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Precambrian basin-margin fan deposits: Mesoproterozoic Bagalkot Group, India

Pradip K. Bose[a] , Subir Sarkar[a], Soumik Mukhopadhyay[a], Bikas Saha[a] and Patrick Eriksson[b]

[a]Department of Geological Sciences, Jadavpur University, Kolkata 700032, India
[b]Department of Geology, **University of Pretoria**, Pretoria 0002, South Africa

Abstract

Three-dimensional facies variability in coarse clastic sedimentary rocks (breccia, conglomerates and coarse-grained sandstones) at the base of the Ramdurg Formation suggests terrestrial scree and fans giving way downslope to fluvial sediments along the margin of the Mesoproterozoic Bagalkot basin in India. In consistency with the basic tenet of Precambrian alluvial sedimentation, fluvial architectural elements and field location-specific consistency in channel-flow direction support an invariably braided pattern for the rivers, although the architectural element-packaging pattern does show distinct changes downslope, with channel belts thinning and becoming more regular in their geometry. With possible persistence of a semi-arid climate, downslope change in flow durability in the channels was controlled primarily by water discharge, depending on position of the channels with respect to the mean level of the water table–basin-margin slope intersection.

Confined between an unconformity below and a granular lag succeeded by thoroughly wave-featured sandstone, and argillite-carbonate above, the coarse and poorly sorted clastic sedimentary rocks of the basal Ramdurg are interpreted as a base-level lowstand product, for which the sedimentation rate exceeded the rate of space creation for sediment accumulation. Consequently, the fan succession as a whole is coarsening-upward. Fluvial sections, nonetheless, fine upward as the depositional slope gradient became progressively reduced with aggradation of channels. Tectonics-related slope variation along and across the basin-margin, devoid of vegetation, dictated the sediment distribution and sequence building pattern primarily. Eventual termination of this basin-margin depositional system was caused by later enhancement in the rate of base-profile rise.

Article Outline

1. Introduction

Basin-margin sedimentary cones are, more often than not, coarse-grained and bear special significance from a geological and economic point of view. Their lithology, facies spectrum and internal organization provide important clues for past tectonic and climatic settings, though source rock composition may also exert a significant influence. Basin-margin sedimentary cones often contain important economic placer deposits, notably of gold, diamonds, and uranium. Preferential occurrence of such cones at tectonically active margins makes them prone to fragmentation, transportation of the fragments to variable distances and even destruction. Their reconstruction is therefore often difficult and likely to be more so in older records.

Nonetheless, in the Precambrian, the general lack of vegetation on hill slopes could have engendered more such sedimentary cones, as these conditions readily induced slope failure, landslides as well as debris-flows. However, published reports are not that common, particularly for scree cone deposits, and alluvial fan deposits can easily be mistaken for coarse-grained braided fluvial deposits (e.g., Els, 1998) if palaeoslope data have not been collected (cf. Blair and McPherson, 1994). Channel systems within the Precambrian were predominantly braided ([Cotter, 1978], [Friend, 1978], [Long, 1978], [Fuller, 1985] and [Long, 2004]) due to lack of sediment-binding vegetation and due to poorly developed soils. The generally aggressive Precambrian palaeoweathering conditions, especially under the early greenhouse gas-dominated palaeo-atmosphere, provided more labile material (Donaldson and de Kemp, 1998) and this greater availability of fines would have promoted mass-flow and hyperconcentrated flow processes (Long, 2004), including possibly those in non-fan fluvial systems (Buck and Minter, 1985). Distinction of fan and fluvial systems with coarse-grained facies thus remains a challenge for Precambrian-aged deposits (e.g., Eriksson et al., 2006). Precambrian conditions further ensured more effective wind activity although preservation of aeolianites amidst frequently avulsing river channels may, however, have required some specific optimum conditions (Tirsgaard and Øxnevad, 1998).

In this context, good preservation of the whole range of terrestrial sedimentary cones – scree cone, alluvial fan and fan-delta – at the base of the Mesoproterozoic Bagalkot Group, Karnataka, India, notwithstanding folding and metamorphism (Jayaprakash et al., 1987), is indeed, fortuitous. Also fortuitous is the retention in these rocks of fine distinctions between deposits in rivers of varied longevity as well as local preservation of aeolian strata.

This paper seeks confirmation for the Precambrian alluvial sedimentation scenario, as envisaged above, in the Mesoproterozoic Ramdurg Formation at the base of the Bagalkot Group. The work has been done at three different locations, viz Ramthal, Salgundi and Bilgi, where breccias, conglomerates and poorly sorted sandstones rest upon the basement rock – granite, BIF or mica schists (Fig. 1a). All three locations are in the eastern sector of the east–west elongated exposure area of the Bagalkot Group, covering its northern, eastern and southern fringes. The studied stratigraphic interval includes the basal Salgundi Conglomerate and the lower part of the Saundatti Quartzite (Fig. 1b), capped by thick wave-featured sandstone followed further upward by carbonates and argillites belonging to the upper part of the Saundatti Quartzite (Fig. 1b). After a brief account of the facies constituents of the studied stratigraphic interval, classified on the basis of their inferred genetic processes, the paper examines the palaeogeography of the facies in the three study locations separately. Location-specific and facies-specific palaeocurrent patterns outline the palaeodrainage pattern and in conjunction with facies distribution patterns, indicate the general palaeoslope direction. Regional variability in palaeocurrent direction remains ambiguous, as there is no way to negate the effect of multiple folding of the Group. The paper further considers the facies architectural pattern, the fluvial architectural elements and their packaging in channel-belts, in order to help constrain the spatial variation in sedimentation pattern and to assess its possible intrabasinal and extrabasinal controls.

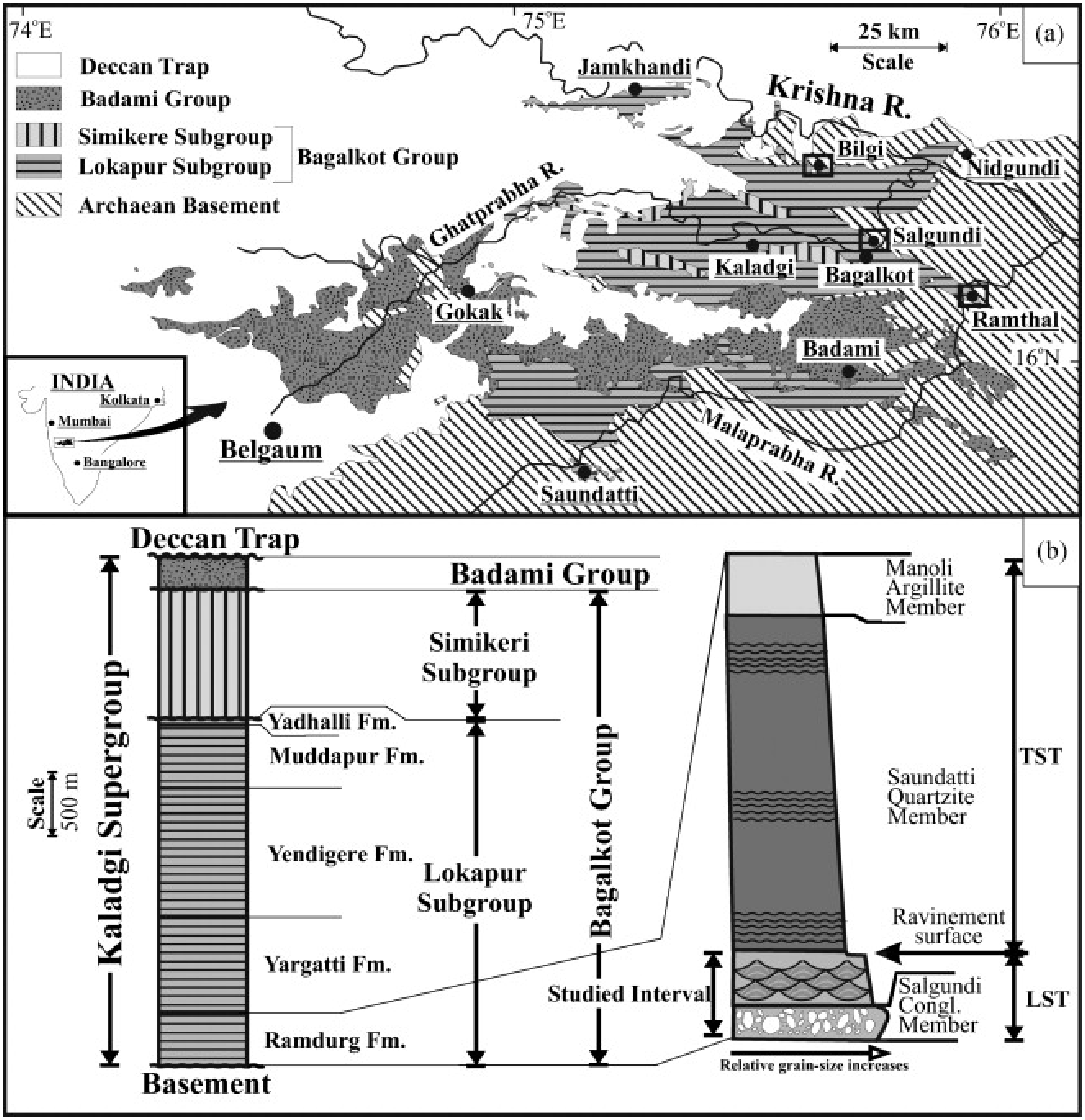


Fig. 1. (a) Outcrop distribution of rocks of the Kaladgi Supergroup, including the Bagalkot Group, India. Study locations are marked (squares) (modified after **Jayaprakash et al., 1987**). (b) Kaladgi Stratigraphy, highlighting its basal Ramdurg Formation (modified after **Jayaprakash et al., 1987**). Studied interval and sequence stratigraphic frame for the Ramdurg Formation are also indicated on the right.

2. Geological background

The Bagalkot Group, forming the lower part of the Kaladgi Supergroup, is about 4250 m thick, well exposed around Bagalkot, Karnataka (Fig. 1a) and is dominated by siliciclastic rocks ([Viswanathaiah, 1977], [Jayaprakash et al., 1987], [Peshwa et al., 1989], [Kale, 1991] and [Kale et al., 1996]). The granitic basement rocks have been dated as 3.29–2.6 Ga on the basis of the Rb–Sr ratio using a [^{87}Sr/^{86}Sr] vs. [^{87}Rb/^{87}Rb] plot ([Jayaram et al., 1983] and [Rao et al., 1999]), while the Bagalkot Group has been assigned a Middle Riphean age on the basis of a stromatolite assemblage found at the mid-level of the Bagalkot Group ([Viswanathaiah and Gowda, 1975], [Raha and Sastry, 1982] and [Garuraja, 1983]). Subsequently Jayaprakash et al. (1987) reviewed the stromatolite assemblage to reconfirm its inferred age of ca.1260–1000 Ma.

The Bagalkot Group comprises two subgroups, lower Lokapur and upper Simikeri. The Lokapur Subgroup comprises five formations. The basal Ramdurg Formation, up to 475 m thick is overall fining-upward and is constituted by three Members, the Salgundi Conglomerate, Saundatti Quartzite and Manoli Argillite in ascending order (Fig. 1b). This paper focuses upon the Salgundi Conglomerate (up to 31 m thick) and the basal 40 m of the Saundatti Quartzite. Petrographically, the Salgundi Conglomerate is both oligomictic and polymictic. The Saundatti Quartzite comprises litharenites and arkoses within its basal segment, but becomes quartzarenitic in the upper levels.

The Bagalkot Group is interpreted by some to have been deposited within an intracratonic rift basin (Radhakrishna and Vaidyanathan, 1994) while others tacitly assume it to be largely marine ([Viswanathaiah, 1977], [Jayaprakash et al., 1987], [Peshwa et al., 1989] and [Kale et al., 1996]). The facies analysis carried out so far on the sedimentary rocks constituting the Kaladgi Supergroup was based solely on broad lithological categories like conglomerate, sandstone, shale and carbonate (Kale et al., 1996) and was thus too superficial to grasp the great variability in depositional mechanism and palaeogeography that underpinned development of the Bagalkot Group. In this study we make a more detailed, facies-based study of only the basal ruditic portion of the Group, up to 70 m in thickness.

3. Facies

Facies constituents of the Salgundi Conglomerate Member and the studied basal segment of the Saundatti Quartzite Member, taking into account their lithology, sedimentary structures, body geometry, and facies associations, are described and interpreted in Table 1. The facies are basically process-related, but may have direct palaeoenvironmental and palaeogeographic import (Fig. 2, Fig. 3 and Fig. 4).

Table 1.

Facies constituents of the Salgundi Conglomerate and the basal part of the Saundatti Quartzite beneath the 10 s of meters of the entirely wave-featured marine or lacustrine segment

Description	**Interpretation**
A_1. Clast-supported chaotic breccias, thick, up to about 2 m, rapidly wedging away from the basement exposure, generally found at the bottom of the formation, having base jagged as clasts frequently penetrate into the substratum and clast composition restricted to that of the basement in immediate vicinity (**Fig. 2**a and b).	Scree Breccia facies (**Selley, 1965**): Penetration of clasts into the underlying substrata indicates free-fall of clasts. The facies resembles those described by **Blair and McPherson (1994)** as rock avalanche wedges.
A_2. Matrix-supported conglomerate, clasts having distinctly smaller size and less angularity with respect to those in facies A_1. Beds have planar bases, in contrast to their tops rugged as clast protrude above the bed surface and geometry lenticular, with discernibly convex upward at places, internally massive, up to 80 cm thick and 8 m long in exposures (**Fig. 2**c).	Debris-flow conglomerate facies (**Blair and McPherson, 1994**): Chaotic orientation of clasts and their protrusion above bed surface indicate high matrix strength of the parent flows.

Description	**Interpretation**
A_3. Distinctly poorer in matrix than A_2, yet matrix-supported, up to 50 cm thick, and of maximum preserved outcrop length about 3 m, devoid of grading, but its most distinctive feature is bed-parallel or long axis imbrication of elongated clasts (**Fig. 2**d). Closely associated with A_2, locally grading laterally into it.	Sheared mass-flow conglomerate facies (**Bose and Sarkar, 1991**). Bed-parallel orientation is a manifestation of flow-internal shear; long axis imbrication of clasts indicates settling through dispersion (**Walker, 1984**).
A_4. Conglomerate broadly similar to that of A_2, but possesses a relatively greater clast concentration and reverse grading, albeit feeble (**Fig. 2**e). Associated with A_2, but not as common in occurrence.	Modified grain-flow conglomerate facies (e.g., **[Lowe, 1976]**, **[Middleton and Hampton, 1976]**, **[Schultz, 1984]**, **[Mack and Rasmussen, 1984]**, **[Nemec and Postma, 1993]**, **[Mulder and Alexander, 2001]**, **[Davis et al., 2002]** and **[Gani, 2004]**): Reverse grading manifests dispersive pressure.
A_5. Slightly convex upward conglomerate beds, clast-supported at base, but progressively enriched in sand upwards. Locally bear crude cross-strata, especially in its top sandy part. Outcrop length generally less than 6 m, bed-thickness up to 70 cm (**Fig. 2**f).	Sieve conglomerate facies (**Todd, 1989**). It is thought to represent bedforms, which were frozen because of rapid draining out of water; sand infiltrated from above as the flow waned.
A_6. Clast-supported sheet conglomerate showing little lateral variability in thickness ($\sim$80 cm) within which clasts are often bed-parallel or imbricated with their intermediate axis (**Fig. 2**g). This facies occurs in close association with A_5 and locally with A_2.	Sheet flow conglomerate facies (**[Hein, 1982]**, **[Fisher, 1971]** and **[Enos, 1977]**). Clast-supported nature in conjunction with sheet-like bed geometry and intermediate axis clast imbrication indicate deposition from high energy tractive flow (**Walker, 1984**).

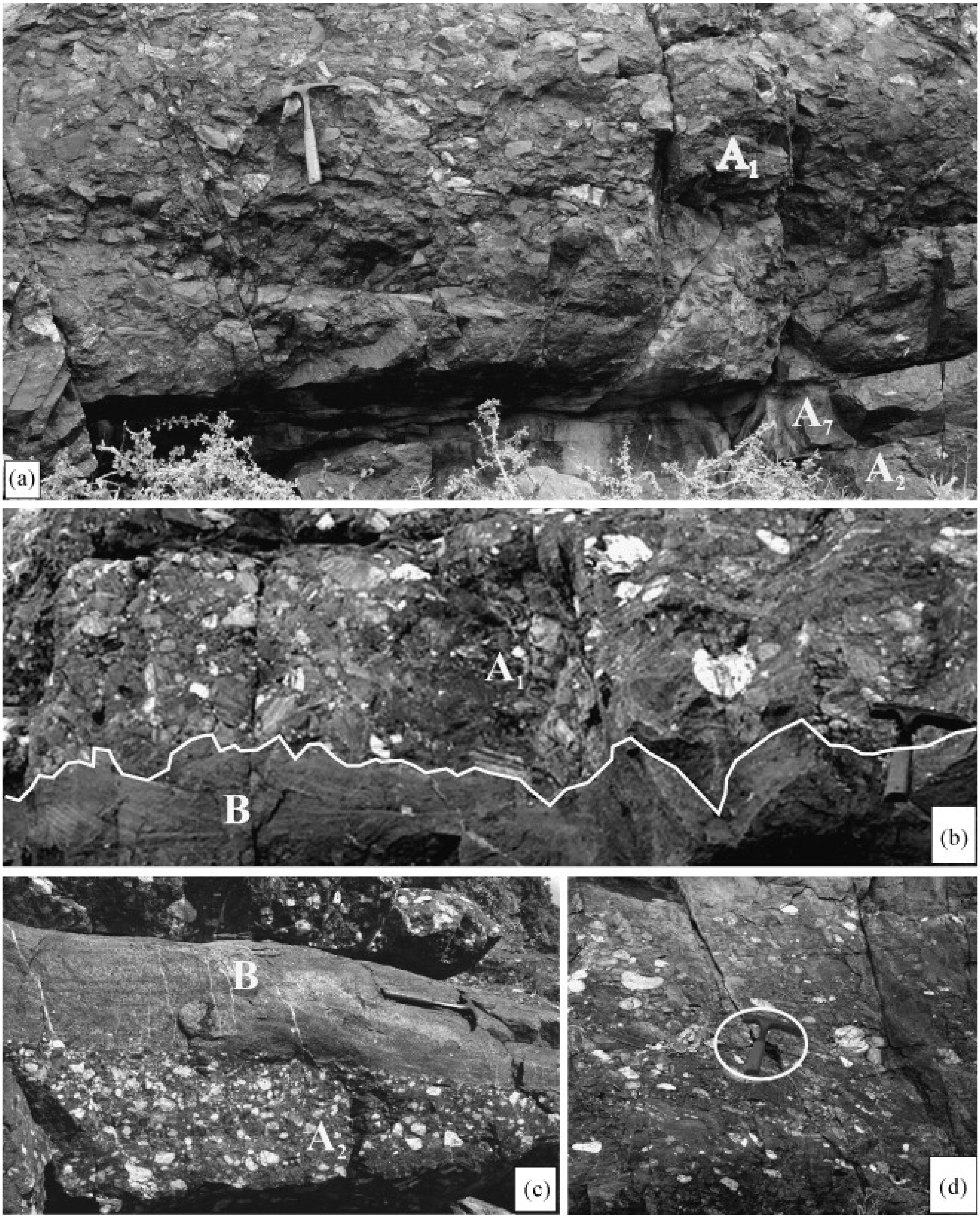
Description	**Interpretation**
A_7. Thin (>5 cm) almost sheet-like granular sandstone pinching on sides (maximum measured outcrop length ~ 20 cm) with minor erosion at base; internally massive, but may give way upward gradationally to crudely defined cross-strata followed by planar laminae (**Fig. 2**a). All conglomeratic facies together make a preferred facies association that locally incorporates sandy A_7 and B (described below); in turn, isolated lenses of A_2, A_5 and A_6 occur within facies B and also in facies association C described below.	Hillwash sandstone facies: General massiveness manifests rapid settling, possibly from grainflow (**Shanmugam, 2000**). Gradational upward transition from massiveness to crude cross-strata apparently manifests decreasing sediment saturation in the flow, while the planar laminae at top of beds indicates increase in flow shear with rapid decrease in flow depth at the penultimate stage of deposition. Deposition possibly took place from minor water flows arisen from occasional rain on steep hillslope.
B. Granular/pebbly sandstone characterized by juxtaposition of lenticular channel-form bodies (**Fig. 2**h; measured width <12 m and thickness <90 cm) with marked erosion at bottom, and internally either massive or trough cross-stratified but may be planar laminated at top (**Fig. 2**i). This facies is volumetrically important not only the Saundatti Quartzite, but also of the Salgundi Conglomerate at places. In close association with conglomerates it is rich in pebbles (<2 cm in length), scattered randomly within beds despite presence of crude cross-strata (**Fig. 2**j), but beyond that pebbles, generally of smaller size, concentrate along the channel bases (**Fig.**	Streamlet granular sandstone facies: The poorly sorted granular sandstone with channel geometry is possibly of fluvial origin. Crudely cross-stratified bodies with randomly strewn pebbles suggest deposition from high-velocity river flashflood (**[Pfluger and Seilacher, 1991]** and **[Blair and McPherson, 1994]**).

Description	**Interpretation**
2h). Pebbly sandstone bodies are often intercalated with pebble-free coarse sandstone.	
C_1. Solitary set of scallop-based trough cross-strata of average thickness 80 cm passing downcurrent into down-dip cross-strata in poorly sorted granular sandstone (**Fig. 3**a and b), pebbles concentrate along the foreset bases; traced incompletely though, up to 120 m in paleocurrent direction and 7.5 m transverse to it, having distinct convex upward geometry in the latter direction (**Fig. 3**c). The down-dip cross-strata are granule-free, less steep. The smaller cross-strata dip in the same direction as the larger ones and their sets are about 7 cm (**Fig. 3**a). On instances, immediately under surfaces that truncate their tops, there are thin (<5 cm) patches of crinkled adhesion laminae and inversely graded translatent strata, traced laterally up to ∼2 m (**Fig. 3**d and e).	Fluvial bar facies (a): The poorly sorted facies revealing unimodal paleocurrent direction (see next section) is possibly of fluvial channel origin. Steeper foresets laterally transiting into downdip cross-strata manifests slackening of current. Aeolian features like adhesion laminae and translatent strata evince emergence of bars above water surface, although remaining within water capillary zone.
C_2. Tabular cross-strata of set thickness ∼ 20 cm in granule-free, yet poorly sorted sandstone. Where found in lateral contact with C_1 they recline on the bar flank having orientation almost at right angle to that of attached C_1 cross-strata. This facies could never be traced more than 70 cm in dip direction of the cross-strata.	Fluvial Bar-attached facies: This facies presumably formed by sand avalanching down the flank of the bars. Operation of a secondary current at an angle to the bar axes, possibly at low water stage when bar configurations could influence the channel flow direction, is suggested.

Description	**Interpretation**
C_3. Characterized by granular sediment, internally characterized by laterally discontinuous planar laminae and sheet-like geometry, although eroded on sides. Granule size matches with the coarsest fraction of C_1 and C_2 combined on which it overlies erosionally. Its maximum outcrop length measured is about 2 m and thickness $\sim$5 cm.	Bar-top facies (1a): Formed apparently at low water stage when bar top was reworked by a strong flow, possibly during emergence. Finer fraction of bar-top sediment was winnowed out leaving the granules as erosional lag.
C_4. Characterized by trough cosets in poorly sorted medium to fine-grained sandstone of lenticular geometry with concave upward base (**Fig. 3**f). The cosets are, on average, 30–35 cm thick, while their constituent sets are mostly around 8–9 cm. The facies units are up to 1.5 m thick and laterally traceable up to 6 m generally terminating against C_1, interrelationship between the two facies being onlapping and downlapping. Palaeocurrent direction determined from this facies, more or less, follows that derived from C_1 (see next section).	Fluvial Channel-floor Facies (a): This poorly sorted sandstone in lateral equivalence to inferred fluvial bars is considered as channel-floor deposit formed principally by dune migration.
D_1. Like C_1 this facies is also characterized by solitary sets of trough cross-strata (thickness up to 60 cm) traced incompletely up to about 100 m, but the sandstone is granule-free, medium to fine grained and the foresets do not have scalloped bases, although back-flow	Fluvial Bar Facies (b): Like C_1, this finer grained facies is also attributed to migration of bars, but at relatively downstream part, under flow relatively weaker, but more steady, both in terms of intensity and direction; no evidence of secondary flow, such as, bar-flank accretion deposit, like C_2,

Description	**Interpretation**
ripples and small cross-stratified scour-fills locally occurs at top of them (**Fig. 4**a). Aeolian features, as those in $C_{1,}$ are also conspicuous in absence. Cross-strata orientation is area-wise highly consistent (see next section). Maximum measured outcrop length of this facies in the direction of large cross-strata is about 30 m.	was found associated. Only slight flow unsteadiness is reflected in the bar-top scours. Smaller height of the bars suggests lower flow depth.
D_2. Broadly similar to C_3 in appearance, but finer grained even with respect to D_1 on which it invariably rests and its internal planar laminae are well defined and laterally persistent (**Fig. 4**b). Its thickness is around 10 cm and maximum preserved outcrop length 2.5 m.	Bar-top facies (b): Like C_3, this facies is also interpreted as a product of reworking of previously deposited bar-top sediments, but selectively the finer fraction, presumably during falling water stage, but at relatively low shear, perhaps without or before emergence of the bar (cf. **[Cant, 1978]** and **[Kirk, 1983]**).
D_3. Like C_4 this facies is also characterized by trough cosets, differing only by finer sand grain-size, shorter set and coset thicknesses, up to 6 cm and 20 cm, respectively. Laterally this facies is of lenticular geometry, passing into D_1. The paleocurrent direction derived from it roughly conforms that of the associated large cross-strata. D_1, D_2 and D_3 together constitute a preferred association.	Channel-floor facies (b): Like C_4 this facies is also attributed to migration of smaller dunes along river channel floor accommodating possibly relatively shallower water depth at more downstream part.
E. This facies occurs only at top of the studied stratigraphic segment, overlying	Transitional facies: Because of alternations between unidirectional traction-dominated

Description	**Interpretation**
either facies B or facies association D and is characterized frequently by wave features, like wave ripples (**Fig. 4**c), wavy laminae, quasi-planar strata, hummocky cross-strata, chevron cross-strata and occasional off-shoots in well sorted fine grained sandstone. These beds are, however, intercalated with sandstone beds of distinctly coarser grain size and poorer sorting. When this facies overlies facies B, the intercalated beds are closer in appearance to that and internally characterized by cosets of small troughs only (subfacies E_B). When overlies facies association D it is more akin to that and internally characterized by cosets of small troughs passing laterally into low angle cross-strata of larger set thickness (subfacies E_D). The facies is laterally extensive, have tabular geometry and base always demarcated by a thin and broadly wavy laterally persistent well-sorted granule lag. Granular lags, albeit laterally impersistent, are present, also at the base of wave-featured beds in subfacies E_B).	and wave-dominated deposits and position of its single unit just beneath the 10 s of meters thick entirely wave featured marine or lacustrine stratigraphic segment (discussed below) this facies is identified as transitional between the fluvial and marine/lacustrine environments.


A_1
A_7
(a)
A_2
A_1
B
(b)
B
A_2
(c)
(d)

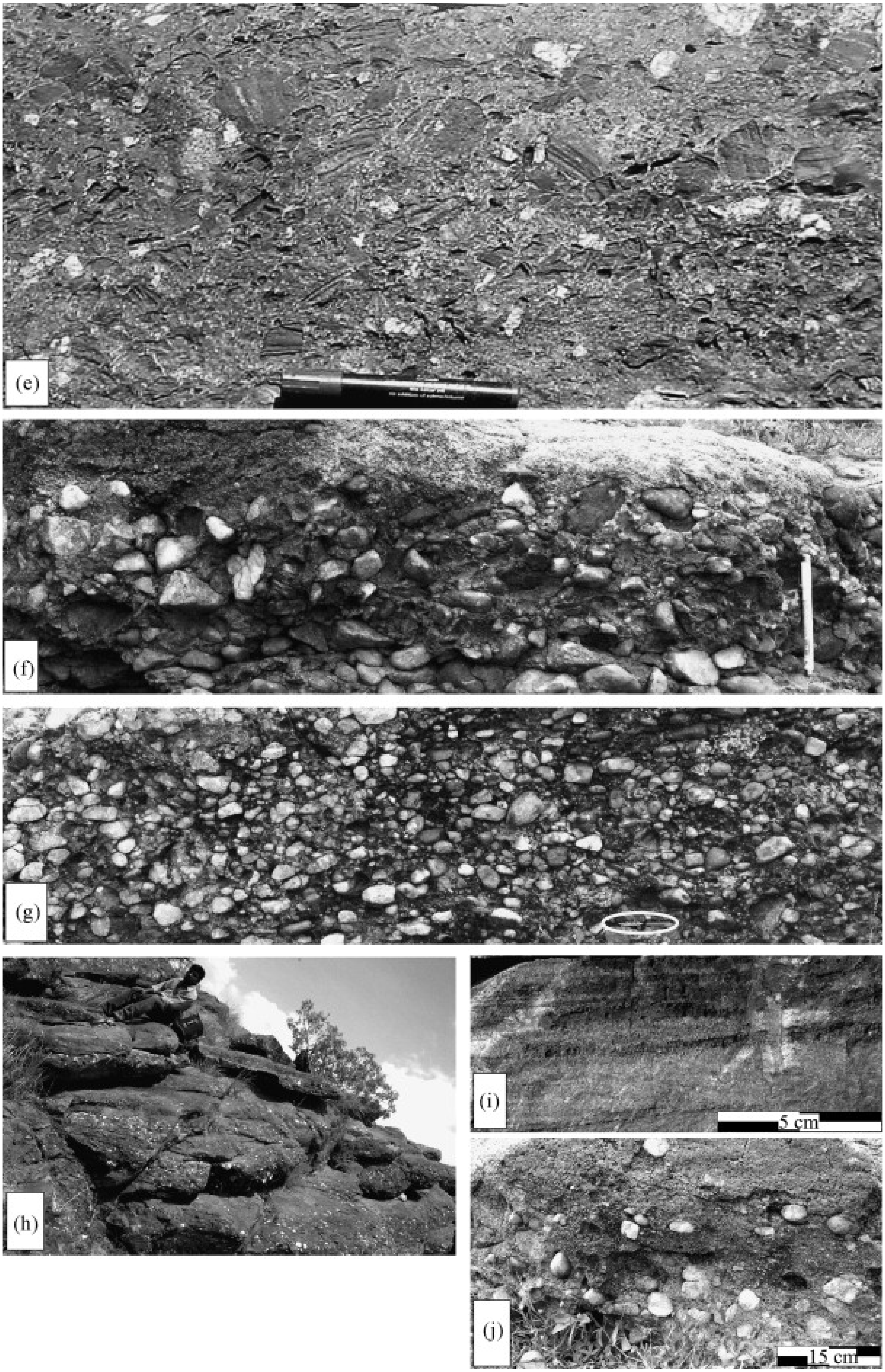

(e)
(f)
(g)
(h)
(i)
5 cm
(j)
15 cm

Fig. 2. Facies in Salgundi Conglomerate Member: (a) Scree breccia (A_1) overlying a hillwash (A_7) that, in turn, overlies a debris-flow conglomerate (A_2) at Ramthal. Note, angular tabular shape of the clasts, lack of matching boundaries between adjacent clasts and clast-supported fabric within facies A_1. (b) Scree facies (A_1) overlying a small channel facies (B) near the top of the proximal section at Salgundi. Note strongly jagged base of the scree because of deep clast penetration. (c) Debris-flow facies (A_2) underlying a streamlet facies (B) at Salgundi. Note irregular top of the debris-flow body. (d) Long-axis pebble imbrication in facies A_3, internally sheared debris-flow at Salgundi. (e) Modified grainflow facies (A_4) with reverse grading at Salgundi (pen length 12 cm). (f) Sieve facies (A_5) at Bilgi, with greater sand infiltration upward changing the basal clast-supported fabric into a matrix-supported fabric (pen length 13 cm). (g) Sheet-flow facies (A_6) at Bilgi. Note clast-supported fabric and preferred leftward intermediate-axis imbrication of clasts (pen length 14 cm). (h) Small channel facies (B) characterized by numerous small channels juxtaposed laterally and vertically. Note pebble lag at base of the channels. (i) Trough cross-strata followed upward by planar laminae in channel-fills within small channel facies (B) at Salgundi. (j) Pebbly flash-flood deposit within facies B. Note crude cross-strata and pebbles reclining on the foresets.

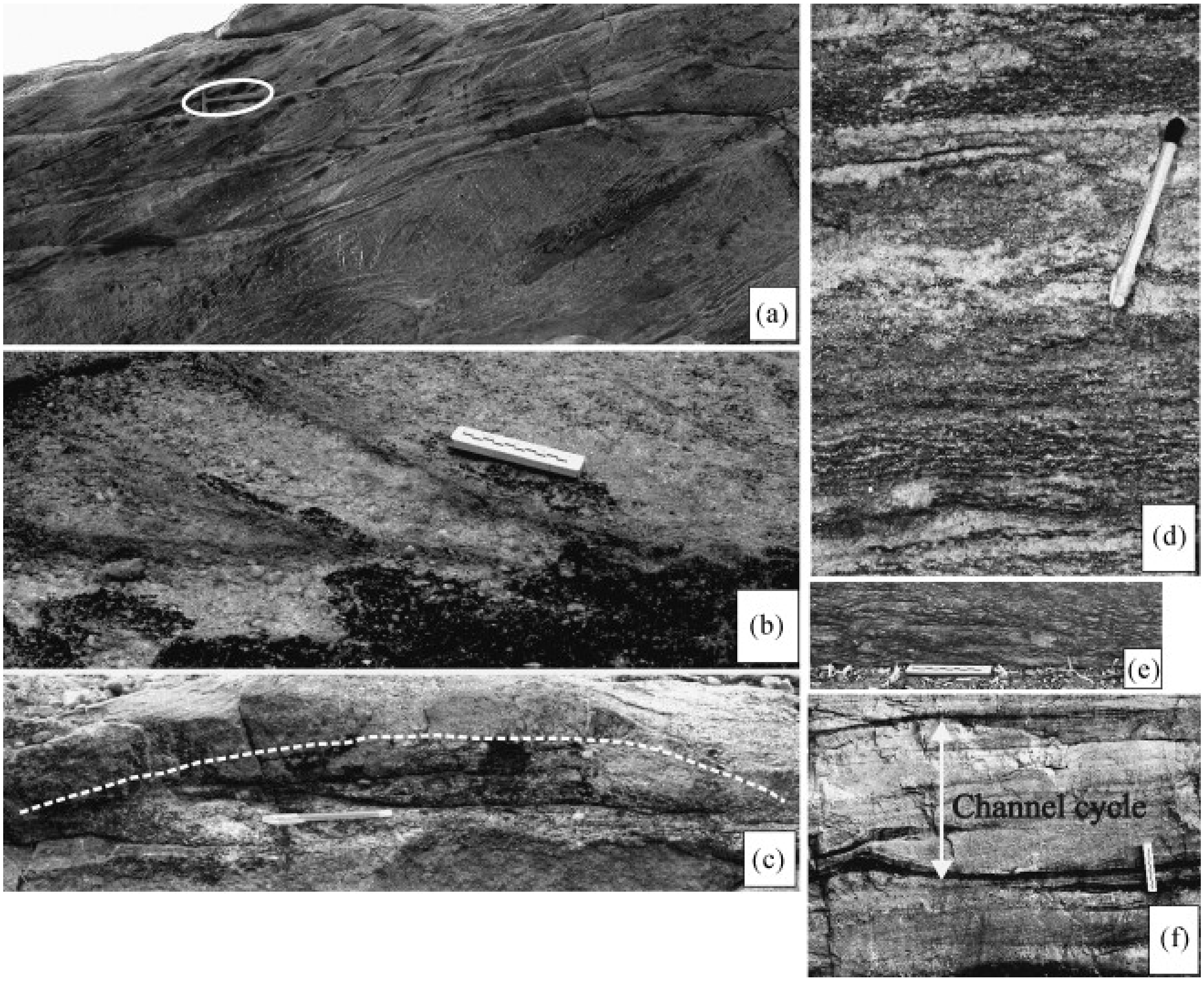


Fig. 3. (a) A longitudinal bar with Downstream Accretion Element (DAE) in facies C_1. (b) Scalloped base of foresets within a bar in facies C_1 (bar length 10 cm). (c) Transverse section of a bar in facies C_1 displaying vertically accreted layers (one layer-interface highlighted, pen length 13 cm). (d) Adhesion laminae below and above the match stick (length 2.5 cm). (e) Translatent strata within facies C_1 (bar length 10 cm). (f) A complete channel-floor facies, C_4, unit (centre) bounded by concave-up base and nearly flat top, both well demarcated by thick ferruginous coats (dark): relics of similar coats in between cross-stratified beds indicate breaks in sedimentation.

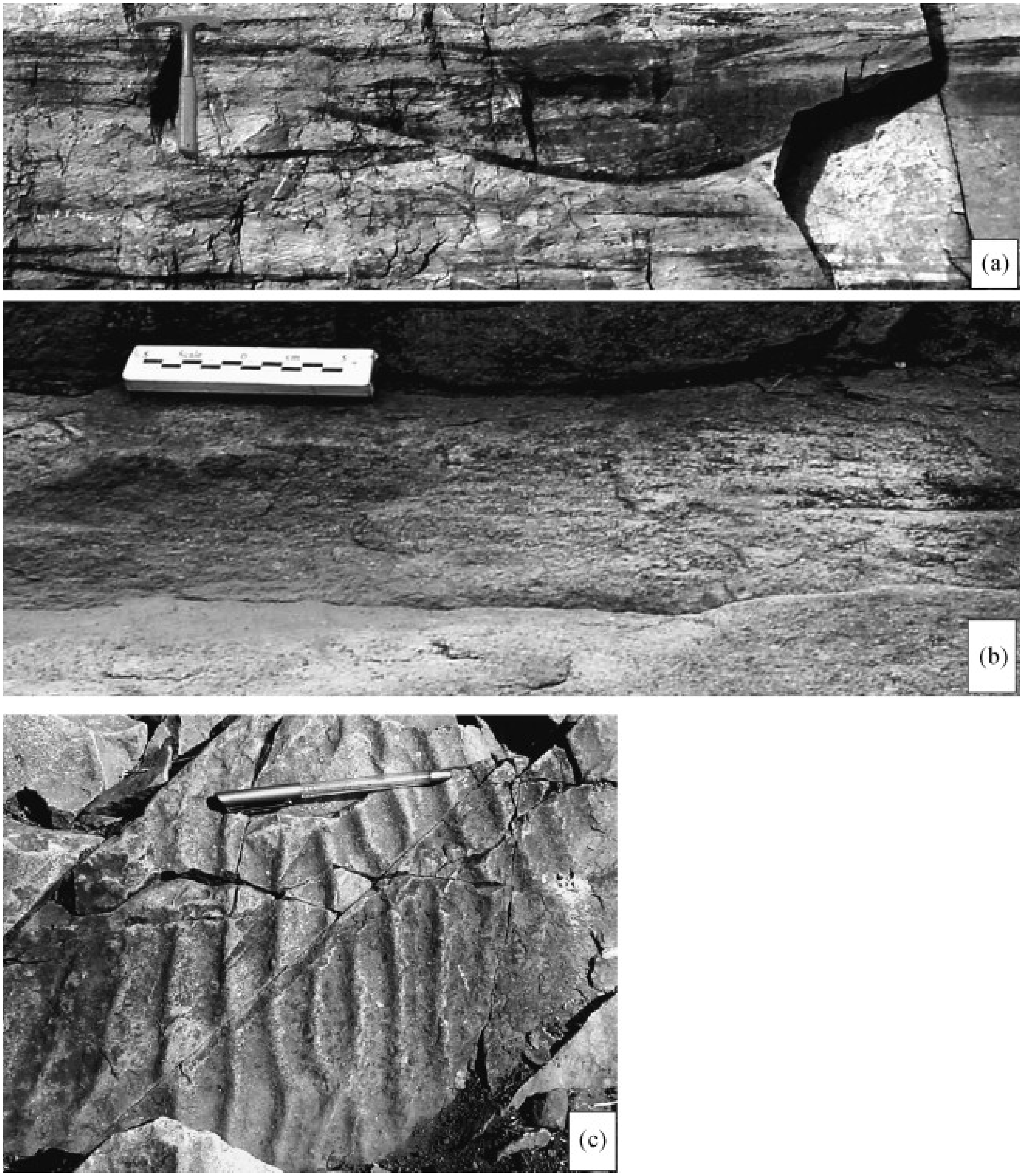


Fig. 4. (a) Small bar-top scour in facies D_1 at Ramthal. (b) Fine-grained planar laminae in facies D_2. (c) Wave ripples in transitional facies E at Salgundi (pen length13 cm).

The facies association A is the coarsest among all and is presumed to have been closest to the basin-margin. Its scree-breccias of inferred rock-fall origin possibly accumulated at the base of steep fault-scarps, generally delimiting the sedimentary basin. Various lens-shaped constituents of this association, including the scree juxtapose each other, laterally and vertically, giving rise to a facies mosaic. It locally incorporates isolated or clustered lenses of facies B. In turn, isolated lenses of association A's conglomeratic facies, comparatively finer grained, occur where sandy facies B or the association C dominates, presumably at some distance from the basin-margin. Facies association D and facies E are, however, completely free of A-type consituents and constitute the finest grade of sediment in the studied assemblage, and were possibly deposited farthest from the sediment entry points into the basin.

4. Facies architecture

Facies architecture at Ramthal and Salgundi was perceived on visual appreciation of both lateral and vertical transitions, but is framed here on the basis of measured vertical facies successions at three different spots in two of the field locations, moving successively downslope away from the basin-margin, along the river-flow direction, as much as the outcrops permit. The vertical sections are accordingly named below as ‘proximal’, ‘middle’ and ‘distal’ for these two field locations. At the Bilgi location, however, exposures only allowed erection of a single continuous synthetic vertical section, moving in the dip direction, up a gentle hill-slope.

4.1. Location 1, around Ramthal (Fig. 1 and Fig. 5)

Sections at both ends of the roughly downslope stretch of 200 m have the metasedimentary basement exposed underneath (Fig. 5).

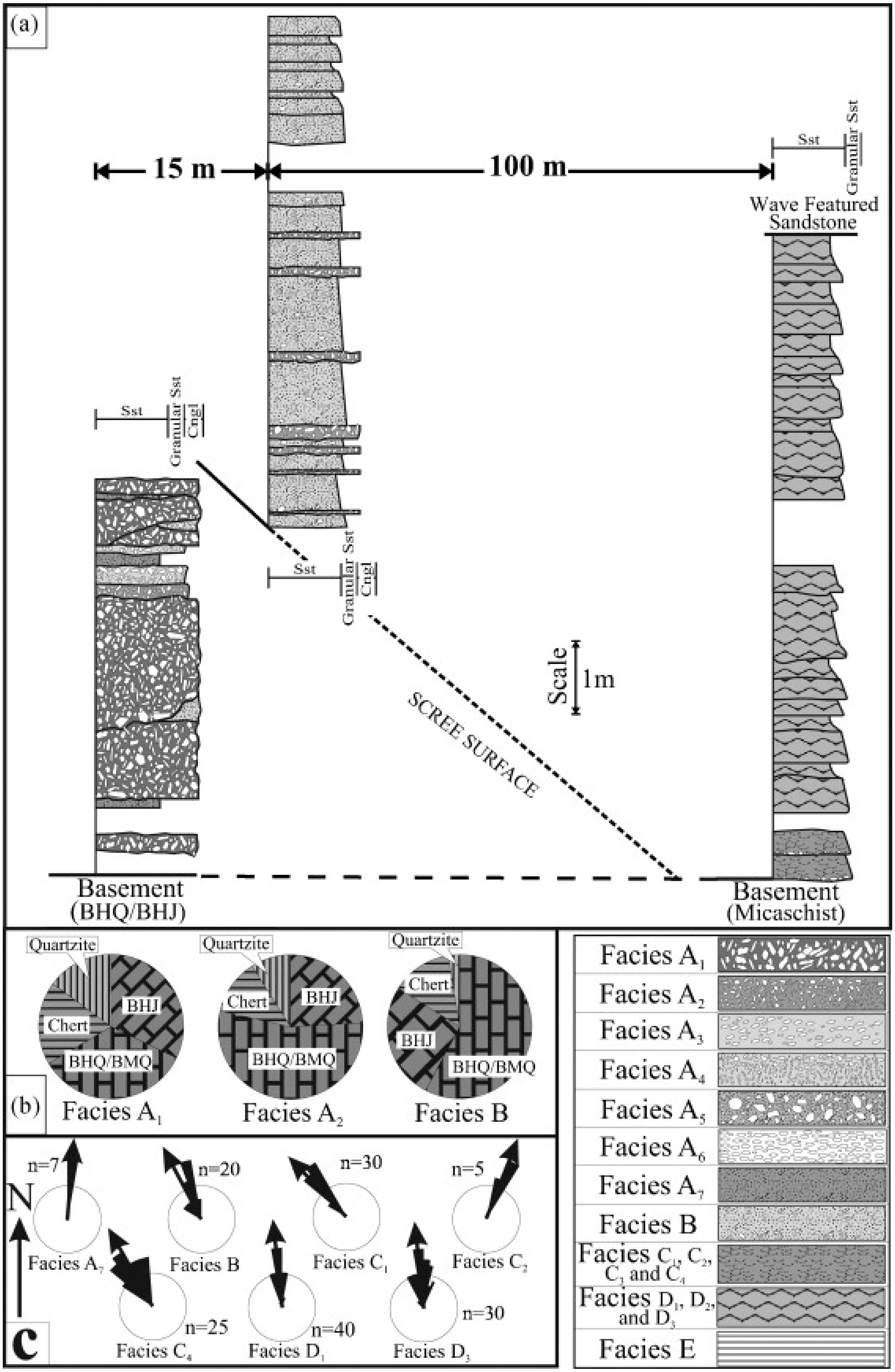

(a)
15 m
100 m
Sst
Granular Sst
Cngl
Wave Featured Sandstone
SCREE SURFACE
Scale
1m
Basement (BHQ/BHJ)
Basement (Micaschist)
(b)
Quartzite
Chert
BHJ
BHQ/BMQ
Facies A_1
Facies A_2
Facies B
c
N
n=7
Facies A_7
n=20
Facies B
n=30
Facies C_1
n=5
Facies C_2
n=25
Facies C_4
n=40
Facies D_1
n=30
Facies D_3
Facies A_1
Facies A_2
Facies A_3
Facies A_4
Facies A_5
Facies A_6
Facies A_7
Facies B
Facies C_1, C_2, C_3 and C_4
Facies D_1, D_2, and D_3
Facies E

Fig. 5. (a) Basin-margin facies distribution in three sections moving along dip direction from left to right at location Ramthal, with tentative reconstruction of the scree cone surface. (b) Clast composition in breccia and conglomerate of different origin. (c) Cross-strata azimuths in different sandy facies. Symbols used for the facies comprising the stratigraphic segments under focus in all three study locations are presented at the bottom right.

4.1.1. Proximal section

Five distinctive facies, viz., scree (A_1), debris-flow (A_2), modified grain-flow (A_4), hill wash (A_7) and streamlet facies (B) (Table 1) comprise this section, resting directly on BIF (Fig. 5a). All breccias and conglomerates are made up of clasts derived largely, if not entirely, from the immediate basement of iron formation (Fig. 5b). The scree breccia beds dominate by far, and are disparately thicker and coarser than any other conglomerate bed in the entire Bagalkot Group; they rapidly wedge out in the downcurrent direction. Trough cross-strata of facies A_7 and B have discrete orientations, but the former facies yielded only seven readings in a single bed (Fig. 5c). For both the cases, however, the orientation is remarkably consistent, irrespective of relative positions of the sections, proximal, middle or distal.

4.1.2. Middle section

This section, just 15 m downcurrent from the inferred proximal section rests, at least partially, on the scree breccia at its upcurrent or upslope margin. It is dominantly sandy, comprising two distinct facies, viz. the dominant streamlet facies (B) infrequently intervened by thin debris-flow facies A_2 (Fig. 5a). However, facies A_4 characterized by reverse grading, that is closely associated with facies A_2 in the proximal section, is absent in this medial section.

4.1.3. Distal section

This section, situated about 100 m away from the middle section in the depositional dip direction, is made up mostly of fluvial facies D_1, D_2 and D_3, except in a thin basal segment occupied by facies C_1 (Fig. 5a). The section rests directly on the basement rock, mica schist.

4.1.4. Interpretation

The proximal section at Ramthal suggests a base-of-slope scree cone deposit. Deep penetration of clasts into the sediment substratum rupturing many of its internal laminae, a general absence of matching, mutually fitting boundaries between adjacent clasts, the high angularity of the clasts, their derivation from the basement in the immediate vicinity together strongly support the inferred scree or rockfall (*sensu stricto*) origin of the dominant facies, A_1. Occasional mild rainfall-induced deposition is inferred from the interpreted hillwash facies (A_7) that covered the surfaces of instantaneously deposited scree beds. The presence of current-generated structures, though poorly preserved, indicates a relatively low density for the flows depositing A_7. However, the inferred debris-flow (A_2) and sheared mass flow ($A_{3)}$ deposits are interpreted to reflect high density, coarse-grained, rain-induced flows which occasionally turned viscous and deposited these facies. Higher particle concentrations in these mass-flows might have led to deposition of occasional modified grain flow deposits (A_4), The dominantly cross-stratified streamlet facies B, on the other hand, is ascribed to fluidal traction currents induced by heavy rainfall. The common presence of planar laminae on top of trough cross-strata within palaeochannel confinement in this facies, indicates late-stage sheet flow deposition (Olsen, 1989). Facies A_7 cross-strata, which maintain a very high degree of palaeocurrent consistency suggest a straight course for hill wash, presumably owing to the steep slope of the scree cone. Their high angle relationship with palaeocurrent trends in facies B, may suggest local slope control on the hill wash. Superproximal terrestrial palaeogeography, immediately adjacent to the basin-margin is implied for the facies assemblage of this section.

Facies B dominance in the middle section in the Ramthal field area suggests deposition mainly through a network of incised channels. The hillwash facies that is absent in this section apparently remained confined to the proximal site. Randomly scattered over-sized pebbles within many facies B channel-fill sandstones depict rapid deposition from high-velocity flash floods ([Frostick and Reid, 1989] and [Pfluger and Seilacher, 1991]). Debris-flows occasionally encroached upon this inferred ‘middle’ depositional site, but the modified grain flows (Facies A_4) also presumably froze on the scree cone itself because of rapid release of potential energy on the steep scree slope ([Campbell, 1989], [Campbell et al., 1995] and [Peakall et al., 2001]). Deposition apparently took place lower down on the scree cone. Up-section, interbedded debris-flow facies become progressively reduced in frequency, and facies B palaeo-channels become wider, the preserved width of channels increasing from 1.5 m, on average, in the preceding proximal section to 4 m in this middle section. Progressive slope reduction of the sedimentary cone is inferred. Facies B occurs, though only occasionally, in association with facies A_1, A_2, A_4 and A_7 in the proximal section at Ramthal, but there it tends to segregate from those four coarser grained facies implying deposition in a relatively distal palaeogeographic position.

Mass-flows as well as facies B apparently did not encroach upon the inferred distal site at Ramthal, and the pebble-free and thoroughly stratified fluvial facies D_1, D_2 and D_3 make up almost the entire section, with facies association C forming only a thin unit at its base. Decrease in grain size and fine stratification in the sandstone indicate rapid reduction in flow velocity and sedimentation rate, presumably on an alluvial plain fringing the scree cone. Palaeocurrent patterns inferred from troughs, large and small, in both the facies associations C and D still maintain a high consistency (Fig. 5c).

4.2. Location II, Salgundi Hill (Fig. 1 and Fig. 6)

4.2.1. Proximal section

This measured section is dominated by conglomerate and is upward-coarsening (Fig. 6a), its basal part being more sandy than conglomeratic. Clast composition is variable, indicating contribution to the sediment budget from both the plutonic and metasedimentary sources (Fig. 6b). Five pebbly facies, viz. inferred debris-flow (A_2); sieve (A_5), sheet conglomerate (A_6), streamlet (B) facies and very rare scree facies (A_1) (Table 1) constitute this section (Fig. 6a).

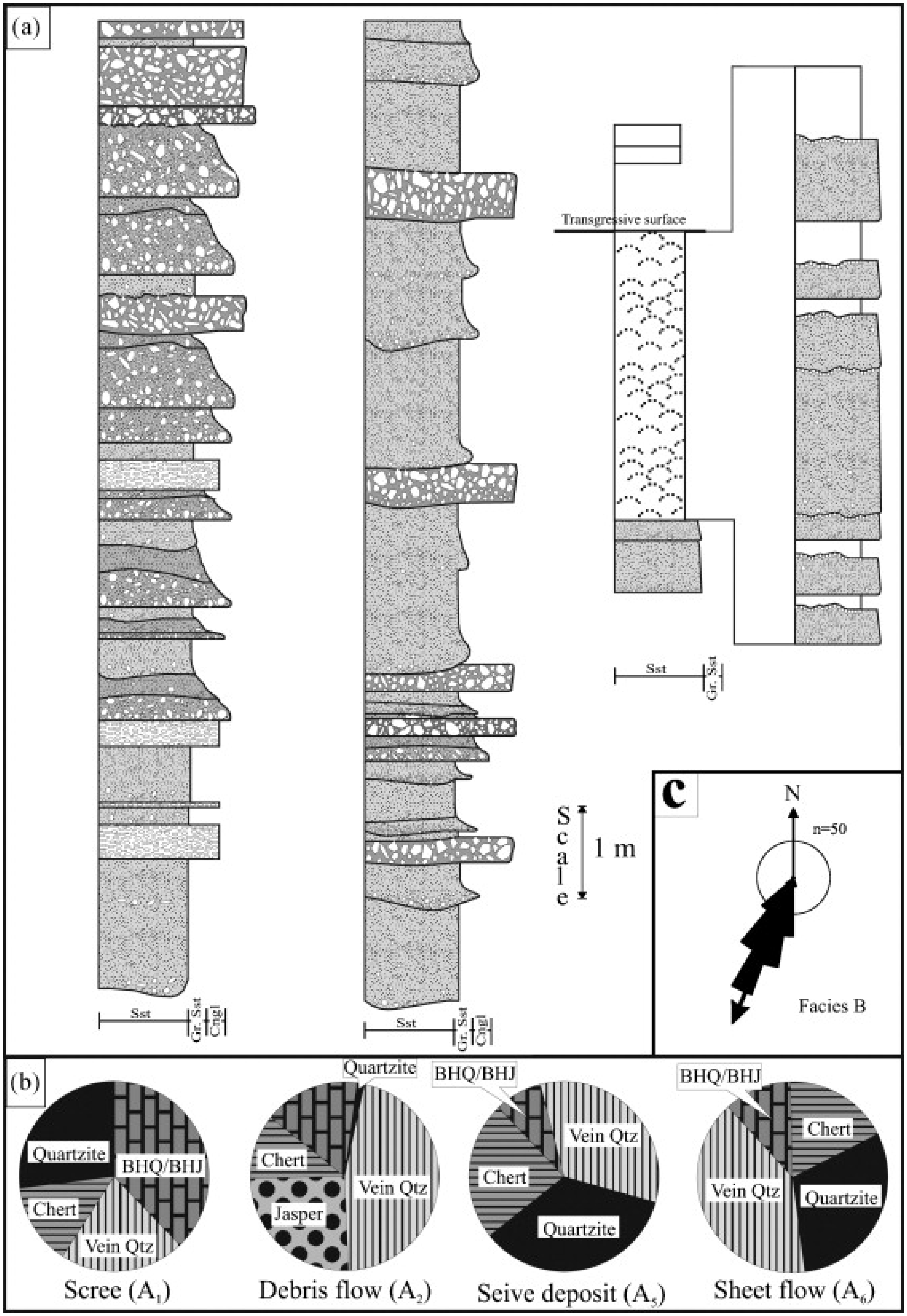

(a)
Transgressive surface
Sst
Gr. Sst
Cngl
Scale
1 m
c
N
n=50
Facies B
(b)
Quartzite
BHQ/BHJ
Chert
Vein Qtz
Jasper
Scree (A1)
Debris flow (A2)
Seive deposit (A5)
Sheet flow (A6)

Fig. 6. (a) Facies distribution in three sections moving in dip-parallel direction from left to right at location Salgundi (for symbols see **Fig. 5**). (b) Clast composition in conglomeratic facies of varied origins. (c) Cross-bedding azimuth in small channel facies (B).

4.2.2. Middle section

This section consists of three of the inferred proximal facies, viz. A_2, A_5 and B with rare occurrence of the sheared mass-flow conglomerate facies A_3 (Fig. 6a). Conglomerate beds thicken upward; however, amalgamated conglomerate beds, though rare, occur in the lower portion of the measured section. No significant segregation of any facies exists in any part of the section. Clast composition in conglomerates in this and the proximal section indicates that though the metasedimentary basement rocks contributed substantially to the sediment budget, a large share of vein quartz came possibly from the granitic basement (Fig. 6b)

4.2.3. Distal section

This section is made almost entirely of the sandy transitional facies (E) before passing upward into thick wave-featured sandstones deposited in the inferred standing body of water. Here this facies is made up of interbedding between thin facies B-equivalents (subfacies E_1) and the wave-featured component. A single 70 cm thick facies B unit, however, occurs at the base of this section and is terminated by a thin laterally extensive and well-sorted granule lag before passing upward into subfacies E_B (Fig. 6a). Facies associations C and D are altogether absent. The subfacies E_B unit overall fines upward with increasing dominance of relatively finer grained wave-featured sandstone. Orientation of cross-strata, combining readings from all the facies B units and B-equivalent units within subfacies E_B, irrespective of wide variability in their stratigraphic positions, is fairly consistent (Fig. 6c).

4.2.4. Interpretation

The profound coarsening-upward trend in the proximal section with increasing abundance of coarse-grained mass-flow products supports progradation of an alluvial fan formed in a semi-arid climate (cf. [Rust and Koster, 1984], [Nilsen, 1985] and [Blair and McPherson, 1994]). The basal part of the inferred proximal fan section is made entirely of facies B channeled sandstones and indicates deposition below the intersection point between the fan surface and the water table (e.g., [Heward, 1978] and [Talbot and Williams, 1979]). The immediately overlying assemblage, dominated by sieve (A_5) and sheet (A_6) facies with subordinate incorporation of streamlet (B) facies and rare debris-flow (A_2) facies, possibly formed immediately beneath the intersection point (cf. [Hooke and Le, 1967] and [Rahn, 1967]). However, it should be noted that sieve deposits typically occur in proximal fan regions or during early stages of fan growth, with sheet-flood deposits forming in either medial or lower fan segments depending on stage of fan development (see Blair and McPherson, 1994; their Figures 20–22). Thickness of this medial assemblage in the proximal measured section at Salgundi Hill of ca. 6 m can be attributed to movement of the water table up and down the fan, seasonally or in a longer cycle. In contrast, the debris-flow facies, along with a few units of sieve (A_5) facies, sheared mass flow (A_3) facies as well as streamlet (B) facies, dominates the topmost part of this measured section, made of the coarsest sedimentary rocks and had presumably been deposited above the intersection point and near the apex of the fan. The isolated minor facies B channels, floored by pebble lags which pinch out in the direction that the internal channel-fill cross-strata dip into, possibly reflect river channels well above the intersection point, disappearing rapidly because of water percolating downward through loose and coarse sediment, and also joints, fractures and other pore spaces in the basement rock to re-emerge only at the ‘intersection’ level. Occurrence of inferred scree deposits within this top part of the fan (Fig. 6a) suggests considerable relief generation and thereby implies tectonic uplift of the basement interrupting basin-filling.

In the inferred mid-fan section at Location II, Salgundi Hill, facies B dominates, whereas thin facies A_2 occurs locally, and facies A_5 is very rarely interbedded. Traction current dominance and rare extension of mass-flow lobes, presumably below the ‘intersection’ level is implied. The distal measured section at Salgundi Hill, on the other hand, has facies B only at its base, but is otherwise made up of subfacies E_B only, before passing upward into the thick wave-featured sandstone deposited in the standing body of water, whether lake or sea. Deposition at this site presumably took place well below the intersection point, at the distal fan fringe that was intermittently encroached upon by a standing body of water. The studied basin-margin sediment pile at the Salgundi location should, as a whole, better be called a combination of a fan and a fan-delta, and more specifically, a shallow water, shelf-type fan-delta (cf. [Nemec and Steel, 1984], [Massari and Colella, 1988], [Postma, 1990] and [Wescott and Ethridge, 1990]). Subfacies E_B at the distal section depicts pulsatory transgression of the standing body of water, and the granular lag at its base presumably formed when the standing body of water encroached upon the fan. Laterally discontinuous granular lags within the subfacies are possibly of wave-winnowing origin ([Clifton, 1973] and [Levell, 1980]).

4.3. Location III, Bilgi Hill (Fig. 1 and Fig. 7)

The single section measured here, moving up the steady gentle southern slope of Bilgi Hill, is conglomeratic in its basal 2 m only and sandy, but still carrying pebbles or grit almost throughout the rest of the section (Fig. 7a). While pebble population in the conglomerate is generally better sorted and the clasts are smaller at this location, the sandstone is almost always very poorly to moderately sorted. The majority of the pebbles appear to have been derived from the nearby granitic basement (Fig. 7b).

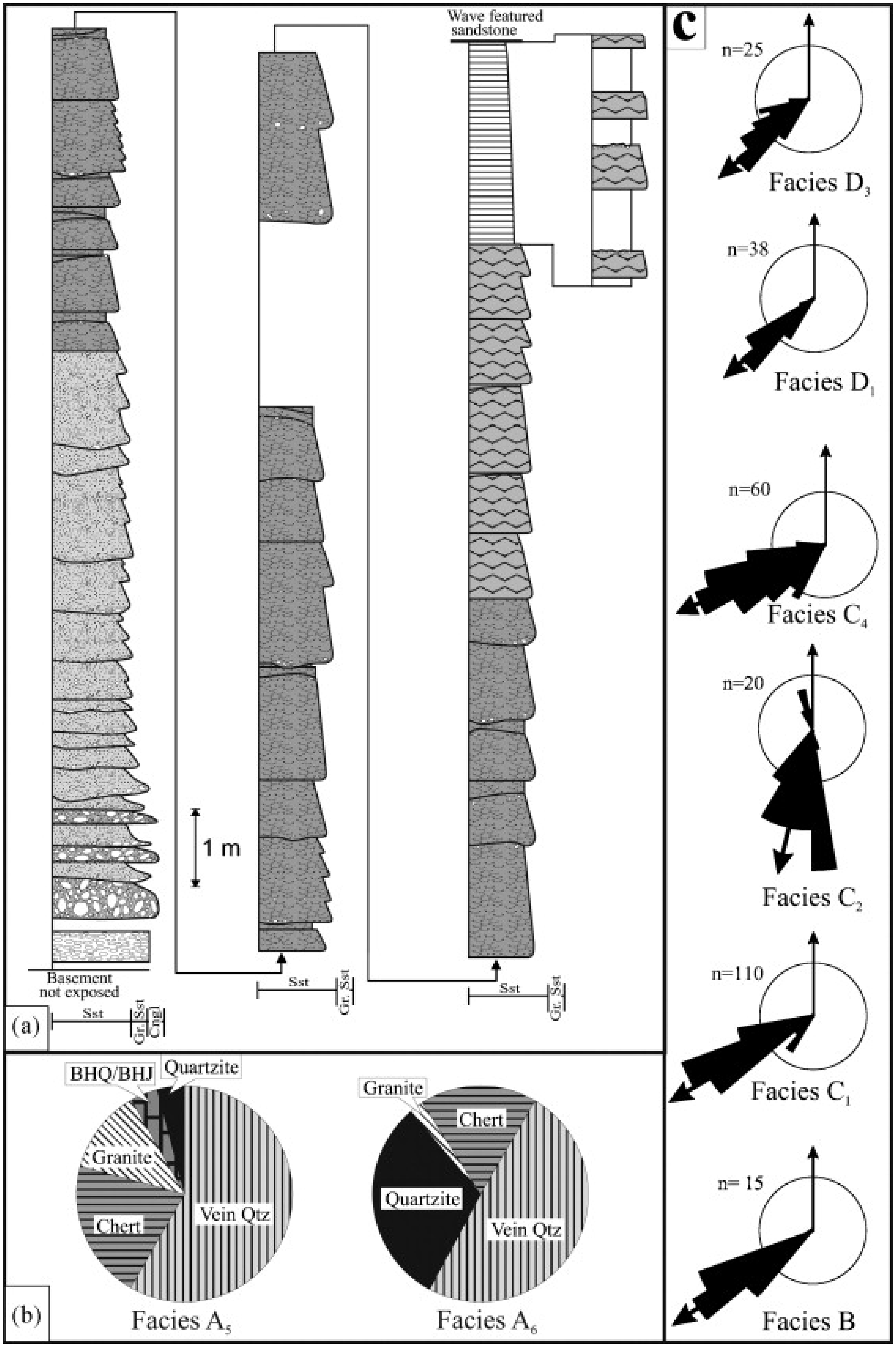

Wave featured sandstone
1 m
Basement not exposed
Sst
Gr, Sst
Cngl
(a)
Sst
Gr, Sst
Sst
Gr, Sst
BHQ/BHJ
Quartzite
Granite
Chert
Vein Qtz
Facies A5
Granite
Chert
Quartzite
Vein Qtz
Facies A6
(b)
c
n=25
Facies D3
n=38
Facies D1
n=60
Facies C4
n=20
Facies C2
n=110
Facies C1
n= 15
Facies B

Fig. 7. (a) Basin-margin facies distribution in Bilgi section (for symbols see **Fig. 5**), highlighting vertical variation in relative thickness between wave-featured sandstone and facies association D-equivalent within facies E. (b) Clast composition variation in conglomeratic facies and (c) facies-specific cross-strata azimuths are on right. Conglomeratic sieve (A_4) and sheet (A_6) facies dominate the basal part, while in the rest of the section the streamlet facies (B) is followed upward by facies association C, the latter enclosing the inferred aeolian patches (facies C_1). Facies association D that succeeds the facies association C is very thin, around 4 m. Further upward the transitional subfacies E_D dominates at the topmost part of the section, within which wave-featured beds thicken upwards at the cost of the former. The Bilgi section, as a whole, is fining-upward, even across the granule lag at the base of non-repetitive subfacies E_D. Orientation of large and small trough cross-strata within facies B, associations C, D and in the D-equivalent fluvial component within subfacies E_D is, once again, fairly consistent (Fig. 7c).

4.3.1. Interpretation

The conglomerates remaining almost entirely confined to the basal segment, the section most probably reflects the distal fringe of an alluvial fan, the proximal part of which, presumably, has not been preserved. Facies B and association C sandstones that overlie this conglomerate are interpreted as pebbly fluvial deposits, intervened by lenses of inferred high-velocity flash flood deposits. Deposition is thought to have taken place within a distal fan setting with a reasonable gradient. In contrast, the pebble-free fluvial facies association D, overlying facies association C, though thin, was perhaps deposited beyond the fan fringe and may represent fluvial deposition on an adjacent plain. Further upward in the succession, subfacies E_D records interfingering between the fluvial environment and the standing body of water. The granular lag at the base of this subfacies is a transgressive lag, as in case of $E_{B,}$ and the vein quartz and chert clasts in this lag were likely derived from the facies association C lying at shallow depth. A river course, though short, thus apparently separated the alluvial fan and the standing body of water.

5. Fluvial architectural elements and their packaging

Fluvial architectural elements (based on those described in Miall, 1996) in the studied stratigraphic interval of the Ramdurg Formation are described for the fluvial facies B and E (fluvial components) and facies associations C and D, and are interpreted in Table 2.

Table 2.

Fluvial archtectural elements

Architec-tural element	**Description**	**Interpretation**	**Facies constituents**
Downstream accretion element	Convex upward sandstone bodies, with or without granules and pebbles, internally characterized by large-scale trough cross-beds, confining smaller down-dip trough cross-strata while making angle lesser than 15° with bedding (**Fig. 3**a). Both large and small cross-strata dip in the same direction (**Fig. 8**a).	Inferred as bar. Ripples from stoss of the bar moved down its lee face when that turned gentler.	C_1, D_1 and E (low angle single set of cross-strata in E possibly the toe part of bar).
Lateral accretion Element	Inclined sheet of tabular cross-stratified sandstone free of granule or pebble. In up-dip direction the sheets, at places, found reclined on the flank of convex-up DA element bodies and LSE (described below) may overlie them (**Fig. 8**b). Cross-strata dip direction is at high angle	Accretion evidently took place at high angle to bar migration direction. Relationship with DA and LS identifies this element not as a bank-attached bedform, but as bar-flank accretion. Sand that was transported across the bar crest apparently avalanched	Facies C_3.

Architec-tural element	**Description**	**Interpretation**	**Facies constituents**
	to that of DA (**Fig. 5** and **Fig. 7**). Measured maximum vertical height of the element is 20 cm and outcrop length nearly a meter.	down the bar flank. Existence of a secondary flow is implied and it presumably became effective when the along-channel flow driving the bars declined.	
Laminated sand-sheet element	Thin sand sheets, may or may not be granule-rich, characterized internally by planar laminae and on bed-top by parting lineation. Overlies the preceding elements (**Fig. 8**c).	Formed during low flow stage reworking sediment already settled on top of DA and LA elements.	C_2 and D_2.
Small channel element	Sandstone, pebbly or not, lenticular in geometry. Internally characterized by cosets of small-scale trough cross-strata. Base generally concave-up, but convex upward when overlying isolated bodies of SB or SGF elements described below. Top generally flat. Maintain onlap or downlap relationship with DA and LA elements when associated. Maximum measured outcrop width exceeds 100 m along current direction and	Small channels. When associated with DA and LA considered as channel-floor deposit in between bars-related elements.	Facies B, C_4, D_3, E (cosets of small scale troughs)

Architectural element	**Description**	**Interpretation**	**Facies constituents**
	thickness <2 m.		
Sandy bedform element	Made of pebbly sandstone, characteristically having convex-up geometry and internal cross-strata, mostly crude. Pebbles tend to concentrate at the base and generally reclined on the crudely defined foresets. Outcrop width and vertical height of this element are 2 m and 40 cm respectively.	Rapid deposition of coarse clastics at high velocity traction current, possibly during flash floods, is implied.	Common in facies B and also incorporated as small isolated bodies within facies C_4.
Sediment gravity flow element	Pebbly sandstone, lenticular in shape, with discernible upward convexity at places and internally generally massive (**Fig. 8**d), but locally crudely cross-stratified. Pebbles are generally chaotically arranged.	Coarse clastic deposition from viscous flows, possibly during flash floods. Where cross-stratified, the flow turned relatively fluidal, presumably through sediment shedding.	Common within facies B and C_4 in form of isolated lenses rarely exceeding 5 m in width within B and 2 m in C_4.; vertical thickness does not exceed 80 cm.

The fluvial architectural element packaging pattern at the base of the Bagalkot Group is distinctly different for various stratigraphic units dominated by one or more of the inferred fluvial facies and facies associations. For example, facies B, where thick, appears as a mosaic of small channel elements without intervention of any master erosion surface. This package we call type I.

In contrast, facies associations C and D are distinctly divided into multiple architectural element packages, each bounded below and above by laterally persistent master erosion surfaces with distinct iron-oxide coating, unless eroded out. Each of the packages associated with facies association C is constituted by rows, up to three stacked one above another, of bar-related elements, viz. downstream accretion element, lateral accretion element and laminated sand-sheet element, and small channel elements intervening between them as well as infrequently occurring sandy bed-form elements and sediment gravity flow elements. These packages are <7 m thick, roughly tabular in geometry, their bounding surfaces being undulated with incisions often as deep as 0.5 m (type II) and stacked one above another.

On the other hand, packages within facies association D are thinner, <5 m, and sheet-like, with little scouring at base not exceeding 5 cm in depth (type III). Each of them is constituted only by downstream accretion elements, laminated sand-sheet elements and small channel elements. These packages, in both the facies associations C and D are comparable with the channel-belts of Holbrook (2001).

In type IV, typifying the facies E of the Ramdurg Formation, fluvial beds or bedsets are packaged with marine or lacustrine beds or bedsets, and within the latter the channel elements and bar elements remain laterally juxtaposed. The low angle cross-sets possibly represent toes of largely eroded downstream accretion elements and the laterally adjacent cosets of small troughs constitute the small channel elements between them, as in package type III, with the exception that laminated sand-sheet elements are absent.
Lack of master erosion surfaces in package type I is a possible consequence of channel incisions being too frequent and too close to each other. The package pattern that is a hallmark of facies B units suggests formation of a network of interconnected channels, a braided pattern. Omission surfaces conspicuously coated by iron-oxide, often partially eroded, within single channel-fills indicate rapid abandonment and reoccupation of channels (Fig. 3f). So do local occurrences of hydroplastic deformation of cross-beds, resulting in overturning (Fig. 8e). The frequent presence of massive or crudely stratified flash flood deposits incorporating randomly over-sized pebbles further corroborates a

highly unsteady nature of the flow. Low flow regime bedforms passing upward into high flow regime planar laminae without any discernible decrease in sediment grain-size also points to sheet flow generation for draining out of water from the ephemeral channels (cf., Olsen, 1989).

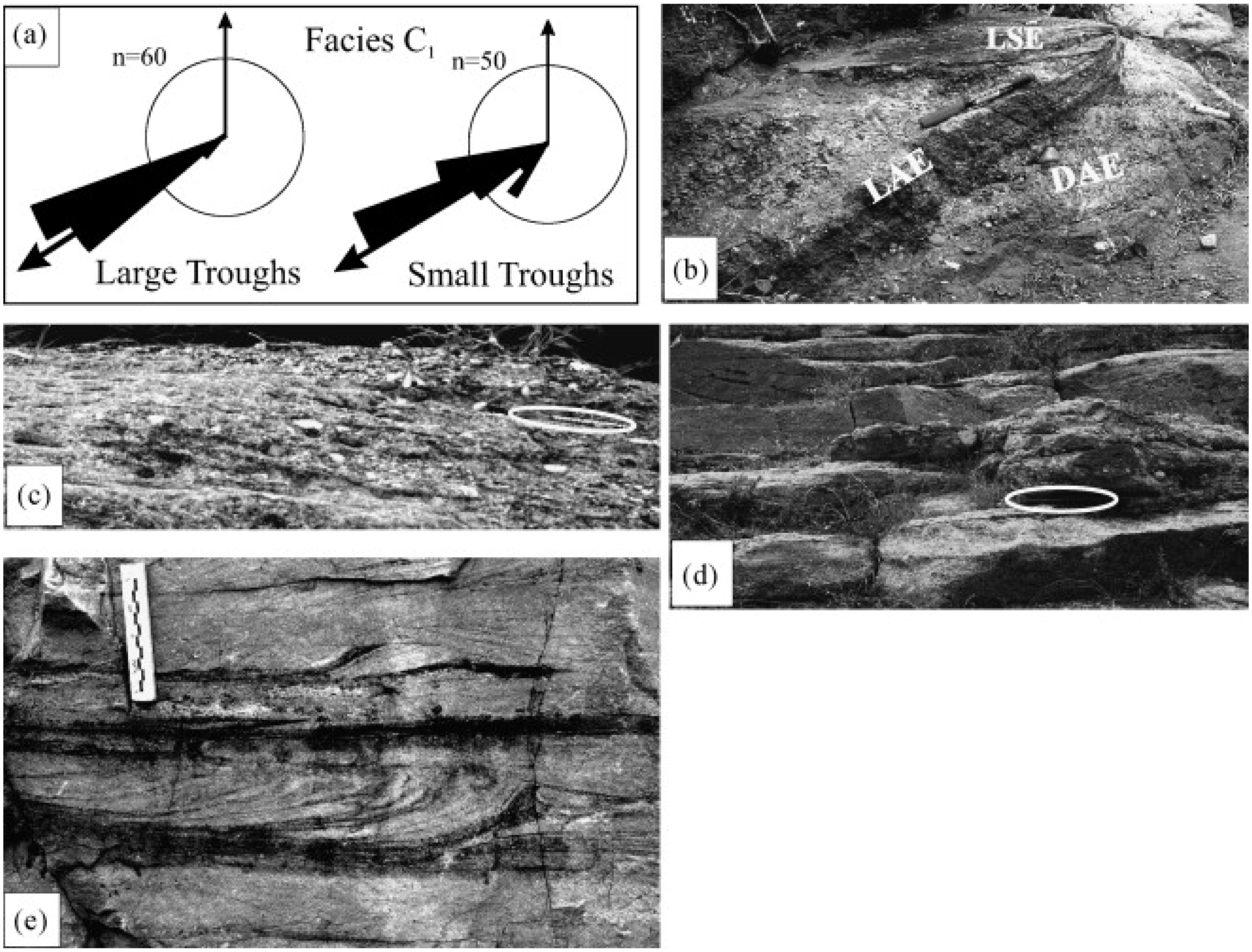


Fig. 8. (a) Similar orientations of small and large troughs within facies C_1 at Bilgi. (b) Lateral Accretion Element (LAE) in relation to DAE and LSE within facies association C (pen length 14 cm). (c) Laminated Sand Sheet Element (LSE, granule-rich) on top of a facies C_1 (pen length 13 cm) deposit. (d) Convex-up body of a sediment gravity-flow element of flash-flood origin, encased within facies association C at Bilgi. Hammer for scale, encircled. (e) Overturned cross-strata in type I fluvial package.

Unsteadiness of water flow, possibly to a lesser extent, is also reflected in the distinctly scoured bases of the type II packages, stacked vertically one on top of the other. Scalloped bases of large-scale foresets also depict directional variability of the flow driving the bars in the downstream direction ([Rubin, 1987] and [Sarkar et al., 1999]). The bar-attached lateral accretion element further indicates existence of a secondary flow component that possibly gained importance in sediment transport with dwindling of the along-channel component. Local incorporation of sediment gravity-flow elements and pebble-bearing sandy bedform elements also subscribes to flow variability, albeit at a larger scale and over longer intervals. Local preservation of aeolian features, like adhesion laminae and translatent strata on bar flanks, within packages of type II further supports a considerable amount of water depth fluctuation within the channels.

Downstream accretion elements and small channel elements both commonly rest on the type II package boundaries, transiting laterally one to the other. The laminated sand-sheet element, on the other hand, generally underlies the package boundaries and overlies the downstream accretion as well as the lateral accretion elements. All three of these elements are bar-related, but separate status for each of them is supported by their different geometries and manifestation of different flow conditions and stages. The bars represented by the downstream accretion element, passing laterally into small channel elements or the lateral accretion elements were thus apparently mid-channel bars, and depict a braided pattern of the river (cf., Holbrook et al., 2006). The inter-relationship between the bar-related elements and small channel elements is onlapping and downlapping. The latter being more common, small channel elements are generally thinner than the downstream or lateral accretion elements, laterally adjacent to or overlying them. Locally occurring sediment gravity flow and sandy bedform elements, generally resting on the package boundaries and overlain by small channel elements, probably formed when vigorous flash floods extended to the relatively distal depositional palaeogeography of the facies association C (Fig. 8d). Every package of type II, bounded below and above by undulated master erosion surfaces, likely represents individual wide channel-belts aggraded one above the other (Holbrook, 2001). The channels were probably semiperennial, never becoming completely dry, although occurrence of minor aeolian features immediately under the package boundaries indicates emergence of bar-tops above the water surface. This contention vindicates the idea of Tirsgaard and Øxnevad (1998) that preservation of aeolian imprints within river channel deposits is best ensured if the river channels are semiperennial in nature. Lack of basal scours and absence of scallop-based foresets, in package III, constituted by a set of downstream accretion elements, laminated sand-sheet elements and small channel elements, in contrast, testify to a nearly stable flow character. Planar laminae and small scours at bar-tops indicate only a limited scale of flow unsteadiness at the end of the channel-filling process. The limited variation in grain-size between various elements constituting package III also corroborates this contention. The channels in this case thus appear to be perennial. Considering all aspects, the river channels appear to have been shallower and wider with respect to those represented in package II, the velocity of the flow declining consequently.

Type IV packages characterize facies E and reflect a coupling of a relatively coarser fluvial sandstone unit, followed upward by a finer and distinctly better sorted marine or lacustrine sandstone unit, representing transgression of the standing body of water. The contact between the two components (coarser and finer) is often demarcated by a granular wave winnowed lag in subfacies E_B. Depletion in thickness of the finer component up the facies E packages speaks for overall transgression with a fluctuating rate. The small scale cross-strata within the fluvial units are possibly minor erosional remnants of mid-channel bars with small channels between them. The channels, at the sea or lake margin, had possibly been mostly perennial.

Despite the palaeogeography-related variation in architectural element packaging pattern, the fluvial channels were apparently universally braided. The complete absence of flood-plain deposits and the location-specific consistent channel-flow direction further corroborate this contention (cf., [Cant, 1978] and [Cant and Walker, 1978]). This braiding of rivers, notwithstanding other significant differences in their nature, is perfectly consistent with the Precambrian depositional setting (e.g., Long, 2004).

6. Discussion

6.1. Basin-margin configuration

The Bagalkot basin-margin is interpreted to have been steep at all three of the locations where the Salgundi Conglomerate is exposed along with the pebbly and granular basal part of the Saundatti Quartzite. The margin is inferred to have been steepest at Ramthal at the easternmost end of the studied stretch; the base-of-slope clastic sedimentary rocks are coarsest there out of the three study locations, and accumulated dominantly through free-fall processes. The vertical stack of scree deposits points to frequent tectonic activity, repeatedly creating slopes steeper than the angle-of-repose. Although deposits of such superproximal scree cone affinity are absent at the other two Ramthal sections, viz. the medial and distal sections, the rapid downslope transition of the scree cone deposits to inferred fluvial package III deposits on the plains, with short intervention of package I and negligible occurrence of package II deposits, makes the steepness of the basin-margin apparent.

At the Salgundi measured sections, in contrast, conglomerate dominantly of mass-flow origin gives way downslope to a huge stretch of package I, omitting package II and III deposits completely. It is apparent that the network of rapidly avulsing streamlets debouched directly into the standing body of water. Their channel deposits at Salgundi clearly maintain their high-slope character even at the distal end of the inferred fan, but no sharp slope break was discerned, as had been evident at Ramthal. Dominance of mass-flow and traction current deposits, however, indicates a depositional slope generally below that of the angle-of-repose. The occurrence of scree deposits, although rare, well above the base of the succession, however, indicates occasional uplift of basement blocks. Nonetheless, tectonic activity was not apparently as frequent as it had been at Ramthal and the palaeoslope was, more or less, constant.

At the Bilgi field site, where only the distal fringe of an inferred fan is present, package I is poorly developed, but scour-based wide channel belts of package II affinity drained the site. Conglomerate, mostly restricted to the base of the studied section, represents a dominantly traction deposit. The surface of the Bilgi fan, at least at its distal part, with thinner and still wider channel belts, thus appears to have been even gentler than that of the Salgundi fan and there is no evidence of syndepositional tectonism. Away from Ramthal and towards Bilgi, intensity of tectonic activity became reduced.

6.2. Bedrock composition vs. tectonic control

Analysis of successive measured sections down the slope of the preserved alluvial sedimentary cones emphasizes spatial rather than temporal variation, except at Bilgi. Altogether, the seven individual sections studied herein amply illustrate lateral changes in the nature and organization of sediment during the earliest development phase of the Ramdurg Formation, both in dip-parallel and normal directions. Little change in palaeoclimate along the Bagalkot basin margin is expected along the studied stretch, which is only 47 km long. Prominent Fe-oxide coating as found on top of facies B channels, is present also on most of the contact surfaces between vertically stacked fluvial channel belt deposits in packages II and III, irrespective of palaeogeographic variability implied between them, and this suggests no significant change in the semi-arid climate conducive for mass-flow dominated coarse clastic alluvial fans, either in time, or the space encompassed by the studied stratigraphic segment. In this inferred uniform palaeoclimatic background, bedrock composition could have assumed an enhanced role in determining basin-margin slope and the nature of deposits upon it. Bedrock composition does, indeed, change along the studied stretch significantly. A metasedimentary source contributed dominantly in the southeastern sector, at Ramthal; and the granitic basement contributed most sediment to the westernmost sector, Bilgi; both the sources made comparable contributions at Salgundi, roughly in the middle (Fig. 1a).

Hooke and Le (1967), Bull (1972) and Blair and McPherson (1994) have discussed the potential importance of bedrock for fan deposition, while Blair (1999) and Nichols and Thompson (2005) have demonstrated clearly that bedrock composition does influence basin-margin deposition. Along the margin of the Bagalkot basin, as indicated earlier, the steepest slope was generated in association with the metasedimentary basement, while the crystalline basement gave rise to relatively gentler slopes. This scenario is not likely to arise where bedrock composition held the commanding role. The closely jointed and well-laminated metasedimentary source that delivered the blocky or rectangular clasts of the scree facies at Ramthal should have been more rapidly weathered than the crystalline source at Bilgi. The basin-margin at Ramthal should have been gentler in that case and the concomitant lower bed load: suspension load ratio in the sediment budget should have encouraged more sediment gravity-flow deposits (cf. Nichols and Thompson, 2005). Contrary to this expectation sediment gravity-flow products are relatively subordinate in occurrence at Ramthal. It thus seems plausible that the basin-margin was held at a steeper slope than the angle-of-repose for a considerable period of time as a direct consequence of syndepositional tectonics and, in turn, this affected the nature of the coarse immature sediment at the base of the Bagalkot Group. From this point of view, between the three studied locations, Ramthal was presumably tectonically most active. Like scree deposits at different stratigraphic levels, overturned cross-bedding in the fluvial deposits, formed apparently both on hill slopes (package I) and on plains (package III), also corroborates tectonic disturbance, though not unequivocally (cf., Allen and Narayan, 1964). The inferred scree facies has been encountered at Salgundi also, albeit rarely, but not at all at Bilgi.

6.3. Control on flow duration

Flow duration in an alluvial channel depends on sustainability of water source and position of channel with respect to the water table. Rates of snow-melting and rainfall, in general, determine the sustainability of the source, climate being the ultimate arbitrator. On the other hand, tectonics, primarily designing the topography, combines with climate to control the position of the water table, except where sea level fluctuation also plays an important role. The apparent variation in river-flow durability in the basinward direction at the Bagalkot basin-margin was probably controlled mainly by seasonal water table fluctuation, accentuated substantially in a semi-arid climate, which was generally dry, but with heavy seasonal rainfall and in complete absence of vegetated soil that holds water. The observed association with sieve conglomerates evinces water percolating down rapidly from channels in package I at the fan apex, the more rapidly incising channels consuming most of the water, leaving the shallower ones high and dry. The infiltrated water understandably re-emerged at the ‘intersection’ level. Low water discharge close to the ‘intersection’ level because of low hydrographic pressure in connivance with semi-arid climate also encouraged the ephemeral nature of the package I channels. Enhanced hydrographic pressure in a downslope direction ensured increasing sustainability of flow, semiperennial for package II and perennial for package III channels. Sustainability of flow down a hill slope and adjacent plains commonly changes with position of the channels with respect to the ‘intersection’ level, without any major change in climate. In the basal Ramdurg deposits, the semi-arid climate and complete absence of vegetated soil presumably accentuated the effect.

Package thickness variation between types II and III indicates downslope shallowing and perhaps also broadening of the channels of the Ramdurg rivers. The flows turned increasingly steady and weaker with loss of slope gradient. The inferred rapid change in gradient across the scree cone margin can be held responsible for omission of the fluvial package II at Ramthal. On the other hand, poor development of package I at Bilgi is attributable to the relatively low overall slope gradient. One can assume a gradient less than that of the Ramthal scree cone and more than that of the Bilgi fan for the fan–delta interpreted at Salgundi, where package I was deposited in substantial quantities, with complete absence of packages II and III. This assumption is consistent with the previous observation that tectonic activity was most intense at Ramthal and declined progressively away from there. The basin-margin was closest to the standing body of water where it was steepest, and farthest removed where it was at its most gentle (Fig. 9). In accordance with this suggestion, the transitional facies, E, is altogether absent at Ramthal and achieved its maximum preserved thickness at Bilgi (compare Fig. 5, Fig. 6 and Fig. 7). Tectonics thus appears to have been the prime factor in determining palaeogeomorphology and fluvial facies characteristics along the studied stretch of the Bagalkot basin-margin.

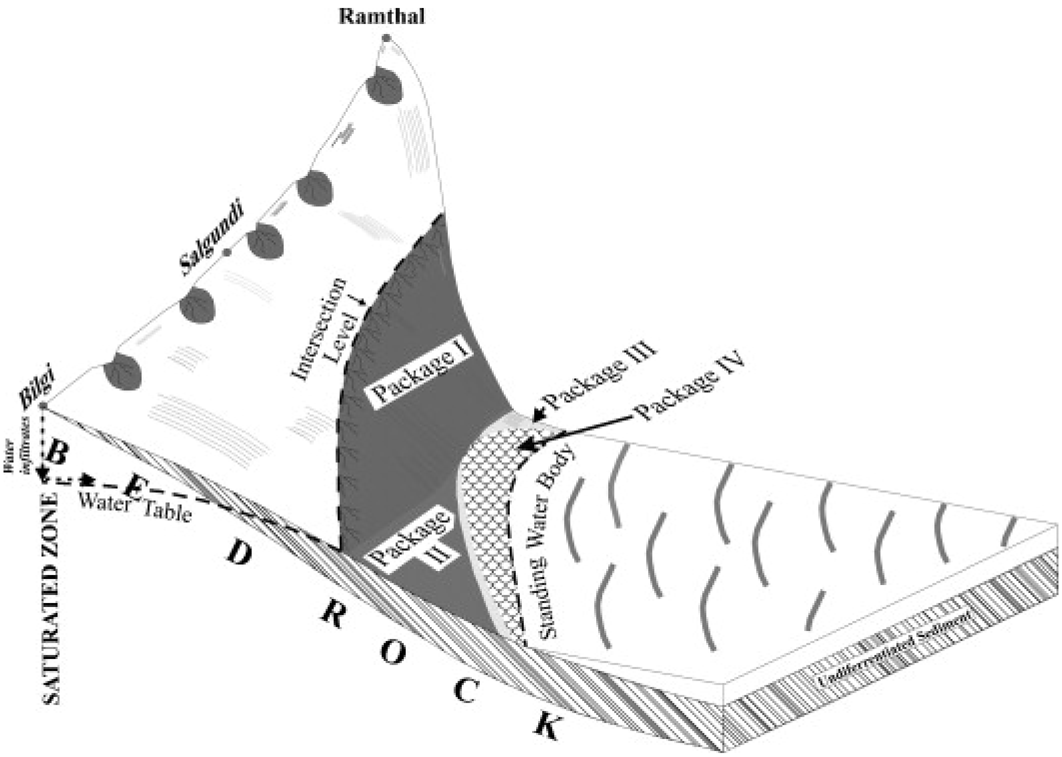


Fig. 9. Cartoon depicting spatial distribution of fluvial packages Type I, II and III, shown only in reference to the water table and postulating slope control on distance of the standing water body from the basin-margin.

6.4. Base profile change

The Ramdurg Formation, as a whole, is fining-upward having coarser clastics at its base and argillites at the top; the latter, with carbonate rocks, constitute the next younger Formation, Yargatti, entirely. Its studied basal segment is interrupted near the top by a granular lag, upon which rests the non-repetitive facies E that is again upward-fining within itself, gradually losing fluvial deposits. Facies E is, therefore, a part of a transgressive systems tract (TST) that continues further upward. The stratigraphic segment underlying the lag and resting on an unconformity is interpreted as a lowstand systems tract (LST) (Fig. 1b). Progradation in the LST is most pronounced in the Salgundi Conglomerate Member in the proximal section at the Salgundi field location (Fig. 6a). The fluvial succession of the Saundatti Quartzite, overlying the Salgundi Conglomerate, suggests channel aggradation, presumably as a result of slow rise of river base profile (cf., Blum and Tornqvist, 2000). Its fining-upward trend and onlapping of distal facies on proximal facies is attributable to loss of slope gradient through the aggradation (cf., Catuneanu, 2006).

As the standing body of water transgressed, it eventually drowned the alluvial sedimentary cones. This passage appears to have been most rapid at Ramthal, as evinced by the total absence of the transitional facies E. At Salgundi, the transitional facies is present, but only in the form of subfacies E_B. In contrast, at Bilgi, subfacies E_D substitutes for the former subfacies, rendering the slowest transgressive transition. This observation may at first appear antithetic to the perception that transgressions and regressions should be more rapid on gentler slopes, but actually reflects the better development of transgressive–regressive tongues on a slope in response to fluctuating rates of overall transgression before the final drowning of the basin-margin. Apparently, tectonically-induced basin-margin slope gradient was the dominant control on the nature of the fluvial-marine/lacustrine transition in the study area as well.

7. Conclusions

A scree cone, a fan-delta and an alluvial fan characterised the eastern sector of the Mesoproterozoic Bagalkot basin-margin, India. In a semi-arid climate, the rivers evolved from ephemeral to perennial, through semi-perennial, down the basin-margin slope. Wide seasonal fluctuation of the water table under a semi-arid climate and complete absence of vegetated soil was mainly responsible for this change in flow durability. Irrespective of the wide variability in flow duration within them, the channels always had a braided pattern, as can be predicted for Precambrian alluvial systems in general.

The basal segment of the Ramdurg Formation under focus here, is a product of base-level lowstand. In consequence, the proximal fan is profoundly progradational, though the distal fluvial succession is aggradational owing to progressive loss of the depositional slope gradient. A standing body of water subsequently transgressed upon the fan complex. Short-scale transgressions and regressions at the transition between the basal lowstand and the younger transgressive systems tract are best recorded where the tectonics-induced slope was comparatively gentle, being farthest from the most active part of the basin margin. Tectonics-related basin-margin gradient played the commanding role in determining the depositional strike- and dip-parallel variations in mode of sediment transport and deposition, drainage pattern and sequence architecture, especially fluvial, against the backdrop of a rise in base-profile, which was initially slow, but became enhanced later.

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Corresponding author. Fax.: +91 33 2414 6781.