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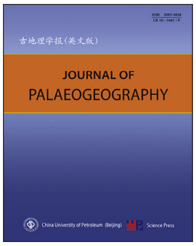

Multi-origin of soft-sediment deformation structures and seismites

The response of stromatolites to seismic shocks: Tomboliths from the Palaeoproterozoic Chaibasa Formation, E India

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Abstract It is demonstrated here for the first time how Palaeoproterozoic stromatolites survived seismic disturbance of their substrate. The stromatolites under study could have been cyanobacteria or any other photoautotrophic microbes, which formed mats that covered a substrate of very fine-grained sandstones and mudstones of the Chaibasa Fm. in eastern India. The sediments represent a shelf environment. The local abundance of the stromatolites suggests that the low-energy environment formed a suitable habitat. The common phases of tectonic quiescence were, however, occasionally interrupted by seismic shocks. These were sufficiently strong to deform the mat layers, the lower parts of which might already have been (semi-) consolidated. The mats became partly folded, partly faulted, and already consolidated parts of the stromatolite layers broke off. This can be deduced from the angular shapes of part of the broken-off fragments. It appears, however, that part of these fragments were still sufficiently soft to become rounded and deformed by rolling over the seafloor, probably under the influence of tidal currents. When come to rest, these fragments served as a new substrate for new generations of the micro-organisms. These micro-organisms thus survived by continued growth on the reworked fragments and built up new stromatolites that may show an 'angular disconformity' with the stromatolites of their substrate. It thus is shown that stromatolites have an adequate response to a sudden disturbance of their habitat, and that they survive earthquakes by colonization of broken-off fragments. We call the 'healed' fragments 'tomboliths' (tumbled stones).

Keywords Stromatolites, Seismic shocks, Soft-sediment deformation structures, Palaeoproterozoic, Singhbhum craton, Tomboliths, India

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1. Introduction

An extensive classification work on soft-sediment deformation structures (SSDS) in siliciclastic sediments (Van Loon, 2009) depicted some structures that were described as enigmatic (Fig. 1) because no satisfactory genetic interpretation could be provided at the time. These enigmatic SSDS had been found in the Palaeoproterozoic Chaibasa Formation (E India). They were recently investigated again, and a reconstruction of their genesis is now possible.

As will be detailed below, the structures represent stromatolitic microbial mats that were broken up into fragments. The only feasible mechanism that can be held responsible is a number of seismic shocks, in combination with shock-induced rolling over the sea floor. Although stromatolites are sedimentary structures that represent traces of the oldest macroscopically biogenic activity, dating back to the Archaean, earlier reports about their response to earthquakes are not known. The response by the stromatolites, viz. colonizing the fragments on the sea floor, took place in phases, suggesting several earthquake events (possibly an earthquake with some aftershocks).

1.1. Geographical and geological setting

The rock unit under study forms part of the Palaeoproterozoic supracrustal rocks of the Singhbhum craton in E India. The study area is located near Dhalbhumgarh (22°31′39.5724″N, 86°33′39.1968″E; Fig. 2) and represents the lowermost part of the ~2.2 Ga old Chaibasa Formation (Sarkar *et al.*, 1986). This formation is 6—8 km thick and consists in the study area of shallow-marine mudstones and very fine-grained sandstones with a greenschist to amphibolite facies (Mazumder, 2005; Saha, 1994). The Chaibasa Formation has been considered up to a few years ago as entirely siliciclastic (Mazumder, 2005; and references therein).

Mudstones and very fine-grained sandstones with small current ripples and horizontal laminae dominate the study site (Mallik *et al.*, 2012), but some levels with very thin, very fine-grained sandstones occur as well. The mudstone units are mostly several decimeters thick, whereas the very fine sandstones rarely exceed 4 cm in thickness, more commonly forming laminae of maximally a few mm thick, but often less. No distinct, unambiguous wave-generated structures have been observed so far in the fine-grained sediments, which therefore likely accumulated below the storm wave base (Bose *et al.*, 1997; Mazumder, 2005; Mazumder *et al.*, 2009, 2012). The fine-grained character of this facies, without any coarse material, rules out supply by a nearby river. Probably the sediments accumulated on a distal shelf. This distal shelf was affected by tidal activity, as indicated by the numerous mud drapes over sandy ripple sets and ripple trains, and by small-scale current ripples revealing opposite current directions (Mallik *et al.*, 2012). The presence of scarce channels, up to several decimeters deep, with shapes indicating a meandering pattern of the current, fits into a distal but still tidal environment (Mazumder *et al.*, 2006, 2009, 2012).

Fig. 1 Two well-developed tomboliths. Note the 'angular unconformities' between the various sets of laminations. Color slightly adapted to increase the contrast between the laminae.

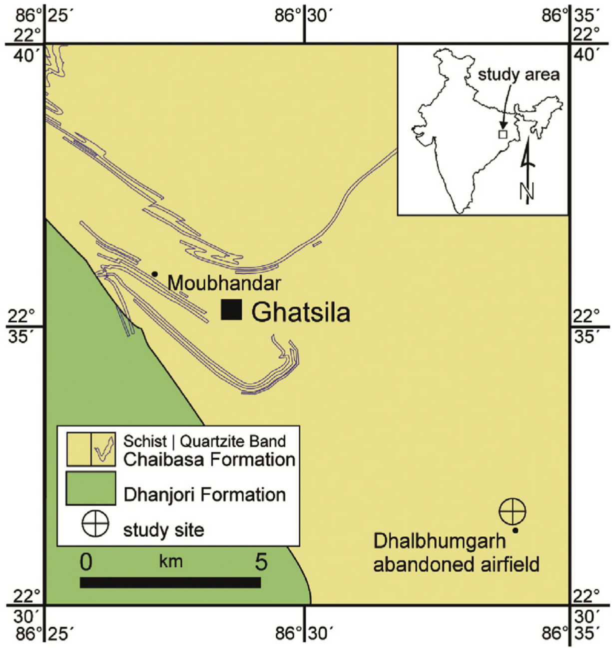

Fig. 2 Location and geological setting of the study area.

1.2. *The stromatolites*

The structures under study form part of a level that is embedded between the 'normal' alternating muddy and fine-sandy laminae. The laminae within this level are much thinner than those in the 'normal' sediments and show deformations (Fig. 3). This finely laminated unit has been recognized in the field by Nora Noffke, an expert in siliciclastic stromatolites (Noffke, 2010; Noffke and Chafetz, 2012), as a typical form of microbial mats, most probably due to the activity of cyanobacteria or other photoautotrophic microorganisms (see also Van Loon and Mazumder, 2013). This was a surprising finding, because the entire Palaeoproterozoic of the Singhbhum craton was considered as devoid of any trace of biological activity. In the meantime, we have found the frequent occurrence of microbial material in a much thicker part of the Chaibasa Formation.

Although most stromatolites in the geological record are found in calcareous sediments, it is now well known that they occur (although much rarer) also in siliciclastic rocks, even from the Archaean (Braga and Martín, 2000; Draganits and Noffke, 2004; Noffke *et al.*, 2002). The Chaibasa Formation now can be considered as a fine example.

The presence of slimy material at the sedimentary surface unavoidable affected the properties of the uppermost sediments. This may explain why the 'normal' sediments became strongly deformed,

Fig. 3 Seismically-induced internal deformations in a tomboliths-containing layer.

sometimes even chaotically, by a process that can be interpreted satisfactorily only as a series of seismically-induced shocks, whereas the sediments covered by microbial mats reacted in a different way.

2. Description of the enigmatic structures

The ideally ball-shaped structures under study (which are called here 'tomboliths' — tumbled stones — for reasons explained below) are not common features in the large outcrop, but several dozens of examples have been found, all in the same level consisting of a few layers that jointly are about half a meter thick; commonly, several specimens occur closely together (Fig. 4), as in the case of the two best developed specimens (Fig. 1). In all cases, they occur in a fine-grained, finely laminated level that shows abundant soft-sediment deformation structures (Fig. 3) and that laterally show the stromatolitic lamination that must be ascribed to microbial activity.

The size of the best developed tomboliths in the exposure is up to about a decimeter (some larger structures that are interpreted as having a similar origin are up to a few dm, but they are less characteristically developed). They can be described best as ball-shaped fine-sediment masses with a largely smooth — though locally irregular — surface and with an interior that seems, at first sight, to be composed of sets of parallel laminae that sometimes form angular unconformities. These 'angular unconformities' do not show a regular pattern: the angles differ in an apparently haphazard way. Some irregular depressions may occur in the surface of the balls (Fig. 5A) and, in addition, some fragile, laminated 'spines' or 'flames' seem to grow locally from the surface of some balls (Fig. 5B).

Fig. 4 Concentration of small-scale tomboliths. Coin (diameter 26 mm) for scale.

The 'angular unconformities' (Fig. 6) in the balls are formed by the same finely-laminated units that occur also in the broken up layer, both in deformed and undeformed (or less deformed) parts.

3. Genetic interpretation

The size of the tomboliths (up to a few decimeters) is in such a strong contrast with the fine character of their host rock, that it seems unlikely — if not physically impossible — that they have been transported from a truly coarse-grained (and remote) facies to the study site. It seems much more likely that they are derived from the same level (which has the same grain size and which shows similar features) in which they are present now. Supply by mass transport can be excluded on the basis of the sedimentary characteristics (fine lamination preserved, no material with a different composition, no grading, *etc.*).

The overall outer shape of the tomboliths and their occurrence in deposits with a very fine sandy to muddy character strongly suggests that they are essentially mud balls; they are interpreted here in this way, indeed, taking into account that an explanation then is still required for the irregularities of the balls surfaces. The reason for an interpretation as mud balls is not only their outer shape, but also the fact that they are found exclusively in a layer that has been strongly disturbed, including fragmentation that resulted in the presence of 'clasts' ranging from angular to well-rounded in shape. Some of the angular and less rounded fragments show internally the same structure (with 'angular unconformities') as the more characteristic balls.

The explanation as mud balls does, however, not explain several of the characteristics mentioned above. A logical interpretation of the tomboliths requires, considering their characteristics, (1) a process of laminae formation, (2) a process of fragmentation of the layer, (3) a process of rounding, (4) a process responsible for the formation of the 'angular unconformities', and (5) a process responsible for the locally irregular surface of the balls.

3.1. Origin of the fine, irregular lamination

The fine, but irregular lamination which was not easily explainable when the Chaibasa Fm. was considered as entirely siliciclastic, has now been recognized as due to accumulation of fine siliciclastic

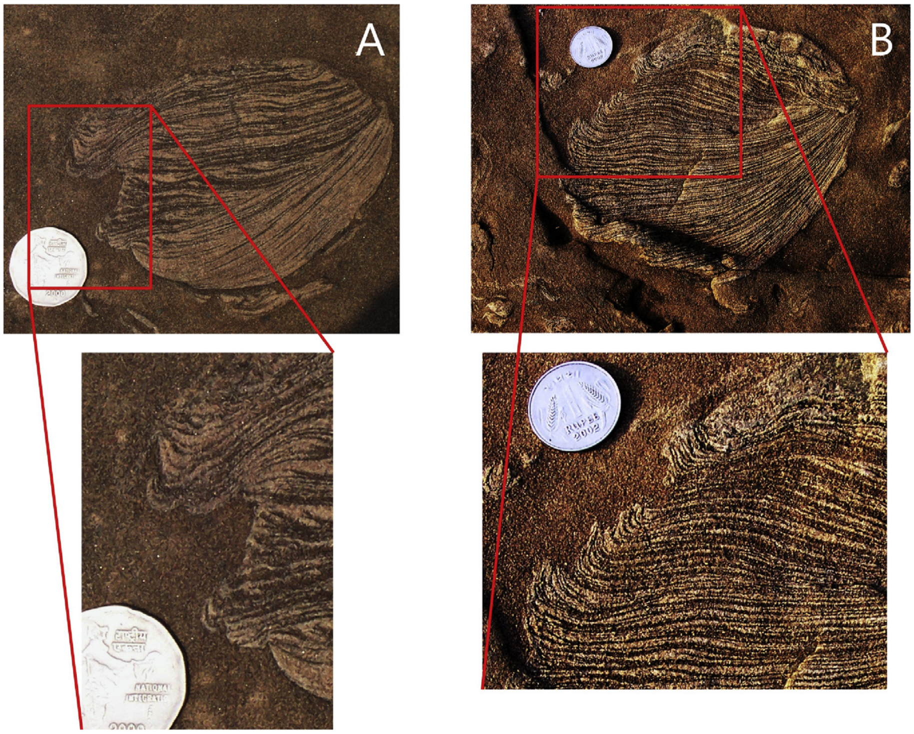

Fig. 5 Irregularities at the surface of tomboliths. Color contrasts increased to make the lamination more clear. A—Small depressions; coin (diameter 25 mm) for scale; B—Flames that appear to grow out of the tombolith surface; coin (diameter 25 mm) for scale.

particles on biofilms of micro-organisms, most probably cyanobacteria, but possibly other photoautotrophic micro-organisms. This explains why the fine lamination is rarely truly horizontal, but rather shows irregular 'folds', convolutions and wrinkles (cf. Eriksson and Truswell, 2006; Van Loon and Su, 2013).

3.2. *Origin of the fragmentation*

The process of fragmentation must be considered in the context of the fact that the entire Chaibasa Fm. has been deposited in a tectonically highly active basin where frequent earthquakes occurred. Unconsolidated sediments tend to become broken-up and internally also otherwise deformed under such conditions, as shown by numerous authors (a.o. Gruszka and Van Loon, 2007; Mazumder *et al.*, 2009); some of these layers fulfil the criteria set for seismites (cf. Sims, 1975; Van Loon, 2014; Van Loon and Pisarska-Jamroży, 2014), although it should be kept in mind that these criteria for recognizing seismites should be used with utmost care (Moretti and Van Loon, 2014) because the geological context plays a major role.

The fragmentation that led to the formation of tomboliths is interpreted as the result of one or more earthquake-induced shockwaves that affected the differentially consolidated and occasionally slightly lithified stromatolites, giving rise to folding-like deformation of still plastic (semi-consolidated) parts of the stromatolite unit and breaking-up of more rigid (strongly consolidated or slightly lithified) parts.

3.3. *Origin of the rounded fragments*

Rounding of the mud balls may have taken place during several phases, but these can, as a rule, not be reconstructed anymore because the last rounding phase may have erased the morphological characteristics of any previous surfaces. Although apparently a number of tomboliths did, probably as a result of a more or less platy shape, not really get a ball shape (Fig. 7), a number of successive rounding phases are likely, as balls change their position at a sedimentary surface more easily than angular fragments do.

The movement of the fragments over the sedimentary surface, as either rolling balls or sliding plates, may in principle have been caused by several processes, most likely the tidal currents that were present, as indicated by the numerous small current ripples with opposite directions and by the channels of maximally a few decimeters deep (but see the Discussion section). It is, obviously, well possible that several rounding phases took place as a result of tidal

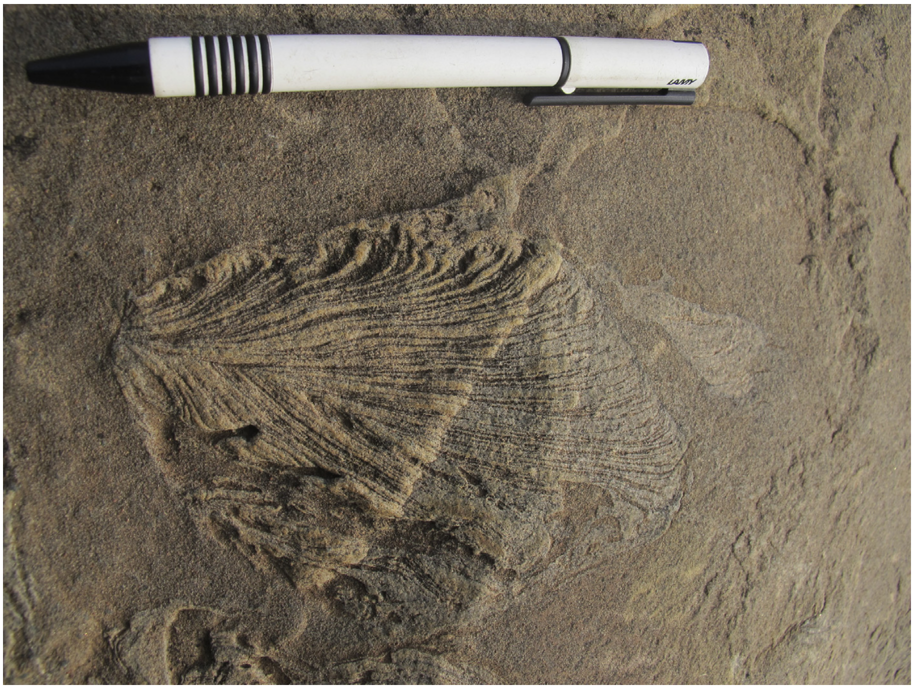

Fig. 6 Distinctly different orientations of laminated units in a tombolith. Pen (17 cm) for scale.

action, but it can certainly not be excluded that movement over the sea floor as a result of repeated seismic shocks (aftershocks?) played a role as well.

3.4. Origin of the 'angular unconformities'

When already more or less rounded fragments rolled over the sedimentary surface, they must occasionally inevitably have come to rest in a position that differed from the original one. This implies that the stromatolite lamination in these fragments will no longer have been more or less parallel to the sedimentary surface. When the fragments were colonised again by the micro-organisms, this led to new — in principle roughly horizontal — stromatolite laminae on the surface of the fragments that had an inclined

Fig. 7 Relatively badly rounded fragments of a broken-up stromatolitic layer with post-breakup laminae at an angle with earlier lamination. Coin (diameter 23 mm) for scale.

Fig. 8 Fine microbially-induced lamination in a relatively slightly deformed part of a tomboliths-containing, seismically affected layer.

position with respect to the older lamination Thus an ‘angular unconformity’ originated between the old and the new laminae. As the rolling may have taken place a couple of times, several ‘angular unconformities’ may be present in a single tombolith.

The platier fragments show ‘angular unconformities’ only in a very few cases, and the unconformities are in these cases only a few degrees. This must be ascribed to their movement over the sedimentary surface: they will have slid a bit rather than rolled. As the platy fragments always represent parts that were broken off parallel to the stromatolite bedding, this implies that the original lamination remained as a rule more or less parallel to the sedimentary surface and that, after movement over the sea floor, the new generation of micro-organisms produced a lamination roughly parallel to the already existing one.

3.5. *Origin of the irregular surfaces of the tomboliths*

The rolling process of the semi-consolidated to slightly lithified tomboliths must sometimes have destroyed their rounded outlines. They may have bumped against other objects that may have been more lithified, which explains the (rare) occurrence of depressions in the balls' surfaces. Wherever a new generation of cyanobacteria colonized the balls, one side of the ball may have provided more favourable conditions than another side, so that the micro-organisms grew in one place somewhat more rapidly than elsewhere; this explains the (small and rare) local ‘flames’ of laminated material extending to outside the overall ball-shaped outline of the tomboliths. The bending of such flames might also be ascribed to a next phase of rolling, deforming all semi-consolidated ‘flames’ into one direction.

4. Discussion

Tomboliths are a kind of feature that has not been described hitherto, but that sheds light on the response of stromatolites to seismic shocks. Our interpretation of the genesis of the tomboliths is based on three main presumptions: (1) the tomboliths represent fragments of a broken-up stromatolite, (2) the breaking-up was a result of seismic shocks, and (3) the fragments must have been displaced. It seems worthwhile to discuss these presumptions here.

4.1. *Stromatolite origin of the tomboliths*

All tomboliths occur in a level that is built mainly by stromatolites (Fig. 8). The internal characteristics of the tomboliths are identical to those of the stromatolites that were not broken up, apart from the presence in the tomboliths of ‘angular unconformities’. This strongly suggests that the tomboliths also consist of sedimentary material that was trapped by slimy microbial mats.

It is true that most of the fine-sandy layers at the study site are also laminated, but the lamination is, apart from the stromatolite interval, much more regular and the laminae are thicker. Moreover, the ‘normally’ laminated layers contain numerous small current ripples, of which the characteristics (opposite current directions, drapes) indicate deposition in a fairly quiet environment with some tidal influence. These features are absent in the stromatolite level and in the tomboliths.

The above considerations make us deduce that the various features can be explained satisfactorily only if the tomboliths represent fragments that were broken-off from stromatolites.

4.2. *The breaking-up process*

It is interesting that the 'normal' sediments, showing a less fine and more regular lamination as well as small current ripples, nowhere were found to be broken up into fragments comparable to the tomboliths, even where these sediments have been completely deformed by seismic activity that resulted in the formation of seismites (see Mazumder *et al.*, 2006). Apparently the microbial mats were more susceptible to brittle deformation than the 'normal' sediments, possibly because they had a more irregular surface, because they were in a more consolidated state and/or because the 'regular' sediments were only whirled up during a seismic shock (but no signs of this last process, *e.g.* in the form of graded bedding caused by the settling of the whirled up particles have been found; it should be kept in mind, however, that the sediments are well sorted, so that no clear grading is to be expected as a result of whirling up of sediments).

Apart from the deformations in the purely clastic sediments that are interpreted to be due to seismic activity, there are hardly any signs of processes that indicate an energy high enough to break up a stromatolite layer: the feature pointing at the highest energy is a single channel of only a few decimeters deep. Although this channel implies erosion of the muddy and fine-sandy sediments, the current in the channel cannot have had an energy high enough to fragment a semi-consolidated to slightly lithified stromatolite.

On the basis of the above, it must be deduced that only a seismic shock (or, more probably, a series of seismic shock) must be held responsible for the fragmentation of part of the stromatolite level and, consequently, for the formation of the tomboliths. It is interesting in this context to note that stromatolites that were turned into breccias by tectonic activity have been described by various authors (*e.g.* Álvaro *et al.*, 2005; Eriksson and Truswell, 2006), but that none of them described features that can be compared with the tomboliths under study here.

4.3. *Movements of the tomboliths*

Most of the tomboliths show an upward directed growth during the last phase of their growth. This growth may, however, have started on a previous surface composed of stromatolite lamination indicating growth in a different direction. This can be explained satisfactorily if the tombolith had earlier an upper surface that was positioned in a direction that differed from the last one; in other words: the fragment must have undergone a rotational movement. Considering that the growth direction in some tomboliths changed significantly several times, it must be deduced that the fragment rotated during several phases, with stable positions in between during which a new microbial mat could develop on its upper surface.

Rotation in the quiet sedimentary environment (shelf below at least fair-weather wave base but most probably even below storm wave base) might in principle be due to (tidal) current action, or earthquakes. As pointed out above, the tidal currents were, however, so weak that they cannot have resulted in the fragmentation of a consolidated or even slightly lithified stromatolite layer. The same holds for wave activity: if the sedimentary surface had been positioned above storm wave base, it might be expected that at least some traces of wave activity would be present in the shelf succession that is several kilometers thick; wave ripples have nowhere been found, however, so that there is no reason to presume that wave activity affected the sea bottom so strongly that semi-consolidated or partly lithified sediments could be broken up.

Considering the fact that tectonic activity evidently affected the sediments, for instance in the form of seismites (the formation of which requires a magnitude of at least M = 4.5—5), it seems that seismic shocks were the only process that could make the tomboliths move over the sedimentary surface, especially as the overall fine-sandy sea floor must have been hardly cohesive. Ground motion may have resulted in movement of the broken-up fragments; more or less equidimensional fragments of semi-consolidated material will have started rolling, and slightly lithified fragments may have slid over some small distances, sometimes resulting in rounding of their edges.

4.4. *The underlying trigger mechanism*

It was argued in the above sections that the features described in the present contribution can be explained satisfactorily only by seismic shocks. It is impossible, however, to deduce a trigger mechanism directly from the sedimentary record: the trigger can only be revealed by eliminating all other possible triggers. That is why particularly the combination of features is so important for the analysis of the underlying trigger mechanism responsible for the formation of tomboliths. As seismic shocks can explain all the features, and as we could not find any other trigger mechanism that could do so, we must deduce that seismic activity is the underlying trigger.

This is not surprising, as it has been found by several authors that the Chaibasa Fm. was affected by synsedimentary tectonics, resulting in features such as seismites (*e.g.* Mazumder *et al.*, 2006) that fulfil all criteria. Moreover, the presence of abundant soft-sediment deformation structures — which are by themselves not diagnostic of any particular trigger mechanism — but in only a very limited number of layers is consistent with previous studies (Bhattacharya and Bandyopadhaya, 1998; Bose *et al.*, 1997; Mazumder, 2005) that indicate deposition in a tectonically active, seismically affected basin. Almost all the soft-sediment deformation structures occur in facies deposited below storm wave base (Bose *et al.*, 1997; Mazumder, 2005), which implies that many mechanisms that might in principle result in specific deformations are impossible or highly unlikely.

The frequent repetition of strongly deformed layers in between undeformed layers, as present in the sedimentary succession, strongly suggests earthquakes with close aftershocks (Bose *et al.*, 1997; Owen, 1995; Seilacher, 1984). Although the deformed horizon with the tomboliths cannot be traced beyond a kilometer (because of lack of larger exposures), the exposure-wide continuity of the deformation and the occurrence of similar layers at other levels, in combination with the inferred subtidal to deep-sea setting of the sediments, strongly favours the interpretation of the deformed layers, including that with the tomboliths, as seismites.

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

It must be deduced from the above that there are strong indications for earthquakes as a trigger for the soft-sediment deformation process. 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 palaeoseismic 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.

5. Conclusions

It must be deduced that earthquakes in the tectonically active basin triggered seismic shocks that resulted in the breaking-up of layers with a fine lamination that was due to the trapping of sedimentary particles by slimy microbial mats produced by what probably were cyanobacteria, or possibly other autophototrophic micro-organisms. Fragments of the broken-up semi-consolidated layers moved over the sea bottom, rolling or sliding under the influence of aftershocks some of the fragments thus became rounded, forming some kind of mud balls, whereas other fragments remained platier, though commonly with rounded edges.

The position of the stromatolitic laminae in the displaced balls was not always (sub)parallel to the sedimentary surface, as had been the case before the breaking-up of the stromatolite layer, but was commonly at some (steeper or more gentle) angle with the sedimentary surface. Cyanobacteria colonised the broken-up fragments again, resulting in new fine laminae; these developed roughly parallel to the bedding plane, and therefore commonly at an angle to the stromatolitic laminae in the displaced mud balls. Thus, ‘angular unconformities’ were formed. This process could be repeated several times, resulting in fragments that show a number of apparently haphazard angular unconformities; these record, in fact, the successive positions of the fragment with respect to the bedding plane.

Although environments where tidal activity is combined with fine sandy layers that cyanobacteria think a favourable substratum are fairly common, a combination with frequent seismic activity is much rarer. It is nevertheless remarkable that the resulting features, which have been baptised ‘tomboliths’, never have been described and analyzed before.

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