Aseismic Tectonism-Induced Soft-Sediment Deformation in a Tranquil Palaeogeography: Chikkshelikere Limestone Member, Proterozoic Kaladgi Basin, Southern India

Soumik Mukhopadhyay, Adrita Choudhuri, Nivedita Chakraborty and Subir Sarkar

Abstract The wide spectrum of synsedimentary deformation products occurring almost at all stratigraphic levels within the ~40 m-thick section of the Chikkshelikere Limestone Member of tentative Mesoproterozoic age in India is evaluated for its origin. Among the two principal facies components, both carbonate, of this Member the dark micritic facies generally underwent brittle deformation, and the light microsparry facies responded in ductile fashion to the same deformational stress. Breccia patches, hardly having any boundary, abound at almost every stratigraphic level within the Chikkshelikere Limestone Member. The third facies constituting less than 3% by volume of the Member is of laterally persistent carbonate intraclastic conglomerate beds. The dark facies is of massive micrite, while the light facies is made up of interlocking microspar crystals, but bears minor wave-current structures, and rare minute erosional features at its base. Non-luminiscent character of the former under CL is reminiscent of oxidizing basin-floor environment, while the bright orange luminescence of the latter testifies pervasive burial recrystallization. The dark micritic facies is interpreted as indigenous and the light microsparry facies as allochthonous, possibly laid by highly energy-depleted storm wave-cum-current. Mineralogical as well as geochemical analyses indicate preferred dolomitization and carbon enrichment in the dark micritic facies. Selective pyritization is also observed along the base of the same facies. These features collectively suggest selective microbial mat proliferation within this facies. Despite early induration being the rule for carbonate sediments, microbial mat growth apparently enhanced its rate within the dark micritic facies

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and caused a viscosity contrast between the two principal facies. Both the facies underwent ductile deformation in slump folds generated on the sediment surface, but then acquired and accentuated viscosity contrast led them later to respond differently to similar deformational stress. However, in micro-graben structures both the facies underwent brittle deformation indicating pervasive cementation with longer residence time. Breccia patches, where present, elicit liquefaction, occasionally followed by fluidization, rarely the porewater is poured out on the sediment surface. The intraclastic conglomerate beds are massflow products. Indentation on the bed-roofs and shear fold on their tops elicit subsurface occurrence of the flows. Only those intraclastic beds without indentation on their roofs, but with eroded bases were possibly surficial products. Frequent liquefaction and fluidization without any stratigraphic selectivity and lateral continuity is hardly attributable to seismicity. Aseismic tectonism such that relates to geoidal tilt possibly accounts for the small-scale SSDs distributed all over the Chikkshelikere Limestone Member better. Slow warping of strata engendered frequent pore-water overpressuring that caused the synsedimentary deformation including intraclastic conglomerate beds emplaced under and above the sediment surface.

Keywords Geoidal tilt · Tranquil palaeogeography · Viscosity contrast
Microbial mat-induction · Ubiquitous SSDs · Chikkshelikere Limestone Member

Introduction

Alternate layers with viscosity contrasts make sedimentary packages inherently unstable (Yih 1967; Thorpe 1971; Chen 1991). Minor triggers like, a mild jerk or slight tilt sets them in motion. Pore-water destabilization induces ductile folding or ready flowage in the less viscous layers and ruptures in the more viscous layers disturbing pore-water pressure system further thereby (Ramberg 1955; Tikoff and Teyssier 1994; Jones and Tanner 1995). Porewater pressure that increases in consequence is likely to be hydrostatic, but turns directional once the encasement is pierced (Peacock 2003). Disturbances, seismic or aseismic, thus readily cause deformation.

Layer contrast, as envisaged above, and SSDs are commonplace within the Chikkshelikere Limestone Member of the Proterozoic Kaladgi Basin, Karnataka, India (Fig. 1). The work has been done in a section up to ~1 km in width and ~40 m in vertical thickness (Fig. 2). Pillai and Kale (2011) held high frequency seismicity of the young Precambrian earth responsible for this very frequent vertical repetition of the SSDs. The snag in this contention, however, is that the immediately older and the younger carbonate members, viz. the Chitrabhanukot dolomite and Naganur dolomite (Fig. 1b) seldom bear SSDs. Besides, within the Chikkshelikere Limestone Member the SSDs do not show any stratigraphic selectivity. In the latter the deformed layers are not also laterally persistent. Total absence of dykes further makes earthquake an unlikely cause for these deformations (Hurst et al. 2003;

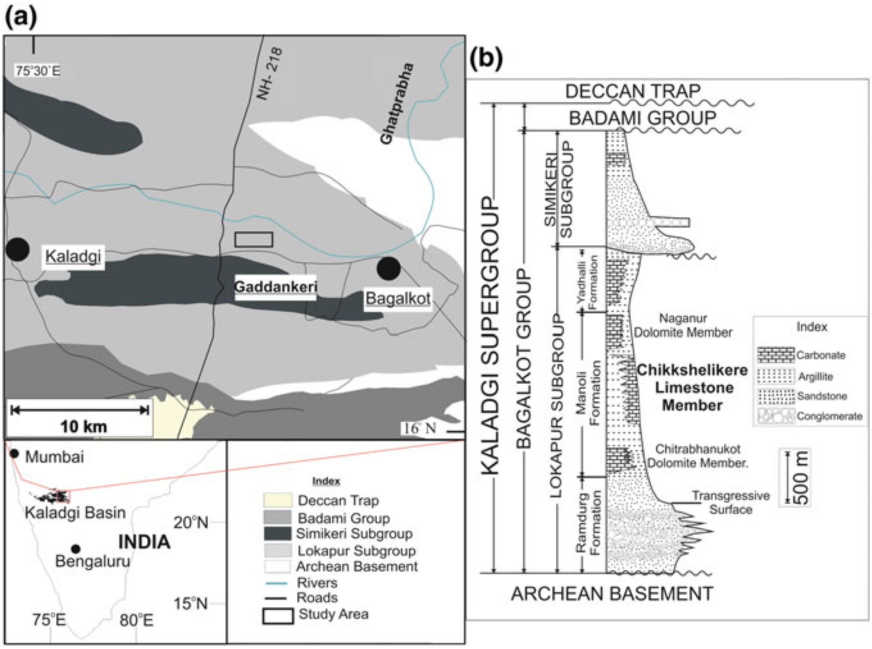


Fig. 1 Regional geology around the study area delineated and map of southern India within the inset (**a**); Litholog of the Kaladgi Supergroup highlighting stratigraphic context of the Chikkshelikere Limestone Member and the carbonate members underlying and overlying (**b**)

Goździk and Van Loon 2007; Van Loon 2009; Põldsaar and Ainsaar 2015). Patches of flat clast breccias in various forms are the typical products of synsedimentary deformation within the Chikkshelikere Limestone Member.

We are exploring for a more realistic causes for this unusual high frequency occurrence of SSDs of small scale in typical association with flat clast breccias and intraclastic conglomerates as found within the Chikkshelikere Limestone Member. We also inquire into the possible role of the two layer system in this mater. Since carbonate flat clast breccias and conglomerates are generally correlated with high depositional energy (Mount and Kidder 1993; Chen et al. 2009, 2011; Van Loon et al. 2013; Chen and Lee 2013) the paper builds up on reconstruction of the palaeoenvironment of deposition, and mineralogical and geochemical differences between the two contrasting layers that basically make up the Chikkshelikere limestone.

Geological Background

The Chikkshelikere Limestone Member belongs to the upper part of the Lokapur Subgroup at the base of the Bagalkot Group that, in turn, occupies the basal part of the bipartite Kaladgi Supergroup and the Badami Group overlies it (Fig. 1b).

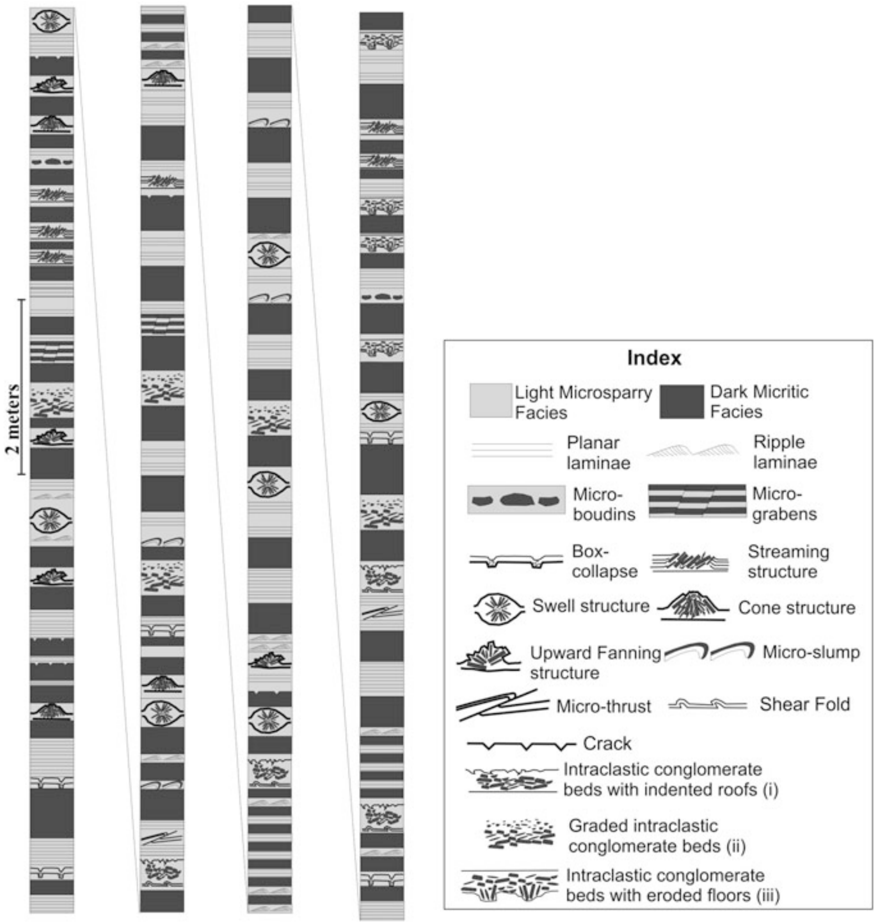


Fig. 2 Vertical succession of the sedimentary facies and structures, including those of penecontemporaneous deformation origin, in the measured section of the Chikkshelikere Limestone Member erected at the study location

The Supergroup built up in an intracratonic basin created by rifting accompanied by strike-slip faults (Radhakrishnan and Vaidyanathan 1994; Dey 2015). As may be anticipated extraclastic or lithoclastic conglomerates of varied compositions and different transport directions recur at multiple levels within the Kaladgi Supergroup (Naqvi 2005; Bose et al. 2008; Dey et al. 2009). Yet argillites occupy significant portions of each of the Groups and Subgroups constituting it, and they enclose carbonate members of lenticular shape. One of the latter in the Lokapur Subgroup is the Chikkshelikere Limestone Member and it is underlain and overlain by two other carbonate members, viz., Chitrabhanukut Dolomite and Naganur Dolomite respectively (Fig. 1b). The latter two members, unlike the Chikkshelikere

Limestone Member are stromatolitic and seldom bear any SSD. On the basis of stromatolite morphologies, the Bagalkot Group of which the Chikkshelikere Limestone Member is a part, is tentatively dated as Mesoproterozoic (Sharma and Pandey 2012). No skeletal fossil has ever been found therein. The Bagalkot Group, as a whole, has suffered multiple folding and is lightly metamorphosed.

Methodology

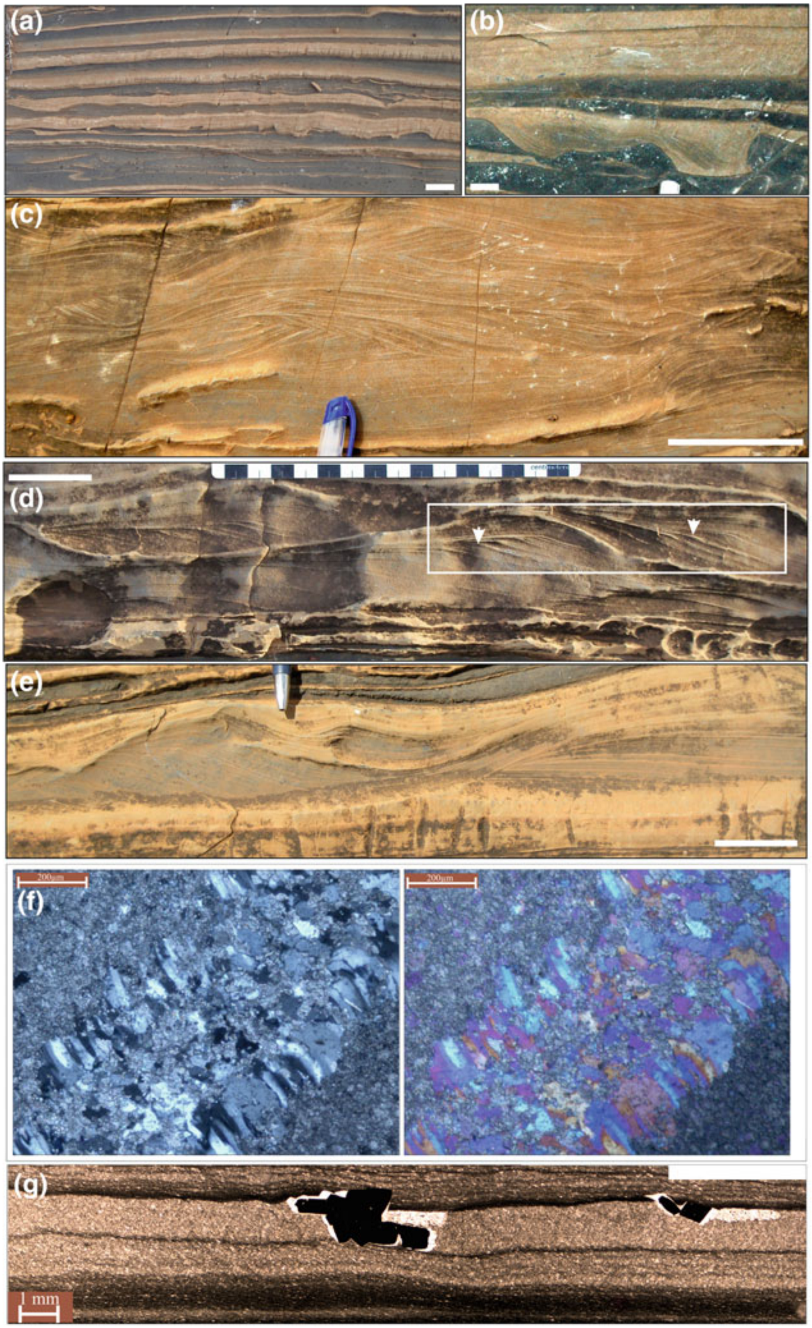
For documentation of sedimentary structures, extensive field work with usual field equipments like camera, hammer, was carried out. Fresh bedding planes or freshly prized open surfaces along with weathered planar surfaces were preferred for greater accentuation and documentation of all the sedimentary structures. Several block samples were collected, one part was used to prepare polished sections and the other halves were utilized for petrographic thin sections and geochemical studies. Thin sections were gold coated before studying under Scanning Electron Microscope with facility for energy dispersive spectroscopy (EDS) at the Geological Survey of India (GSI), Kolkata using a Zeiss Evo 40 (Oxford Inca Penta FETX 3, Model-7636).

Chikkshelikere Palaeogeography and Palaeoenvironment

Facies

Repeated alternations between two facies characterize the Chikkshelikere Limestone Member; one is dark and the other is light colored. The stratal pattern in this member, disregarding the SSDs barring the syndepositional load casts, is predominantly none other than even lamination or bedding (Fig. 2). The dark micritic facies is internally massive. The light microsparry facies is also mostly massive or graded and occasionally loaded at base, but may also be locally (cm-scale) cross-laminated. Bases of the light microsparry facies units are always sharper than their tops (Fig. 3a) and locally scoured to a maximum depth of 1.5 cm. On top of the dark micritic facies the scours bear minor stepped irregularities (Fig. 3b).

The third, but a minor facies ($\sim 3\%$ by volume) is constituted by intraclastic conglomerate beds that are generally parallel-sided, but also wedging or laterally non-uniform in geometry (Fig. 2). Their average thickness is about 30 cm. These beds are internally devoid of current structure, but normally graded on certain instances. Clasts are derived from the dark facies and are mostly oriented parallel to bedding. The fine-grained matrix is comparatively lighter in color than the clasts.


(a)
(b)
(c)
(d)
(e)
(f)
200μm
200μm
(g)
1 mm

◀**Fig. 3** Alternate dark micritic and light microsparry facies. The bases of the latter are always sharper than their tops (**a**); stepped and slightly irregular scoured surface on the dark micritic facies. The scour is filled by fine accretionary laminae of the light microsparry facies. The inclination of the accretionary laminae decreases progressively upward (**b**); Wave ripple laminae within light microsparry facies (**c**); Subcritical to supercritical ripple climb (arrowed) in the light microsparry facies (**d**); Median ripple between two larger wave ripples (**e**); A zoned crack-fill: chert at the centre and chalcedony on the fringe. Note presence of large number of length-slow chalcedony crystals (left photo under plane polarised light and right photo after insertion of gypsum plate) (**f**); Diagenetic cubic pyrite crystals concentrate preferably along base of the dark micritic facies (**g**). Length of the bar is 5 cm

The cross-laminae within the light microsparry facies are predominantly wavy (Fig. 3c), locally chevron-like (Fig. 3c) or unidirectional cross-laminated. The cross-laminae are, at places, low-angled and may drape pre-existing bedforms. Ripple-drift is commonplace. The ripples often have brink points below their crests and these brink points tend to disappear upward as the ripple lee angles reduce progressively (Fig. 3d). Progressive decrease in cross-lamina dip is noted also within the scour-filling cross-sets also. On rare bedding plane exposures, the ripples have straight to broadly sinuous crests with occasional bifurcations. There are minute median ripples in between the larger ripples (Fig. 3e).

Petrography and Mineralogy

The dark constituents, whether in form of beds, laminae or chips are made of micritic carbonate, while the light constituents are of microspar carbonate. In the latter well formed, zoned and mutually fitting carbonate crystals present interlocking texture. Chemical staining and XRD identify the carbonate minerals constituting the dark micritic facies as both calcite (av. 30%) and dolomite (av. 24%) in roughly comparable amount, and those of the light microsparry facies as calcite dominantly (80%) and dolomite subordinately (av. 7%). Another remarkable variation between the two principal facies is in quartz content (fine grained), on average 46% within the dark micritic facies and only 13% in the light microsparry facies.

Besides, chalcedony fills cracks, many of which have successive zones differing from each other in crystal morphology and interference color (Fig. 3f). The fact is that among them many are length-slow (Fig. 3f). Another diagenetic mineral that deserves mention is pyrite, that preferably concentrate along the base of the dark micritic facies (Fig. 3g).

Interpretation

Amongst the two principal facies, the dark massive micritic facies have been precipitated insitu, while the light microsparry facies, often cross-laminated, is allochthonous, derived from outside the depositional site presumably during storms. The light microsparry facies must have been made up of non-cohesive granular, possibly silty carbonates, now thoroughly recrystallized into mutually interlocking microspars. Overall fine-grained nature of the dominant lithologies, general even nature of the beds/laminae, especially those of the indigenous facies attests to deposition primarily in a calm and quiet lake or lagoon. Even nature of its laminae suggests overall slow rate of sedimentation. In contrast, load casts at the base of light microsparry facies point to comparatively rapid sedimentation intermittently. The ripple forms as described above and also the presence of median ripples attest to deposition from oscillatory flows. Since only small-scale bedforms were generated, the flows had essentially been weak. Very limited occurrence and scale of erosional features strongly corroborate this contention. The storm-induced flows apparently disturbed the tranquility of the depositional basin only mildly at intervals. The ripple-drifts and low-angle draping cross-laminae testify suspension fall-out in considerable proportion. The below-crest brink points suggest ripple migration under suspension cloud that prevented flow detachment at the ripple crests. Upward disappearance of the ripple-brink points and decrease of ripple-lee slopes point to the fact that suspension-cloud progressively became denser and perforce turned the flow tangential (Imbrie and Buchenan 1965; Swift and Rice 1984; Bose et al. 1997). Waning nature of the flows is an imperative. The depositional basin must have been shallow so that even these weak wave-cum-current flows could touch the basin-floor. Thickness of both the principal facies varies widely from paper-thin to around 10 cm. Thickening of the light microsparry facies and their amalgamation appear to represent further basin shallowing. The granular materials delivered by the storms must have been some kind of carbonate allochems whose identity is now completely obliterated by extensive recrystallization. However, because of the Precambrian age of the sediment, it can be assumed that the allochems were either limeclasts or ooids. Between the two principal facies, the dark facies had evidently been preferred for persistent dolomitization, presumably penecontemporaneously. Relative abundance of length-slow chalcedony suggests prevalence of hypersaline condition within most parts of the Chikkshelikere depositional basin. The intraclastic conglomerate beds are possible products of mass-flows induced by the deformations whose forms are described below.

Deformation Structures

Between the two principal facies constituents the dark micritic facies has generally created the flat clasts, while the light microsparry facies has undergone ductile folding, often in a complicated fashion or complete liquefaction. The flat clast breccias bodies are generally patchy in occurrence, disrupt lamina sets from which they are generated, have indistinct boundaries grading laterally into undeformed sediments. Dark micritic facies is, at places, partially brecciated and at many other places the pristine laminae can often be reconstructed merely by rotating the clasts (Fig. 4). The flat clasts often have beveled edges, but in some clusters they are distinctly crumpled. Variation in the arrangement of elongated clasts gives rise to different forms of deformation structures described below.

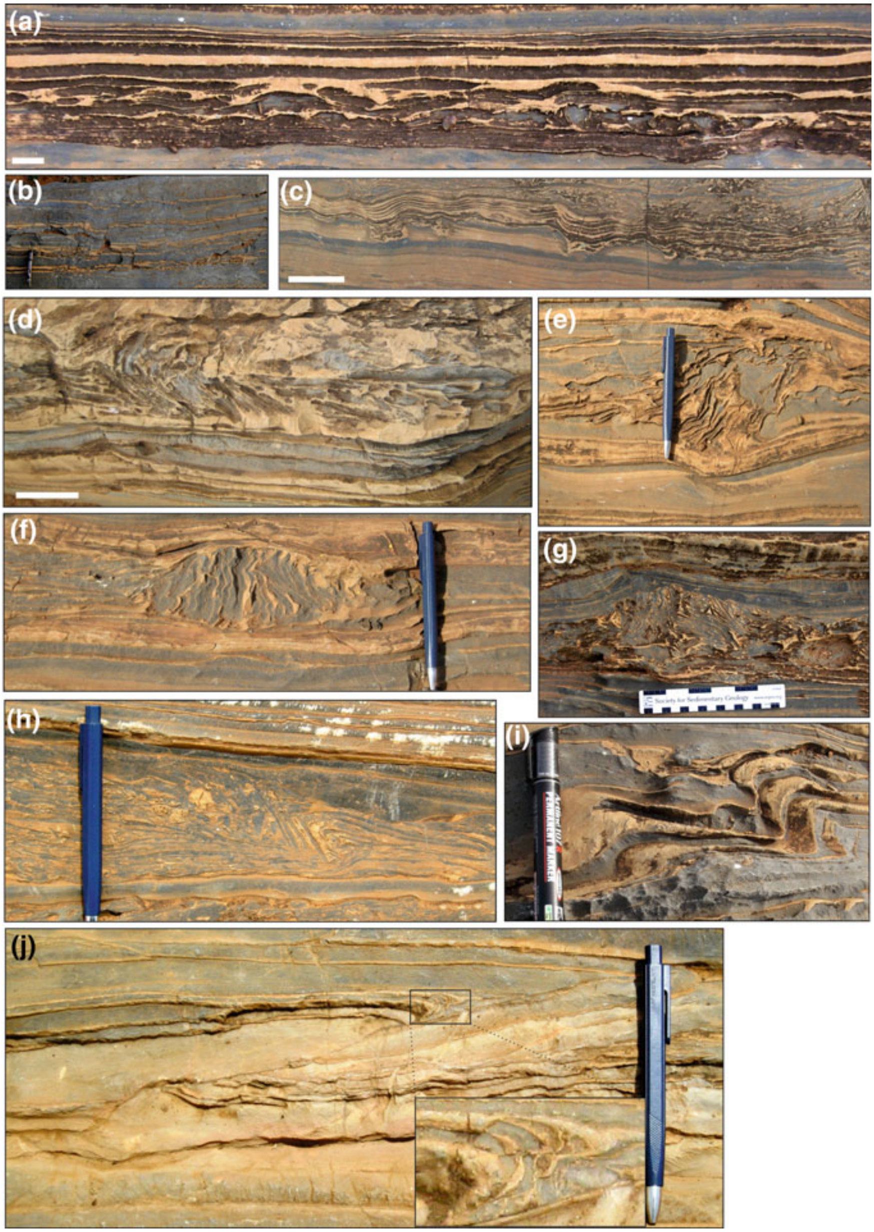
Micro-boudins: The dark micritic facies often form laterally detached lenses within the encasing light microsparry facies (Fig. 5a). The lenses are about 8 cm in length and thickness around 2.5 cm. On certain instances the microboudins are rhomboidal in shape.

Micro-grabens: Stepped micro-graben with maximum vertical displacement around 2 cm bounded below and above by undisturbed laminae is locally present (Fig. 5b). Both the light and dark laminae have acquired sharp beveled edges along the fault planes. Lamina displacement is more conspicuous with respect to the light laminae.

Box-collapse: Flat-based small box-like areas, laterally bounded by fractures, occur at irregular intervals along the base of certain beds. Internally disrupted primary laminae characterize them; dark clasts float within massive light microsparry matrix. Overlying laminaset sags into the boxes (Fig. 5c). The upward expanding boxes measure up to 5 cm in width and their depth ranges up to 3.5 cm.

S*treaming structure*: Strings of clasts, straight or winding, pierce through surrounding sediment. Primary laminae flanking them are often fractured. Primary laminae, fractured or not, on both sides of these streams of clasts often show tendency to upturn (Fig. 5d).

Fig. 4 Sporadic occurrence of breccia patches arising from local disruptions. The clasts can be traced into the primary laminae within the sediment hosting them



Swell structure: Small lensoid breccias bodies within which dark clasts float chaotically within light-colored matrix and undisrupted laminasets below and above wrap around them giving an impression of local swelling (Fig. 5e). The clasts

◂**Fig. 5** Dark micritic facies components formed the row of micro-boudins encased by light microsparry facies (**a**); Micro-grabens within which both the dark micritic and the light microsparry facies deformed in brittle fashion (**b**); Box-collapse structures at irregular intervals along a particular stratigraphic level. The immediately overlying laminae sag down selectively within the boxes (**c**); Streaming structure made of string of clasts piercing through layers of bed parallel clasts. Some of the upward directed clasts are bent (**d**); Lensoid swell structure showing localized thickening of intraclastic breccia in which the clasts are oriented erratically. The underlying and the overlying laminae wrap around the breccia. The overlying lamina has its lower surface indented (**e**); Cone-shaped breccia body (centre) having the subvertical clasts intensely crumpled. Laminae bounding the breccia patch both below and above are intact (**f**); The dark clasts are fanned out upward to constitute a faning structure in breccia. The clasts appear to have bevelled edges, yet many of them are crumpled (**g**); Clasts define a shear fold within a breccia bed (**h**); Micro-slump fold within which both the dark micritic and the light microsparry facies deformed in ductile fashion (**i**); A micro-thrust is bounded below and above by undeformed strata. The enlarged hinge of the drag fold at the tip of the hanging wall (below) shows selective fragmentation of the dark micritic facies (**j**). Length of the bar is 5 cm and of the pen is 14 cm

within swells are chaotic in orientation and may impinge both the floor and the roof of the swell.

Cone structure: This is the most conspicuous type of clast arrangement in patchy breccias. Bed-parallel clast fabric is disturbed at places to present this type of structure. Clasts are rotated upward and tend to converge at top of the structure. The undisrupted continuous laminae bounding the base of this structure are not affected, but those bounding the top often heave up distinctly and are locally impinged by the clasts. Crumpling of clasts is most pronounced within this structure (Fig. 5f).

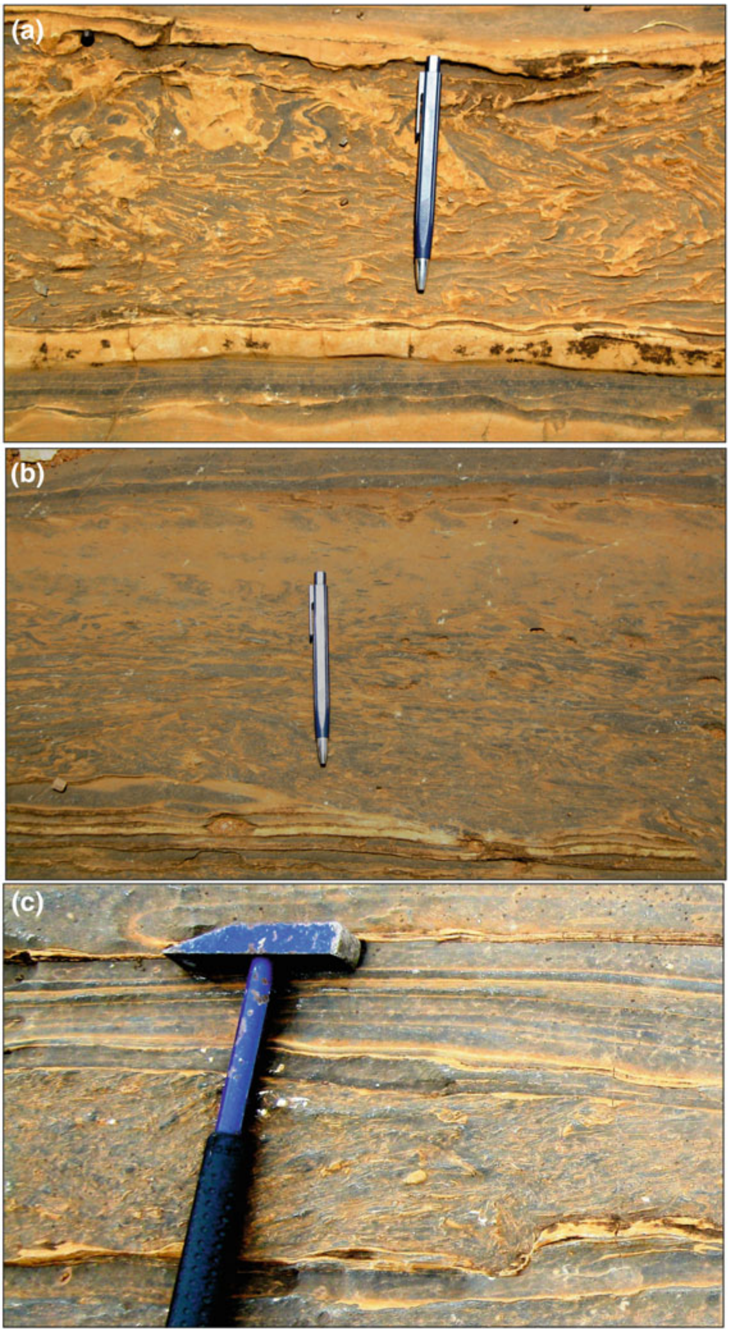
Upward fanning structure: Next in abundance is this structure wherein the clasts fan out upward in distinct patches amidst clasts generally oriented parallel to the bedding or slightly upturned at the margin of this structure (Fig. 5g). The underlying laminae show little deformation, but the overlying laminae wrap around the top edge of the upward-oriented clasts smoothly without any disruption.

Shear fold at base: Undisrupted laminae bounding the base of intraclstic beds in which the clasts are, more or less, bed-parallel often bear minute shear folds at places (Fig. 5h). The fold amplitudes are about 2.5 cm.

Micro-slump: The laminae irrespective of their lithologic difference are, at places, coherently deformed into small slump folds. No clast has been generated (Fig. 5i). The amplitude of the folds is around 3 cm.

Micro-thrust: Micro-thrusts bounded by undeformed laminasets are locally present. The throw of these faults are in centimetre-scale. The pinching edge of hanging wall may bear shear fold twisted backward, while the edge of the foot-wall is upturned along the fault plane (Fig. 5j). Both the lithologies participate, more or less, similarly in the faulting, but within the tight drag folds the dark micritic facies is, nonetheless, fragmented on certain instances.

Intraclastic conglomerate beds: The laterally persistent intraclastic conglomerate beds of lithology exactly similar to that of the breccias patches described above are considered here as deformation structure as they represent the maximum extent of deformation attained in this formation. One advantage in this approach is to have the entire range of products of synsedimentary deformation in the Chikkshelikere


(a)
(b)
(c)

◂**Fig. 6** A conglomerate bed with uneven roof has the lower bounding lamina intact but the upper bounding lamina indented. The lamina immediately underlying the breccia is shear folded. Shear folds in vertical stack are present within the breccia bed also. Overall the clasts are bed-parallel or imbricated (**a**); A graded conglomerate bed has a few large clasts floating at its top. Base of the bed is intact but the upper bounding surface is indented (**b**); Conglomerate/breccia beds with uneven floors having eroded bottom but its upper bounding surface is smooth and not indented. The clasts are generally bed-parallel but at slope-break (on right of the handle of the hammer) the clasts are chaotic in orientation and often at high angle to the bedding plane (**c**)

Limestone Member for an integrated analysis. The conglomerate beds are of several forms:

Intraclastic conglomerate beds with indented roofs (i): There are a few clast-supported beds that have parallel-sided or wedging geometries. Their roofs are dented, though their floors are not (Fig. 6a). The floor-laminae may, nevertheless, be shear-folded in microscopic scale (Fig. 6a). Distinct shear folds also occur within some of these intraclastlc conglomerate beds and these shear folds are defined by strings of clasts. On some instances there may be multiple folds one succeeding another vertically (Fig. 6a). The constituent clasts are, however, broadly bed-parallel in orientation within these beds.

Graded intraclastic conglomerate beds (ii): Some matrix-supported intraclastic beds also have selectively indented roofs. Clasts within them are mostly oriented bed-parallel or imbricated and the beds are graded, but some relatively large clasts may float at top of the beds (Fig. 6b).

Intraclastic conglomerate beds with eroded floors (iii): These conglomerate beds are clast-supported beds and have their roofs smooth, but bottoms irregular, dented, eroded and stepped at places. The majority of clasts are bed-parallel, but they turn almost vertical where the lower bounding surface is sharply eroded and the bed thickens (Fig. 6c).

Interpretation

Lack of any well-defined boundary and ready traceability of the clasts into the undeformed walls attest to in situ origin of the breccias patches within the Chikkshelikere Limestone Member. Partial fragmentation of beds of dark micritic facies otherwise intact rules out generation of clasts elsewhere before their emplacement as has been invoked in case of some other similar carbonate intraclastic conglomerates (e.g. Mount and Kidder 1993; Chen et al. 2009, 2011; Van Loon et al. 2013), Evidence of large-scale wave-reworking is singularly absent within the Chikkshelikere Limestone Member. Heavy suspension cloud severely dampened whatever turbulence the storm-induced flows inherited before encroaching upon the depositional site for the Chikkshelikere Limestone Member. Porewater overpressure, liquefaction and fludization along with slump and slide appear to have caused deformation (Bose et al. 1997) and consequent clast generation selectively from the dark micritic facies. While creating the slump folds at the sediment-water interface the two principal facies differed little in response to the deformational stress (Fig. 3i). Difference, at least, to a low degree, was, nevertheless, achieved when the top-truncated micro-thrusts and the micro-boudins developed. The dark micritic facies generated clasts at the tight hinge of the drag fold created at the upper tip of the hanging wall of the micro-thrust, while the light microsparry facies underwent ductile folding. Apparently the viscosity contrast between the two main facies gradually increased to a significant level soon after deposition. Evidently the dark micritic facies had earned cohesiveness much earlier than the light microsparry facies prior to the compression that led to thrusting. The same is implied in case of formation of micro-boudins from the dark micritic facies, while the light microsparry facies underwent free flowage around them. Intense crumpling of subvertical clasts, nonetheless, indicates that the clasts still retained considerable degree of softness even after undergoing brittle fragmentation. Apparently they turned cohesive, but little cemented. Incomplete consolidation of clasts is though implied, there is no denying that the dark micritic facies acquired brittleness earlier than the light microsparry facies. As the boudins and the micro-grabens attest to extension, the micro-thrusts, albeit rare in occurrence, point to compression.

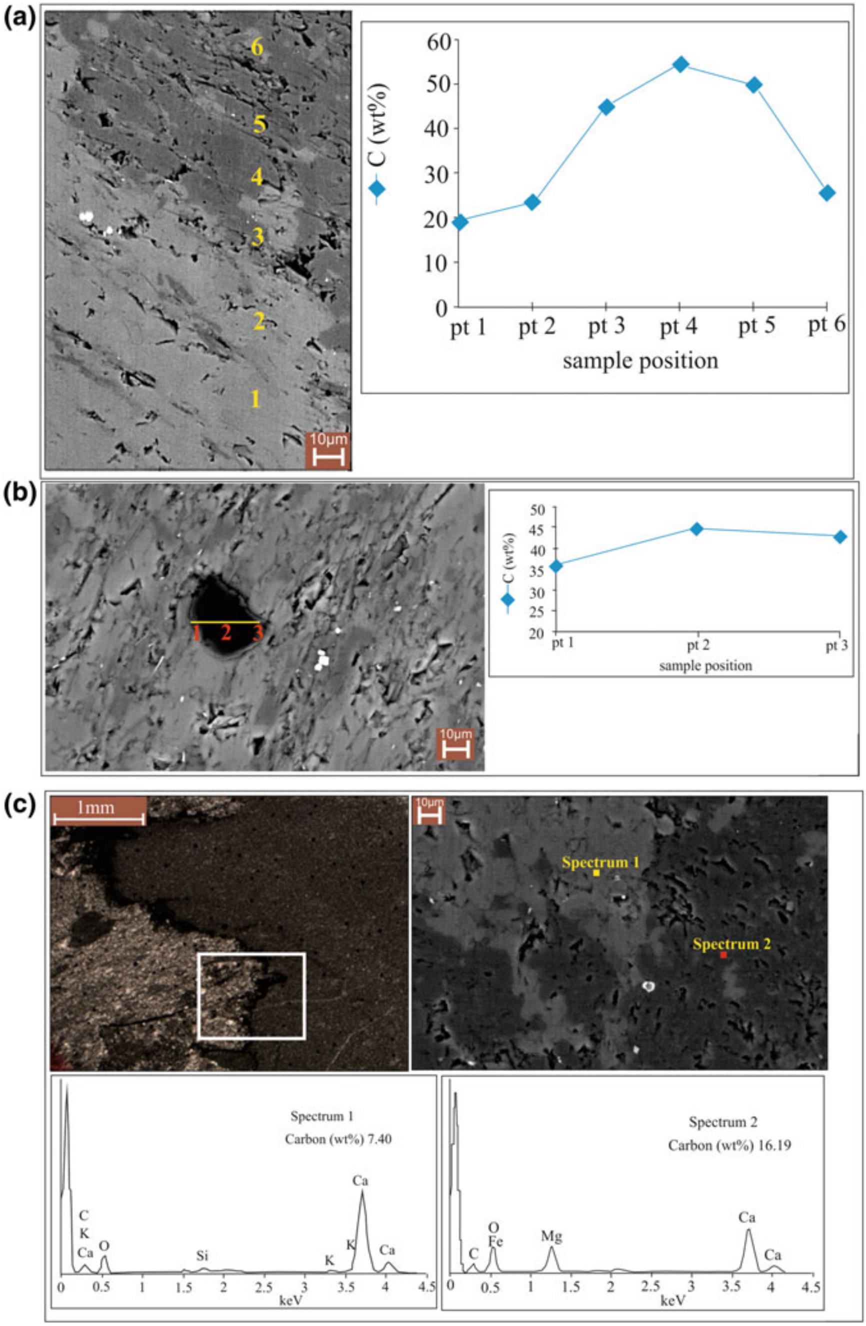
Building up of hydrostatic pressure under sediment cover seems responsible for the lensoid and the box-collapse structures. Localized liquefaction is apparent in both the cases (Sarkar et al. 2014). In case of the latter fluidization possibly followed. Because of dewatering cracks defining the box developed and the overlying laminasets collapsed into the boxes. Experimental work on hydrostatic pressure generation documents liquefaction, blister formation and localized swelling of laminae as envisaged in case of the swells. Blister bursting, fludization and collapse of overlying lamina might have followed in case of box-collapse. The dewatering process induced cracking (Nichols et al. 1994; Peacock 2003). Forceful injection of displaced porewater through narrow orifices is the most likely explanation of the streaming clasts. Clast transportation of limited scale is envisaged. Partial relaxation of subsurface porewater overpressure through narrow conduits possibly gave rise to the cone structures; laminae were upturned and resultant stretching fragmented the cohesive dark micritic facies selectively. The upward-pointing clasts impinge into the roof of the breccias bodies implying existence of a sediment cover. On instances where the displaced water gushed out through the sediment cover the dark clasts possibly assumed the upward fanning structure. The laminae overlying the fan structures are intact, simply draping tips of the upward-pointing clasts suggesting absence of the sediment cover.

Indented nature of roofs of the conglomerate beds (i) suggests subsurface flowage. Presence of shear folds on their floors, nonetheless, attests to generation of strong shear by the moving sediment-fluid mixture. Bed-parallel arrangement of the majority of clasts indicates that the flow itself had been internally sheared (Enos 1977). Stack of multiple shear folds inside the beds presumably arose from deformation of compound cross-strata or beds with ripple drifts. The indented roofs of the graded conglomerate beds (ii) also indicate subsurface flows of comparatively lower viscosity that allowed the clasts to sink, larger clasts preceding the smaller clasts. Shear developed by friction between the flow-top and the roof possibly held back a few large clasts on top of the flows (Seth et al. 1990 and ref therein). The conglomerate beds (iii) without indentation on their roofs, but having erosional marks on their floors, indicate pouring out of the flows onto the sediment surface. Although bed-parallel clast orientation suggests deposition from laminar flow, localized basal erosion suggests its temporary transformation to turbulent flow because of change in depositional slope. Chaotic clast orientation at the minor slope breaks on the depositional substratum corroborates this contention (Fisher 1981; Bose and Sarkar 1991). The micro-grabens encased by undisturbed laminae are exceptional as both the main facies-components have undergone brittle deformation together. Both the components must have acquired consolidation sufficient enough to turn brittle. The structure presumably developed after a longer residence time of the sediment, possibly at a relatively greater depth.

Geochemical Characteristics of the Main Facies-Components

Both the principal constituent facies of the Chikkshelikere Limestone Member are of carbonate composition, but the above discussion makes it apparent that in one consolidation commenced earlier than in the other. To find the reason a deeper look into the chemistry of the two facies is deemed necessary. The dark micritic facies component is typically non-luminescent while the light microsparry facies component displays bright orange color under cathode luminescence. SEM back scattered images reveal three major components in the Chikkshelikere rocks with three different grey-scales, viz. light grey, grey and dark patches in both the dominant facies (Fig. 7a). The upward transition from the light microsparry facies to the dark micritic facies is gradational, though the reverse transition is sharp. All the three color components are present within both the facies. However, the light facies is dominated by light components, while the dark facies is constituted mainly by the grey and dark components. EDS application reveals a correlation with carbon content: deeper the color, higher is the carbon content. Rare small, round-edged, elliptical dark clasts present within the light-colored facies are, as expected, highly carbon-rich (Fig. 7b). The carbon content in grey and dark patches far exceeds what can be accounted for by their calcite or dolomite mineralogy (Deer et al. 1966). In the transition from the light to the dark facies always reveals an overall increase in carbon content (Fig. 7a).

Like the round-edged elliptical clasts, the elongated, sharp-edged clasts, common in occurrence in this Member, are also considerably richer in carbon than the matrix between them (Fig. 7c). Concentration of opaque cubic crystals along the dark streaks, especially along the base of the dark facies, has been mentioned above and EDS application confirm their prior identification as pyrite with high content of Fe and S.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keV
keV

◂**Fig. 7** The light microsparry facies component grades upward into the dark micritic facies (from bottom to top). Both the facies components have light grey, grey and dark patches. The light microsparry facies is dominated by light grey and grey components while dark micritic facies is dominated by grey and dark patches. The EDS curve documents increasing in carbon content in the transition from the light microsparry facies to the dark micritic facies. Within the latter the carbonate content drops within a small grey patch (**a**); High carbon content within a dark micritic clast (left) is revealed in the EDS curve (right) (**b**); A portion of a dark micritic clast is on right and associated light microsparrymatrix is on left (left). The rectangle straddles the clast margin and is enlarged on right. EDS reveal comparatively much higher carbon content within the dark clast than to the light matrix (**c**)

Interpretation

The dark micritic facies turning cohesive with little cementation is best explained by preferred microbial mat growth within it. High carbon content of the facies is consistent with this contention. The aforementioned correlation of dark color of the sediment constituents with increasing carbon content is likely to reflect variable rate of microbial mat growth. Carbon content in the dark patches far exceeds what can be accounted for by their carbonate composition and hence the dark facies is identified as possible microbial mat (Chen et al. 2013). Its enrichment in Mg and preferred dolomitization are consistent with the purported microbial infestation (van Lith et al. 2003; Bontognali et al. 2010; Hips et al. 2015). Selective pyritization within the dark facies is further corroborative, being a possible product of microbial mat decomposition (Schieber 2007). Comparatively higher content of quartz within the dark micritic facies is attributable to trapping of floating siliciclastics by microbial filaments. Having compositional similarity with the dark micritic facies the elongated clasts are also likely to be microbial mat fragments. The rare round-edged minute clasts within the light microsparry facies indicate that the storm-generated flows carried very small microbial mat chips (Schieber 2007). Gas accumulation underneath makes microbial mats readily buoyant and hence there is no need to assume high flow intensity for erosion of these minute mat chips. Being carbonate in composition both the principal facies were presumably prone to early cementation, but selective proliferation of microbial mat apparently enhanced cohesiveness of the dark micritic facies comparatively earlier. Slow accretion of this facies in a quiet palaeoenvironment had been especially conducive for this microbial mat proliferation. Prolific activity of sulphate reducing bacteria as evident in selective pyritization should have also preferred the dark micritic facies for comparatively rapid cementation (Visscher et al. 2000; Dupraz et al. 2009). CL variation between the two principal facies is in perfect match with this observation. Possibly because of cementation at or very near the sediment-water interface the dark micritic facies earned non-luminiscent character; iron in form of Fe_2O_3 and manganese as Mn_3O_4 on the basin-floor suppressed the luminiscence. On the other hand, probable dominance of MnO_2 over FeO subsurface made the light facies brightly luminescent (Sarkar et al. 2014). Large proportion of iron must have already been withdrawn from the aqueous system by pyrite when the facies underwent thorough recrystallization. Carbonate intraclasts, in general, may have varied origin, but within the Chikkshelikere Limestone Member lamina-selective microbial mat growth possibly played an important role in generation of the flat intraclasts only from the dark micritic facies.

In the slump folds created on the sediment surface both the facies behaved in ductile fashion, but the rate of consolidation differed afterwards. Microbial mat growth and metabolism made the dark micritic facies selectively amenable to brittle deformation ere long. In the micro-grabens both the facies, however, underwent brittle deformation because carbonate sediment consolidation became pervasive by that time, possibly at a relatively greater depth.

Ultimate Cause of Deformation

The majority of penecontemporaneous deformation structures in the Chikkshelikere Limestone Member were induced by frequent liquefaction and fluidization at the depositional site. The clasts within them were mostly subjected to minimal transportation, merely rotated almost in situ. The scale of their transportation within the streaming structures, in the fanning structures or in the intrclastic conglomerates cannot be ascertained, but certainly all of them remained within the same depositional locale. Indentations on their roofs and more importantly shear-folds on top of some graded beds (Conglomerate ii) bear clear evidence of subsurface flows (Fig. 8). Only Conglomerate (iii) was possibly a product of surficial flow and might

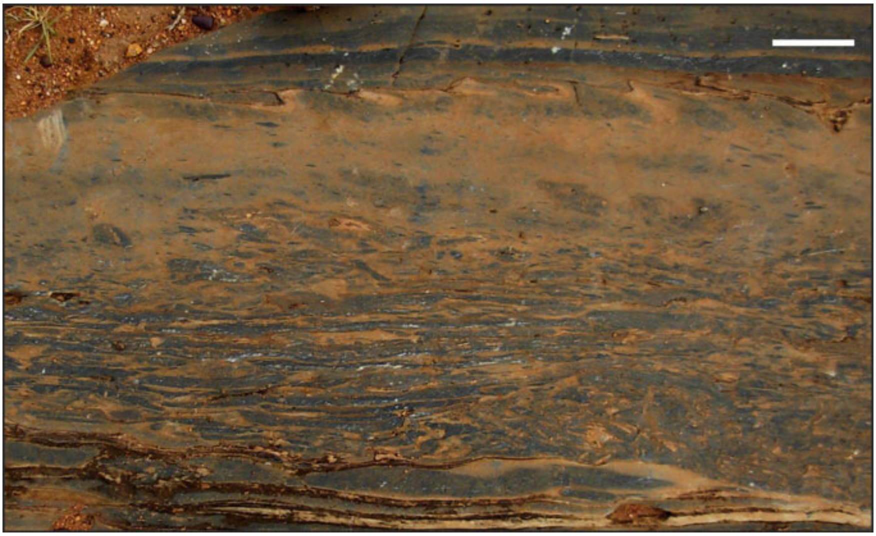

Fig. 8 Graded intraclastic conglomerate bed with shear folds at top. Length of the bar is 5 cm

have been subjected to transportation to reckon with. Even then the little difference of these conglomerates with sediment encasing them, except in grain fabric, rules out long transportation.

What was the triggering mechanism for the evident liquefaction and fluidization? Since evidence of sediment reworking is minimal, storm wave pounding (e.g. Mount and Kidder 1993; Van Loon et al. 2013; Chen 2014) is not a viable mechanism to explain these SSDs. In the Chikkshelikere sheltered depositional palaeogeography tranquility was so little disturbed during the storms that the power of turbulence in the flows to lift the clasts in suspension, as envisaged by Mount and Kidder (1993) could hardly ever arise. In the hypersaline Chikkshelikere depositional environment, evaporite minerals might have been precipitated and their dissolution could have also created the SSDs, but collapse structures should not have been so rare in that case (Bachmann and Aref 2005).

The deformation features cited may not relate to seismic events (Shanmugam 2016), as stated earlier, but their presence in almost every strata most certainly indicates the tectonic grain of the depositional area. Aseismic tectonism, such as long-term geoidal tilt in the strike-slip setting then appears, though not unequivocally, to be the most likely mechanism to account for these SSDs spread all over the Chikkshelikere Limestone Member. Multiple folding, however, renders determination of the tilt direction of the Chikkshelikere depositional basin impossible. Slump folds on depositional surfaces and directional subsurface massflows often with unidirectional shear folds at their bases, nonetheless, support this contention. Slow warping and slide of strata could have often created pore-water overpressuring and the deformation structures in consequence.

Conclusions

The tranquil hypersaline lacustrine or lagoonal palaeogeography of deposition promoted selective microbial mat growth within the slowly accreting indigenous dark micritic facies component of the tentatively Mesoproterozoic Chikkshelikere Limestone Member in India. Undermat proliferation of sulfate-reducing bacteria also selectively enhanced the rate of early cementation in the same. In contrast, the allochthonous facies, also carbonate, of light microsparry and driven by weak storm-induced flow remained ductile till consolidation of the carbonate sediments became all-pervasive. In slump folds generated on sediment surface both the facies behaved in the same ductile fashion. Otherwise the dark micritic facies generally underwent brittle fragmentation, while the light microsparry facies responded with intricate folding or ready flowage. Varieties of edge-wise breccias bodies and conglomerate beds formed in consequence. With longer residence time, however, both the carbonate facies turned brittle.

Aseismic tectonism related to long-term geoidal tilt in the strike-slip basinal setting provides perhaps the best explanation for the shallow-depth deformational features almost omnipresent within the Chikkshelikere Limestone Member. Slump folds on depositional surfaces and unidirectional shear folds at the base of subsurface mass flows are consistent with this scheme, although multiple post-depositional folding in the formation prevents determination of the direction of basin-tilt. The palaeogeography of the Chikkshelikere Limestone Member had thus been truly tranquil both in terms of depositional energy as well as tectonism despite having ubiquitous SSDs.

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References

Bachmann, G. H., & Aref, A. M. (2005). A seismite in Triassic gypsum deposits (Grabfeld Formation, Ladinian), southwestern Germany. *Sedimentary Geology, 180,* 75–89.

Bontognali, T. R. R., Vasconcelos, C. G., Warthmann, R. J., Bernasconi, S. M., Dupraz, C., Strohmenger, C. J., et al. (2010). Dolomite formation within microbial mats in the coastal sabkha of Abu Dhabi (United Arab Emirates). *Sedimentology, 57,* 824–844.

Bose, P. K., & Sarkar, S. (1991). Basinal autoclastic massflow regime in Precambrian Chanda Limestone Formation, Adilabad, India. *Sedimentary Geology, 73,* 299–315.

Bose, P. K., Mazumder, R., & Sarkar, S. (1997a). Tidal sandwaves and related storm deposits in the transgressive Protoproterozoic Chaibasa Formation, India. *Precambrian Research, 84,* 63–81.

Bose, P. K., Banerjee, S., & Sarkar, S. (1997b). Slope-controlled seismic deformation and tectonic framework of deposition of Koldaha shale, India. *Tectonophysics, 269,* 151–169.

Bose, P. K., Sarkar, S., Mukhopadhyay, S., Saha, B., & Eriksson, P. G. (2008). Precambrian basin-margin fan deposits: Mesoproterozoic Bagalkot Group, India. *Precambrian Research, 162,* 264–283.

Chen, K. (1991). Interfacial instability due to elastic stratification in concentric coextrusion of two viscoelastic fluids. *Journal of non-newtonian fluid mechanics, 40,* 155–175.

Chen, J. (2014). Surface and subsurface reworking by storms on a Cambrian carbonate platform: evidence from limestone breccias and conglomerates. *Geologos, 20,* 13–23.

Chen, J., & Lee, H. S. (2013). Soft-sediment deformation structures in Cambrian siliciclastic and carbonate storm deposits (Shandong Province, China): Differential liquefaction and fluidization triggered by storm-wave loading. *Sedimentary Geology, 288,* 81–94.

Chen, J., Chough, S. K., Chun, S. S., & Han, Z. (2009). Limestone pseudoconglomerates in the Late Cambrian Gushan and Chaomidian formations (Shandong Province, China): Soft-sediment deformation induced by storm-wave loading. *Sedimentology, 56,* 1174–1195.

Chen, J., Chough, S. K., Chun, S. S., Han, Z., & Lee, J. H. (2011). An extensive erosion surface of a strongly deformed limestone bed in the Gushan and Chaomidian formations (late Middle Cambrian to Furongian), Shandong Province, China: Sequence–stratigraphic implications. *Sedimentary Geology, 233,* 129–149.

Chen, Z., Zhou, C., Meyer, M., Xiang, K., Schiffbauer, J. D., Yuan, X., et al. (2013). Trace fossil evidence for Ediacaran bilaterian animals with complex behaviors. *Precambrian Research, 224,* 690–701.

Deer, W. A., Howie, R. A., & Zussman, J. (1966). *An introduction to the rock-forming minerals* (pp. 1–528). London: Longman Group Limited.

Dey, S. (2015). Geological history of the Kaladgi–Badami and Bhima basins, south India: sedimentation in a Proterozoic intracratonic setup. In R. Mazumder, & P. G. Eriksson (Eds.), *Precambrian basins of India stratigraphic and tectonic context* (pp. 283–296). Memoirs of Geological Society of London.

Dey, S., Rai, A. K., & Chaki, A. (2009). Palaeoweathering, composition and tectonics of provenance of the Proterozoic intracratonic Kaladgi-Badami basin, Karnataka, southern India: Evidence from sandstone petrography and geochemistry. *Journal of Asian Earth Sciences, 34,* 703–715.

Dupraz, C., Reid, R. P., Braissant, O., Decho, A. W., Norman, R. S., & Visscher, P. T. (2009). Processes of carbonate precipitation in modern microbial mats. *Earth Science Reviews, 96,* 141–162.

Enos, P. (1977). Flow regimes in debris flow. *Sedimentology, 24,* 133–142.

Fisher, R. V. (1981). Flow transformation in sediment gravity flows. *Geology, 11,* 273–274.

Goździk, J., & Van Loon, A. J. (2007). The origin of a giant downward directed clastic dyke in a kame (Bełchatów mine, central Poland). In B. Gruszka, A. J. Van Loon, & T. Zieliński (Eds.), *Quaternary geology—bridging the gap between East and West* (Vol 193, pp. 71–79). Sedimentary Geology.

Hips, K., Haas, J., Poros, Z., Kele, S., & Budai, T. (2015). Dolomitization of Triassic microbial mat deposits (Hungary): Origin of microcrystalline dolomite. *Sedimentary Geology, 318,* 113–129.

Hurst, A., Cartwright, J., Huuse, M., Jonk, R., Schwab, A., Duranti, D., et al. (2003). Significance of large-scale sand injectites as long-term fluid conduits: Evidence from seismic data. *Geofluids, 3,* 263–274.

Imbrie, J., & Buchenan, H. (1965). Sedimentary structures in modern carbonate sands of the Bahamas. In G. W. Middleton (Ed.), *Primary sedimentary structures and their hydrodynamic interpretation* (Vol. 12, pp. 149–172). SEPM Special Publication.

Jones, R. R., & Tanner, P. W. G. (1995). Strain partitioning in transpression zones. *Journal of Structural Geology, 17,* 793–802.

Mount, J. F., & Kidder, D. (1993). Combined flow origin of edgewise intraclast conglomerates: Sellick Hill formation (Lower Cambrian), South Australia. *Sedimentology, 40,* 315–329.

Naqvi, S. M. (2005). *Geology and evolution of the indian plate (From Hadean to Holocene- 4 Ga to 4 Ka)* (pp. 109–110). Capital Publishing Company.

Nichols, R. J., Sparks, R. S. J., & Wilson, C. J. N. (1994). Experimental studies of the fluidization of layered sediments and the formation of fluid escape structures. *Sedimentology, 41,* 233–253.

Peacock, D. C. P. (2003). A simple experiment to demonstrate over pressured fluids and soft sediment deformation. *Journal of Geoscience Education, 51,* 410–414.

Pillai, S. P., & Kale, V. S. (2011). Seismites in the Lokapur subgroup of the Proterozoic Kaladgi basin, South India: A testimony to syn-sedimentary tectonism. *Sedimentary Geology, 240,* 1–13.

Põldsaar, K., & Ainsaar, L. (2015). Soft-sediment deformation structures in the cambrian (series 2) tidal deposits (NW Estonia): Implications for identifying endogenic triggering mechanisms in ancient sedimentary record. *Palaeoworld, 24,* 16–35.

Radhakrishna, B. P., & Vaidyanadhan, R. (1994). *Geology of Karnataka* (p. 298). Bangalore.: Geological Society of India.

Ramberg, H. (1955). Natural and experimental boudinage and pinch-and-swell structures. *Journal of Geology, 63,* 512–526.

Sarkar, S., Choudhuri, A., Banerjee, S., Van Loon, A. J. T., & Bose, P. K. (2014). Seismic and non-seismic soft-sediment deformation structures in the Proterozoic Bhander Limestone, central India. *Geologos, 20*, 79–93.

Schieber, J. (2007). Microbial mats on muddy substrates-examples of possible sedimentary features and underlying processes. In J. Schieber, P. K. Bose, P. G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann, & O. Catuneanu (Eds.), *Atlas of microbial mat features preserved within the siliciclastic rock record* (pp.117–133). Atlases in Geoscience.

Seth, A., Sarkar, S., & Bose, P. K. (1990). Synsedimentary seismic activity in an immature passive margin basin, lower member of Katrol formation, Upper Jurassic, Kutch, India. *Sedimentary Geololgy, 68,* 279–291.

Shanmugam, G. (2016). The seismite problem. *Journal of Palaeogeography, 5,* 318–362.

Sharma, M., & Pandey, S. K. (2012). Stromatolites of the Kaladgi basin, Karnataka, India: Systematics, biostratigraphy and age implications. *The Palaeobotanist, 61,* 103–121.

Swift, D. J. P., & Rice, D. D. (1984). Sand bodies on muddy shelves: A model for sedimentation in the western interior cretaceous seaway, North America. In R. W. Tillman & C. T. Siemers (Eds.), *Siliclastic shelf sediments* (Vol. 34, pp. 43–62). SEPM Special Publication.

Thorpe, S. A. (1971). Experiments on the instability of stratified shear flow: Miscible fluids. *Journal of Fluid Mechanics, 46,* 299–319.

Tikoff, B., & Teyssier, C. (1994). Strain modeling of displacement-field partitioning in transpressional orogens. *Journal of Structural Geology, 16,* 1575–1588.

van Lith, Y., Warthmann, R., Vasconcelos, C., & McKenzie, J. A. (2003). Sulphate-reducing bacteria induce low-temperature Ca-dolomite and high Mg-calcite formation. *Geobiology, 1,* 71–79.

Van Loon, A. J. T. (2009). Soft-sediment deformation structures in siliciclastic sediments: An overview. *Geologos, 15,* 3–55.

Van Loon, A. J. T., Han, Z., & Han, Y. (2013). Origin of the vertically orientated clasts in brecciated shallow-marine limestones of the Chaomidian formation (Furongian, Shandong Province, China). *Sedimentology, 60,* 1059–1070.

Visscher, P. T., Reid, R. P., & Bebout, B. M. (2000). Microscale observations of sulfate reduction: Correlation of microbial activity with lithified micritic laminae in modern marine stromatolites. *Geology, 28,* 919–922.

Yih, C. S. (1967). Instability due to viscosity stratification. *Journal of Fluid Mechanics, 27,* 337–350.