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**SOFT-SEDIMENTARY DEFORMATIONAL STRUCTURES: SEISMITES OR PENECONTemporaneous, A STUDY FROM THE PALEOPROTEROZOIC LESSER HIMALAYAN SUCCESSION, INDIA**

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**PALEOPROTEROZOIC SEDIMENTARY SUCCESSION OF THE LESSER HIMALAYA CONTAINS SOFT-SEDIMENTARY DEFORMATIONAL STRUCTURES (SSDS) CAUSED DURING FLUIDIZATION AND LIQUEFACTION INDUCED BY SEISMIC ACTIVITY. Morphologically, the SSDS ARE REPRESENTED BY CONVOLUTE BEDDING/LAMINATION, BALL-AND-PILLOW, PSEUDONODULES, AND DEFORMED CROSS-STRATIFICATION AND FLAME STRUCTURES. AFTER EXAMINING ALL OTHER FACTORS, IT IS INFERRED THAT THE SSDS ARE THE RESULT OF SHOCKS, WHICH CAN ONLY BE EXPLAINED SATISFACTORILY AS TRIGGERED BY EARTHQUAKES.**

**KEYWORDS:** Damtha Group, Lesser Himalaya, palaeoproterozoic, seismites, soft-sedimentary deformational structures.

**SOFT-SEDIMENTARY deformational structures (SSDS) are a record of processes during a deformational event that affected unconsolidated sediments at or near the contemporary surface prior to, or soon after burial. SSDS can develop only in the presence of susceptible sediments; forces that can cause deformation, and trigger mechanism. When the trigger is related to seismic shocks, the deformed layers are defined as seismites. Liquefaction or fluidization is the most important agent for the development of SSDS in water-saturated and cohesionless sediments. Liquefaction/fluidization in unconsolidated sediments may be triggered by several processes like seismic shaking, overloading, groundwater movements and effect of storm waves. The most sensitive sediments are fine-grained (silty) material with contrasting grain size, such as alternately homogenous fine sand or silt and shale beds. Seismites are found more commonly in alluvial plains, tidal flats, deltaic, estuarine, bay head and lacustrine/palustrine domains. In general, seismic shock-induced deformational structures are associated with earthquakes of magnitude > 5 (ref. 5). From the Indian subcontinent, the seismogenic Proterozoic SSDS were perhaps first documented from the Mesoproterozoic Koldhaha shale of the Vindhyian basin. Subsequently, Bhatacharya and Bandyopadhyay, and Mazumder *et al.* also reported the same from the Palaeoproterozoic tidal

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succession of Chaibasa Formation, Singhbhum crustal province. SDDS interpreted as seismites have been described from Indian sedimentary succession as old as 2100 Ma (ref. 9). SDDS are often reported as ‘penaecontemporaneous’ in the literature, especially from the Damtha Group of the Garhwal Lesser Himalaya. However, till date these structures lacked proper documentation about their genesis. The present study intends to establish whether the SDDS of the Damtha Group could be considered as seismites. The study is concentrated within the argillite-siliciclastic succession of the Damtha Group, having a lateral stretch of nearly 110 km from Chakrata to Satpuli through Naibag-Damtha, Shyvupuri sections (Figure 1).

The sedimentary succession in the Lesser Himalaya discussed in this communication, particularly in the western sector is exposed roughly in two linear belts (Figure 1). The southern belt represents the oldest sediments (Damtha Group) in the Lesser Himalaya10,11. The Damtha Group comprises basal argillite and argillite-siliciclastic rhythms of Chakrata Formation and upper, fine to medium (occasionally coarse) grained siliciclastic arenites with prolific interbedded mafic volcanic flows12 of Rautgara Formation. The age of the syn-sedimentary 1.8 Ga mafic volcanics13 makes the Damtha Group, the oldest (older than 1.8 Ga) sedimentary succession in the Lesser Himalayan belt. The Palaeoproterozoic Damtha Group of sediments exhibits depositional sedimentary structures, such as parallel and wavy laminations/stratification, wave and current ripples, small to medium scale trough cross-stratification, flaser bedding, flute casts, load casts, tool marks, scour marks and interbedded SDDS (e.g. ball and pillow, pseudonodules, convolute laminations/stratification and deformed cross-stratification). The Damtha Group preserves a thick package of shelf deposits. The lower part of the shelf succession is characterized by argillite (mud)-dominated (Chakrata Formation) succession with signatures of deposition in tidal environments, whereas its upper part (Rautgara Formation) comprises sand bodies, often amalgamated as extensive sand sheets. The development of a thick coarsegrained upward sand-dominated succession overlying an argillite (mud)-dominated shelf sequence with a sharp interface points to an abrupt fall in relative sea-level with consequent changes in the depositional processes. However, Rupke14 and Valdiya11 have argued that the presence of graded bedding and syn-sedimentary (soft-sediment) deformational structures suggest deep marine depositional environment but the latter features are not exclusive to deep marine environment as these could also develop under conditions of relatively rapid sedimentation and basin instability15. Further, the sedimentary structures and the absence of ideal Bouma sequence also favours shallow marine muddy shelf conditions of deposition. Rapid sedimentation is in conformity with the moderate to low textural maturity of the sediments and the rift setting inferred from the associated volcanics16. The gradual upward shift from argillite (mud)-dominated to siliciclastic (sand)-dominated (Rautgara/Nagthat Formation) and subaerially erupted volcanics-dominated packages coupled with the occurrence of several gravelly beds in the upper part favours unstable basin.

Sims17 proposed the seven-point criteria for relating the SDDS as palaeo-seismites in the rock records. These are (i) proximity to coeval active seismic zones; (ii) presence of potentially liquefiable sediments, (iii) similarity to structures formed experimentally, (iv) small-scale internal structures within deformed beds, (v) deformed structures sandwiched between undeformed beds, (vi) zones of structures correlatable over large areas, and (vii) absence of slopes. Most of the structures mentioned here are similar and already been recognized as related to seismic activity2,4,8,17-20. The Palaeoproterozoic sediments of the Chakrata Formation (Figure 1) bear clear fingerprints of seismic events generally confined to contrasting grain size zones (siliciclastic–argillite interface) and sandwiched between undeformed beds (Figure 2a). The most extensive outcrops of the SDDS in the Chakrata Formation are described here.

Convoluted bedding/lamination structures have widespread distribution throughout the lateral transect. Convolute bedding consists of regular to irregular contortions of laminated beds and is few millimetres to 30 cm thick. These thin-contorted laminae beds alternate within sandstone (siliciclastic)/siltstone and shale (Figure 2b), observed on top of the sandstone (siliciclastic)/siltstone and shale alterations which are undisturbed and are planned off towards its top. Some of these contorted laminations are continuous and others are discrete lobes and may be called as ‘load convolution’21. The internal lamination is better preserved and is thicker in the troughs than near the crests, where fluid-escape channels often pierce locally (Figure 2c).

Ball-and-pillow structures are commonly noticed in all the studied sections; however they are more prevalent along Naibag–Damtha section. Ball-and-pillow structures are 10–40 cm thick, also referred as saucer structure22 and load structures, which have become detached and foanded into underlying shale and form a series of shallow bowl-like structures (Figure 2d). In some cases, ball or pillows may exhibit bedding that has been completely upturned to form concentrically laminated ‘ovoids’. Entire saucers may be inclined slightly from the horizontal; however, in most cases the orientations do not show consistency. Some of the soft-sediment deformed beds show sand-in-sand loading23 internally massive with convex lower and plano-convex upper surfaces resemble the pillow-beds. Pseudonodules vary in size (0.1–0.2 m in width and 0.05–0.25 m in height) and geometry (from semicircular to elliptical). Laterally persistent pseudonodule-bearing mud layers (Figure 2e) are commonly observed in the
**Figure 1.**  
- **a.** Map showing the divisions of the Himalayan orogen.  
- **b.** A part of geological map of the western Garhwal Lesser Himalaya (Valdiya1).  
- **c.** Generalized lithology of the Damtha Group of sediments.  
- **d.** Lithosections at three different locations, showing the distribution of SSDS zones from the Chakrata Formation of the Palaeoproterozoic Damtha Group. Note: SSDS are abundant in the ND section.
siliciclastic–argillite alternation (rhythmite) facies and noticed in abundance around the Chakrata and Damtha regions. The pseudonodules show low relief and truncation in the lower and upper part respectively. Pseudonodules are irregular and show a form-discordant relationship among their boundaries. Kuenen34 described his experiments on formation of pseudonodules, with testing of a scaled earthquake-trigger.

In the siliciclastic (sandy) facies around Nainbag–Damtha and Shivpuri section, the trough cross-stratifications are deformed to varying degrees and exhibit a different type of fold pattern. Lateral alternations of deformed and undeformed zones occur regionally in cross-stratified/deformed cross-stratified units. In their simplest form, the deformations appear as recumbent folds that pass into undeformed foresets. This type of structure is rare in other sections.

The flame-like injection structures observed in the Chakrata Formation are penetrative in nature, which in cross-section, may attain amplitudes of up to 20 cm. Silty shale injection in the form of smaller shale tongues, occurs laterally between ball and pillow structures and larger sandy beds (Figure 2e and f). Smaller tongues, primarily composed of shale are termed flame structures. Dimension-wise these features are larger in the Nainbag–Damtha section.

It is generally agreed that convolute bedding/lamination occurs due to partial liquefaction and loss of strength in sediments associated with dewatering processes25,26. The most commonly invoked mechanism involves elevation of pore pressures in sediment layers; as may occur during sudden episodes of consolidation (e.g. earthquake shaking). During the shaking events the pore pressures are temporarily elevated resulting in
the loss of grain-to-grain contact and temporary loss of strength because of localized expulsion of pore water\textsuperscript{27–29}. The convolute structures are restricted to certain intervals, suggesting that the required conditions were met only in specific moments of time. The occurrence of undeformed horizons above and underneath strengthens the hypothesis of a seismic origin of the convolutions\textsuperscript{30}.

Experimental studies show that a reverse density gradient is sufficient to create considerable deformation, given a mechanism of episodic loading to destabilize the mud for ball-and-pillow structures to generate\textsuperscript{31}. The fact that most interbedded muds and coarser grained beds do not show load casting at their interfaces indicates that formation of large scale-load and pillow structures is not a normal or typical process. However, Hildebrandt and Egenhoff\textsuperscript{29} interpret the development of load structures in two stages in a situation similar to that of the present case as: (i) high sedimentation rates in an intercalated mud and sandstones facing tectonic activity (in this case, triggered by syn-sedimentary mafic volcanics) causing seismic shaking and potential fine-grained sands undergo liquefaction and (ii) the sediment water mixture intrudes in the overlying strata and rises along vertical or steep inclined conduits as soon as the forces of the pore fluid exerted on the sediment grains exceed the downward directed gravity force.

Roep and Everts\textsuperscript{23} explained that the sand-in-sand loading may be due to overloading, sliding or seismic shock. We prefer a seismic origin on the basis of the occurrence within undeformed layers. The size and nature of these pillow-beds may indicate an earthquake with a magnitude of 6–7 on the Richter scale\textsuperscript{23}.

The pseudonodules genetically related to ball-and-pillows that propagate as an intra-formational phenomenon and formed in response to density contrasts in unstable layered systems. They are not connected to any particular environment and are known in both shallow-water settings and turbidite deposits, being indicative of rapid sedimentation of the unit with which they are associated\textsuperscript{35}. The occurrence of undeformed silty sandstone draping the pseudonodule suggests: (i) deformation took place shortly after deposition, and (ii) sedimentation continued thereafter in a calm set-up. This implies that the deformation was syn-sedimentary or otherwise there was a short break in sedimentation. The striking lateral persistence of the pseudonodule-bearing silty sandstone beds points to a mechanism that affected a large area. Further, the deep foundering of the pseudonodules well into the silty shale/sandstone beds suggests that the mud bed was presumably in a quasi-liquid state after a shaking\textsuperscript{32}. The truncated top indicates that the erosion occurred shortly after deformation. Field study infers that the intensity of deformations had apparently been uniform for each layer of these beds although it may be different in other horizons. The sandwiched pseudonodule beds between undeformed beds suggest that the deformation took place due to forceful escaping of entrapped pore water. Such forceful escaping of entrapped pore water and that too within fine sediments where porosity and permeability is low, the triggering process cannot be reconstructed on the basis of the structures themselves but an external mechanism, such as an earthquake induced shock\textsuperscript{37}.

The deformed cross-stratified sets are overlain by deformed or undeformed cross-stratified sets but their boundaries invariably remain undisturbed, thus establishing unequivocally that the deformation processes occurred before burial (meta-depositional stage\textsuperscript{3}). Complex recumbent folds imply total fluidization of a bed\textsuperscript{33}. The stratigraphic position and the distortion of bedding suggest that the structures are seismogenic. The feature was formed by distortion of liquefied sand that was cross-stratified at the time of deformation.

The presence of flames is a diagnostic feature of a deformation process referred to as reverse density gradation. The alignment of elongate, platy particles parallel to the margins of the sediment wedge appears to reflect a shear fabric produced by the passage of sediment containing larger particles through a constricted ‘conduit’ between adjacent balls or pillows. Foundering layers of denser sediment may trigger the upward movement of initially underlying liquefied/fluidized thixotropic mud and contained particles\textsuperscript{34}.

SSDS refer to the disturbance of primary features in unconsolidated sediments while they are at or very close to the sediment surface, and typically occur during or shortly after sedimentation. The detection of suitable proxy of seismic events in ancient succession, if possible, is of paramount importance in interpreting palaeoenvironmental conditions such as hydrodynamic conditions, palaeo-slope orientation, or syn-sedimentary seismic or tectonic activity. The ability to distinguish between SSDS created by seismic activity and those created by normal sedimentary processes is problematic and controversial\textsuperscript{38}. For the main causative mechanism, a number of possible explanations exist to account for the genesis of SSDS. Both liquefaction and fluidization could have a non-seismic or seismic origin. Recently, Foix et al.\textsuperscript{36} and Owen and Moretti\textsuperscript{37} have listed various cases for the trigger mechanism such as the action of storm waves; cryogenic/thermokarstic perturbations; subglacial hydrofracturing; near surface gravity slide, and steep depositional slope or rapid sediment accumulation. The seismic trigger is, however, the most common mechanism of liquefaction and/or fluidization of poorly consolidated sediments\textsuperscript{2,35,38}. The role of storm waves, cryogenic/thermokarstic perturbations, subglacial hydrofracturing and steep slope or rapid sediment accumulation are ruled out as supporting sedimentological features are not discernable in the Chakrata Formation of the Damtha Group. However, the SSDS observed in the Palaeoproterozoic Chakrata Formation nearly fulfill the criteria for correlating the structures with seismites as proposed by Sims\textsuperscript{37}. 
In this study, an earthquake-induced shock is argued as the trigger mechanism for many of the different varieties of SSDS within the Lesser Himalayan successions. There is always a question whether the SSDS are really seismically induced or are normal penecontemporaneous features and should be used with caution. However, recent studies trying to authenticate these SSDS genetically have discovered that soft-sediment deformation features arising from recent seismic activity are extremely similar to those which can be caused by normal sedimentary processes. For example, SSDS have developed in a major slump at Itola in the Dhadhari rivers basin of Gujarat alluvial plain. Raj et al. have also shown pseudonodules, pinching and folding, convolute folds, concave-up paths, clay diapirs, flamed convolutions and minor faults as SSDS relating to activity of seismic event along the Dhadhari lineament during Mid-Late Holocene and also compared them with the 2001 Bhuj earthquake that generated similar SSDS.

Field studies also suggest that the frequent repetition of deformative forces temporally throughout the studied column particularly, as evident from the vertical distribution of the deformed layers (Figure 1 d), strongly suggests earthquakes. Moreover the frequent repetition of the sedimentary processes generating SSDS that too with deformative forces equivalent to seismic shocks with $M > 5$ (ref. 40) throughout is unlikely. Thus we attribute the Lesser Himalayan SSDS as seismites, because of the following: (i) origin due to liquefaction, (ii) slow deposition rate which would account for overloading, (iii) no evidence of slumping and sliding that would indicate a slope control, (iv) presence of undeformed horizons sandwiching the deformed units, (v) the Davtha Group succession was deposited in a part of Palaeoproterozoic period (1.8 Ga) where seismic activity would be expected in connection with rifing and penecontemporaneous mafic volcanism, (vi) a wide variety of SSDS can be traced laterally along the same stratigraphic horizon for nearly up to 110 km (from Chakrata to Shivpuri sections), and (vii) the SSDS occur between undeformed beds suggesting they were apart from the normal sedimentary processes.

In summary, the Palaeoproterozoic shallow marine succession of the Chakrata Formation of the Davtha Group possibly records syn-sedimentary basinal tectonic activity in the form of seismites. In terms of time contemporaneity, the Palaeoproterozoic Davtha Group of the Lesser Himalayan basin and the Chaibasa Formation, a part of the North Singhbum Fold Belt (mobile belt), were tectonically active in the Indian craton.


Quantitative hydrogeological and geomorphological analyses for groundwater potential assessment in hard rock terrains

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Hydrogeological and geomorphological parameters have been quantitatively correlated with groundwater availability. Weathered rock thickness has the highest control on availability of groundwater followed by lineament density whereas drainage density is seen to have minimum influence. A poor correlation is noticed between borewell depth and yield. The amplitude of seasonal variations in groundwater levels is noted to be higher in the low lying plains compared to the hilly regions. The groundwater potential zonation map, prepared using data merging techniques and assigning weightages based on the quantitative analyses of parameters on a GIS platform shows that more than 45% of borewells falling in the area under the category of excellent water availability are high-yielding.

Keywords: Geomorphology, groundwater potential zonation maps, hard rock hydrogeology, quantitative analysis.

Quantitative availability and chemical quality of groundwater is influenced by various natural environments such as geology, topography and geomorphology apart from anthropogenic factors. Rock type, rock structure, presence and density of fractures, joints and lineaments, degree and extent of weathering, landforms types, drainage density, soil type and land cover are some of the generally used parameters in deciding the suitability of an area for groundwater development. In most groundwater development projects, these parameters are considered and groundwater potential zonation maps prepared by assigning weightages and merging them on a geographic information system (GIS) platform. However, the individual weightages of each of the parameters (themes) are assigned based on general perceptions rather than a quantitative analysis of these parameters. Subba Rao has used quantitative methods of characterizing hydrogeomorphological parameters to identify recharge sites in hard rock areas. The present study is an attempt to understand the extent of geological and geomorphic controls on the availability of groundwater, in an area underlain by hard crystalline rock formations.

The upper Swetha watershed, forming part of the Vellar river basin is located partly in the Namakkal and

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