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Soft-sediment deformation structures in the Earth's oldest seismites

Rajat Mazumder [a,*], A.J. (Tom) van Loon [b], Makoto Arima [c]

[a] *Department für Geo- und Umweltwissenschaften, Geologie, Ludwig-Maximilians-Universität München Luisenstr. 37, D-80333 München, Germany*
[b] *Faculty of Earth Sciences, University of Silesia, Bedzinska 60, 41-200 Sosnowiec, Poland*
[c] *Department of Environment and Natural Sciences, Graduate School of Environment and Information Sciences, Yokohama National University, 79-7, Tokiwadai, Hodogaya Yokohama 240-8501, Japan*

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Abstract

The Chaibasa Formation in Eastern India, which was deposited between 2100 and 1600 million years ago, shows deformations that must have formed when the sediments were not yet consolidated. Some of these deformation structures have never been described before. Here they are described, depicted and their origin is analysed. We show that they must be the result of shocks, which can only be explained satisfactorily as triggered by earthquakes. The layers containing these deformation structures are termed "seismites". They are among the earliest records of earthquakes known in the Earth's history.

Keywords: Soft-sediment deformation structures; Seismites; Proterozoic; India; Chaibasa Fm.

1. Introduction

The Chaibasa Formation in Eastern India (Fig. 1), which is entirely siliciclastic, is 6–8 km thick. It is underlain by a granitic basement and siliciclastic sediments, and overlain by the Dhalbhum Formation (Saha, 1994; Bose et al., 1997). The formation cannot be dated directly, but the underlying volcanics are 2100 million years old (Roy et al., 2002a) and the minimum age of overlying lavas is 1600 million years (Roy et al., 2002b). The rocks suffered several post-depositional deformation phases, as well as greenschist to amphibolite facies metamorphism around 1600 Ma ago (Naha, 1965; Mazumder, 2005). Although the rocks described here are metamorphosed, we will refer to them as sandstones and mud/siltstones, to emphasize their character, as it was when the sediment layers described here were deformed.

The Chaibasa Formation consists of alternations of sandstones, heterolithic units (very fine sandstone/siltstone/mudstone) and shales (Fig. 2). Layers with soft-sediment deformation structures are abundant in its upper part. These structures show a wide variety of shapes and occur in units that are separated by undeformed intervals. Trigger mechanisms for the deformations have been analysed following the approach suggested by Owen (1987), including distinction between syndepositional and metadepositional deformation (Nagtegaal, 1963; Allen, 1982; Owen, 1995), and reconstruction of the deformational mechanisms.

Deformation can take place after a bed has been covered by younger layers (postdepositional deforma-

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* Corresponding author. Tel.: +49 89 2180 6560; fax: +49 89 2180 6514.
E-mail addresses: mrajat2003@yahoo.com (R. Mazumder), tvanloon@ultra.cto.us.edu.pl (A.J.(T). van Loon), arima@ed.ynu.ac.jp (M. Arima).

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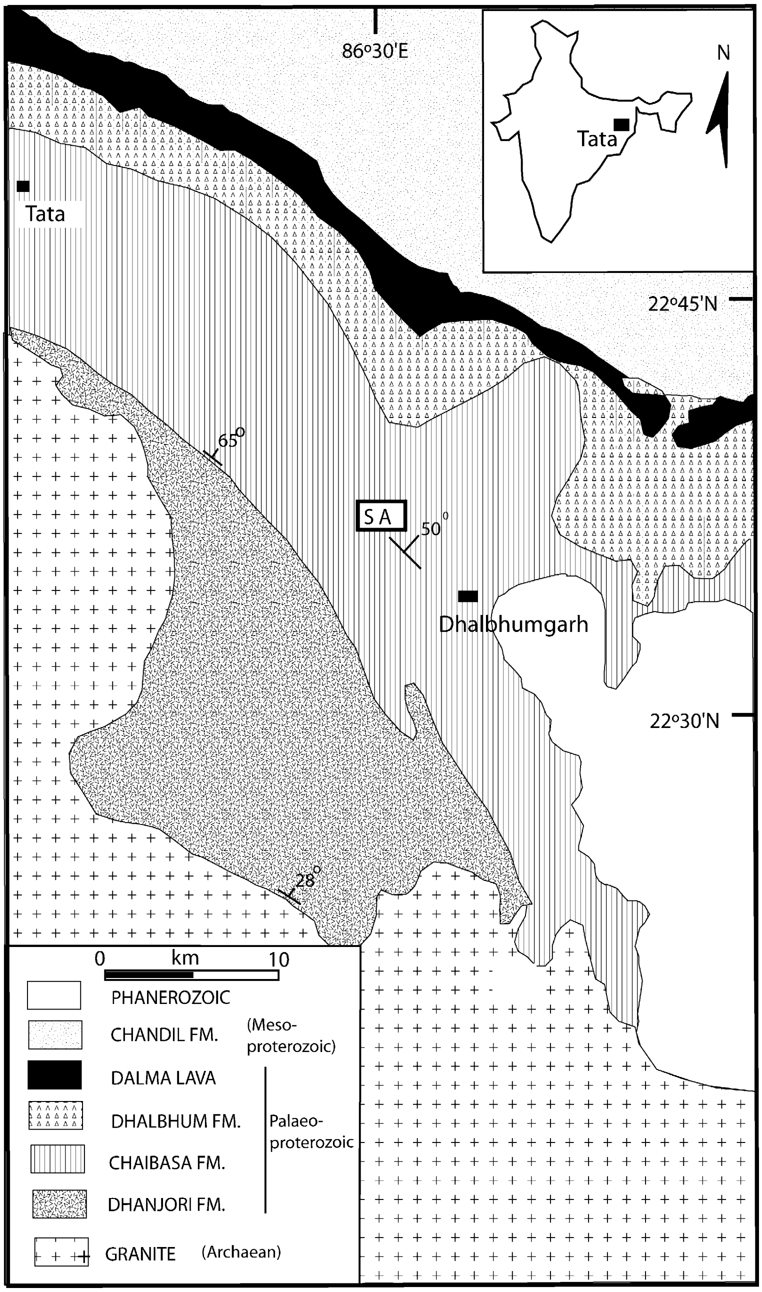

Fig. 1. Location map and schematic geological map Chaibasa and its bounding formations (modified after Saha, 1994). The study area (SA) is detailed in Fig. 2A.

tion); during the depositional process (syndepositional deformation); and after deposition but before the sediment is covered by a younger layer (metadepositional deformation). Determining whether deformation was syndepositional or metadepositional is of great importance for genetic interpretation. Seismic influences, for instance, may easily affect subaqueous sediments that are still being deposited and have had no time for consolidation, however slight; whereas metadepositional deformation affects surficial sediments that already have achieved some degree of consolidation. Relatively few mechanisms can cause metadepositional deformation, and a shock (whether or not induced by earthquakes) is one of those mechanisms.

Because the Chaibasa Formation was deposited in an active tectonic setting (Mazumder, 2005), analysis of

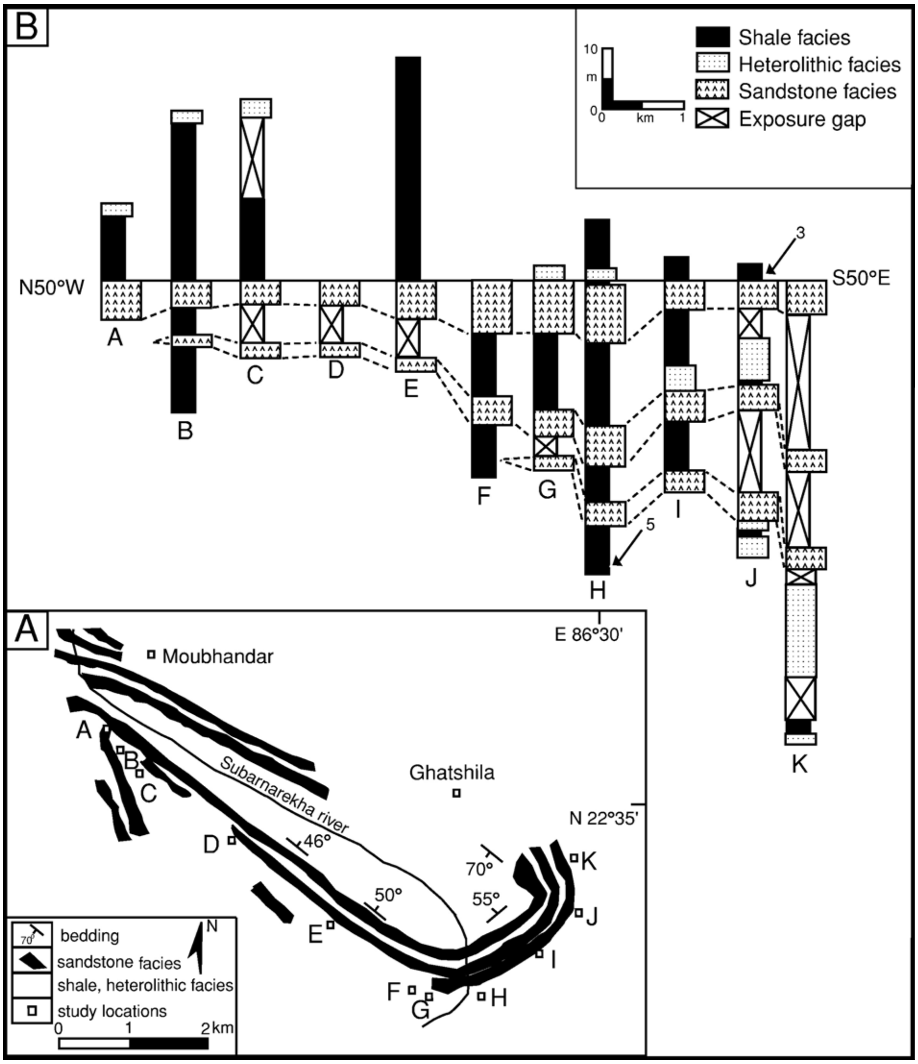

Fig. 2. A: Sites of sections and lithological units of the formation in and around Ghatshila (modified after Naha, 1965). B: Vertical and lateral lithofacies development in the Chaibasa Formation (modified after Bose et al., 1997). The numbers 3 and 5 refer to the stratigraphic positions of the structures presented in Figs. 3 and 5, respectively.

the deformation structures was directed first at the distinction between tectonic and non-tectonic (sedimentary) deformation. These may be interrelated, as tectonic shocks can lead to pressure gradients that induce the deformation of surficial, non-consolidated sediments. In particular, the topmost sedimentary layer can become strongly disorganized, if it consists of material that is susceptible to shock-induced deformation. Such layers, which tend to show more or less similar deformation structures over long distances, are known as 'seismites' (Seilacher, 1984). The present investigation was therefore directed at establishing whether specific deformed layers in the sedimentary succession under study should be considered as seismites.

Recognition of seismites is hampered by the fact that earthquakes are just one of the trigger mechanisms that induce soft-sediment deformation. A combination of three or four of the following characteristics, in layers with an abundance of such structures, is commonly considered diagnostic for an earthquake origin (Sims, 1973, 1975; Obermeier, 1996; Anand and Jain, 1987; Rosetti, 1999; Jones and Omoto, 2000): (1) the restriction of the soft-sediment deformation structures to discrete stratigraphic horizons; (2) lateral continuity of the deformation structures over long distances; (3) recurrence of such deformed layers over time; (4) consistent deflection of paleocurrent trends from their usual pattern, within the deformed unit; (5) confinement between

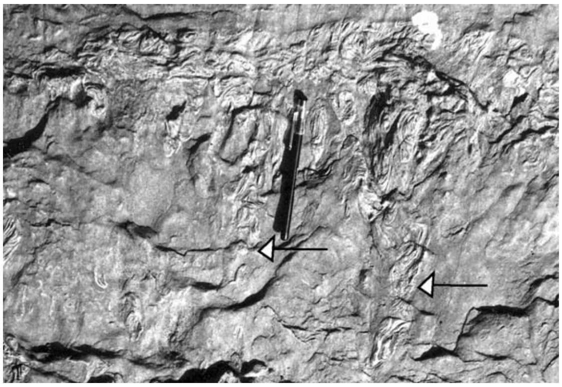

Fig. 3. Inverted cone-shaped sets of contorted laminae in Chaibasa shale. Length of pen 16 cm.

undeformed strata or strata with deformations distinctly different in origin; and (6) a preferred association with wedges of intraclastic breccias, conglomerates and massive sandstones.

2. The soft-sediment deformation structures

The wide variety of soft-sediment deformation structures in the Chaibasa Formation can be grouped into syn- and metadepositional types. The first category comprises pillows, cone-shaped contorted-lamina sets, tabular depressions, and sagged ripple trains. The second category includes penecontemporaneous thrusts, contorted mud balls, chaotic beds, and collapse structures. Descriptions of all these structures will be published elsewhere. Here, only those that are relevant to reconstructions of the trigger mechanism will be considered.

Laterally continuous rows of pillow-shaped deformation structures occur within siltstone beds at several stratigraphic levels. Commonly, similar structures have been attributed to loading of unconsolidated material by denser sediment in a two-layer system, but a seismic origin has also been suggested (Montenat et al., 1987; Cojan and Thiry, 1992; Roep and Everts, 1992; Rodriguez-Pascua et al., 2000). The Chaibasa pillow structures developed syndepositionally (in water far below wave base), so that no deformational mechanisms can have acted apart from shock-induced liquefaction of certain specific layers.

In a muddy deep-sea facies, inverted cone-shaped structures occur (Fig. 3). Their configuration, in combination with their internal structure, suggests that cracks formed on the mud surface and that a silt/mud-laden current in-filled the cracks. Erosional features indicate repeated enlargement of the cracks. Considering the repeated enlargement of the cracks and their successive infillings, a series of earthquake-induced shocks, taking place within a relatively short time, may well have been the trigger mechanism.

In the same muddy deep-sea facies in which the cone-shaped structures are found, there is a bed that displays several tabular depressions (Fig. 4). As far as can be seen in the exposures, all depressions are roughly the same size, averaging 48 cm wide and 36 cm deep. The laminae of the adjacent sediment are truncated at the margins of the depressions, which are in-filled with alternating silt and mud laminae that end abruptly against the steep part of the depression's wall, but tend to conform with the geometry of the wall where it is gently inclined. The laminae immediately underlying the structures do not exhibit any significant degree of deformation, so that the depressions must be erosional features that later were gradually in-filled.

Fig. 4. Tabular depression in the Chaibasa shale near Dhalbhumgarh (22°29′S, 86°30′E). Note the lithological and structural similarity of the sediments inside and outside the depression. Length of knife 7 cm.

It is known (Fig. 3) that sometimes vertical cracks developed in the semi-consolidated sedimentary surface. Such cracks may locally have formed more or less rectangular patterns, thus isolating silt/mud blocks from their adjacent sediment. Lifting and removal of such isolated blocks from their original positions would result in tabular depressions that show all the characteristics described above. This raises the question of the mechanism that lifted the blocks, and the agent that transported them away from their original locations. Deep-sea currents are unlikely to have been strong enough to lift the blocks. Turbidity currents can disturb the sedimentary surface and lift blocks of fine-grained sediment, but there are no signs of such mass-flow activity. Seismogenic tsunami, however, are full water-depth waves that can modify the seabed. An earthquake-induced shock therefore seems the most likely trigger mechanism for detaching a weakly consolidated silt/mud block that, being water-saturated and therefore not significantly heavier than water, could be lifted and transported by a tsunami generated by the same earthquake. This would leave behind a more or less rectangular hole that gradually became in-filled by laminated sediment.

At some horizons in the same muddy deep-sea facies, vertically stacked and sagged ripple trains occur within a succession of alternating mud and silt laminae. The sagging of the ripple trains presumably took place because of partial liquefaction of the underlying mud. This may have been caused by an earthquake-induced shock; but it may alternatively be due to simple pressure resulting from differential loading (Lowe, 1975; Jones and Omoto, 2000).

In the upper part of the Chaibasa mudstones, confined fault planes occur with lengths up to a maximum of a few decimeters. The faults do not affect the under- and overlying layers. A metadepositional genesis is evident from their intercalation between unfaulted layers. The faults indicate, moreover, that some consolidation must have taken place before the faulting occurred. This implies that the stress that was exerted on the sediments was not insignificant. As no indications are present that differential compaction can have played a role, a shock triggered by an earthquake seems the most logical mechanism for the faulting.

Thick (~30 cm), massive siltstones contain occasionally isolated “floating” mud balls that internally exhibit contorted fine silt laminae with upturned margins. Such loaded mud balls are difficult to explain unless a relatively low density of the silt is assumed. Such conditions may have been present as a result of the development of a strong hydrostatic stress within the siltstone beds under an impervious cover of mud (Schwab and Lee, 1988). The configuration indicates late-stage breakup of the overlying mud beds and liquefaction of the silt. The cause of the liquefaction under the influence of a suddenly increased hydrostatic stress cannot be determined on the basis of the structures themselves, but an earthquake-induced shock is most likely considering the depositional conditions.

Some mudstone beds, up to 70 cm thick, show a chaotic internal structure. These beds show, between their sharp lower and upper contacts, silt-rich deformation structures such as convolutions and pillows (mainly in the upper parts of such beds), together with load

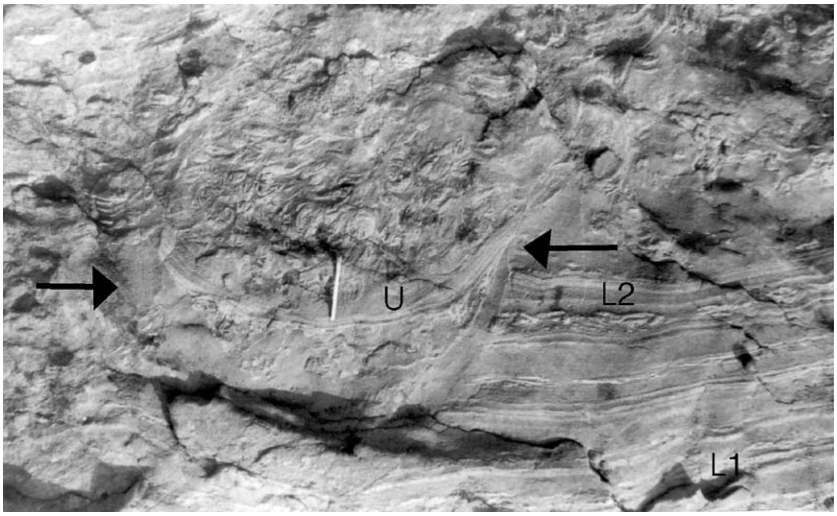

Fig. 5. One of the collapse structures in the Chaibasa shale. Note the difference in deformation between the lower bed (with units L1 and L2) and the upper bed (unit U). In both units the intensity of deformation decreases upwards. Length of match 42 mm.

casts and pseudonodules (mainly in the lower parts) that float within the muddy matrix. Some of these load structures have rotated so that they have become inverted. Liquefaction occurred locally. The stress that caused these deformations apparently had a uniform intensity throughout each individual bed. The undisturbed beds below and above the deformed beds suggest that the deformation took place because entrapped pore water was forced to find a way out. The mechanism that triggered this process cannot be reconstructed on the basis of the structures themselves but an external mechanism, such as an earthquake-induced shock, must have been responsible.

Collapse structures, observed in a silty shale, involve two of vertically juxtaposed beds (Fig. 5). The lower bed is chaotically deformed, but the overlying bed shows no internal deformation, apart from a few vertical fractures. The chaotic character of the lower bed must be due to a stress field that forced water-saturated sediment to move laterally, thus causing collapse of the overlying bed. The upwards-diminishing intensity of the deformations in the lower bed, in combination with the lack of internal deformation within the upper bed, indicates that the deforming force came from beneath. The force was apparently not strong enough to cause deformation above the contact plane between the two beds, which served as a shear plane. The chaotic deformation was thus confined beneath the sediment surface. The applied stress must have been hydrostatic, at least until the rupture and collapse of the deforming overlying bed.

3. Trigger mechanisms

Soft-sediment deformation structures are by themselves not diagnostic of any particular triggering mechanism, but their abundance in the Chaibasa Fm. is consistent with previous studies (Bose et al., 1997; Bhattacharya and Bandyopadhaya, 1998; Mazumder, 2005) that indicate deposition in a tectonically active basin. Almost all these deformation structures occur in facies deposited below storm wave base (Bose et al., 1997; Mazumder, 2005), which implies that many deformational mechanisms are impossible or highly unlikely. The frequent repetition of deformative forces, as evident from the vertical distribution of the deformed layers, strongly suggests earthquakes with close aftershocks (Seilacher, 1984; Owen, 1995; Bose et al., 1997). Although the deformed horizons cannot be traced beyond a kilometer, because of lack of larger exposures), the exposure-wide continuity of the deformation and the occurrence of such deformations in all exposures (Fig. 2), in combination with the inferred subtidal to deep-sea setting of the sediments, strongly favours the interpretation of the deformed layers as seismites. One of the strongest arguments for earthquakes as triggers of the deformation is the occurrence of strongly deformed layers interbedded between unaffected layers of similar grain size.

4. Discussion

Many of the soft-sediment deformation structures in the Chaibasa Fm. must be due to shocks. Considering the fact that most of these structures were formed syn- or metadepositionally in a deep-water environment, and also considering the fact that sedimentation took place in a tectonically active basin, a seismite origin of many of the deformed layers is by far more likely than any other origin. Strong evidence for such an origin is provided in particular by the collapse structures and the tabular depressions. In the case of the collapse structures, a shear plane developed between a bed with chaotic fabric and the overlying internally undeformed bed that collapsed. Earthquake waves cannot propagate across shear planes (Schwab and Lee, 1988), which explains the contrasting degrees of deformation in the two layers. In the case of the tabular depressions, a mechanism must have been active that enabled a large block of sediment, isolated from its adjacent material by more or less vertical cracks, to start moving upwards and to drift away, leaving a hole that gradually became filled up with laminated sediment. Considering that this process took place below storm wave base, hardly any other process than a fairly large shock can have triggered the movement of the block and its lifting. An earthquake seems by far the most plausible trigger mechanism.

Comparable arguments hold for the interpretation of the trigger mechanism that was responsible for numerous other soft-sediment deformation structures. It is beyond the scope of this paper to deal with all these structures, as a seismic origin has been advocated for them in many other sedimentary units worldwide (Allen, 1982; Montenat et al., 1987; Cojan and Thiry, 1992; Roep and Everts, 1992).

It must be deduced from the above that several of the soft-sediment deformation structures show characteristics that are strong indications for earthquakes as a trigger. In addition, numerous other structures can be explained, just as well if not better, as due to earthquakes, rather than as results of other triggers. Interpretation of the majority of the soft-sediment deformation structures in specified horizons of the Chaibasa Fm. as paleoseismic features is unavoidable (although, obviously, not all deformations need necessarily be due to seismic shocks). Given that the palaeogeographic setting of this formation, particularly during the later phase of sedimentation, was in a tectonically active area, the seismite character of these layers becomes even more logical. The occurrence of mass-flow deposits in this formation in both shallow and deep marine settings further strengthens this hypothesis.

5. Oldest unambiguous record

As the Chaibasa Fm. is dated as late Paleoproterozoic (between 2100 and 1600 million years ago), the seismites in the formation reflect the occurrence of earthquakes in a fairly early history of the Earth. The occurrence of structures that might be ascribed to earthquake-induced shocks has been mentioned earlier (Bose et al., 1997; Bhattacharya and Bandyopadhaya, 1998), but these reports did not provide descriptions of the structures in any detail, nor did they provide a genetic analysis that proved the seismite character of the layers with the deformation structures. Pickard et al. (2004) mentioned a bed in the early Proterozoic Dales Gorge Member of western Australia that "shows complex folding and intricate crumpling that is more pronounced towards the top, and that appears to be related to the plastic deformation of mainly bedded chert. Soft-sediment deformation probably resulted from liquefaction due to earthquake-induced sediment shaking." The Dales Gorge deformation structures are far older than the ones described in the present contribution, but the presumed seismic origin of the structures is not based on structured observations; nor are data provided by Pickard et al. (2004) that fulfil the required number of diagnostic criteria for seismites, mentioned in our Introduction. The deformed Dales Gorge beds can therefore, in our opinion, not (yet?) be considered as unambiguous seismites.

Other Precambrian sediments with deformed layers with possible seismites have been described by Long (2004). His dating (Huronian) is insufficiently precise, however, to establish whether the sediments that he describes are younger or older than the Chaibasa Formation. In addition, the seismic origin of the deformation structures that he describes is, at least, questionable: he mentions "seismic- or gravity-induced rotational sliding of blocks", and considers water-escape structures as evidence of tectonic activity, not mentioning that similar structures occur in Recent deposits that have not been affected by tectonic activity.

Much older seismites have recently been reported by Schneiderhan et al. (2005) from South Africa. These layers, built of pyroclastic material, date from the Archaean and therefore predate by far the Indian seismites described in the present contribution. The sediments involved form part of a sedimentary succession in an active basin affected by volcanism, but the paleogeographic setting and the sedimentary facies are not dealt with in detail. The interpretation of the layers as seismites is based mainly on the occurrences of syn-sedimentary faults and breccias, convolute lamination, syneresis cracks and graben-like down-sagging structures. These structures, in our opinion, cannot be considered as diagnostic for seismic deformation, however, particularly because the required presence of other criteria (see Section 1) is not mentioned.

In our opinion, the deformed layers described in the present contribution therefore represent the oldest unambiguous seismites that are known from the Earth's history.

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