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REVIEW

Earthquake induced soft sediment deformation structures in the Paleoproterozoic Vempalle Formation (Cuddapah basin, India)

Madhumita Panja[1] · **Gopal Chakrabarti**[2] · **Debasish Shome**[1]

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Abstract
Soft sediment deformation structures (SSDS) are preserved in a homogenous dolomudstone lithology of crinkly laminated and heterolithic facies of the Paleoproterozoic Vempalle Formation in the Cuddapah Basin. This basin was formed on the eroded basement rocks of the Eastern Dharwar Craton, India. Deformation structures preserved in this succession include combination of breccia and folds, intrastratal faults, cracks, and dikes belonging mostly to a brittle deformation regime associated with ductile imprints. Based on the observed SSDS, their lateral homogeneity and traceability, draping by undeformed strata, proximity of faults as well as apparent lack of storm signatures and gravity induced mass movement, these fine-grained deformed beds can be tentatively ascribed to a large to intermediate depth earthquake with Richter magnitude scale 4 and above, generated during reactivation of basement faults owing to plume related mantle activity. The occurrence of SSDS in the Vempalle Formation emphasizes the role of downwarping along pre-existing planes of weakness in the Archean basement in the evolution of the Cuddapah Basin, analogous to subsidence in present-day continental margin.

Keywords Deformation structures · Vempalle Formation · Cuddapah Basin · India

Introduction

There is no gainsaying that tectonic activity must have occurred during sedimentation in many if not most sedimentary basins. However, the evidence for occasional seismic events is often overlooked or misinterpreted (van Loon 2009, Van Loon 2014; Sarkar et al. 2014; Törő and Pratt 2016). The recognition of such seismic signatures, generally called Earthquake induced deformation features or "seismites" (Seilacher 1969, 1984; Owen 1987; Pratt 1994, Hurst et al. 2011) occur in the form of a variety of soft sediment deformation structures such as convolute bedding, folds and sedimentary dikes, which are preserved in layered heterolithic sediments with contrasting granulometry and composition. These seismites are characteristic of most fluvial, lacustrine, coastal, deltaic and turbidite systems, is now broadly established. Seismites provide valuable insights into basin dynamics, patterns and episodicity of regional syn-sedimentary seismicity (e.g., Pratt 1994, 2001; Weidlich and Bernecker 2004; Marco and Agnon 2005; van Loon 2009; Martín-Chivelet et al. 2011; Patil Pillai and Kale 2011; El Taki and Pratt 2012; Törő and Pratt 2015, 2016).

In the present study, we document Paleoproterozoic examples of syn-sedimentary deformation, expressed in both soft ductile and brittle finely laminated peritidal dolomudstone of the Vempalle Formation, Cuddapah Basin, central India. We characterize these deformed deposits and their structures to highlight the deformation mechanisms and driving forces in an extensional tectonic regime.

Geological setting

Geologic setting of the Cuddapah basin

Peninsular India is composed of a number of cratonic nuclei: the Dharwar, Bastar, Singbhum, and Aravalli-Bundelkhand cratons, and an extensive southern granulite province (Naqvi 2005). Cratonization of India was

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✉ Madhumita Panja
madhumitapanja34@gmail.com

Gopal Chakrabarti
gl_chak@yahoo.co.in

[1] Department of Geological Sciences, Jadavpur University, Kolkata 700032, India

[2] Education Directorate, Government of West Bengal, Kolkata 700091, India

polyphase, but largely complete by 2.5 Ga (Naqvi 2005; Ramakrishnan and Vaidyanadhan 2008; Meert and Pandit 2015), providing a large, relatively stable cratonic framework for the genesis of the widespread intracratonic ''Purana'' basins. The term ''Purana'' is used for all unfossiliferous sedimentary deposits that unconformably overlie penetratively deformed and metamorphosed cratonic elements of India (Holland 1909). These deposits include both major basins as well as a number of smaller regions that may represent erosional remnants of primary basins (Kale and Phansalkar 1991; Chakrabarti et al. 2006; Ramakrishnan and Vaidyanadhan 2008). The distinctly crescent-shaped Cuddapah Basin preserves nearly 12 km of sedimentary and volcanic strata that are assigned to the Cuddapah Supergroup and the unconformably overlying Kurnool Group (Nagaraja Rao et al. 1987; Fig. 1). These strata rest unconformably on the basement rocks of the Dharwar craton, which is composed of Archean TTG gneisses and greenstone belts, as well as several early Paleoproterozoic mafic dike swarms (Nagaraja Rao et al. 1987; Murthy et al. 1987).

The origin of the Cuddapah Basin is still debatable, whether the basin development was variously interpreted as a series of thermal upwarping, rifting, and crustal thinning events (Nagaraja Rao et al. 1987; Chakraborty 2000; Chatterjee and Bhattacharji 2001; Choudhuri et al. 2002; Mohanty 2011; Saha and Tripathy 2012), although a foreland basin scenario has also been suggested (Singh and Mishra 2002). The Papaghni sub-basin opened as a back-arc extensional basin at ~ 2 Ga as a result of westerly directed subduction of oceanic crust beneath the eastern Indian continental margin (Absar et al. 2016). Block faulting has been attributed, in part, to emplacement of a large mafic–ultramafic body under the southwestern part of the basin, from which a variety of mafic sills emanate (Mishra et al. 1987). Strata in the western basin (Papaghni, Srisailam, and Kurnool sub-basins) remain unmetamorphosed and relatively undeformed (Meijerink et al. 1984). The original structure in the eastern part of the basin (Nallamalai and Palnad sub-basins) is obscured by deformation and metamorphism within the Nallamalai Fold Belt (Saha and Chakraborty 2003), which is associated with the uplift of lower crustal

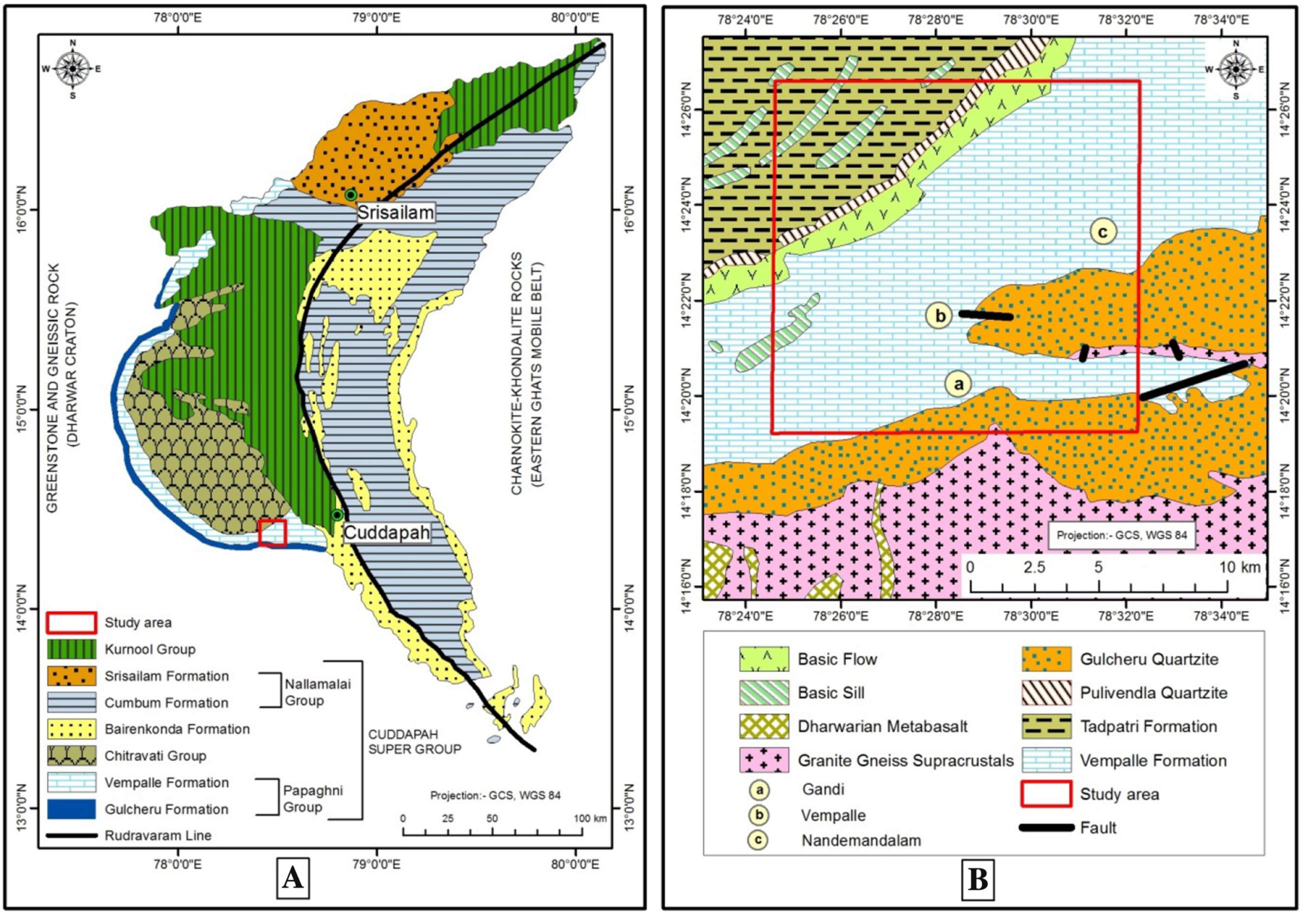


Fig. 1 **a** Geological map of the Cuddapah Basin, India (after GSI 1981). **b** Detailed geological map of the southernmost Papaghni sub-basin showing location of the studied sections (modified after Zachariah et al. 1999)

rocks during development of the Cambrian Eastern Ghats Mobile Belt (Biswal et al. 2007).

Regional stratigraphy of the Cuddapah basin

The general stratigraphy of the Cuddapah basin comprise the Cuddapah Supergroup and its unconformably overlying Kurnool Group. The Cuddapah Supergroup consists of the Papaghni, Chitravati and Nallamalai groups, each separated by regional unconformities (Table 1). Each of these groups is composed, broadly, of a fining-upward succession from quartzite at the base to shale at the top, and is interpreted to represent a shallow-marine shelf that underwent periodic transgressive and regressive events (Chakrabarti and Shome 2007, 2010, 2011; Chakrabarti et al. 2009; Saha and Tripathy 2012; Tripathy and Saha 2013) associated with a combination of tectonic reorganization and eustatic sea level changes (Patranabis-Deb et al. 2012). Whereas the relatively undeformed Papaghni and Chitravati groups, exposed in the western part of the basin, were deposited during successive thermal upwarping and rifting events, the highly deformed Nallamalai Group exposed in the eastern part of the basin likely represents development of active convergence along the eastern margin of the basin (Mishra 2011). The Kurnool Group likely records resumption of an extensional regime via reactivation of basement normal faults in the western part (Chakraborty et al. 2010). Within this context, the Vempalle Formation of the lowermost Papaghni Group, reaching 1500 m in thickness, represents the only regional carbonate deposition within the Cuddapah Supergroup. The Vempalle Formation conformably overlies basal siliciclastic strata of the Gulcheru Formation and is associated with a number of basic volcanic flows in its upper reaches (Murthy et al. 1987). The Vempalle Formation is then overlain with possible unconformity by coarse-grained siliciclastic strata of the basal Chitarvati Group. The Vempalle Formation contains stromatolitic dolomite and dolomitic shale, with subordinate sandstone, and was deposited on a carbonate ramp (Nagaraja Rao et al. 1987; Roy et al. 1990; Dhana Raju et al. 1993).

Geochronological constraints

The age of the Vempalle Formation is broadly constrained by radiogenic isotope ages of a series of mafic dikes and sills. Ages reported from the Vempalle Formation, are from mineralized and non-mineralized dolomite, as c. 1900–2000 Ma by Pb–Pb method (Rai et al. 2015), 1841 ± 71 Ma by K–Ar method(Murthy et al. 1987) and 1756 ± 29 Ma by Pb–Pb method (Zachariah et al. 1999). More recently, the age of the Pulivendla sills has been reanalyzed by 40Ar–39Ar laser fusion techniques on phlogopite, providing an improved age of 1899 ± 20 Ma (Anand et al. 2003).This older age is in good agreement with a recent high-precision U–Pb

Table 1 Stratigraphy of the Cuddapah basin (after Saha and Tripathy 2012)

Supergroup	Group	Formation	Lithology
	Kurnool group	Nandyal shale	Shale
		Koilkuntala Limestone	Limestone
		Paniam Quartzite	Quartzite
		Owk Shale	Shale
		Narji Limestone	Limestone
		Banganapalli Quartzite	Quartzite
Unconformity			
Cuddapah supergroup		Srisailam Formation	Pebbly grit, quartzite, heterolithic shales
		Tectonic contact	
	Nallamalai group	Cumbum Formation(≈ Pullampet Shale)	Shale, dolomitic limestone, quartzite
		Eairenkonda Quartzite(≈ Nagari Quartzite)	Pebbly grit , quartzite, heterolithic shales
		tectonic contact	
		Gandikota Quartzite	
	Chitravati group	Tadpatri Formation	Shale, ash fall tuffs, quartzite, stromatolitic dolomite with malic flows, sills and dykes
		Pullivendula quartzite	Conglomerate and quartzite
		Unconformity	
	Papaghni group	Vempalle Formation	Stromatolitic dolomite, shale, basic flows and intrusives.
		Gulcheru Quartzite	Conglomerate. feldspathic sandstone and quartzite
		Unconformity	
		Archean granites and gneisses	

(baddeleyite) age of 1885 ± 4 Ma obtained on a similar mafic sill in the Chitarvati Group (French et al. 2008). These ages constrain the Vempalle Formation to have been deposited between approximately 2.1 and 1.9 Ga or within the late Paleoproterozoic (Orosirian period).

Studied sections and methods

The Vempalle Formation is well exposed in the southwestern sector of the Cuddapah Basin. Three sections were chosen for sedimentological investigation: the first one exposed on the northern and southern banks of the Papaghni river, beside the Rayachoti–Vempalle Highway, 5 km from the town of Vempalle, near Gandi temple (14°20′2.51″N, 78°28′52.96″E), in and around Kummarampalle and Chintalamadugupalle village; one exposed beside Vempalle town, on northern and southern banks of the river, near V. Swamy temple and around Jr. Vasavi College (14°21′27.74″N, 78°28′16.46″E; 14°21′28.86″N, 78°27′46.63″E) and a third exposed beside Vempalle–Cuddapah Highway, 8 km from the town of Vempalle, in and around Nandimandalam village (14°24′33.84″N, 78°31′39.22″E). A representative lithology has been constructed based on sedimentological and stratigraphic information gathered from these sections (Fig. 2).

Facies associations of the Vempalle Formation

The Vempalle Formation in the study areas is represented by eleven distinct lithofacies types that include (1) Cross bedded gritty quartzite facies, (2) Heterolithic facies, (3) Red shale facies, (4) Lime mudstone/Dolomudstone facies, (5) Massive dolomite facies, (6) Laminite facies, (7) Intraformational conglomerate facies, (8) Columnar stromatolite facies, (9) Domal stromatolite facies, (10) Conical stromatolite facies and (11) Oolitic grainstone facies (Table 2).

These facies types can be grouped into 3 facies associations, they are: tidal flat, intertidal and subtidal (Table 2).

These facies associations are situated on a low-gradient, carbonate ramp that inherited its depositional gradient from the shallow antecedent topography of the Gulcheru siliciclastic shelf (Chakrabarti et al. 2014, 2015).

Earthquake induced soft sediments deformation structures (SSDS)

SSDS are preserved in dolomudstone lithology of crinkly laminated and heterolithic facies and can be grouped into three types of seismites on the basis of their morphology (Table 3): (1) brecciation and folding in the lenticular thin bedded dolomite (similar to some tepee structures); (2) small dikes in the siliciclastic mudstones; and (3) small dikes in the dolomudstone (similar to some molar-tooth structures). These are mostly brittle deformation structures with ductile imprints. Cracks are also preserved in heterolithic facies, which is a brittle deformation structure.

Brecciation and folding

Combination of brecciation and folding in the lenticular thin-bedded dolomite generates some tepee-like structures and are commonly found in heterolithic facies, usually associated with asymmetric folds (Figs. 3, 4), subvertical to lateral cracks/fractures and microfaults/cracks. These structures are defined by roughly and regularly spaced, broad and subangular, decimeter- centimeter sized clasts forming synforms separated by narrow, cuspate antiforms of darker interbeds of silicified carbonates. They have been squeezed around the clasts to some extent (Fig. 3) and vary in size from 2 to 25 cm in height and 3–40 cm width.

Folds of different shapes and sizes ranging from simple, open harmonic to tight isoclinals, disharmonic are found in several deformed layers of heterolithic and laminite facies.

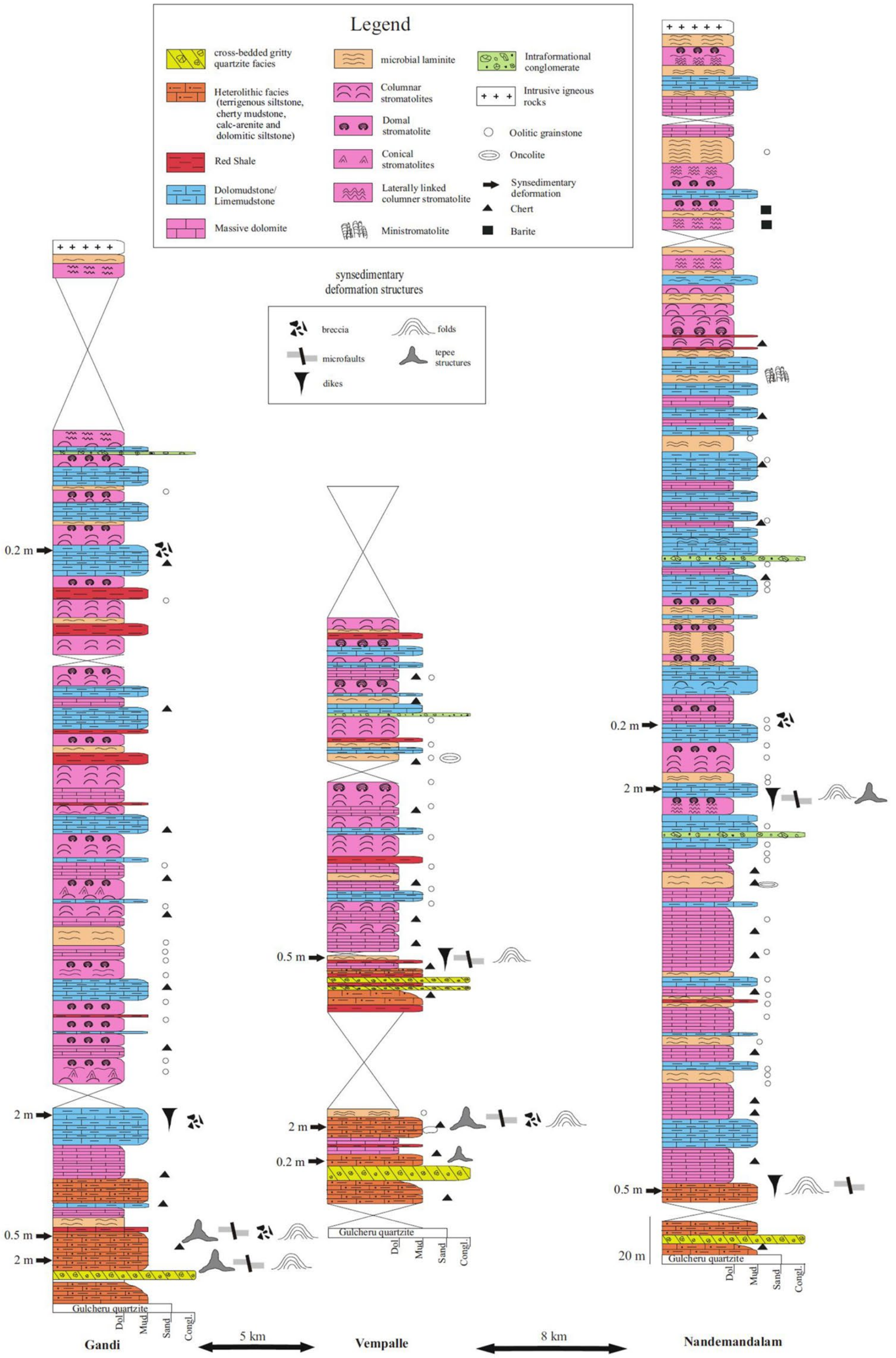
Thin layered, unconsolidated carbonate rocks form asymmetric folds. The characteristic feature of this folded layer is that there is always an undeformed base below the folded unit (Fig. 4). The asymmetric folds which are several cm high (Fig. 5) and extended laterally for less than 2 meters, are also common.

Interpretation: These breccias formed by extension and brittle to semi-brittle deformation and most likely triggered by seismic activity (Su and Sun 2012). Development of disorganized fabric in the brecciated layer suggests liquefaction and flowage (Seilacher 1969). The possible role of vibratory ground shaking by earthquake waves during propagation may be involved for occurrence of irregular lower contact and flat upper contact of the brecciated unit (Pratt 2002a, b). The occurrence of such brecciated layer separated by short interval of undisturbed phase further argues for recurrence of earthquakes.

These tepee structures are produced due to earthquake tremor which helps to compress unconsolidated sediments and subsequent upward intrusion of the plastic material through the zone of relative weakness in the already consolidated overlying layer (Montenat et al. 2007; Su and Sun 2012; Törő and Pratt 2015).

These asymmetric structures are formed under plastic deformational phase. They indicate that the sediment was still soft or semi-cohesive during deformation. When thin layered, unconsolidated carbonate rocks are placed under asymmetrical compressional stress during an earthquake, they form accordion folds that dip in the direction of the stronger stress (Su and Sun 2012). Folds under quasi-solid

Fig. 2 Measured stratigraphic sections of the Vempalle Formation



state are points to hydroplastic rheology of sediments (Martín-Chivelet et al. 2011).

The folded laminated layer sandwiched between undeformed units cannot be explained by slope failure, under the influence of rapid sedimentation and loading. Also their recurrence points to the disturbance occurred in discrete events several times. Hence, it is strongly favored that the folded layers are the product of drastic reduction of shear strength produced by earthquake shaking (Owen 1987). Some similar examples of folded structures have been recognized in seismites of lake sediments (e.g., Rodríguez-Pascua et al. 2000; Marco and Agnon 2005; Spalluto et al. 2007).

Plastic deformation in stromatolitic/laminite layer must have happened at the sediment–water interface or at very

Table 2 Summarized table of the facies types recognized in the Vempalle Formation, Cuddapah basin

Fades association	Fades types	Sedimentary features	Interpretation
Supratidal	Cross bedded getty quarzrite fades	White to greyish-brown, trough cross bedding with paleo flow to the SSE to SE and SW , thin beds (2–15 cm) of shale mudstone with mudcracks are occasionally found interbedded with quartzite sandstone	Generated by small sand dunes, wave-influenced; pebble sized conglomerate represents probably a transgressive lag deposit
	Heterolithic fades	Interbedding of terrigenous siltstone, cherty mudstone, calc-arenite and dolomitic siltstone contains SSDS, cross-stratification and syneresis cracks	Storm dominated shallow marine environment, periodically exposed. SSDS produced due to earthquake tremor
Intertidal	Laminite fades	Thinly{mm thick) interbedded units, wrinkled, rolled and ptygmatic folded laminae indicate compaction effect,, sometimes form laterally linked, low-relief (2–10 cm) stromatolites	Subjected to high energy wave agents, deformed laminite s experienced slight deformation from either tectonic activity siesmic activity or loading (Elmore 19S3)
	Red shale fades	Red coloured, dm to m thick shale, mudcracks are common which curls upward rain drop imprints found	Shallow, quiet water environment, mudcracks indicate exposure in arid supratidal sabkha settings (Shinn 1983)
Subtidal	Dolomudstone Lime mudstone fades	Massive to laminated, 20 cm to 1 m thick beds, dewatering features present maybe straight, curved, sinusoidal sigmoidal or jagged, diagenetic concretions present commonly	Quiet, poorly oxygenated waters below storm wave base
	Oolitic grainstone fades	Fine-to coarse-grained, well-sorted oolitic grain stone, wavy microbial laminae and small-scale cross -lamination present. Beds are 10–50 cm thick	Higher wave agitated environment
	Massive dolomite fades	Light to tan grey in colour, at few places dark grey in colour, diagenetic concretions present commonly, interbedded with dolomudstone, common reddish brown stylolites.	Restricted , shallow subtidal environment
	Intraformational conglomerate fades	Matrix supported, very poorly sorted and composed of rounded to sub-rounded, tabular clasts, ranging from 0.5 mm to 4 mm diameter sized clasts within a dolomite matrix; clast composed of dolomite, mudstone	High energy storm events (Chakrabarti et al. 2014)
	Columnar stromatolite fades	Columns generally are 10–60 cm long and 3–10 cm wide and may be solitary or branching, at places show inclination (5°–8°)	Subtidal environments under high energy condition, inclination of columns may represent the dominance of unidirectional waves or currents (Hoffman 1967)
	Domal stromatolite fades	Forming laterally linked (Logan et al. 1964) or isolated mounds with generally low-relief (< 1 m). Domes are hemispherical to slightly elongated	Shallow subtidal environments under episodic agitation
	Conical stromatolite fades	Observed average height of 10 cm and width of 4 cm, with 10 centimetres of synoptic relief. Steeply dipping (> 70°) with narrow, acute apexes. Fades are laterally discontinuous	Quiet water environment, below wave base

Table 3 Summarized table of the SSDS recognized in the Vempalle Formation, Cuddapah basin

Litho fades	Deformation types	Deformation features	Description	Interpretation
Heterolithic fades	Brittle deformation features with minor ductile	combination of brecciation and folding	Buckling and brecciation of light grey thin to medium bedded dolomite forming antiform tepee structures characterised by buckled margins and several fractures, the darker interbeds of silicidfied carbonates have been squeezed around the clasts to some extent 2–25 cm height and 3–40 cm width. Simple, open harmonic to tight isoclinals, disharmonic folds of mm to cm scale, undeformed base along with faults with displacements from mm to cm scale	Teepees involving desiccation, thermal expansion and contraction fluctuating groundwater pore pressure or diagenetic force of crystallization and can be explained as breccias generated by sporadic episodes of strong ground motion from earthquakes that emanated from a syndepostionally active fault system nearby (Pratt 2002a). These breccias are likely formed by extension and brittle to semi-brittle deformation, most likely triggered by seismic activity (Su and Sun 2012). Recurrence of folded layer points to the disturbance occurring in discrete events several times. Folds are the product of drastic reduction of shear strength produced by earthquake shaking (Owen 1987). The intrastratal faiths are likely to be formed by extension under brittle to semi-brittle deformation, most likely triggered by seismic activity
Both Heterolithic and Laminite fades	Brittle deformation features	arrays of small dikes in the siliciclastic: mudstones	Cracks about 2-20 mm wide, few cm long and vary from ragged lenses to lines which may be straight, curved, sinusoidal, sigmoidal or jagged	Cracks are formed as instantaneous intrastratal shrinkage and dewatering, usually accompanied by liquefaction and injection of interbedded silts in all directions during ground shaking by syn-sedimentary earthquake (Pratt 1994) due to association of other syn-sedimentary earthquake induced SSDS
Both Heterolithic and Laminite fades	Brittle deformation features	array of small dikes in the dolomudstone	Microspar filed dykelets, a few mm to a cm wide	Vein arrays and dykelets are likely to be formed by short wavelength shear waves which segregates the finer particles (Brothers et al. 1996; Ohsumi and Ogawa 2008; El Taki and Pratt 2012)

Fig. 3 Tepee-like structures involve folding, thrusting, displacement, faulting and brecciation in the lenticular thin bedded dolomite along with darker interbeds of silicified carbonates, which have been squeezed around the clasts from Gandi, 25 m above base. Scale: Length of chisel 10 cm

Fig. 4 Deformed units associated with asymmetric folding, faults are overlain and underlain by undeformed units from Gandi, 25 m above base. Scale: length of hammer 31.8 cm

shallow burial depth due to the likelihood of early diagenetic cementation (Sumner 1997). Small-scale folds and convoluted bedding have been reported in microbialites from both shallow- and deeper-marine settings (Pratt 1994; Schieber 1999; Kahle 2002; Schieber et al. 2007; Pruss et al. 2010; Martín-Chivelet et al. 2011). Here, folded stromatolites/laminites intercalated within dolomudstone, indicate an overall low-energy setting. Where folding is associated with fluid-escape and disruption indicating increased pore pressure, deformation must have occurred intrastratally.

Contemporaneous folding and brecciation indicates that the sediment was in a semi-cohesive state when combined brittle–ductile deformation occurred. Deformation is focused within distinct intervals which indicate that shearing was concentrated at these horizons.

Fig. 5 Larger folds consisting of laterally folded lamina where the upper surface of folded interval is truncated by planar surface whereas the degree of folding dies out downward, from Gandi, 80 m above base; Scale: length of scale 15 cm

The intrastratal faults are likely to be formed by extension under brittle to semi-brittle deformation, most likely triggered by seismic activity. They are brought about by unequal confining load, gravitational instability and shear stress resulting in brittle failure (Owen 1987). The associated folds indicate that deformation sometimes occurred in the brittle–ductile field transition within semi-cohesive sediment. Gradual disappearance of the microfaults upwards and downwards indicate that they formed intrastratally, and not at the sediment–water interface (Pratt 1994; Kahle 2002; El Taki and Pratt 2012; Törő and Pratt 2015).

Dikes in siliciclastic mudstones

Network of small dikes are found at the top of mudstone layer in heterolithic facies (Fig. 6). In the plan view, they are about 2–20 mm wide, few cm long and vary from ragged lenses to lines which may be straight, curved, sinusoidal, sigmoidal or jagged. They may be parallel or randomly oriented and either discrete or interconnected. Resulting configurations are thus often rectangular to polygonal with variable degrees of completeness. In some units, individual cracks penetrate numerous beds. Cracked beds typically exhibit tabular pattern. In some lime-mudstones layer, cracks may be preserved initially as small cavities (cf. Weaver 1989). However, they are filled with silt and sand derived from either overlying or underlying thin beds and laminae.

Interpretation: the cracks may be formed due to the effects of fluctuating salinity (Plummer & Gostin 1981). The cracks can be interpreted as instantaneous intrastratal shrinkage

Fig. 6 Cracks of various width filled with weathered dololutite that has injected from lower heterolithic facies, developed on red coloured laminated mudstone, from Gandi (Kummarampalle), 60 m above base. Length of hammer 31.8 cm

Fig. 7 Plane and locally lenticular-laminated argillaceous dolomudstone (subtidal association) with mostly upwardly directed dikes composed of dolomicrospar (molar-tooth structure). Rock surface cuts dikes giving varying widths, indicating they form a reticulate pattern on the bedding plane, from Gandi, + 60 m above base. Length of hammer 31.8 cm

and dewatering, usually accompanied by liquefaction and injection of interbedded silts in all directions during ground shaking by syn-sedimentary earthquake (Pratt 1994) due to association of other syn-sedimentary earthquake induced SSDS. Syneresis cracks are widely recognized sedimentary structures in argillaceous rocks. They are common in Proterozoic strata and Phanerozoic lacustrine facies. These are mainly formed due to subaqueous shrinkage whereby salinity changes caused deflocculation of clay (Pratt 1994).

Dikes in dolomudstone

Generally sedimentary vein-arrays and dykelets which found within heterolithic facies, are described as centimeter- to meter-scale cracks or fissures filled with sediment that differs in lithology from their host, irrespective of the infilling sediment and its source, or the process of formation although they may be filled with clay, silt, or carbonate mud (e.g., Montenat et al. 2007). Sporadically present intervals of arrays of mainly vertically oriented predominately wide, filled with clayey dolomicrite are also observed in intercalated carbonate mudstone and calcareous siltstone and laminite layer (Fig. 7). Microspar filled dykelets, a few mm to a cm wide are also associated with such vein arrayed layer. Short (< 10 cm) downward tapering dikes are mostly common in intervals of laminated or thinly bedded dolomitic siltstone at several places. The infill of the dikes is usually structureless or internally churned showing mixing of the sediment and lacking vertical or horizontal lamination (Fig. 8). Host sediments commonly show folding, loading, microfaults.

In cross-section, the dikes are vertical to subvertical features and penetrate downwards from multiple horizons of structureless silt intervals with rip-up clasts of massive dolostones. The dikes show irregular widening and narrowing, and individual dikes may break up into multiple swarms along with sideway protrusion, forming a dense network. The shale layer lying on this layer exhibiting profuse development of mudcracks and raindrop imprints.

Interpretation: Sedimentary dikes and sills generally form by dewatering, fluidization, and injection of granular material at elevated pore pressure leading to the formation of upward-propagating dikes (e.g., Hurst et al. 2011). However, dyke network in the studied section, are usually downward-tapering features, indicating downward propagation.

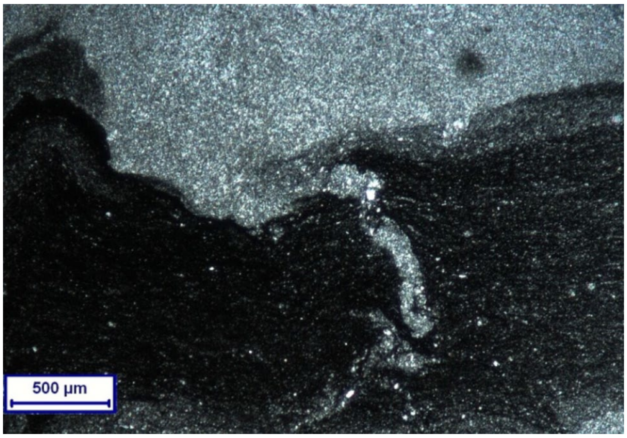


Fig. 8 Photomicrographs of dikes within dolomudstone, dikes filled with dolomicrospar with some admixed subangular silt, under crossed-polarized light from Gandi (Kummarampalle), 25 m above base

Vein arrays and dykelets are likely to be formed by short wavelength shear waves which segregates the finer particles (Ohsumi and Ogawa 2008; El Taki and Pratt 2012).

The dense network of dikes and associated brecciation of the host deposits, the common sideway protrusions (sills), and the structureless nature of the sedimentary fill together indicate short-lived elevated stresses and forceful injection of the remobilized sediments into fractures (e.g., Daley 1971; Owen 1987).

The deformed and structureless infill, along with the isolated cracks, indicates that dike fills are resulted from the remobilization and injection of liquidized granular material. In the case of dikes that occur in sublittoral deposits, upward emplacement, if present, together with the lack of scouring features by erosive lake-floor processes, indicate an intrastratal origin, which requires elevated pressure (e.g., Hempton and Dewey 1983; Alfaro et al. 1997; Pratt 1998; Rodríguez-Pascua et al. 2000; Berra and Felletti 2011; Plaziat et al. 1990).

Discussion

Origin of deformation

The series of syn-sedimentary deformation features preserved in the Vempalle Formation have been generated by a variety of triggering mechanisms, which are grouped into two types (1) non-seismic and (2) seismic.

Non-seismic mechanisms

Non-seismic mechanisms include essentially gravitational slumping, storm impacts, biogenic activity, rapid sedimentation and cryogenic/thermokarstic perturbations. Gravitational slumping as a triggering mechanism is ruled out owing to deposition of sediments in shallow epicontinental sea on an initially flat bottom, and there is no evidence of requisite slope as revealed from facies analysis of the Vempalle sediments (Chakrabarti et al. 2014). The influence of storms on sediments as revealed by the occurrence of hummocks or swales or gutter casts are not found in the area of study which point to a general tranquil depositional environment below effective wave base (Pratt and Haidl 2008; Patil Pillai and Kale 2011). Rapid sedimentation often acts as a triggering mechanism to deformation. The abundance of planar lamination preserved throughout the Vempalle Formation clearly falsifies the above argument (El Taki and Pratt 2012). Sometimes during orogeny, syn-sedimentary deformation takes place (Ortner 2007). This process also seems unlikely given the absence of regional compression throughout this formation. Dominance of stromatolites points to tropical humid climate (Pratt 2001) and hence, cryogenic/thermokarstic perturbation or subglacial hydrofracturing as triggering mechanism for deformation is not favored. The possibility of abundant bioturbation in Vempalle carbonates of Paleoproterozoic age based on the available geochronological information seems quite unlikely on biological evolutionary ground during Paleoproterozoic (cf. Patil Pillai and Kale 2011).

Seismic mechanism

Some of the SSDS may be attributed to have been produced due to slope failure or storm if we ignore the geometry of substrate without significant gradients; the persistence of flat uniform bedding during the deposition of more than 1 km of thick sediments (Nagaraja Rao et al. 1987) seems to be enigmatic. Hence earthquake induced strong ground shaking seems to be the most plausible alternative as triggering mechanism of SSDS of dolomudstone of the Vempalle Formation owing to paucity of evidence in favor of other non-seismic triggering mechanism discussed above. The seismic activity may be associated with the reactivation of basement fault of the Cuddapah basin (Fig. 1) during the deposition of the Vempalle Formation. There are numerous examples of such types of SSDS associated with reactivation of basement fault (e.g., Singh and Jain 2007; Törő and Pratt 2016; Ezquerro et al. 2016; Basilone et al. 2016; Liesa et al. 2016; Verma et al. 2017).

The SSDS of the Vempalle carbonates grossly fit into the criteria that permit the interpretation on soft sediment deformation as initiated by seismic activity are summarized below (Sims 1973, 1975; Hempton and Dewey 1983; Anand and Jain 1987; Rossetti 1999; Ettensohn et al. 2002; Wheeler 2002; Töro et al. 2015; Törő and Pratt 2015, 2016).

1. Wide ranging occurrences in different facies (crinkly laminite facies and heterolithic facies) of transgressive supratidal facies association points to environmentally independent triggering mechanism for deformation (cf. Patil Pillai and Kale 2011).
2. The structures present in a sedimentary succession of rift basin. Seismic phenomenon is common in such rift basin due to movements of intra-basinal faults.
3. The soft sediment deformation structures are restricted to stratigraphic levels punctuated by entirely undeformed strata. This clearly indicates the instantaneous nature of the triggering mechanism affecting only specific beds.
4. Lack of fixed periodicity is one of the criteria for earthquake. Here also, there is no fixed interval between the seismic events which produced SSDS. Hence the deformation events are episodic in nature.
5. The deformed sediments are mostly fine-grained and thinly laminated lacking any evidence for gravity induced mass movement or sudden sediment loading.

6. Lateral traceability of the deformed layer over several hundreds of meters (Patil Pillai and Kale 2011).
7. Proximity to faults (Fig. 1).
8. The absence of structures indicating abrupt fluid escape.

Earthquake characterization

Surface and near surface sediments respond to seismicity by a wide variety of ways such as plastic deformation, brittle deformation and liquefaction owing to the combination of compression and extension, variable directed shear stresses and cyclic pore pressure increase (Obermeier 1996; Trifunac 2011). Many authors (Berra and Felletti 2011) consider Richter magnitude > 5 as the lowest magnitude that can produce significant liquefaction near surface, water saturated, semi-consolidated or unconsolidated sediments. Whereas laboratory experiments simulating earthquake shaking have produced the formation of convolute bedding (Owen 1996; Moretti et al. 1999), vein arrays are formed by short wavelength S-waves segregating the finer particles (Brothers et al. 1996; Ohsumi and Ogawa 2008). Loop-bedding structures (small scale boudins) seem to be developed in lacustrine, cohesive laminated sediments correspond to seismicity with magnitude < 4 (Rodríguez-Pascua et al. 2000). Most of these studies correlating between seismically induced structures and earthquake intensity should, however, be applied very carefully while predicting the seismic intensity from SSDS in a particular study area (Martín-Chivelet et al. 2011).

Liquefaction phenomena decrease as one move from the epicenter (Sims 1975; Mohindra and Bagati 1996; Moretti and Tropeano 1996; Blanc et al. 1998; Galli 2000). Hence, distance from the foci of the earthquake is also very important to predict the magnitude of earthquake from the preserved SSDS. Besides these general criteria, interpretations of paleo-seismicity heavily depend on the local stratigraphic/tectonic setting (Berra and Felletti 2011). A shallow (< 5) hypocentral depth remits in severe ground shaking close to the epicentral area than a deeper earthquake and thus creates more liquefaction structures. Away from epicenter, however, intensity of ground shaking gets diminished for a shallower earthquake than a deeper one (Obermeier 1996). As a result, deeper earthquakes can generate liquefaction at greater distance from the epicenter than shallower earthquakes. The observed seismically induced deformation structure of both ductile and brittle nature of high density seems to indicate that the study area is close to the basement faults bordering the extensional basin which are reactivated repeatedly during the evolution of Cuddapah basin (Tripathy and Saha 2013) and that seismic activity is frequent. It also follows that the intensity of earthquakes affecting Vempalle sediments have in all probability of magnitude of approximately 4 or greater and have repeatedly affected deposition in the study area producing widespread sediment failure, folding, faulting, cracking, etc., in unconsolidated or semi-consolidated state.

The paucity of some deformation structures such as flames, ball and pillow structures, sand dykes, sand volcanoes, pseudo-nodules, load structures, etc., which are commonly related to seismicity are due to the control exerted by partially consolidated laminites. The calcareous fine-grained of the Vempalle sediments with layer cohesion resists liquefaction or fluidization with more ease than greater grain size (Allen 1982), whereas the absence of sandy deposits and mostly homogenous nature of deposits prohibits the development of density gradients and consequent gravitational instabilities within the sediments, the texture and the rheology of the semi-consolidated, thinly laminated deposits strongly favors the nature of SSDS and their degree of deformation (Martín-Chivelet et al. 2011) in addition to seismic trigger. Hence, the deformed beds of the Vempalle Formation with apparent absence of liquefaction/fluidization structures do not seem to be necessarily point to a low intensity earthquake. The wide lateral extent of the deformed beds and also the great homogeneity of its deformational features seem to indicate probably a large, deep-seated earthquake affecting wide areas in the basin.

Tectonism and sedimentation

The occurrence of SSDS in the Vempalle Formation is also very significant given the fact that a fault bounded or possibly a rift model for the early stage of evolution of the Cuddapah basin (Ramakrishnan and Vaidyanadhan 2008). The early fill in the Cuddapah basin like all other Purana basins in India is thought to have been formed by Proterozoic shallow-marine transgression on the eroded crystalline basement of the Indian shield (Saha and Tripathy 2012; Tripathy and Saha 2013) and subsidence of sediments seems to have been thermally (i.e., thermal relaxation following a plume) rather than tectonically controlled (Chakrabarti et al. 2014). While we do not gainsay the possibility of thermal subsidence having merit during the earliest phase of basin initiation (particularly during the deposition of basal Gulcheru Formation), the occurrence of seismites along with facies distribution patterns (Chakrabarti et al. 2014) suggests that brittle failure of the upper crustal domain (as well as hydroplastic response), downwarping along pre-existing planes of weakness in the Archean basement plays an important role in the later evolution of the Cuddapah basin, particularly during the deposition of Vempalle Formation similar to the subsidence observed in present-day continental margins (Patil Pillai and Kale 2011). The unconsolidated or semi-consolidated sediments of the Vempalle Formation which are subjected to an earthquake probably causes instability in sediments related to the reactivation of basement faults dissecting the original continental margin. The magnitude of the seismic events were enough to fluidize and liquefy the sediments and thus to produce a plethora of SSDS, within several kilometers of the faults (cf. Kundu et al. 2011).Thus the SSDS may be the result of seismotectonic sequences in the broad extensional set-up of the Cuddapah Basin during Paleoproterozoic time. However, this postulate is amenable to further scrutiny of entire Cuddapah sediments and also of global Proterozoic epicratonic sediments correlative to the Cuddapah Basin.

Conclusions

The soft sediment deformation forms early after sedimentation in the fine-grained, semi-consolidated cohesive sediments of crinkly laminite and heterolithic facies of the carbonate dominated Vempalle Formation. Deformation takes place in the finely laminated dolomudstone beds on a nearly horizontal surface in an extensional regime during development of a low gradient ramp, where distribution of laminites are depth partitioned (Chakrabarti et al. 2014). In the absence of well defined slope, deformation could start shortly after reduction of cohesive behavior of fine-grained sediments which behaves in a hydroplastic way. The coexistence of ductile deformation features like boudinage or loop-bedding, diapirs, convolute bedding and folds with other brittle features like intrastratal faults, syn-sedimentary breccias, cracks and vein-arrays points to deformation occurring in ductile–brittle transition. The deformed sediments quickly recover its viscosity and shear strength after the cessation of the rapid, intense deformation episode and this favors the preservation of all SSDS without any subsequent change. The flat lying non-deformed laminites drape over these deformed sediments in a quiet environment without significant disturbance. These SSDS are best explained by seismic activity, probably associated with reactivated basement faults as a result of plume activity in crust-mantle boundary which may be related to assembly and fragmentation of Paleoproterozoic Columbia Supercontinent (Nance et al. 2014). The unconsolidated to semi-consolidated sediments are subjected to ground tremors generated during dislocations of the basin floor during earthquake which causes instabilities in sediments resulting in the observed SSDS. The occurrence of seismites in the epicratonic Cuddapah basin on Eastern Dharwar craton, initiated to rifting of eroded Archean crust and subsequent transgressive encroachment of the contemporary sea onto the Archean crust (Singh 1980; Radhakrishna 1987; Jayaprakash 2007), points also to the intimate interplay of tectonism and sedimentation during Paleo-Mesoproterozoic times on the Eastern Dharwar Craton.

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