Neoproterozoic tsunamiite : Upper Bhander Sandstone, Central India

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abstract

This paper addresses a distinctive event bedset encased by coastal erg-margin deposits, at a preferred stratigraphic level near the base of the Neoproterozoic Upper Bhander Sandstone in central India. The bedset is composed of couplets of sandstone beds that exhibit incisive amalgamation although they differ in geometry, structures (at soles, within and at tops of beds), vertical grain-size variation as well as palaeocurrent pattern and direction. The wide extent of the bedset is evident from several exposures spread over a distance of more than 50 km roughly in strike-parallel direction. Flow and depositional dynamics interpreted from the coupled event beds are more consistent with a tsunami origin than alternative palaeogeography-compatible models of climate-induced storm, flash flood or accentuated tide deposits. A palaeotsunamiite model is thus discussed, with separate incoming and outgoing components. Considering the overall depositional setting to be an epeiric sea coast in an intracratonic sag basin, the relevant bedset is inferred to reflect the record of a teletsunamiite; it would also be one of the very few Precambrian tsunamiites known so far. Exceptional preservation of this possible tsunamiite was facilitated by sheltered deposition behind the backshore zone and the berm, as well as by rapid burial by wind-deflated sands and advancing aeolian dunes.

Keywords:
Palaeotsunamiite
Run-up product
Draw-down product
Flow dynamics
Upper Bhander Sandstone
Intracratonic sag

1. Introduction

Although they should have been commonplace in the geological record, the pre-Quaternary examples of tsunamiites are extremely poor (Dawson and Stewart, 2007). Low preservation potential may be a reason (Liew et al., 2008), but the difficulty in distinguishing their records from those of other catastrophic or ultra-high energy marine events is perhaps of greater relevance (Pratt, 2002; Morton et al., 2007; Pratt and Bordonaro, 2007; Dawson and Stewart, 2008). Tsunamiites are complete mismatches or incongruences in their respective associations, but so also are the products of other catastrophic events, such as, storm, flash flood, earthquake, etc. (Fujiwara and Kamataki, 2008). Their internal features are not exclusive, but are shared with beds of other event or even non-event origins, and their deposits are also variable in character (Shiki et al., 2008). Varied mechanisms, such as deep-sea earthquake, meteorite impact, volcanism and giant marine slides, have the potential to generate tsunamis; overall, very shallow long period waves are generated. Whatever their root cause, tsunamis are always accompanied by ground seiches and therefore, an association of potential seismic evidence does not necessarily warrant a tsunamiite interpretation.

The marked geological, environmental and even social significance of tsunamiites (Dawson and Shi, 2000; Peters et al., 2007) is amply highlighted by the widespread effects of the deep-sea earthquake-induced 2004 tsunami in the Indian Ocean (Borrero, 2005; Goto et al., 2008), as well as by the purportedly meteorite impact-related tsunami at the K-T boundary (Bourgeois et al., 1988; Albertão and Martins, 1996; Tada et al., 2002). Their widespread impact notwithstanding, palaeotsunamiites generally lack an extended lateral continuity because reworking is the rule rather than the exception in the shallow water regions where the direct tsunami influence on sedimentation pattern and deposition is felt (Weiss and Bahlburg, 2006; Shiki et al., 2008 and references therein). The failure to recognise ancient tsunamiites, nonetheless, means a major loss of geological information; in the case of fossil-free tsunamiites, especially in sand grade sediment, the identification problem becomes further compounded (Scheffers, 2008).

The possible tsunamiite bedset addressed here from the basal part of the prograding Upper Bhander Sandstone, central India (Fig. 1A and B) is sandy and, being Neoproterozoic in age (~600 My; Ray, 2006) is also free of shelly fossils (cf, Hassler et al., 2000; Pratt, 2001). Its suite of sedimentary features, structural and textural, strongly suggests tumultuous or ‘convulsive deposition’ (Clifton, 1988) and erosion, and reflects a depositional condition drastically different from that of all other beds of the Upper Bhander Sandstone; flow and depositional dynamics inferred from this bedset seem to be more in accord with a tsunami interpretation than any other high energy natural event that is palaeogeographically compatible. A

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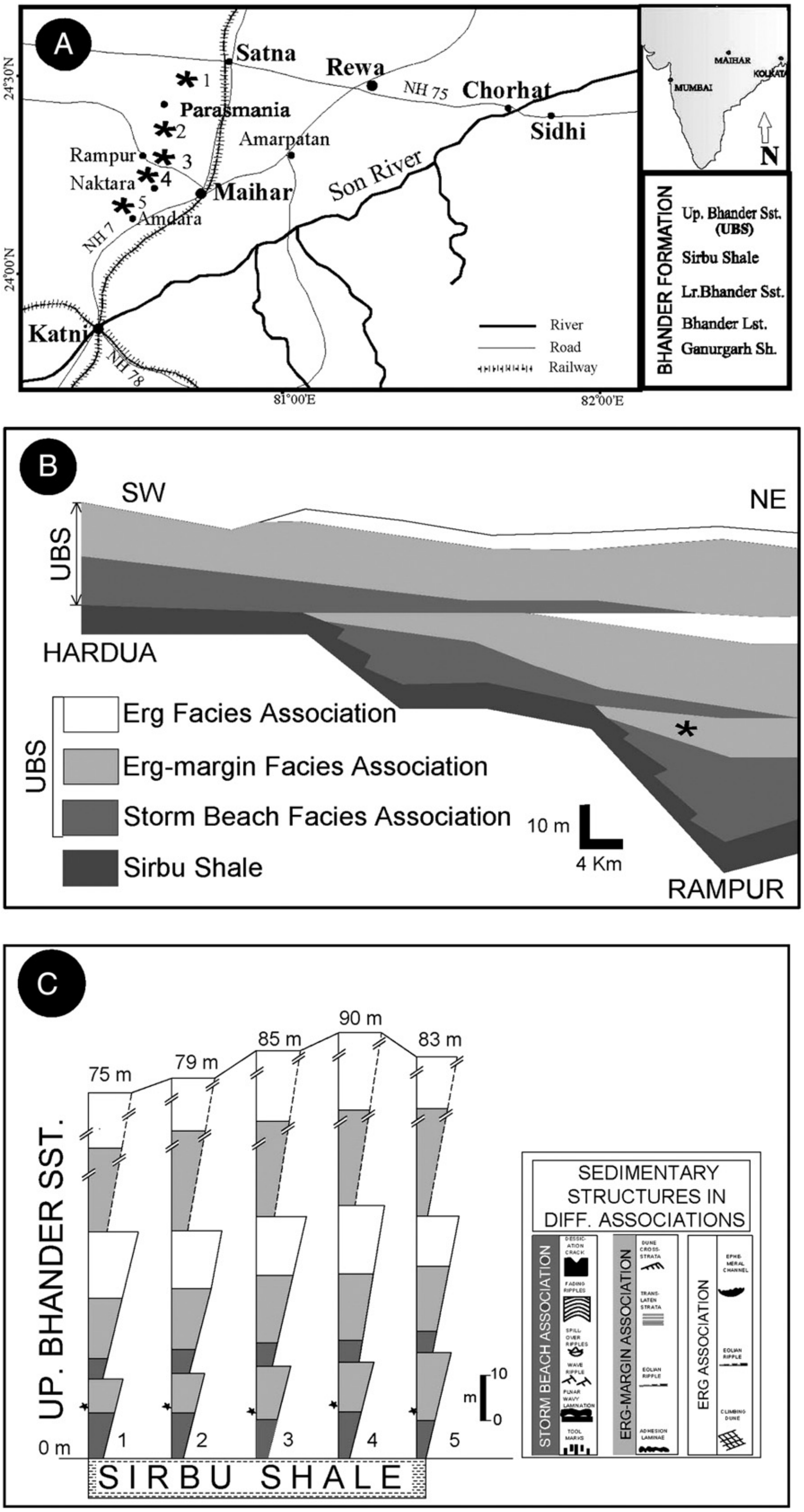

Fig. 1. Regional and geological backgrounds (* indicates location of the bedset under consideration): (A) location map with exposures of the Upper Bhander Sandstone bedset addressed (map of India and stratigraphic subdivisions of the Bhander Formation within inset), (B) Profile roughly in depositional dip direction showing distribution of facies associations constituting the Upper Bhander Sandstone (UBS) that overlies the Sirbu Shale (level of the concerned bedset marked *), (C) Logs at the locations marked in (A) depicting vertical distribution of the facies associations that constitute the Upper Bhander Sandstone, illustrating the two basal drying- upward parasequence sets bounded below and above by major marine flooding surfaces. Characteristic primary sedimentary structures of the facies associations are presented within the inset.

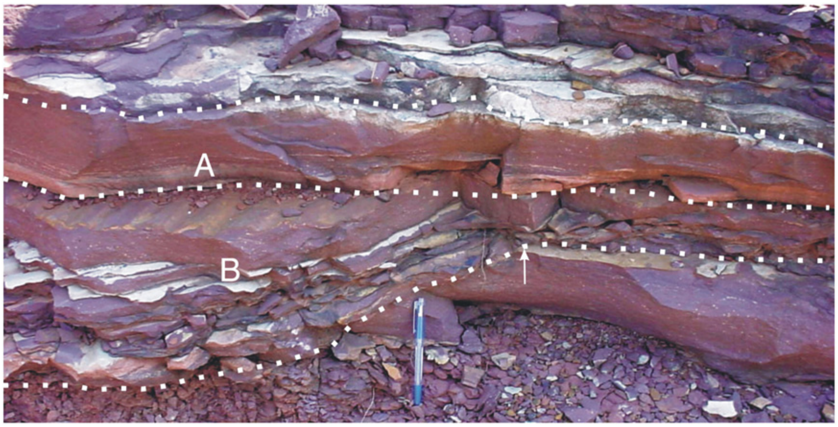

Fig. 2. A bed couplet with contrasting components outlined: the basal bed component rapidly thins laterally because of deep erosion on left (arrow), is composed of multiple units of climbing ripple sets draped by pale coloured clay preserving straight and round crested combined flow ripples underneath themselves and also on the bed surface (A). The overlying bed has more laterally uniform thickness, and is internally characterised by massiveness and local graded nature (B) (pen length, 15 cm).

generalised model for palaeotsunamiites, distinguishing between products of run up and retreat is also proposed. This paper will hopefully encourage the search for palaeotsunamiites, even in the absence of fossils and extraclastic conglomerates.

2. Geological background

The Upper Bhander Sandstone, a ca. 90 m-thick member of the Bhander Formation, at the top of the Upper Vindhyan Group (Vindhyan Supergroup), India is well exposed along the River Son. The focus here is upon a distinctive bedset traced along a range of hills, several hundred metres high, from north-east of Parasmania to south of Amdara village, for a distance over 50 km, in direction approximately parallel to the depositional strike (Fig. 1A).

Regional study revealed cm-scale synsedimentary slides in opposite directions, in response to mild extension of the intracratonic sag regime of deposition, resulting in depositional slope generation at times (Sarkar et al., 2004). The formation, being only mildly deformed post-depositionally, has subhorizontal beds dipping gently to the northwest, and is also virtually unmetamorphosed. Because of punctuated coastal progradation during deposition of the Bhander Formation, the Upper Bhander Sandstone rests on the open shelf succession of the Sirbu Shale (Sarkar et al., 2002; Fig. 1B) and its own inferred palaeogeography repeatedly transits upward from a storm-affected beach to a coastal erg setting, through an erg-margin. Bose et al. (1999) and Simpson et al. (2004) provide a detailed account of the facies constituting the Upper Bhander Sandstone, except for the two amalgamated bed couplets addressed here. Storm beds are common within the Upper Bhander Sandstone, and Bose et al. (1999) and Sarkar et al. (2004) have described and interpreted them in detail.

As a result of the low gradient of the inferred epeiric coastal tract, the supralittoral storm beds in the Upper Bhander Sandstone are amalgamated (Sarkar et al., 2004). They are made of well sorted sandstone, overall graded and transforming upward into thin reddish mudstone**.** Their bases are sharp, erosional as well as carved with tool marks like prod and groove casts, and locally, brush marks. Within them planar and wavy laminae pass upwards into bidirectional spill-over ripples capped by reddish mudstone, replete with desiccation cracks. Individual storm beds are up to 12 cm thick, thinning out eastward in the landward direction (Bose et al., 1999; Sarkar et al., 2004; Simpson et al., 2004 and many others).

The erg-margin facies association, <20 m in thickness, overlying the storm-related beach deposits, is also well laminated and well sorted. Internally, these erg-margin units are dominated by sets of crenulated adhesion laminae, pin-stripe and low angle, planar, inversely graded translatent strata, as well as aeolian impact ripples characterised by long wave length vs. short height (ratio >9) and concentration of coarsest grain fraction along crests. Solitary sets of grainfall–grainflow dune cross-strata occur locally (Bose et al., 1999; Simpson et al., 2004).

The erg facies association, more dominant towards the top of the formation, is characterised by large scale climbing dune cross-strata. The foresets are often inversely graded. Less frequent in occurrence are plane beds, pin-stripe lamination and impact ripples. The sandstone is characteristically well sorted. The maximum (preserved) thickness of the erg facies association, around 5 m, is achieved at the topmost part of the formation (Bose et al., 1999; Simpson et al., 2004).

2.1. Paleogeographic ambience of the concerned bedset

Bose et al. (1999) also recorded within the Upper Bhander Sandstone, metres-scale coastal parasequences and decametres-scale parasequence sets, vertically stacked, individually drying upward, and separated from each other by marine flooding surfaces. The marine flooding surfaces are overlain by the storm influenced beach facies association that grades up into the erg margin facies association before passing upward, again gradationally, into the climbing dunes of the erg facies association (Fig. 1C). Bose et al.

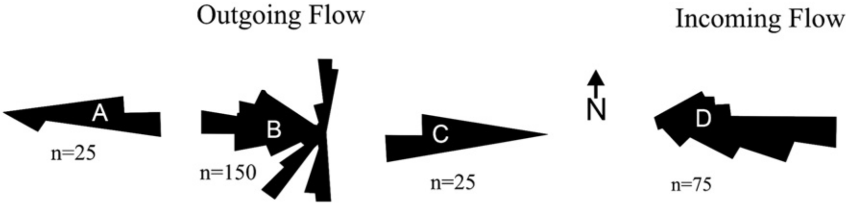

Fig. 3. Diverse orientations of structural elements within the bed couplets: (a) axial planes of slump folds, (b) flutes, (c) slump scars related to the outgoing flow component and (d) asymmetric ripples in relation to the incoming flow component. Note opposite current and/or slope orientations for the two contrasting components of the bed couplets.

Fig. 4. Rows of slump folds (highlighted) separated by listric back-stepping slide planes (solid lines; hammer length 34 cm).

(1999) further documented formation of star dunes on top of some of the parasequences. Although the aeolian climbing dunes and the star dune prompt recognition of the coastal erg facies association in the Upper Bhander Sandstone, in the vegetationless Proterozoic setting its occurrence within or outside the trade wind belts is, nonetheless, difficult to ascertain (Simpson et al., 2004).

The concerned bedset has been encountered exclusively within the basal parasequence of the Upper Bhander Sandstone. Moving in depositional strike direction the bedset has been traced over 50 km, in five hill-top exposures of the formation mentioned above. In all these five exposures, the bedset is dominantly encased by the components of the erg margin facies association; wave rippled sand-sheets intervene only locally. There is, however, little doubt that the palaeogeography of the concerned bedset had been transitional between the supralittoral zone and the coastal aeolian dune field. Close association with warts and adhesion laminae, in particular, suggests a palaeogeography within the ground water capillary fringe zone.

3. The distinctive bedset

Occurring within the coastal Upper Bhander Sandstone erg-margin deposits, this laterally extensive tabular bedset is distinctive because of its poorly developed internal laminae and grain sorting. Sandstone bed couplets, generally two in number in most locations, comprise the bedset (Fig. 1A). Within each couplet one bed component gives way into the other vertically as well as laterally, always sharply though, their body geometries and internal characters being distinctly different (Fig. 2). Directional structures help to distinguish between components engendered by "incoming" and "outgoing" flow components within each couplet (Fig. 3). Encasing deposits clearly identify the palaeogeographic setting of the said bed couplets as being at the coastal erg-margin, landward of the zone dominated by marine processes. Unique, non-recurrent occurrence of this distinctive bedset within the Upper Bhander Sandstone has been recorded on five isolated hill tops along the depositional strike direction (Fig. 1A and C).

3.1. Incoming flow component

The beds referred to here as the products of the incoming flow component of the aforementioned bed-couplets, rest on pronounced concave-up erosional surfaces and have rapidly wedging geometries. They are up to 40 cm in thickness, but thin rapidly landward as they fill and spill over, onlapping the seaward sloping basal scours (Fig. 2). The maximum scour depth recorded so far exceeds 30 cm. Each bed of reddish sandstone overlying these scours is made up of multiple vertically stacked subunits, each comprised of a set of supercritically climbing ripples of heights 2–4 cm and a thin drape of light-coloured clay. The climbing sets may be as thick as 12 cm. On top of the sets, the wave-cum-current combined flow ripples, round-crested and occasionally bifurcating, but distinctly asymmetric, are well preserved under the clay drapes, although their internal cross-laminae are generally faint (Shiki et al., 2008; Fig. 2). Broadly similar combined flow ripples occur also on top of the incoming flow beds too. The "incoming flow" origin of these beds is prompted by the orientation of the only current indicators within them, the ripples; net sediment transport landward according to the palaeogeographic model already reconstructed by Bose et al. (1999), is implied (Fig. 3D). The aspect to be highlighted is that these beds are found only in couplets with the outgoing bed components discussed in the next section.

3.1.1. Flow and depositional dynamics

The beds discussed above were deposited apparently from extra strong marine floods that could encroach upon the erg-margin. The floods evidently caused substantial erosion while running up the slope from the coastal backshore to the erg-margin. The supercritical climb of ripples and general cryptic nature of their internal laminae points to rapid deposition. Intrabed sandstone-clay alternations replete with wave-cum-current combined ripples are tell-tale indicators of the pulsating nature of the flood current (Yokokawa, 1995). Irrespective of the fact that the flow had possibly been non-channelized, individual laminae within the ripples are attributable to seconds-long vortex bursts (Yokokawa et al., 1995). In comparison, the pulsations manifested in sand-clay alternations must have been considerably longer, perhaps in minutes-scale. Separation of successive clay layers by sand layers as thick as 12 cm, however, suggests a wave period inordinately longer than that in fair weather waves. Sufficiently pronounced asymmetry of the ripples, however, indicates dominance of a traction component in the flow and bed load deposition, in contrast to the ebb situation discussed below.

Fig. 5. Close view of two dimensional folds, tight and imbricated, on top of beds related to the outgoing flow component. Note lack of evidence of sagging in the surface underlying them that identifies the plane as that of detachment (chisel length 26 cm).

Fig. 6. Exhumed slump scars in a row (Length of the pen defining the slope direction is 17 cm).

3.2. Outgoing flow component

These sandstone bed components have basal erosion surfaces which are overall planar, ignoring the minor sole features. Their body geometry is tabular, individual beds varying in thickness from 28 cm to nil because of erosion. The beds are generally massive or normally graded. Often they are, however, sharply divided into two parts, viz. (1) a lower part which is massive — a sandy zone, containing mud that usually makes up only between 5 and 10% of the unit; (2) an upper argillaceous zone, with coarse silt-sized grains floating within a reddish mud matrix. In the upper parts of these latter beds, the muddy siltstone is commonly deformed into a continuous zone of small folds (Fig. 4). The folds may be tight, imbricated (Fig. 3A), and locally recumbent, yet their tops are often not truncated and surfaces underlying them, being planar, bear no evidence of sagging (Fig. 5). Exhumed slump scars, in rows, are often clearly associated with them (Fig. 6). Relation of these slump scars with the outgoing flow is assumed because of their seaward slope (Fig. 3C). In the same direction roughly, the tight folds locally pass into breccias first (Fig. 7), and then into the massive sandstone. Soles of the lower sandy part of the beds bear a few gutter casts and numerous flute casts, which are often recurved. The most significant aspects of the flutes are their multiple generations as attested by their mutual cross-cutting relationship, the loaded nature of many (Mastalerz, 1995), and distinct temporal diversions in orientation, although always broadly westward and thus, presumably seaward (Figs. 3B, 8 and 9), while axial planes of the bed-top folds dip in opposite directions (Fig. 3A).

3.2.1. Flow and depositional dynamics

The wide occurrence of these beds of strikingly distinctive character along a selected stratigraphic level clearly relates them to a regional event (Fig. 1C). The seaward flows apparently induced slumping, brecciation and eventual liquefaction of sediment and caused extensive destabilisation of the sediment and mass flow. Flutes and gutters at the bed soles testify to high velocity, as well as to the turbulent and primarily erosional nature of the flow. The commonly massive nature of the beds indicates rapid deposition, and graded bedding attests to vertical settling of sand under temporally waning energy conditions. Loaded flutes, nonetheless, indicate frequent switching between erosion and deposition, eliciting rapid flow accelerations–decelerations, at the initial phase of sedimentation (Fig. 10). Flutes were scoured and immediately filled up, turned loaded thereby before formation of the next set of flutes. Frequent change in flow viscosity, as in slurry, and a package of multiple events of erosion and deposition are implied (cf., Leeder et al., 2005). Overall, these data and interpretations support a highly unsteady nature for the flows, and concomitantly heavy sediment load within them is implied. Interaction of multiple flow vectors is evident from the recurved forms of many flutes (cf., Beukes, 1996) and from the drastic change in the orientation of flutes of successive generations, under the same bed, and at the same spot (Fig. 8). The overall flat nature of the bed sole presented in Fig. 8 denies deflections of current against any pre-existing bedform as the cause of this multidirectionality of flutes (Allen, 1968). Furthermore, this spot-multidirectionality of flutes as expressed in their frequent overlapping indicates vectorial change in the flow through time, not space. As the flow eventually waned, deposition is thought to have finally dominated over erosion, and the flutes of the last few generations were thus preserved; those of older generations had presumably been obliterated.

The folds may locally resemble load casts or pseudonodules, but lack of evidence of compatible deformation underneath them argues against their origin as such. Common preservation of the fold crests

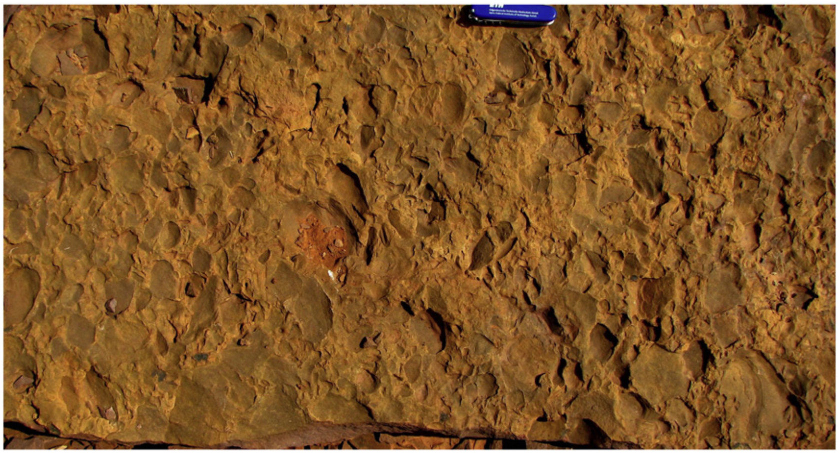

Fig. 7. Breccia generated in muddy sandstone.

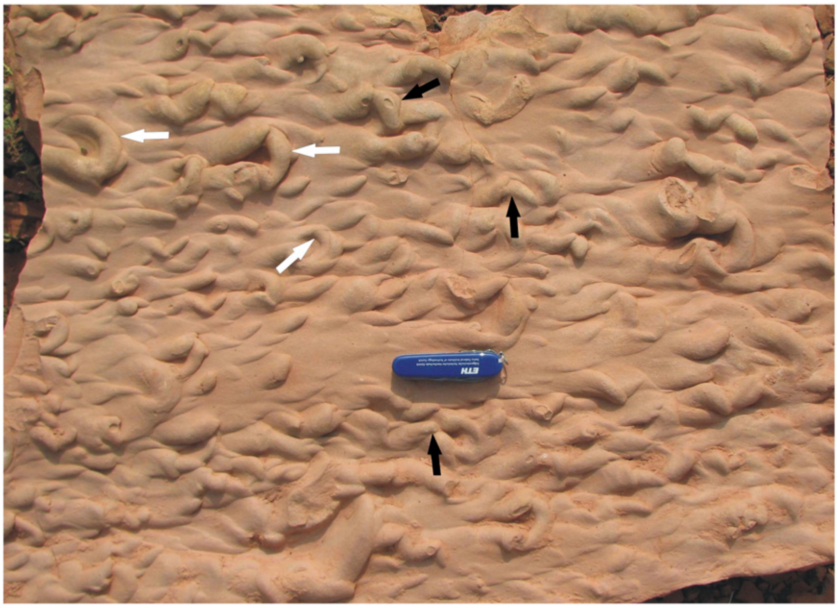

Fig. 8. Spot-multidirectionality in mutually cross-cutting flutes many of which are loaded, domed on inverted sole of a bed (black arrows). Note recurved nature of some flutes (white arrow). Also note effective flatness of the surface setting aside its corrugations because of the small incisions made by the flutes.

indicates fold formation on the sediment surface, although secondary erosion could still decap them. Unlike convolute structures these folds are two-dimensional, close opposite to the dip direction of their axial planes, when imbricated and are thus inferred to depict slumping (cf. Posamentier and Walker, 2006, their Figs. 25, and 107). The planar surface separating the folded muddy top part from the rest of the bed is seen as a shear plane that inhibited penetration of the deformational force downward. A precondition for generation of the slump folds selectively at the top part of the bed was apparently the decline in grain-size that rendered the sediment susceptible to deformation. Preservation of their crests indicates that the folds were not generally subjected to any strong directional shear from above because otherwise they should have been frequently decapped. Hence the tightness and imbrication of the slump folds arose more probably from their movement along the slide surfaces. Rapid large scale draw-down of pore water during the return flow could have caused this movement. Slumps can be induced by earthquake without tsunami, but for the 2D folds occurring at the top of the outgoing tsunamiite bed, especially the recumbent ones, the above-mentioned genetic scheme seems very likely. The row of exhumed slump scars bevelling beds belonging to the inferred erg-margin facies association (Fig. 6) indicates that back-stepping of slides (Fig. 5) caused temporary shifting of the shoreline into the erg-margin. The occurrence of silty, muddy slump folds on top of the resedimented beds indicates that pore water withdrawal and the consequent drag on the slump folds continued to operate even at the penultimate stage of the resedimentation event at the erg-margin. An unusually rapid, but long retreat of seawater is thus implied (Fig. 11).

4. Possible tsunami origin of the event bedset

The occurrence of this distinctive bedset over a long distance, presumably at a single stratigraphic level (although precise lateral correlation is not possible, primarily because of cultivation in intervening lowlands), strongly favours, though not unequivocally, tsunami origin for the event deposit discussed here. Its occurrence commonly within the coastal erg-margin facies association further corroborates this contention; the shoreline presumably shifted temporarily to the erg-margin because of its repeated collapse during the inferred tsunami (cf. Frébourg et al., 2010). Concomitantly, the

Fig. 9. Oblique view of a thin erosional remnant of a palaeotsunamiite bed (light coloured) bearing numerous loaded flutes (arrows) at its base and a sandstone bed characterised by regular alternations between grainflow/grainfall cross-strata of aeolian origin on top. Note reverse grading within many of the light coloured foresets.

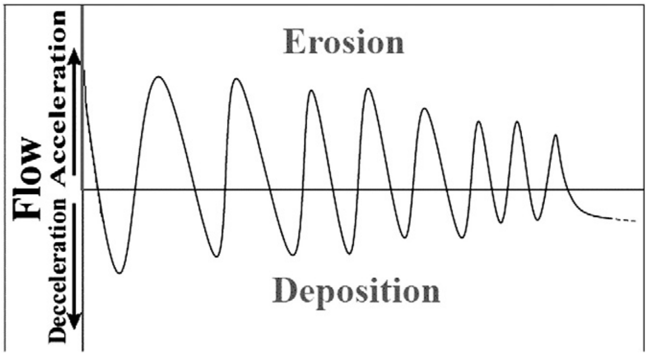

Fig. 10. A cartoon depicting rapid switching between erosion and deposition in response to flow acceleration–deceleration before the onset of continuous deposition.

bedset concerned differs distinctly from the beds that encase, overlie and underlie it and depicts unusual tumultuous deposition accompanied by deep erosion, slumping and sliding against a background of long period waves; an earthquake very possibly thus accompanied the tsunami. In the couplets constituting the studied bedset, the beds bear evidence of net sediment transport in opposite directions, and of contrasting flow and depositional dynamics; one of them can thus plausibly be attributed to tsunami run-up and the other to tsunami retreat.

The inferred tsunami run-up had evidently been deeply erosional and contained a substantial amount of clay. The clay might have been derived from the offshore, but this contention cannot be ascertained because of lack of fossils. The repeated occurrence of clay drapes on top of centimetres-thick sandstones manifests intermittent flow slackening or pulsations with a frequency substantially lower than that of normal waves, and possibly comparable to the circa 10 min time intervals of successive wave trains observed in tsunamis (Murty, 1977; Shi et al., 1995; Benson et al., 1997; Takashimizu and Masuda, 2000; Nanayama and Shigeno, 2006; Shiki et al., 2008). Combined flow ripples present within and on top of the inferred run-up beds, under the clay drapes, are essentially similar to fair-weather wave products found in many nearshore successions, but are often reported from tsunamiites as well (Fujiwara and Kamataki, 2008; Shiki et al., 2008); only those on bed-tops are attributable to wind stress on water which became temporarily stagnated after the run-up events. Despite evidence of rapid deposition, sediment concentration had evidently been lower in the incoming flow than in the outgoing flow (see below). The distinct rapid landward thinning of the flood-related beds is commensurate with similar observations reported from many recent tsunami run-up deposits (Sugawara et al., 2008). Significantly, the possible 8000 BP run-up tsunamiite of Frébourg et al. (2010) on the Tunisian coast shares some field features of fundamental importance with the aforementioned Upper Bhander Sandstone incoming component: distinct basal scour, wedge-shaped geometry, rapid landward thinning, vertical grain-size fluctuations, wave structures, ripples migrating consistently landward, and encasement within coastal aeolianites. These similarities with a recent deposit of known tsunami origin strengthen the tsunamiite interpretation of the Upper Bhander Sandstone bedset under focus significantly.

However, against the inferred epeiric sea background in an intracratonic sag basin envisaged for the Upper Bhander Sandstone, the generation of a steep slope as a prerequisite for inducing slumps in abundance during the flow retreat is highly unlikely (Sarkar et al., 2004). It is, nevertheless, quite possible that the tsunami was earthquake-induced, as most tsunamis are, and it has been independently postulated that many such earthquake events did create slopes in the Upper Vindhyan basin (Bose et al., 2001; Sarkar et al., 2002). It is likely that tsunami retreat down these slopes induced localised collapse of the coastline owing to rapid draw-down of water on an unusually large scale. Repetitive collapse, as evident from the rows of slump folds separated from each other by listric slide planes (Fig. 4), might have caused coastline shift landward across the backshore and

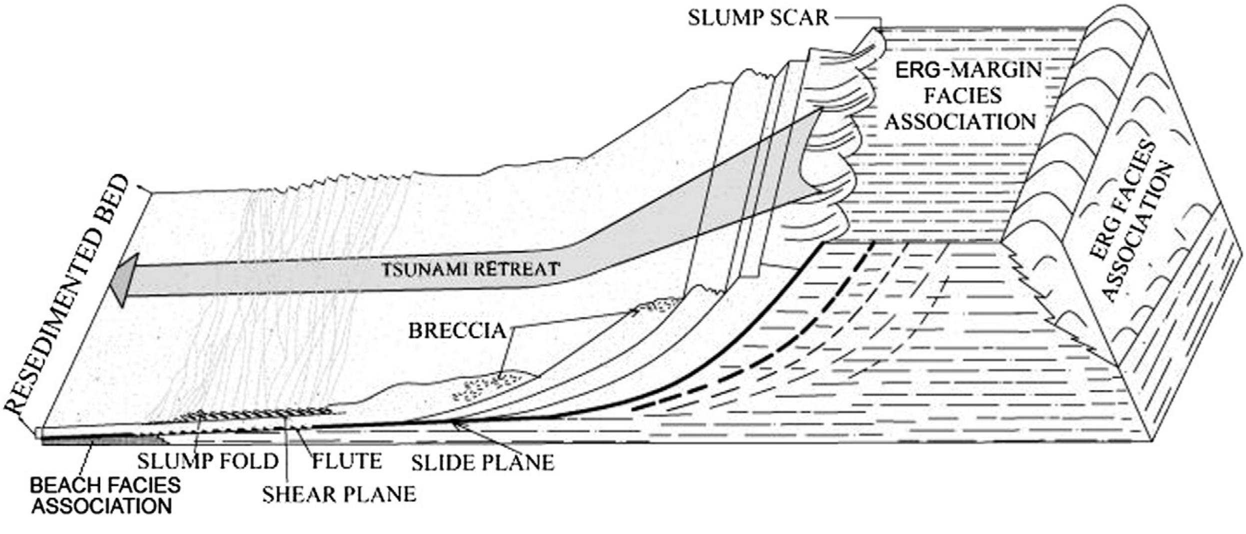

Fig. 11. A cartoon that depicts a depositional scenario envisaged for the Upper Bhander Sandstone during retreat of a tsunami that encroached upon the coastal erg-margin facies association. Slumps initiated brecciation and liquefaction of sediment inducing resedimentation. Prolonged large scale rapid withdrawal of porewater induced slump fold formation on top of the resedimented bed.

the berm to the coastal erg-margin, the palaeogeography where the postulated tsunami bedset is found preserved. The substantial and prolonged drag during the tsunami retreat likely rendered the slump folds imbricate, even locally recumbent.

Possible admixing of well sorted coastal sand with perhaps some additional inland sand and mud, in the outgoing flow, can explain the overall poor sorting of the inferred tsunami ebb deposit; such poor sorting is exceptional within the Upper Bhander Sandstone coastal association of "normal" origin. Abundant slumping and liquefaction of sediment presumably loaded the outgoing flow heavily, as eyewitnesses of tsunamis often mention (e.g., Myles, 1985). Loaded flutes under the outgoing bed components bear an explicit record of this loading, which is unusual for the inferred overall palaeogeography of deposition. Rapid settling of sand from suspension, as also often reported from tsunamiites (Shiki et al., 2008), though not exclusively, is also confirmed by graded bedding. The observed overall seaward flow direction notwithstanding, complex interplay of multiple vectors in the flow on an effectively flat surface is clearly imprinted in the recurved geometry of the flutes and in the significant alterations in their general orientation from one generation to the next. Obstruction created by the curved fronts of the successive incoming waves best explains the evident temporal diversions of the flow lines, primarily slope-controlled.

The studied beds constituting the event bed set differ explicitly in general appearance from the repetitively occurring supralittoral storm beds that have been described in detail from the Upper Bhander Sandstone by earlier workers (e.g., Bose et al., 1999; Simpson et al., 2004). Besides, flutes are, in general, rare under storm beds and those with spot-multidirectionality and loaded nature are not reported from under any storm bed. The Upper Bhander Sandstone storm beds bear abundant tool marks at their soles, but no flutes (Bose et al., 1999; Sarkar et al., 2004). In striking contrast, at the sole of the outgoing flow bed components, flutes are not only present in swarms but are also loaded (Figs. 8 and 9). Unlike storm generated flows, the inferred outgoing tsunami-related flow under discussion here was so heavily loaded with sediment that it apparently behaved like a non-Newtonian fluid, whose viscosity fluctuated rapidly, at the outset at least. Poor grain sorting in the bedset also renders its storm origin unlikely, because storm waves scoop up sediment mainly from the beach face, especially when this aspect is exceptional in the host congregation of facies that makes up the formation. Coupling of the two beds within the studied event bedset, interpreted as products of the incoming and outgoing flow events, one incising into the other, is inconsistent also with a storm origin; extensive shelf-storm beds are deposited entirely by the outgoing flows. Unlike the beds under consideration here, storm beds are commonly finely laminated because of general low flow density. Tight and imbricated slump folds as found on top of the beds deposited by the outgoing flows in the Upper Bhander Sandstone, also have no equivalent in the literature on marine storm beds or supralittoral storm wash-over deposits. Tidal force does induce deformation in soft sediment in shallow seas (Greb and Archer, 2007), but such a strong tide is unlikely to develop in the epeiric wave-dominated seaway where the Upper Bhander Sandstone was deposited. Destabilisation of the sediment pile on the scale noted, as well as the creation of slump folds, especially the strongly imbricated ones, along a sea coast, as noted in case of the concerned bedset, may not be incompatible, but are hardly ever found associated with deposits of climate-induced storms of any kind, viz. winter storms, tornados, cyclones or hurricanes, but are readily compatible with tsunamis that are invariably accompanied by ground seiches.

Flash floods in the erg-margin provide an alternative explanation for slurry generation, flutes at bed soles and poor sorting in deposited sediment (e.g., Rust and Koster, 1984; Langford, 1989; Langford and Chan, 1989; Blair and McPherson, 1994). There is, however, little explanation for the recurved nature of the flutes from such an alternative genetic model, and apparently none for the rapid near-orthogonal temporal shifts in direction of a single outgoing flow, as recorded in changing orientation of flutes in every outcrop. The coupling of beds laid by the oppositely-directed flows is also not in favour of a flash flood origin, nor is the non-channelized geometry of the outgoing bed components and landward thinning of the incoming components. The common presence of wave ripples in the incoming components of the concerned bedset would also be problematic in the case of the alternative flash flood hypothesis, unless ponding at erg-margin is presumed. Ponding over a stretch of 50 km or more is, nonetheless, unusual.

Enhanced tidal amplitude within the confinement of steeply-flanked coastal creeks can also account for many of the characteristics of the bed couplets discussed here. Close association with coastal erg-margin deposits, slumping and sliding of sediment sheets, generation of slurry with adequate water intake within the slumped mass, current reversals, presence of wave ripples and even climbing of bedforms are compatible with such a model (e.g., Pérez, 2001). However, dominance of suspension load over bed load in the ebb, initial supercritical nature of the same flow and its waning through time, and evidence of pulsations in flood, probably in a minutes-length temporal scale, and occurrence of the concerned bed couplets at a specific stratigraphic level are hardly compatible with perpetual tides. The exact time-scale of flow-pulsation is impossible to ascertain, but the rate of net sedimentation reflected in strata-thickness bounded between successive mud drapes appears to be too high for tidal deposits in a peritidal setting (Ginsburg, 1975). Additionally, the absence of channel forms in any of the components of the concerned bedset also argues against the presumed channel confinement. The tabular geometry of the beds laid down by the outgoing flow and of the incoming-outgoing bed couplets also argues against any such profound channel confinement. Above all, the Upper Bhander Sandstone is interpreted to have been deposited along an open, wave-dominated coast and accordingly, no unambiguous tidal feature has ever been reported from its coeval shelf deposits of the Sirbu Shale (Bose et al., 2001; Sarkar et al., 2002).

In all probability, therefore, the unusual high energy bed couplets discussed here, which occur at a preferred stratigraphic level within the coastal erg-margin association of the Upper Bhander Sandstone can be interpreted as a tsunami product, one of the very few Precambrian examples reported so far (e.g., Pratt, 2001). Considering the inferred intracratonic sag origin of the depositional basin (Bose et al., 1999, 2001; Sarkar et al., 2002), the studied bedset can more precisely be postulated to be a teletsunamiite, deposited far away from the earthquake epicentre, had earthquake been the root cause for this tsunami as it is in most other cases. The tsunami here appears to have coincided with earthquake seiches but that was possibly a mild response to the inferred major earthquake at a plate margin, which may typically be more than 1000 km away (Miall, 1997). The implication is that formations developed in quiet tectonic settings can also bear records of tsunami. Tsunamis are expected to be substantially attenuated on epeiric shelves (Mitchell et al., 2010), although tsunamis have been reported from epeiric platforms previously too (Pratt, 2002).

Although talus, soil and vegetation cover obscure the lateral continuity of this possible teletsunamiite, its good preservation at a number of localities over a distance of 50 km along the depositional strike is, indeed, surprising. Apparently its preservation was facilitated by the coastal erg-margin palaeogeography, deposition occurring in a sheltered area behind the berm, and by rapid burial under deflated sand and advancing aeolian dunes (Fig. 9).

5. Towards a provisional model for palaeotsunamiite deposits

Identification of a bedset in the Upper Bhander Sandstone as a possible tsunamiite opens the potential to discuss a more general characterization of palaeotsunamiite. It is apparent that the task is difficult because the criteria for identification of tsunamiites in the rock record are non-unique, that is, the various features identified in tsunamiites can, independently, be found in other types of deposits; however, it is the coincidence of many of these features which is required to identify a tsunamiite. A further concern is that not only are the characters likely to differ between tsunamiites of different events, between those arising from different causal factors and those from different geographic settings, but the studied bedset rightly points out that cardinal differences also exist between products of run-up and retreat of a single tsunami within the same geographic premise (see below). Features would understandably be significantly different between tsunamiites deposited below and above mean sea level, or, in shallow and deep seas. The broad tsunamiite characteristics conceived here are based primarily on the Upper Bhander Sandstone palaeotsunamiites within the premise of a supralittoral zone palaeogeography:

1) palaeotsunamiites are likely to be very scarce because of their susceptibility to reworking and even obliteration, but occur as distinctive bedsets at selected stratigraphic levels, and stand out in their respective sedimentary association in terms of lithology, sedimentary structures, alien fossils or over-sized clast constituents;
2) fortuitous wide preservation of the event relics, whether continuous or discontinuous, renders palaeotsunamiite interpretation very likely, though not unequivocally;
3) intimate coupling of beds of contrasting characters and opposite current indicators, apparently seaward and landward, in the bedsets strengthens the credibility of a palaeotsunamiite interpretation;
4) a) the run-up beds are likely to have wedge-like geometry;
    b) the beds from tsunami retreat, on the contrary, will likely have tabular geometry with overall planar base since heavy sediment load in the flow would tend to suppress turbulence; tool marks and flutes may, nonetheless, be abundant at the bed sole because of the supercritical nature of the inferred downwelling;
5) a) the run-up beds are likely to thin rapidly landward, onlapping the seaward sloping basal scour;
    b) it seems logical to presume that the ebb beds, on the contrary, may have a tendency to thin down the beach face, but slowly, because of progressive shedding of sediment load;
6) a) in inferred run-up beds, traction features dominate despite the settling of substantial amounts of sediment from suspension;
    b) in beds deposited from retreating flows, graded bedding may be common because of comparatively higher sediment concentration within the flow; loaded flutes, in multiple generations and their spot multidirectionality, may be characteristic;
7) a) a ‘saw-tooth’ pattern in upward grain-size variation and intermittent occurrence of clay drapes may be characteristic within the run-up beds deposited under influence of minutes-scale time intervals of wave trains;
    b) progressive upward decline in grain size may, on the other hand, be a significant characteristic of beds of tsunami retreat;
8) a) wave features like wave ripples or troughs resembling swaley cross-strata (Frébourg et al., 2010) are likely to be integral components of the run-up beds; wind stress created on shallow stagnated water may also give rise to wave ripples on reworked bed-tops;
    b) wave features are hardly expected within or on top of resedimented tsunami retreat beds; rows of slump folds, however, often imbricated, may be common on bed-tops, but only if the grain-size composition of the sediment had been conducive for such deformation.

6. Conclusions

A distinctive and widespread sandstone bedset ascribed to a high-energy non-recurring event in the Neoproterozoic Upper Bhander Sandstone, central India, described and interpreted here, is thought to be a possible tsunami record. In the two bed couplets that comprise the set, each component differs in character from the other and both of them differ from all the other beds in the formation that hosts them. Within the couplets, the component attributed to tsunami run-up bears evidence of landward sediment transport, initial deep erosion, progressive rise of sea level while the sediment layers onlapped the scoured base, wave translation in minutes-long intervals and rapid deposition under traction domination. In consequence, these beds are characterised by wedge-shaped geometry, saw-tooth pattern in upward grain-size variation, wave ripples under intermittently accreted clay drapes, climbing ripples and rapid landward thinning. The other component of the couplets bearing seaward-directed current structures has tabular geometry, gutters and swarms of flutes at the bed sole, and massive or graded character within the bed is seen as a likely product of tsunami return-flow. The flutes are loaded, individually reflect interaction of multiple flow vectors and collectively evince repeated directional veering of the downwelling flow lines as they faced obstruction from successive incoming waves. Very high sediment concentration within this outgoing flow and rapid suspension fallout therefrom is implied. Back-stepping slumps caused by rapid pore-fluid withdrawal during the long retreat of sea water shifted the shoreline beyond the backshore. Consequent high sediment loading in the flow and resultant rapid sedimentation hindered grain sorting and lamina formation. In the coastal erg-margin palaeogeography rapid burial under deflated sand and advancing dunes ensured preservation of this catastrophic deposit, spectacularly enough to contribute to preliminary modelling of palaeotsunamiite characteristics, including separate characters for flow run-up and retreat. In the intracratonic epeiric basin where the Upper Bhander Sandstone deposition took place, slope had been created intermittently because of weak extensional tectonics, and this temporary slope generation facilitated a series of slumps during the tsunami retreat. Presumably the concerned bedset was a teletsunamiite deposited far away from the epicentre of the earthquake that induced it.

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