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The life cycle of seismite research

A.J. (Tom) Van Loon

Geological Institute, Adam Mickiewicz University, Maków Polnych 16, 61-606 Poznań, Poland;
email: tvanloon@amu.edu.pl; tom.van.loon@wxs.nl

1. Birth of the seismite concept

Seismites originated during most of the Earth history: they are known already from the Archaean (Schneiderhan et al., 2013). Numerous examples have been described from the Palaeoproterozoic (Fig. 1) and the Mesoproterozoic (Fig. 2), and they are well known results of earthquakes in history and nowadays (Fig. 3). Yet, it was only less than half a century ago that they were recognised as such for the first time; Seilacher (1969, p. 158) proposed the term in the following sentences: "*In this case* [deformation structures formed on a muddy slope sediment; AJvL] *the sliding process may not have had time to develop fully so that the deformational structures became "frozen" in an embryonic stage, without resulting in a major lateral transport. It should be realized that this would be only one type of earthquake beds, or* seismites *(genetic term, proposed herewith)*". A few lines further he states: "*Stronger shocks and paleoslope, on the other hand, may lead to regular slides or turbidity currents, the deposits of which would not be earmarked as seismites any more.*" It is obvious from these sentences that Seilacher (1969) proposed the term 'seismites' for layers that had become affected and deformed by a seismic shock.

Fig. 1. Seismite in the Palaeoproterozoic Chaibasa Formation (Singhbhum craton, E India).

Fig. 2. Seismically deformed stromatolites in the Mesoproterozoic Wumishan Formation (Changping District, China). From Van Loon & Su (2013).

Fig. 3. Recent seismically disturbed estuarine sediments (Baye Mont-St-Michel, France).

Seismites did not became a much studied topic immediately afterwards, but the same researcher published a new article on the subject some 15 years later (Seilacher, 1984), and this new article received much more attention than the previous one, possibly because it was based on a conference presentation. This new article can, in my opinion, be considered as the starting point for more focused research on seismites. It is noteworthy that, in contrast to what numerous later authors stated, Seilacher also in this article used the term 'seismite' to indicate a layer, as, for instance on page 2: "*The major problem for the sedimentologist is the distinction of seismites from other event deposits*". He also is clear on page 10: "*The stratinomic distinction of seismites from other event deposits is a challenging problem, but it depends on the availability of diagnostic criteria*".

2. Unfortunate childhood

Unfortunately, Seilacher (1984) himself used the term 'seismite', though only one time (p. 3), in another sense, viz. to indicate soft-sediment deformation structures (SSDS) that must be ascribed to processes triggered by seismic shocks: "*In the present contribution we will discuss some examples from quiet-water basins with both a high earthquake probability and a good preservation potential for sedimentary structures that could be interpreted as seismites*". Considering the thoroughness of Seilacher in his numerous other publications on a wide variety of topics, this sentence must be considered as 'a slip of the pen': he must have meant that the structures could be used to interpret a layer as a seismite.

This unfortunate usage of the term 'seismite' by Seilacher himself had large consequences, however, as numerous researchers did not read the article carefully enough, and started to use the term to indicate soft-sediment deformation structures that were interpreted to result from a seismic shock. This usage is unfortunate, indeed, because similar deformation structures can also be formed under non-seismic conditions (Van Loon, 2009; Owen & Moretti, 2011). All parameters such as shape and size can be similar for both seismic and non-seismic SSDS (Fig. 4).

This misconception of what a seismite is has led many times to confusion in the childhood of seismite research (roughly the 1985–2005 period): is a layer or a structure meant with the term? If a structure, what kind of deformation is meant with the term? Why this specific deformation structure is called a seismite whereas neighbouring deformation structures are not? Actually, the term 'seismite' became ever more used to describe an SSDS that might occur as just a structure presumed to have originated from a seismic shock, without realising that a seismite is a layer (commonly sandwiched between non-deformed layers) that is characterised by the lateral more or less continuous presence of SSDS that are formed by processes that are inter-

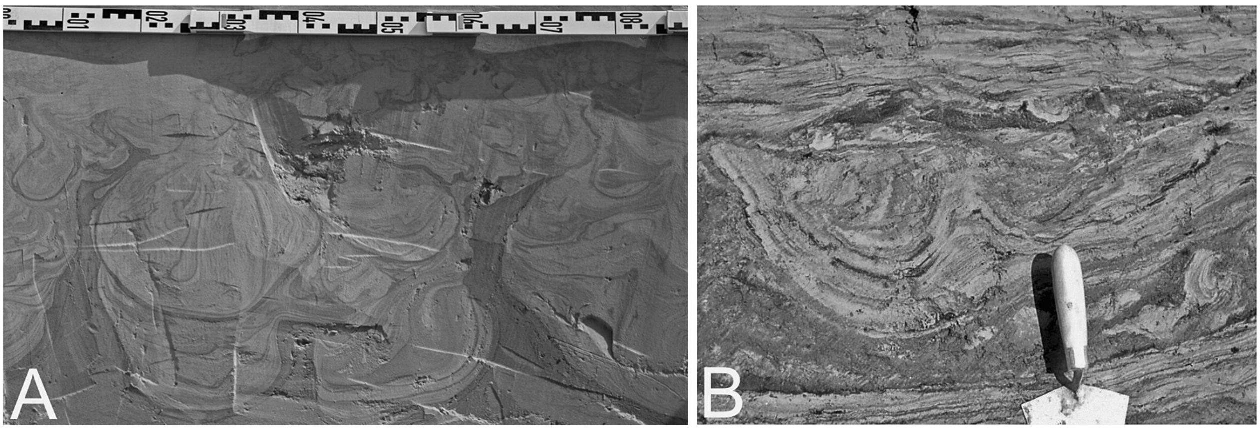

Fig. 4. Loadcasts showing similar characteristics, although one (A) formed due to seismic activity (Siekierki exposure, NW Poland), whereas the other one (B) was formed in a non-tectonically affected area (previous lagoonal Zuiderzee, central Netherlands).

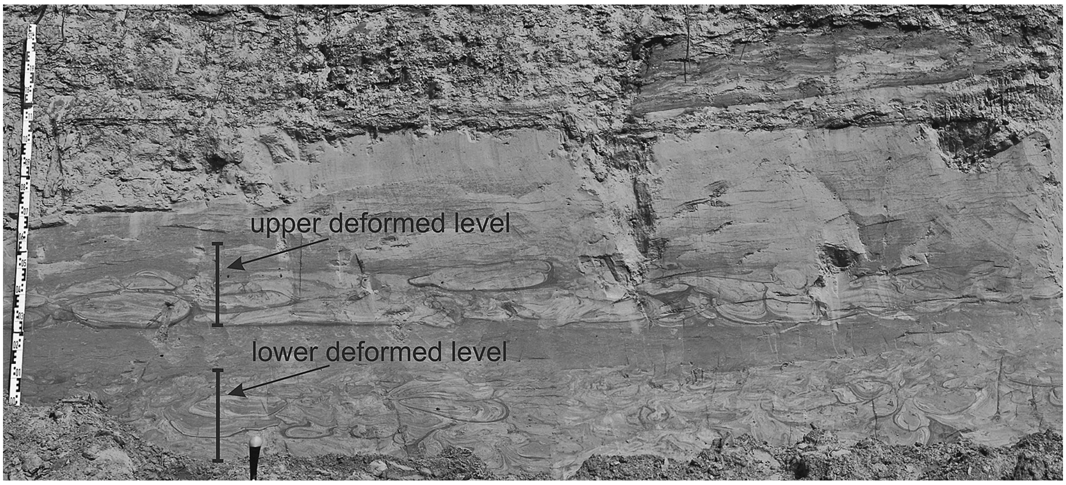

Fig. 5. Two SSDS-rich seismites, formed as a result of successive earthquakes (induced by glacio-isostatic compensation), sandwiched between non-deformed layers (Saalian glaciation, NW Poland). From Moretti & Van Loon (2014).

preted to have been triggered by a seismic shock (Fig. 5).

The use of the term in two ways (deformation structures vs. layers) is particularly unfortunate since single SSDS may or may not be due to seismic activity, whereas seismites are by definition (their seismic origin must be proven or made, at least, highly probable before the term 'seismite' can be given to a layer; see for criteria Sims, 1975, but these criteria should be applied cautiously: Moretti & Van Loon, 2014). If the author of an article does not clearly indicate in which way he uses the term, a reader may well misinterpret the tectonic history of a region.

3. Stage of adolescence

The term 'seismite' is, unfortunately, also after the childhood phase still in use in the sense of seismically induced SSDS (e.g. Santos et al., 2012; Mugnier et al., 2013; Khorzenkov et al., 2014). The term has in the course of time even been used in the sense of a litho-unit that owes its mere existence only indirectly to the occurrence of earthquakes (e.g. Liang et al., 2002); the true nature of such features that might perhaps be best indicated with the term 'pseudoseismites' now fortunately becomes revealed ever more frequently (see, for instance, Van Loon, 2014, this issue).

Fortunately, however, the term 'seismite' becomes increasingly used again in its original meaning (e.g. Tohver et al., 2013; Jiang et al., 2014), as also done in this special issue. This is important, since research of seismites is carried out ever more frequently, and ever more details become available – even though several problems still remain unsolved. This implies that seismite research may have reached by now a stage of adolescence, but not yet of maturity.

Unambiguous reports on seismites become ever more important because of the potential consequences. The occurrence of palaeo-earthquakes, as now commonly presumed on the basis of the recognition of seismites (in its original sense), is of great importance for both fundamental and applied research. The study of seismites therefore has now become a hot topic, with studies both in the field (e.g. Perucca et al., 2014, this issue; Üner, 2014, this issue; Van Loon & Pisarska-Jamroóy, 2014) and in cores (e.g. Mats, 2012; He et al., 2014, this issue).

From a fundamental point of view, the recognition of seismites is important because seismites are proof of seismic activity (which need not be evident otherwise) and because they can help reconstruct the direction of the epicentre as well as the magnitude of the responsible earthquakes. This can be interesting, for instance in a setting where continents collide (Sarkar et al., 2014, this issue) or break up (Qiao et al., 2007). Moreover, seismites in the ancient rock record can give insight in the occurrence of seismic activity that affects environments which cannot be studied well nowadays because of inaccessibility (e.g. the deep-sea; see, for instance, Valente et al., 2014, this issue).

From an applied point of view, seismites are at least equally important. When they are recognised in cores, they indicate that a specific interval has, during sedimentation, been affected by seismic activity. If this concerns a thick interval, it may imply that the lower part of this interval may, if already lithified when the seismic activity was still going on, have been fractured or faulted. This can have consequences for the permeability, which is important for the exploitation of hydrocarbons. If only one or a few seismites are found in drilling cores, these can potentially serve as marker beds that allow correlation between boreholes over a large area, where other features for correlation (different lithologies, microfossils, etc.) are absent. This can help reconstructing the tectonics and palaeogeography of the affected area, which can also be of great importance for hydrocarbon exploration (He et al., 2014, this issue).

4. Upcoming stage of maturity

A stage of maturity will be reached only if (1) the earth-science community acknowledges that seismites are layers, not structures, and (2) if agreement exists about how seismites can be recognised. The original and early researchers (Seilacher, 1969, 1984; Spalletta & Vai, 1984; Kleverlaan, 1987) did not really provide clues that would nowadays be considered as acceptable or convincing.

The first-mentioned aspect should actually now become considered as a solved problem. If one would ask present-day researchers who still apply the term 'seismite' in the sense of a seismically induced SSDS by which criteria they recognise these seismic structures, the answer will probably be surprisingly simple: they apply the term 'seismite' to SSDS in layers that they interpret to be seismites in their original (and nowadays used) sense. In practice this implies that the use of the term 'seismite' for SSDS should immediately be abandoned.

How layers can be recognised as seismites, is out of the focus of this contribution. Many works are devoted to this topic (e.g. Sims, 1973; Montenat et al., 2007; Moretti & Van Loon, 2014); the interested reader is referred to them. The present contribution is more directed (see below) to seismite-related problems that have not yet been solved, and even hardly recognised.

5. The future: a fully grown-up stage

Although complete agreement has not yet been reached regarding the criteria that must be met to interpret a deformed layer as a seismite (dead nature appears sometimes more variable than living nature!), it seems that this leads only rarely to discussions: the overall picture has become commonly clear. Yet, complications make it frequently difficult to explain the precise deformation history of seismically affected sediments. One of the reasons is that earthquakes commonly are followed by aftershocks. These may be strong enough to disturb an already disturbed layer again. Since the sedimentation rate in most environments is relatively low in comparison to the earthquake frequency in areas that are affected by tectonics or volcanism (see Tian et al., 2014, this issue), the same layer may be disturbed by shocks several times, with the consequence that the deformations become ever more complex.

It may also be that the sedimentation rate is relatively high. In such a case it is commonly found that several deformed layers occur stacked (see, e.g. Sarkar et al., 2014, this issue), sometimes with thin intercalations of non-deformed sediment. In the latter case, it is, as a rule, easy to recognise the deformed layers as individual seismites, but in the former case several deformed layers may be in direct contact with each other, which implies that the criterion 'sandwiched between undeformed layers' is then invalid.

We are commonly still not well able to distinguish the correct sequence of events if disturbed layers become disturbed again, sometimes several times. Only when we will be able to make such distinctions, seismite research will have reached a stage of maturity. But there is more: one aspect of seismites seems still entirely overlooked. We are well aware now that seismic shocks lead easily to deformed layers (seismites) in sediments that are susceptible to disturbation. That is why most seismites have been described from lacustrine, lagoonal and shallow-marine sediments: these tend to contain a relatively high percentage of silt, which grain size favours the origination of deformations.

The same sediments that are prone to deformation by seismic shocks are, obviously, also relatively easily deformed by other processes. It is therefore to be expected that seismites may also contain

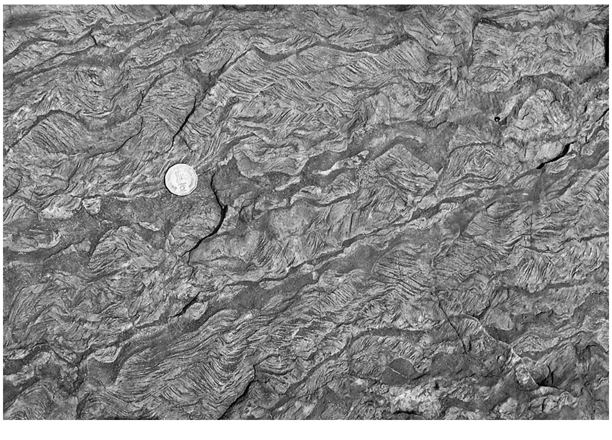

Fig. 6. Chaotically deformed shallow-marine sediments (Palaeoproterozoic Chaibasa Fm., E India), ascribed to a number of earthquakes that affected the same uppermost (laminated) sediments several times.

non-seismic SSDS. These can have originated before or after the seismic shock, and the development of pre-shock SSDS (e.g. loadcasts) may also be re-activated by the seismic shock. Moreover, after shocks have deformed a layer, it may be deformed again by early-diagenetic processes such as the escape of pore-water/sediment mixtures under the influence of an increasing load by ongoing sedimentation. It must thus be recognised that SSDS in a seismite may well have different moments of origin, and that some SSDS may have undergone complex developments. This is most likely the case in some of the complexly deformed seismites (Fig. 6) described from the Palaeoproterozoic Chaibasa Formation in E India (Mazumder et al., 2006, 2009).

6. For now: a new challenge

As mentioned above, not all SSDS in a seismite need have a seismic origin. It may well be – and it seems even probable – that in most seismites both seismogenic and non-seismogenic SSDS occur, probably accompanied by seismically deformed non-seismogenic SSDS.

The unravelling of the origin of the individual SSDS in a seismite now might become a new challenge, particularly for sedimentologists. If sufficient research in this topic were carried out, it might become clear whether there is in practice a difference between seismogenic and non-seismogenic SSDS that might be recognised in the field; a difference that thus far has not been found in experiments that just dealt with SSDS (e.g. Rettger, 1935; Kuenen, 1958; Dżułyński & Walton, 1966; McKee & Goldberg, 1969; Owen, 1987; Nichols et al., 1994) or with the SSDS resulting from shocks, for instance by shaking equipment (e.g. Rogers, 1930; Goodman & Appuhn, 1966; Anketell et al., 1969, 1970; Owen, 1985, 1996; Koga & Matsuoto, 1990; Moretti et al., 1999).

Seismogenic structures in seismites: should they be described as seismites in seismites? Obviously not. One more reason why we should, from now on, all adhere to the term 'seismite' in its original sense: a layer with laterally extensive SSDS originated by a seismic shock. If we all would do so, seismite research will have reached a phase of wisdom.

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