977, 1978, 1994 and 1996) stated that there are fluvial systems which do not fit into a particular model. This implies that it is necessary in such cases to compose a new model on the basis of a combination of characteristics from a number of the standard models. After Miall (1978) had defined the various vertical models, we therefore felt the need to create what he called a “superassemblage model” which would explain the proximal-to-distal changes in fluvial deposits. We approached the analysis of the facies changes in the Sanjauli Formation on the basis of Miall’s considerations and therefore studied how the sediments and facies change laterally. We did so taking into account the changes in discharge of the river and its base-level fluctuations due to changes in the climate. By doing so, we found that the fluvial Sanjauli Formation offers a unique possibility for establishing such a new superassemblage.

1.2. Objectives

The primary objective of the study is to recognize the architectural elements and formulate a combined depositional model, based on spatial/temporal changes in lithofacies, lithofacies associations, geometry of the fluvial channels and bars, and correlation of vertical profiles. Variations in the fluvial architecture were mapped for the purpose, with particular attention to the changes in accommodation space, as related to base-level changes. The data thus obtained were input for the second objective, viz. an attempt to establish a new superassemblage model that differs from the classical ones in such a way that all sedimentary characteristics would fit in it. This approach is consistent with Miall’s opinion that new models should be established in case actual fluvial deposits do not fit into one of the standard models.

2. Geological setting

The Simla Group was originally described as the Infra-Blaini (Kumar and Brookfield, 1987). It constitutes an important stratigraphic unit of the Lesser Himalaya in Himachal Pradesh, India. The Simla Group is bounded by the Chail Thrust in the north and the Giri Fault in the south (Fig. 1) (Kumar and Brookfield, 1987). As defined by Srikanthia and Sharma (1971), it consists of a thick, coarsening-upward clastic succession that unconformably overlies the Shalikarbonates, and that is also unconformably overlain by the tillites of the Blaini Formation (Baliana Group). The Simla Group is divided into four formations (Table 1), viz. the Basantpur Formation (stromatolitic dolostone and dolomudstone), the Kunihar Formation (stromatolitic limestone and sandstone/siltstone heterolithic rocks), the Chaossa Formation (sandstone/siltstone/shale heterolithic...
A new ‘superassemblage’ model explaining facies changes in fluvial environments

Fig. 1 Geological map of the Simla Group (modified after Kumar and Brookfield, 1987).
rocks), and the Sanjauli Formation (conglomerates and pebbly sandstones).

2.1. Stratigraphic context

The Sanjauli Formation is the stratigraphic unit under study here. Its lower part is built of shales, siltstones, coarse gritty sandstones and quartzites. The upper part of the Sanjauli Formation is the coarsest and comprises conglomerates, pebbly sandstones, proto-quartzites, and grey and purple shales. The detrital micas in the Simla Group rocks have a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 860 Ma (Frank et al., 2001), which implies a Neoproterozoic age of the Simla Group.

The earliest indications of a deltaic depositional environment have been recognized in the middle part of the Basantpur Formation. The entire Simla Group is now interpreted as a large muddy deltaic succession formed after the collapse of a shallow-water carbonate platform constituting the Shali Group. The sedimentation in the Proterozoic Simla Basin started in the northern part of the basin with the accumulation of the lower part of the Basantpur Formation. The basin shallowed gradually during deposition of the Kunihar and Chaossa Formations. The deposition of the conglomerates and sandstones in the upper part of the Sanjauli Formation marks the end of the sedimentation in the Simla Basin.

3. Methods

The facies of the rocks in the study area were analyzed in order to determine which facies and facies associations are present. This outcrop-based facies analysis was based on characteristics of the lithology, primary sedimentary structures and geometry of the lithological units. Vertical and lateral facies relationships were studied from representative logs prepared in the study area.

Architectural elements of the Sanjauli Formation were examined in natural exposures and road cuts throughout the area along traverses in and around Kandaghat and from Kandaghat to Sadhupul (Fig. 2). The field data, in the form of sedimentary logs, field sketches, photomosaics and maps were interpreted in order to unravel the 3-D relationships of the various units of the Sanjauli Formation.

4. Facies associations and architectural elements

The fluvial system of the Sanjauli Formation shows a wide variety of lithofacies, which can be ascribed to the development of Scott-type ($G_{11}$), Trollheim-type ($G_{1}$) and Platte-type ($S_{11}$) fluvial deposits, resulting from base-level variations and consequently from fluctuations in accommodation space. The occurrence of massive gravel (lithofacies $G_m$) in combination with gravel showing planar cross-bedding (lithofacies $G_p$), trough cross-bedding (lithofacies $G_t$) and some intercalated sandy channel fills (lithofacies $S_e$) is characteristic of Scott-type ($G_{11}$) fluvial systems, whereas the conglomerate/sandstone facies assemblage ($G_m$, $S_h$ and $S_l$) indicates a Trollheim-type ($G_1$). However, the abundant planar cross-beds ($S_p$), trough cross-beds ($S_t$), cross-stratifications ($S_l$) and intervals of finely laminated siltstone or mudstone ($F_l$) match with the Platte-type ($S_{11}$) vertical profile. This ‘superassemblage’ model suggests a change in sedimentation style from a proximal braided river subjected to stream flows (Scott-type) and alluvial fan debris flows (Trollheim-type) into a sandy braided river (Platte-type). Three major facies associations (sheet-flood deposits, braided channels, floodplain deposits) and three systems tracts (a lowstand systems tract, a transgressive systems tract and a highstand systems tract) have been recognized in the Sanjauli Formation.

Fourteen lithology-based facies (Table 2) have been identified in the Sanjauli Formation. They are grouped in three facies associations (FA-1, FA-2 and FA-3), based on lithology, structure, texture and architectural elements.
4.1. **Braided channels (FA-1)**

4.1.1. *Description*

The tabular sandstone bodies are gravel-dominated and range in thickness from 5.5 to 6.5 m. They show clearly erosive margins (Fig. 3). At several intervals, sandstone bodies are fining upwards, simultaneously decreasing in thickness. The coarse lower parts wedge out laterally, ending against erosional, concave bounding surfaces. In some outcrops, the basal bounding surfaces deeply incise the underlying sediments. Disorganized, coarse conglomerates (lithofacies Gm), planar cross-stratified gravels (Gp), trough cross-stratified conglomerates (Gt), planar cross-stratified sandstones (Sp) and trough cross-stratified sandstones (St) are common in the lower part of the facies association. Convex upward and large-scale inclined surfaces are prominent, and cut-and-fill structures are common.

4.1.2. *Interpretation*

Stacked tabular sand bodies with predominantly parallel lamination typically indicate braided channels (Allen and Fielding, 2007; Bridge, 1985; Bristow and Best, 1993; Foix et al., 2013; Gibling, 2006). The subsequent fining-upward character and the upward decrease in the size of cross-stratifications suggest a steady decline in current energy and/or channel depth.

The sandstone facies consisting of conglomeratic sandstones and medium- to coarse-grained sandstones are interpreted as braided fluvial deposits with low-sinusity channel bars originating from high-discharge phases that also caused fluvial incision (cf.
Table 2 Description and interpretation of sedimentary facies (after Einsele, 2000; Miall, 1985, 1996).

<table>
<thead>
<tr>
<th>Facies code</th>
<th>Lithofacies</th>
<th>Description</th>
<th>Outcrop</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gm</td>
<td>Disorganized conglomerate</td>
<td>Massive, crudely-stratified, clast-supported conglomerate with rounded to subrounded clasts of 10 – 40 cm, and a matrix of coarse, poorly sorted sandstone. Scale: length of the pen-cap: 4.5 cm</td>
<td><img src="image1" alt="Image" /></td>
<td>Non-cohesive debris flow; bedload deposition as diffuse gravel sheets or lag deposits by high-energy floods</td>
</tr>
<tr>
<td>Gms</td>
<td>Massive, matrix-supported gravel</td>
<td>Matrix-supported polymict conglomerates with clasts up to 25 cm, mostly subangular quartz; subangular to rounded pebbles of 1 – 2 cm thick; large clasts within each unit seem floating. Scale: 8 cm</td>
<td><img src="image2" alt="Image" /></td>
<td>Mass-flows deposits from hyperconcentrated or turbulent flows</td>
</tr>
<tr>
<td>Gp</td>
<td>Planar cross-stratified gravel</td>
<td>Clast-supported, planar, cross-stratified conglomerates; cobbles and granules, subrounded to rounded. Scale: 7 cm</td>
<td><img src="image3" alt="Image" /></td>
<td>Linguoid bar, transverse bar</td>
</tr>
<tr>
<td>Gt</td>
<td>Trough cross-stratified gravel</td>
<td>Clast-supported trough cross-stratified conglomerates; cobble and granules with imbrications; normal grading. Scale: 10 cm</td>
<td><img src="image4" alt="Image" /></td>
<td>Transverse bar, channel fill</td>
</tr>
</tbody>
</table>
Table 2 – (continued)

<table>
<thead>
<tr>
<th>Facies code</th>
<th>Lithofacies</th>
<th>Description</th>
<th>Outcrop</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gsh</td>
<td>Gravel/sand-couplets</td>
<td>Gravel/sand couplets, stratified, but no internal stratification; clasts usually of subrounded quartz. Scale: length of the hammer- 33 cm</td>
<td><img src="image1.jpg" alt="Image" /></td>
<td>Sheet flow deposits</td>
</tr>
<tr>
<td>Sm</td>
<td>Massive sandstone</td>
<td>Pebbly, massive medium to coarse sandstone; moderate to good sorting. Scale: 8 cm</td>
<td><img src="image2.jpg" alt="Image" /></td>
<td>Rapid deposition by sediment gravity flow</td>
</tr>
<tr>
<td>Sp</td>
<td>Planar cross-stratified sandstone</td>
<td>Very fine to coarse, planar, cross-stratified arkosic sandstone; occasionally pebbly; moderate to good sorting. Scale: 8 cm</td>
<td><img src="image3.jpg" alt="Image" /></td>
<td>Migration of low-relief ripples under upper-flow regime; simple bars, transverse bedforms, sandwaves (lower flow regime)</td>
</tr>
<tr>
<td>St</td>
<td>Trough cross-stratified sandstone</td>
<td>Immature sandstone and conglomeratic sandstone with medium- to small-scale trough cross-stratification; thick homogeneous deposits with few conglomeratic levels. Scale in the figure: length of the pencil- 19 cm</td>
<td><img src="image4.jpg" alt="Image" /></td>
<td>Dune migration, lower flow regime</td>
</tr>
<tr>
<td>Sr</td>
<td>Ripple cross-laminated sandstone</td>
<td>Very fine to medium sandstone; symmetrical or asymmetrical ripples on upper bedding surface. Scale: 5 cm</td>
<td><img src="image5.jpg" alt="Image" /></td>
<td>2-D or 3-D ripples; wave or current ripples</td>
</tr>
</tbody>
</table>

(continued on next page)
<table>
<thead>
<tr>
<th>Facies code</th>
<th>Lithofacies</th>
<th>Description</th>
<th>Outcrop</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>Erosional scours with intraclasts</td>
<td>Crude cross-bedding. Scale: 6 cm</td>
<td><img src="image1" alt="Image" /></td>
<td>Scour fills</td>
</tr>
<tr>
<td>Sl</td>
<td>Sand, very fine to coarse</td>
<td>Low-angle cross-stratification. Scale: 8 cm; yellow arrows pointing to the cross-stratification</td>
<td><img src="image2" alt="Image" /></td>
<td>Scour fills</td>
</tr>
<tr>
<td>Sh</td>
<td>Sand, very fine to very coarse or even pebbly</td>
<td>Horizontal lamination, parting or streaming lineation. Scale: 8 cm; blue arrows pointing to the parallel lamination</td>
<td><img src="image3" alt="Image" /></td>
<td>Planar bed flow</td>
</tr>
<tr>
<td>Fl</td>
<td>Laminated sandstones, siltstones and mudstones</td>
<td>Parallel laminated dark grey mud. Scale: length of the clinometer-10 cm</td>
<td><img src="image4" alt="Image" /></td>
<td>Suspension deposits, overbank or abandoned channel</td>
</tr>
</tbody>
</table>
Allen, 1982; Blair, 1987). The conglomeratic sandstones at the base of the channels represent channel-lag deposits within the braided channels (Olusola and Akande, 2012). The convex upward large-scale inclined surfaces that show downstream migration are interpreted as braid bars.

4.2. Sheet-flood deposits (FA-2)

4.2.1. Description

The buff and pinkish purple sand bodies show a sheet-like shape. They are intercalated by planar cross-stratified sandstones (Sp) and massive sandstones (Sm) (Fig. 4). Both the basal and the upper bounding surfaces are laterally persistent, sharp and parallel to each other, and the sandstones tend to show an erosional base. The bed thicknesses range from 0.4 to 0.5 m. Sub-rounded quartz and feldspar grains and minor amounts of rock fragments make up the major components of the sandstones, which consist of particles from coarse sand to gravel.

The sheet-like sandstone bodies are separated from each other by a number of laterally non-persistent internal erosional surfaces. The dominating structure is horizontal lamination (Sh). Other common sedimentary structures are massive beds (Sm), low-angle cross-stratification (Sl), planar cross-stratification (Sp), couplets of gravel and sand (Gsh) and ripple cross-lamination (Sr).

The matrix-supported conglomerates (Gms) in this facies association show occasionally cross-stratification (Gp, Gt). Sporadic occurrences of flaser and wavy bedding, mud-draped surfaces, parting lineation and imbricated rip-up mudstone clasts are locally present.

4.2.2. Interpretation

The various characteristics indicate turbulent unconfined currents, and the sheet-like sandstones indicate intermittent high-energy currents in the form of sheetfloods (cf. Blair and McPherson, 1994; Foix et al., 2013; Nichols and Fisher, 2007; Tooth, 1999). Comparable sheet flood deposits have been found as sand deposits in extensive alluvial plains during unconfined overbank inundation (Kraus, 1996; Makaske, 2001; Nichols and Fisher, 2007; Therrien, 2006), sometimes related to short-lived braided rivers (Bell and Suárez, 1995). The laterally continuous, laminated sheet-like sandstone bodies are interpreted as sand-sheet elements (LS) (Table 3). They form vertically stacked products of short-lived and high-energy depositional episodes in the much more commonly low-energy environment that is indicated by its gentle depositional surfaces.

4.3. Floodplain deposits (FA-3)

4.3.1. Description

This lithofacies association consists of pinkish purple and dark grey siltstones, pinkish purple sandstones and dark grey mudstones (Fig. 5). The association extends laterally for hundreds of meters and shows a variable thickness of 2.3–3.4 m. The sandstones are separated by laterally persistent mudstones.

Sedimentary structures are uncommon, with few massive mudstones (Fsm), and only rare horizontally laminated mudstones (Fl). Massive mudstone units (0.2–1.2 m thick) have sporadic intercalations of sandstone and siltstone layers. These are medium- to very fine-grained, and have a tabular shape. The

<table>
<thead>
<tr>
<th>Table 2 – (continued)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies code</td>
</tr>
<tr>
<td>Fsm</td>
</tr>
</tbody>
</table>
interbedded strata show lateral continuity for several
tens of meters, with sharp, horizontal basal contacts,
whereas their upper boundaries are commonly
irregular.

4.3.2. Interpretation

The grey siltstones and mudstones indicate poorly
drained, distal floodplains with standing water (cf. Jo,
The mudstone units with an occasional presence of sandy deposits are interpreted as overbank (OF) deposits (Table 3). The laminated grey mudstones represent floodplain deposits formed in water-logged bodies with reducing conditions (cf. Jo and Chough, 2001; Scherer et al., 2015).

5. Vertical profile models

The idea of facies modelling was presented and worked out in studies such as those by Walker (1976) and Miall (1978). The vertical profile model conceived by Miall (1977, 1978) has now generally been accepted and is considered as the banner model, even though it has been and still is subjected to modifications. Rather than fitting into one of the basic vertical profile models of braided rivers proposed by Miall (1978), the main facies associations of the Sanjauli Formation require a new type, in the way of a 'superassemblage' including the Scott-type ($G_{11}$), the Trollheim-type ($G_1$) and the Platte-type ($S_{11}$) braided-river deposits.

The basal part of the Sanjauli Formation consists mainly of Scott-type ($G_{11}$) braided deposits,
characterized by the predominance of gravel (Gm) with planar cross-bedding (Gp), trough cross-beds (Gt), couplets of gravel and sand (Gsh), trough cross-stratified sandstones (St), rippled sandstones (Sr) and some interbedded sandy channel fill deposits (Se).

The Scott-type (G11) deposits of the Sanjauli Formation are topped by Trollheim-type (G1) sediments, which represent debris-flow deposits that reworked the Scott-type (G11) deposits. Several comparable examples have been described by Blair and McPherson (1992). The Trollheim-type is dominated by (1) parallel laminated pebbly sandstones (Sp), (2) intercalations of finer-grained sediments (Sh) suggestive of debris-flow deposits reworked by subsequent currents, (3) massive matrix-supported gravel (Gms), (4) disorganized conglomerates (Gm), and (5) fining upward sediments.

### Table 3 Facies associations and architectural elements of the Sanjauli Formation (modified after Miall, 1985, 1996).

<table>
<thead>
<tr>
<th>Facies association</th>
<th>Major lithofacies</th>
<th>Grain size</th>
<th>Vertical stacking pattern of architectural elements</th>
<th>Architectural element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braided channel deposits</td>
<td>St, Sp, Sm and Sm, with minor Gm, Sh and Fsm</td>
<td>Pebble to cobble conglomerate, fine- to coarse-grained sandstone with mud clasts</td>
<td>Channel-fill complex (element CH)</td>
<td></td>
</tr>
<tr>
<td>Sheet flood deposits</td>
<td>St, Sp and Sm, with minor Gm, Sh and Fsm</td>
<td>Pebble conglomerate, fine- to coarse-grained sandstone</td>
<td>Sediment gravity flow deposits (element SG)</td>
<td></td>
</tr>
<tr>
<td>Mainly St and Sp</td>
<td>Sm, Sl, and Sr, with minor Gsh, Gp, Gt, Fl and Fsm, and very rare Sp, St</td>
<td>Very fine- to medium-grained sandstone</td>
<td>Lateral accretion macroforms (element LA)</td>
<td></td>
</tr>
<tr>
<td>Floodplain deposits</td>
<td>Fsm and rare Fl</td>
<td>Mudstone and very- to fine-grained siltstone</td>
<td>Laminated sand sheets (element LS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sandy bedforms (element SB)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Overbank fines (element OF)</td>
<td></td>
</tr>
</tbody>
</table>
Overlying the Trollheim-type (G₁) conglomerates are coarse sandstones with abundant planar cross-beds (Sp), trough cross-beds (St), stratified sandstones (Sₖ), massive mudstones (Fₖm) and laminated sandstones (Sh) which resemble Platte-type (S₁₁) braided deposits. Interbedded with the sandstones are finely laminated siltstones or mudstones (Fl) that reach thicknesses of 0.5–1.2 m. The Platte-type (S₁₁) braided deposits are characterized by coarse sands with minor fine-grained deposits (Miall, 1977) which are also similar to the deposits of the Sanjauli Formation that overlies the Trollheim-type (G₁) deposits. The Sanjauli sandstones build simple, tabular sandstone sheets characterized by

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Fig. 5 Thinly laminated silt and shales characterizing well preserved floodplain deposits along the Kandaghat-Chail road. Scale: length of the clinometer-20 cm.
planar cross-beds (Sp) and minor ripples (Sr) that resemble the Platte-type ($S_{11}$) braided-river model. An exception is the thick siltstone beds in the Sanjauli Formation, which are in contrast to the thinner siltstone beds of the Platte-type deposits specified by Miall (1977).

Taking all the above into consideration, the fluviatile sedimentation in the Sanjauli Formation may be considered as a new model in the way of the above-mentioned ‘superassemblages’, as the sediments show in their extent characteristics that reflect an evolution from a Scott-type ($G_{11}$) architecture to a Trollheim-type ($G_{1}$) architecture to eventually a Platte-type ($S_{11}$) braided river (Fig. 6). The Sanjauli Formation thus cannot well be fitted into any of the standard models of Miall (1978) and yet contains many features which seem to fit in a combination of the Scott-type, Trollheim-type and Platte-type vertical models of braided rivers.

6. Sequence stratigraphic architecture

The sequence stratigraphy of the Sanjauli Formation has been established on the basis of its facies associations, their vertical successions and their spatial and temporal relationships. Sequence-stratigraphic units were distinguished in the present contribution through the recognition of flooding surfaces and sequence boundaries.

6.1. Sequence boundaries

The fluviatile incision of the braided river deposits of the Sanjauli Formation into the topmost sediments of the Chaossa Formation (heterolithic sediments consisting of fines, sands and shales that represent a delta) marks a sequence boundary (SB) which has been identified as a type-1 unconformity.

The vertical and lateral facies changes and the distinct differences between the Sanjauli Formation and the fine-grained top of the underlying Chaossa Formation imply that these two formations are genetically different and must be considered as two different sequences.

Three systems tracts have been recognized in the Sanjauli Formation on the basis of the stacking pattern and the facies tendency (Figs. 6 and 7). They owe their presence to base-level fluctuations in the fluviatile system. Development of the systems tracts indicates changes in the discharge pattern, which is reflected in the facies associations.

Fig. 6 Schematic vertical log exhibiting lateral and vertical facies relationship and changes in architectural elements in the Sanjauli braided fluvial system. The Scott-type is evolving to Trollheim-type and Platte-type due to base-level fluctuation. Three different systems tracts, viz., lowstand systems tract (LST), highstand systems tract (HST) and transgressive systems tract (TST), maximum flooding surface (MFS), transgressive surface (TS) and a sequence boundary (SB) have been delineated.
6.1.1. Lowstand systems tract

The development of the Sanjauli Formation started with fluvial incision in response to a falling base-level. The fluvial incision (type-1 unconformity) may have been initiated by a decrease in accommodation space, resulting in the emergence of a lowstand systems tract (LST). The subsequent evolution of the LST in the course of the fall in base-level indicates a culmination of the river incision, which was followed by piling up of sediments, building a lowstand wedge (i.e. prograding fluvial sediments overlying the Chaossa delta and onlapping the unconformity). The LST deposit is characterized by channel infillings, which ended with the initiation of a transgression surface.

6.1.2. Transgressive systems tract

Subsequent to the maximum phase of the lowstand regression, initial flooding phases triggered a transgressive systems tract (TST). The braided river deposits of the Sanjauli Formation pass upwards into medium- and fine-grained channel sandstones with cross-stratification, double mud drapes and bidirectional current ripples.

These strata with clear tidal control are erosionally overlain by a thin pebble and cobble conglomerate, interpreted as a transgression conglomerate (Figs. 6 and 7). The persistent character of the transgression over the pebble and cobble conglomerate is indicated by an upwards-thinning succession of cross-stratified beds, which eventually passed into thin dark shale beds that indicate a condensed succession representing the maximum flooding surface (Figs. 6 and 7).

Amalgamated channel deposits pass upwards into numerous isolated channel sandstones with increasing numbers of fining-upward sequences of trough cross-bedded to ripple-laminated sandstones. The increase in the amount of fine-grained overbank material, as well as the sedimentary structures and the vertical diminishing of the frequency of channel amalgamation imply tidal influence with increasing accommodation space and elevation of the base-level.

6.1.3. Highstand systems tract

Gradual slowing down of the relative base-level rise and a diminishing accommodation space (although continued subsidence still created some accommodation) initiated highstand systems tract (HST) deposits. When the accommodation space reached its minimum level, the river spread and shifted through the floodplains, resulting in reworking of
Sediments and in lateral accretion, accompanied by minor fine-grained vertical accretion.

The change from amalgamated to isolated channel deposits and the accompanying increase in preserved fine-grained sediments record the transition from a transgressive to a highstand systems tract. The HST is characterized by a progressive increase in the volume of overbank sediments.

7. Discussion and conclusions

The standard fluvial facies model of Miall (1977) has long been advocated as the standard in the classification of braided river facies assemblages. It can be deduced from the sedimentary record of the Sanjauli Formation, however, that the fluvial deposits of this formation show characteristics that fit only in a combination of Scott-type, Trollheim-type and Platte-type braided rivers. A new 'superassemblage' model is therefore proposed, after taking the following characteristics into consideration.

1) Scott-type (G1) deposits are characterized by a predominance of gravel (Gm) with planar cross-beds (Gp), trough cross-beds (Gt), couplets of gravel and sand (Gsh), trough cross-stratified sandstones (St), rippled sandstones (Sr) and some interbedded sandy channel-fill deposits (Se). The Scott-type (G1) deposits of the Sanjauli Formation are topped by accumulated debris flow deposits, which comply with the characteristics of Trollheim-type river deposits. The debris flows cannot have travelled far from their source, so that the presence of the Trollheim- and Scott-type profiles in the same braided river deposit reflects variations from fan-proximal to fan-distal (cf. Rust, 1978). The occurrence of a conglomerate/sandstone facies assemblage resembles the Trollheim-type deposit. Poorly sorted, matrix-supported debris flow deposits (Gms) with planar cross-beds (Sp), trough cross-beds (St), stratified sandstones (Sl) and intercalations of finer-grained sediments (Sh) further characterize the Trollheim-type (G1).

2) The Trollheim-type (G1) deposits gradually evolve into stacked sheet-like sandstone bodies, suggesting their deposition in a braided river setting during flash floods. The progressive evolution of Trollheim-type to Platte-type deposits is indicated by the fining-upward tendency from conglomerates to coarse-grained sandstones and eventually to fine-grained sandstones and siltstones. These sandstone and siltstone bodies earmark the amalgamation of the Platte (S11) deposits.

3) The features of Platte-type (S11) deposits are expressed by the tabular sheet-like sandstones with planar cross-beds (Sp) and minor ripples (Sr). Overbank deposits in this area are characterized by siltstones and shales.

Studies of the Proterozoic Simla Basin have previously been focused on structure, tectonics and stratigraphy. In contrast, sedimentological information about the Simla Basin is, in general, insignificant. The present study now sheds light on the sedimentology of the Sanjauli Formation on the basis of outcrop-based facies analysis. The resulting new combined model illustrates the response of the fluvial system to changes in base-level and can be applied to similar successions elsewhere, whether recent or ancient in age.

The main tool used in our sequence stratigraphic approach is the analysis of the stacking pattern of the various units and of the key surfaces that separate units with different stacking patterns. Recognition and correlation of stacking patterns in the braided river Sanjauli siliciclastics, and their interpretation in terms of base-level changes jointly provide a rock-based model that explains the evolution and the significance of the changes in sedimentary architecture. Based on the recognition of stacking patterns and facies tendencies, three hierarchical types of systems tracts (lowstand systems tract, transgressive systems tract, and highstand systems tract) have been recognized in the Sanjauli Formation.

The prograding clastic wedge of the Sanjauli Formation, which incises the delta deposits of the Chaossa Formation, represents a lowstand systems tract (LST) which developed in response to a high supply of clastics during a falling base-level. During this base-level fall period a type-1 unconformity was formed as indicated by the incision of the fluvial sedimentary wedges on the delta deposits of the Chaossa Formation.

The transgressive systems tract (TST), characterized by tidally influenced medium- and fine-grained channel sandstones, was initiated by the first flooding event after the maximum lowstand regression. The culmination of the transgression is marked by the development of a thin dark shale bed on top of the sandstone and has been interpreted as a condensed section. The preservation of fine-grained overbank material and sedimentary structures that indicate tidal influence reflect increased rates of base-level rise and increasing accommodation space.
The highstand systems tract (HST) was deposited when the rate of base-level rise gradually diminished and the accommodation space decreased (continued subsidence still created some accommodation). The HST is characterized mainly by lateral accretion, with minor vertical accumulation of fine-grained sediment.

The sandy braided channel deposits (FA-1) resemble the Proterozoic fluvial styles described by Røe and Hermansen (1993) and Sønderholms and Tirsgaard (1998), which lack, however, the mud content, and are composed of medium- to high-energy facies, reflecting hydrodynamic fluctuations and showing stacked sand bodies. In spite of high discharge rates, which must be ascribed to the absence of vegetation in the Proterozoic, no large quantities of overbank deposits accumulated because of strong reworking resulting from limited accommodation space. Hence, the discharge was continuously high, giving rise to perennial, high-energy streams.

The occurrence of relatively thick overbank sediments in FA-3 reflects increased vertical accretion brought about by an increasing creation of accommodation space. A subsequent increase in the mud/sand ratio suggests a distal shift of the fluvial system. The lack of desiccation structures in the channel deposits and muddy floodplains suggests a perennial fluvial system in a relatively humid climate.

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