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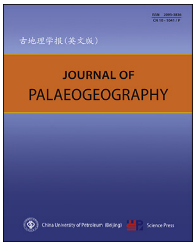

Multi-origin of soft-sediment deformation structures and seismites

Seismites resulting from high-frequency, high-magnitude earthquakes in Latvia caused by Late Glacial glacio-isostatic uplift

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Abstract Geologically extremely rapid changes in altitude by glacial rebound of the Earth crust after retreat of the Scandinavian Ice Sheet at the end of the last Weichselian glaciation influenced the palaeogeography of northern Europe. The uplift of the Earth crust apparently was not gradual, but shock-wise, as the uplift was accompanied by frequent, high-magnitude earthquakes. This can be deduced from strongly deformed layers which are interpreted as seismites. Such seismites have been described from several countries around the Baltic Sea, including Sweden, Germany and Poland.

Now similarly deformed layers that must also be interpreted as seismites, have been discovered also in Latvia, a Baltic country that was covered by an ice sheet during the last glaciation. The seismites were found at two sites: Near Valmiera in the NE part and near Rakuti in the SE part of the country. The seismites were found in sections of about 7 m and 4.5 m high, respectively, that consist mainly of glaciofluvial and glaciolacustrine sands and silts. At the Valmiera site, 7 seismites were found, and at the Rakuti site these were even 12 seismites.

The two sections have not been dated precisely up till now, but lithological correlations and geomorphological characteristics suggest that the sediments at the Valmiera site cannot be older than 14.5 ka. Because the accumulation of the section did not take more than about 1000 years, the average recurrence time of the high-magnitude ($M \geq 4.5$—5.0) earthquakes must have been maximally only 100—150 years, possibly only 6—7 years. The sediments at Rakuti must also have formed within approx. 1000 years (17—16 ka), implying a recurrence time of high-magnitude earthquakes of maximally once per 100—200 years.

Keywords Soft-sediment deformation structures (SSDS), Seismites, Latvia, Glacio-isostatic rebound, Earthquake recurrence time

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1. Introduction

Loading and unloading of the Earth crust as a result of changes in the glacio-isostatic pressure, caused by advancing and retreating land-ice masses during the Pleistocene glaciations resulted in numerous cycles of glacio-isostatic rebound. It is not well known whether downwarping of the Earth crust under the influence of increasing ice thickness was gradual or step-wise, but rebound during deglaciation was at least commonly stepwise, as is known from the occurrence of successive earthquakes (*e.g.*, Mörner, 1989, 1991; Rodríguez-Lopez *et al.*, 2007; Tian *et al.*, 2015). These earthquakes are, if their magnitude was sufficiently high, reflected in layers (seismites) that are characterized by abundant soft-sediment deformation structures (SSDS) that give the affected layer (or sets of layers) a deformed, sometimes even chaotic over long distances (Brandes and Winsemann, 2013; Brandes *et al.*, 2012; Van Loon, 2009; Van Loon and Maulik, 2011). Such layers have been described originally from hard-rock successions consisting of deformation-susceptible sediments from almost all environments, mainly because soft-sediment deformation structures are commonly best visible in lithified rocks.

It is worthwhile to mention here that the term ‘seismites’ was introduced by Seilacher (1969) to indicate layers that were more or less entirely deformed by earthquake-induced processes. Insufficient knowledge of the original literature has, unfortunately, resulted in numerous publications in which the term ‘seismite’ is used for the deformation structures in earthquake-affected layers, but this is a misconception (Van Loon, 2014) that should become obsolete as soon as possible, if only to avoid confusion between layers and soft-sediment deformation structures.

Seismites can develop only if the magnitude of the responsible earthquake is high enough (at least M = 4.5—5.0; see, for instance, Rodríguez-Pascua *et al.*, 2000). Such large earthquakes tend to be followed by aftershocks, which also may have magnitudes that are sufficient to change undisturbed sedimentary layers into strongly deformed ones.

Many seismites are known from countries that were, in whole or in part, covered by land-ice masses during the last ice age (Weichselian, Vistulian), and particularly during the last glacial phase(s) of this glaciation; older Pleistocene seismites were probably largely eroded away by advancing ice masses during later glaciations. Seismites from the Weichselian glaciation are well known in Europe from Germany, Denmark, Sweden and Poland, but also from elsewhere (Brandes *et al.*, 2012; Hampel *et al.*, 2009; Kaufmann *et al.*, 2005; Mörner, 1990, 1991; Muir-Wood, 2000; Van Loon and Pisarska-Jamroży, 2014). It is commonly not well known how often deglaciation led to rebound phases that caused high-magnitude earthquakes that could trigger the development of seismites; nor is it known what is the (average) time interval between two successive large shocks. The present study is intended to shed light on this question.

Somewhat more is known about earthquakes caused by endogenic tectonics. Historical data indicate that a few high-magnitude aftershocks may occur within a relatively short time-span (Matsuda *et al.*, 1978, for instance, mention 800—1500 years for the Kanto District in Japan), but aftershocks are rarely sufficiently strong to induce shock waves that are capable of deforming layers at or near the sedimentary layers over such large lateral distances that these layers may be considered as seismites. Even the geological record of series of successive seismites reflecting repeated tectonically induced earthquakes is fairly scarce. Most publications about successive hard-rock layers with deformations induced by an earthquake while the sediment was still unlithified, estimate the recurrence time as several thousands (*e.g.*, Pantosti *et al.*, 2012: 2150 years) to tens of thousands of years (*e.g.*, Ezquerro *et al.*, 2015: 45,000 years).

Hardly any data are available about the recurrence time of Pleistocene earthquakes triggering seismites, even though the numerous advances and retreats of the large continental ice caps must have resulted in a huge number of rebound-related earthquakes. Reasons for this may be (1) rather gradual rebound instead of rebound in the form of earthquake-inducing faulting; (2) rebound in the form of frequent faulting that induced earthquakes of insufficient magnitude to produce seismites; (3) lack of sufficient exposures in Pleistocene sediments, leaving seismites undetected; and (4) earthquake-affected sediments with a grain-size distribution that is insufficiently susceptible to deformations. Considering all these restrictive conditions, it is not surprising that sections in areas without endogenic tectonic activity with Pleistocene sediments showing a series of seismites are rare.

The Baltic Shield is seismically active; several large faults displacing sediments of the last glaciation indicate intense earthquakes since the retreat of the ice (Mäntyniemi *et al.*, 2004; Mörner, 2004). In contrast, the Baltic Basin of the East European Craton has been considered for a long time to be seismically stable till

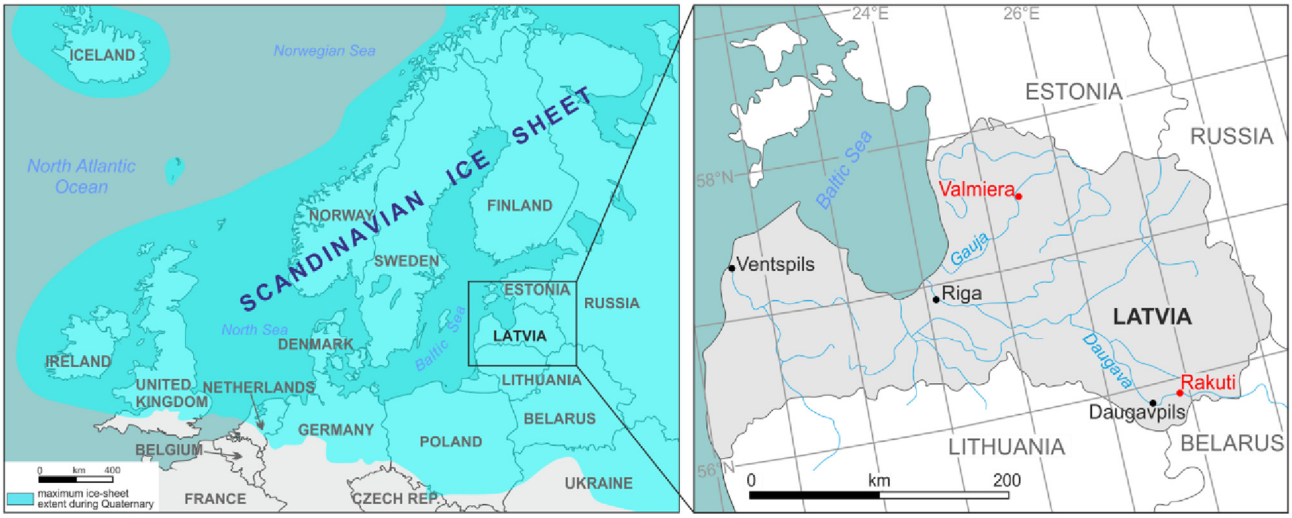

Fig. 1 Location map. Left: The position of Latvia within northern Europe. Right: The position of Valmiera and Rakuti within Latvia.

several earthquakes with magnitudes up to 5.2 have changed this idea (Gregersen *et al.*, 2007; Nikonov and Sildvee, 1991; Šliaupa *et al.*, 2006). Yet, analysis of historical seismic events of Latvia, which is located in the central part of the Baltic Basin (Popovs *et al.*, 2015), indicates that the magnitudes of historical seismic events do not exceed 4.7 (Nikulin, 1996). Historical sources report some moderate earthquakes in southern Latvia, but no earthquakes have been documented in northern Latvia. Faults have been detected in the crystalline basement and in Caledonian and Hercynian structural complexes of Latvia (Lukševičs *et al.*, 2012; Popovs *et al.*, 2015). The epicenters of historical earthquakes mainly coincide with locations of known faults (Nikulin, 2011). During the Pleistocene, Latvia was covered by four glaciations leaving an up to 310 m thick sedimentary cover (Zelčs *et al.*, 2011). These Quaternary sediments have a complex structure with a large amount of small-scale glaciotectonic deformations (Popovs *et al.*, 2015; Zelčs *et al.*, 2011) which hinder tracing of any faults caused by endogenic tectonics. The locations of several potential sites of high seismic sensitivity for large hydropower stations in Latvia (Safronovs and Ņikuļins, 1999), for the disposal of nuclear waste, and for the construction of a nuclear power station that has been planned to be built near the border of Latvia (World Nuclear News, 2008, 2009) make the detection of any evidence on pre-instrumental, and more importantly pre-historical seismic activity of utmost importance. Detection of such faults became particularly clear after the construction of the Ignalina nuclear power plant: It has been decommissioned when it was found only after finishing the construction of the plant that two potentially active tectonic faults are located nearby (Šliaupa *et al.*, 2006).

Here we describe strongly deformed layers from two sites in Latvia. The sediments are situated near Valmiera in NE Latvia along the Gauja River, and near Rakuti in the Daugava River valley, in the SE part of the country (Fig. 1). We interpret the deformational trigger in Section 3 on the basis of the sedimentological characteristics of the deformed layers in combination with their geological context described in Section 2.

2. Description of the SSDS and their context

The sediments at both sites date from less than 20,000 years ago (see Section 4 for more details). The presence of strongly deformed sediments at these sites is remarkable, since no sufficiently strong endogenic activity is known to have occurred there during the Pleistocene or Holocene.

2.1. The Valmiera section

The northern part of Latvia was not affected by strong endogenic tectonic activity during the Pleistocene, nor during historical time; this implies that the Pleistocene deformed layers at Valmiera must be attributed to another process; the only feasible sedimentary process that can cause strongly deformed layers interbedded between non-deformed layers is slumping (or a comparable form of mass transport).

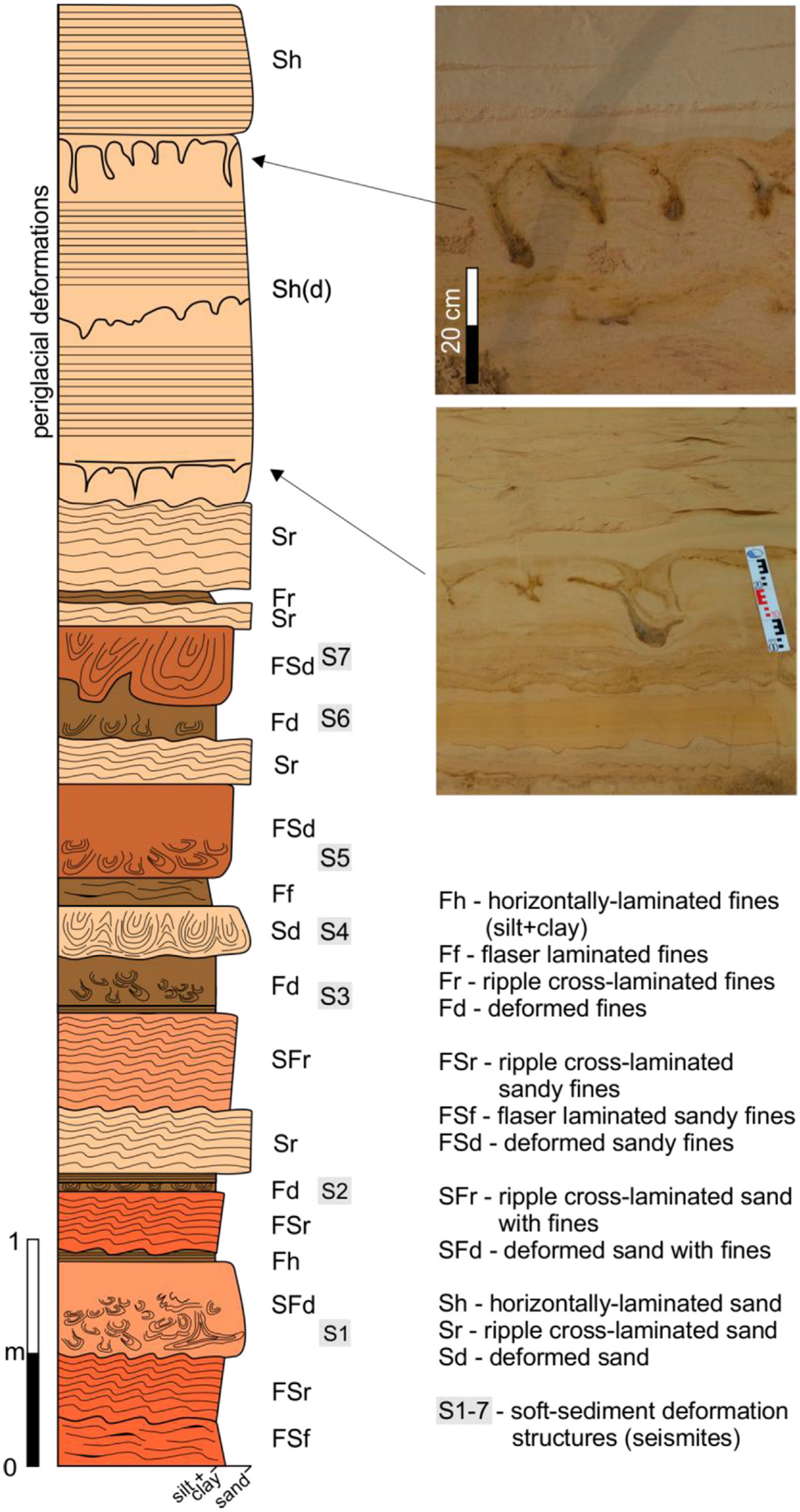

Fig. 2 Schematic sedimentary log of the Valmiera section, showing 7 strongly deformed levels (S1—S7) in its lower part, and several levels with periglacial deformation structures in the top part. Note the differences in style between the periglacial deformations (2 photos at the right) and the deformations in the seismites (Fig. 4 and following figures).

Fig. 3 The Gauja River near Valmiera, with, in an outer meander bend, the main exposure under study. In the background some more (much smaller) exposures are visible.

The characteristics of the deformations, which will be described below, exclude such an origin, however. A tectonic process must therefore be responsible. As no endogenic tectonic activity is known from the Pleistocene in the Valmiera area, it must have been a non-endogenic tectonic process. The only feasible process of such a type is glacio-isostatic rebound of the Earth's crust after retreat of a thick ice cap. Such isostatic rebound may induce earthquakes that leave traces in the form of soft-sediment deformation structures (Brandes and Winsemann, 2013; Brandes *et al.*, 2012; Van Loon, 2009; Van Loon and Maulik, 2011). The Valmiera site (25°26′41″E, 57°32′45″N) is located in a potentially seismically active zone with several faults in Caledonian and Hercynian structural complexes (Nikulin, 2011).

The deformed layers in the section at Valmiera in NE Latvia (Fig. 2) extend over some hundreds of meters, though not all of them could be traced that far because of coverage by vegetation or a thick talus hiding the sediments that are locally exposed in steep cliffs along the Gauja River (Fig. 3). The best cliff section is about 9.3 m high, of which some 7 m were exposed. In this exposed section, seven strongly deformed layers occur (Pisarska-Jamroży *et al.*, 2015), showing abundant SSDS; they occur between undeformed sediments which show similar grain sizes (Fig. 4); the sediments consist of fine-grained sand, very fine-grained sand and admixtures of silt and clay. Most of the soft-sediment deformation structures are load casts, pseudonodules, flames and fluid-escape structures (Fig. 5), but more chaotic deformations occur as well (Fig. 6). This is particularly the combination of SSDS that is common in seismites. The deformation structures in the affected layers can be fairly complex, particularly if the deformational trigger process occurred repeatedly with geologically short time intervals; in such a case the already deformed sediments become further deformed (Fig. 7).

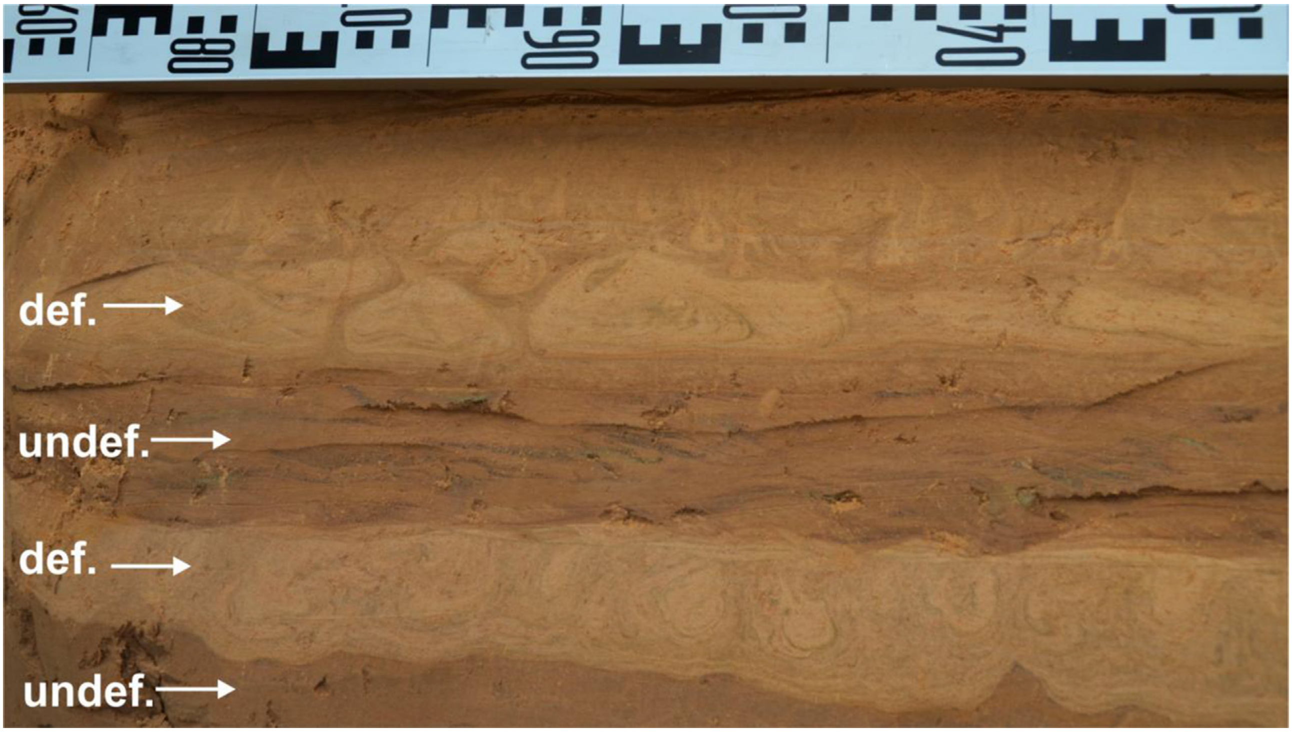

Fig. 4 Two seismites in the Valmiera section, separated by undeformed layers. Note that the seismites have the same grain size as the non-deformed layers. Load casts, pseudonodules, flame structures and water-escape structures are the most common SSDS. The lower deformed layer consists almost exclusively of load casts with flames and water/sediment-escape structures in between. The load casts themselves also show deformations, which suggests a second phase of deformational activity. The tops are truncated and covered locally by a thin level with horizontal lamination, pointing at erosion of the sedimentary surface that was probably irregular due to the loading process by low-energy bottom currents. The upper deformed layer consists mainly of pseudonodules with on top much smaller load casts and other irregular structures. Whereas the base of this deformed layer is clear, the top is not, suggesting that deformations still took place when new sediment was accumulating. Scale (top) in centimeters.

This raises the question whether the deformed layers in the Valmiera section represent seismites, indeed. The question of how seismites can be recognized on the basis of specific criteria has been discussed extensively in the literature. This question, together with the question of whether the strongly deformed layers in the Valmiera section should be interpreted as seismites, is dealt with in Section 3.

The sediments in the Valmiera section are glaciofluvial and glaciolacustrine sands and silts deposited in an ice-dammed lake where a stream could still run through (Krievāns, 2015; Nartišs, 2014). The lake came into being between the formation of the Linkuva and Valdemārpils ice marginal zones (Nartišs, 2014), which means somewhat before 14.5 ka. The deformation of the sediments under study at Valmiera can consequently not be older.

2.2. *The Rakuti section*

A quarry located in the valley of the Daugava River near Rakuti (SE Latvia; Fig. 1) is even more spectacular than the Valmiera site, as it contains at least 12 strongly deformed layers (Fig. 8) in a section of about 5 m thick, of which 4.5 m were exposed. The exposed section (55°53′51″N, 27°05′30″E) consists mainly of late Weichselian fine-grained glaciolacustrine sediments and some more silty/sandy sediments of glaciofluvial origin (Fig. 9); both the sedimentary and the geomorphological setting suggest that the section forms part of a kame terrace (cf., Zelčs *et al.*, 2014).

The section under study is situated in a large quarry in which the exploited sediments represent partly different stratigraphic levels. Recent total-station surveying, determining altitudes with millimeter precision, and high-precision GPS measurements confirm that the two lowermost deformed layers in the section under study can be correlated with similarly deformed layers some 150 m to the west in a section that is truncated by a boulder-rich gravel. This proves that the deformed layers extend over considerable distances.

The strongly deformed layers (Van Loon *et al.*, 2015) are sometimes intercalated between

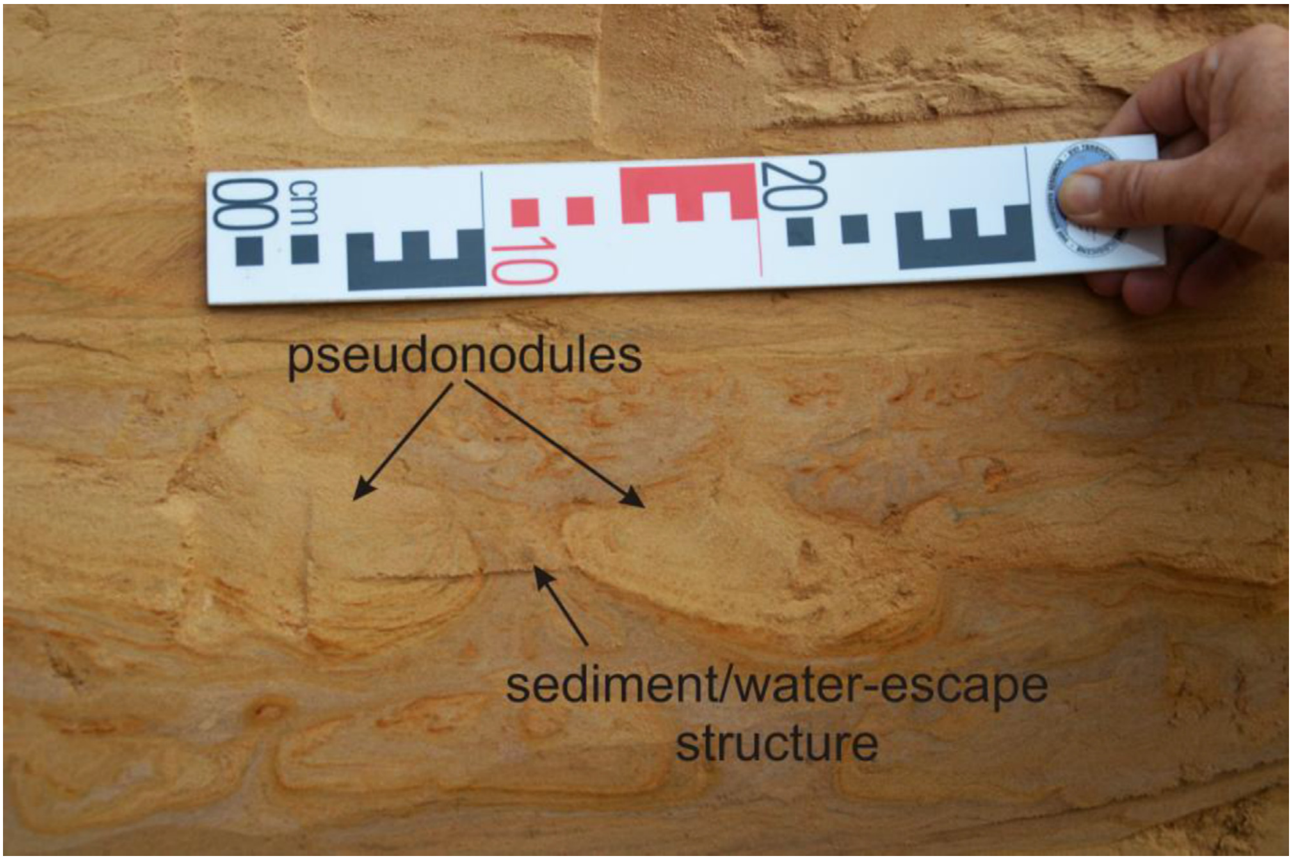

Fig. 5 Details of one of the deformed layers in the Valmiera section. The main SSDS are pseudonodules, but these have become slightly deformed themselves. In between the pseudonodules, flame structures and/or sediment/water-escape structures are present; the precise genetic process of these structures cannot be determined because of later deformation. Small fragments of a broken-up sand layer are floating in the fine matrix between the pseudonodules. The top has clearly been truncated by a bottom current (note the cross-bedding).

undeformed layers (Fig. 10) and sometimes stacked on top of each other (Fig. 11). This indicates that sometimes sufficient time elapsed for accumulation of new sediment layers between the successive processes that resulted in the sedimentary deformations, whereas sometimes such deformational processes followed each other so quickly that insufficiently time was available in between to result in traceable sedimentation. In several cases it even seems that the same layer has been affected more than once by the deformational trigger (Figs. 12 and 13).

The SSDS in the Rakuti section are in all respects very similar to those in the Valmiera section. The most common structures are load casts and related structures such as pseudonodules and flame structures; in addition, fluid-escape structures are common. Wherever deformed layers are stacked upon each other, it is obvious that the deformational process affecting the younger layer affected, as a rule, also the older layer. This commonly resulted in fairly complex SSDS. Moreover, the depositional environment was so shallow that the top parts of SSDS became occasionally truncated, most probably by wave action or a strong bottom current.

The sizes of the SSDS at Rakuti are commonly related to the thickness of the affected layer: The thicker the layer, the larger the SSDS. This is fairly logical, as the deformational process commonly affected the whole layer. Since several of the deformed layers at Rakuti are thicker than those at Valmiera, the SSDS at Rakuti can reach larger sizes in these layers than at Valmiera. This is, however, the only significant difference; in all other aspects, the SSDS at Rakuti and Valmiera are well comparable. This makes it likely that a comparable deformational process affected both the Valmiera and the Rakuti site. Which process triggered the deformations is analyzed in Section 3.

3. Trigger of the deformations

Liquefaction and fluidization are the processes that play the most important role during the

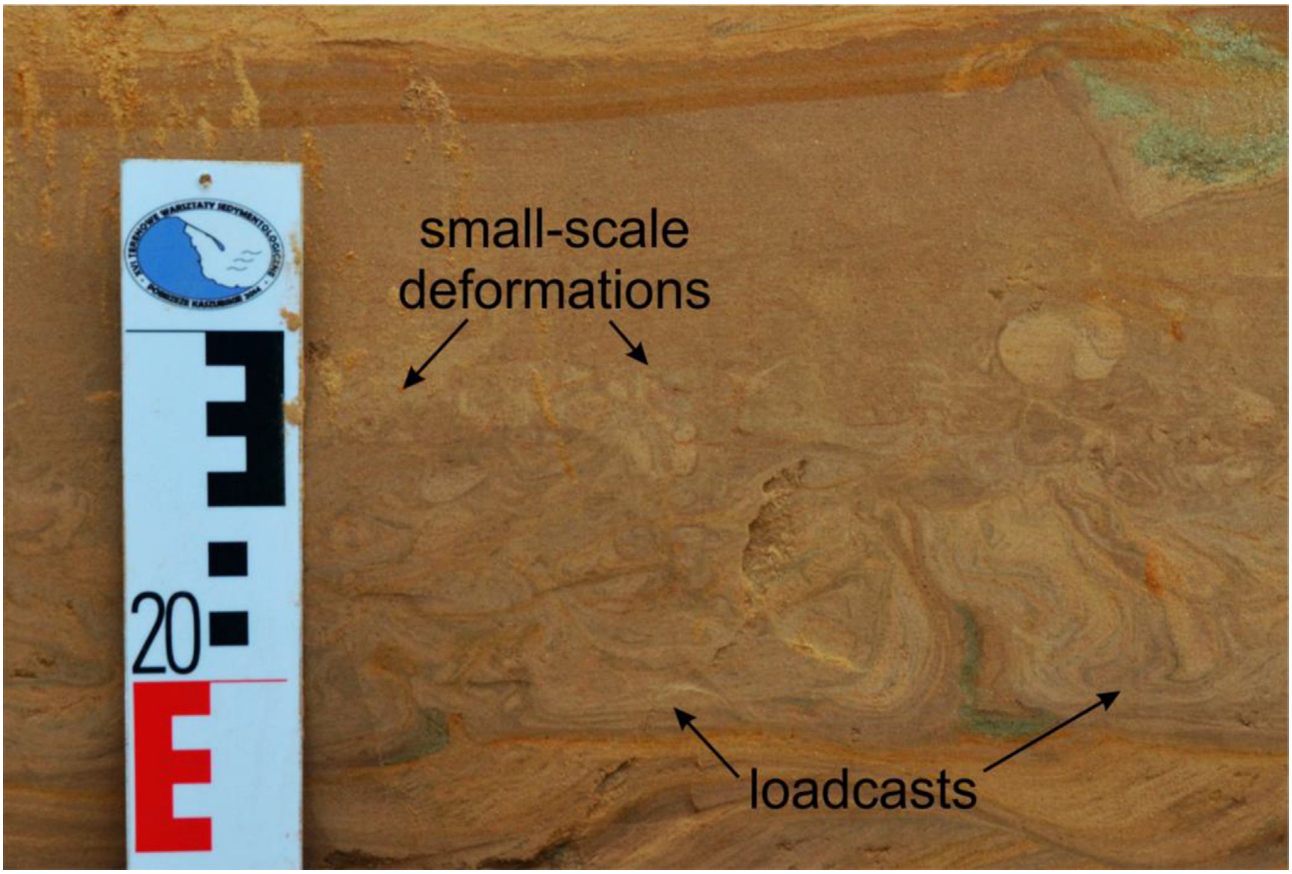

Fig. 6 Details of a layer with chaotic deformations. Deformed, relatively large load casts are visible in the middle and at right, just above the basis of the layer. In the left part and in the higher part of the deformed level, numerous smaller-scale deformations are present, at least partly representing deformed load casts and pseudonodules. This must be ascribed to repeated phases of deformation. Whereas the basis of the deformed layer is sharp, the upper boundary is gradual, indicating ongoing syn-sedimentary deformation of ever less intense character during settling of sediment from suspension. Scale in centimeters.

formation of load casts and associated structures, which represent the most common SSDS in the deformed layers under study, together with fluid-escape structures that also point at liquefaction and fluidization. The final morphologies of the load casts and other SSDS depend mainly on the initial sedimentary setting, the driving force and the duration of the deformable state, whereas the nature of the trigger mechanism seems to play a minor or negligible role (Owen and Moretti, 2011; Owen *et al.*, 2011). SSDS thus can have identical morphologies, independent of whether they were formed due to a seismic shock or by any other trigger mechanism. Several authors have therefore tried to identify criteria which might allow seismically induced SSDS to be distinguished from deformations caused by other trigger mechanisms, in order to cope with this problem (see Moretti and Van Loon, 2014). Sims (1975) stated that seismites could be recognized as such if (1) they occur in a seismically active region, (2) the SSDS are largely restricted to specific stratigraphic horizons, (3) they can be traced or correlated over large areas within a sedimentary basin, and (4) there is no detectable influence of failure or slope movement.

Hilbert-Wolf *et al.* (2009) more recently suggested the following criteria summarizing some studies on the same topic (Obermeier, 1996; Obermeier *et al.*, 1990; Rossetti, 1999; Wheeler, 2002): (1) a clear association with faults as potential triggers; (2) the observed deformations must be consistent with those having a known seismic origin; (3) a widespread occurrence that is temporally constrained; (4) a systematically higher intensity or increase in frequency towards a possible epicenter; (5) lack of indications for any other causal mechanisms; (6) vertical recurrence of deformed layers; (7) a stratigraphic position in between undisturbed layers; and (8) the presence of faults associated with wedges of intraformational breccias, conglomerates, or massive sandstones.

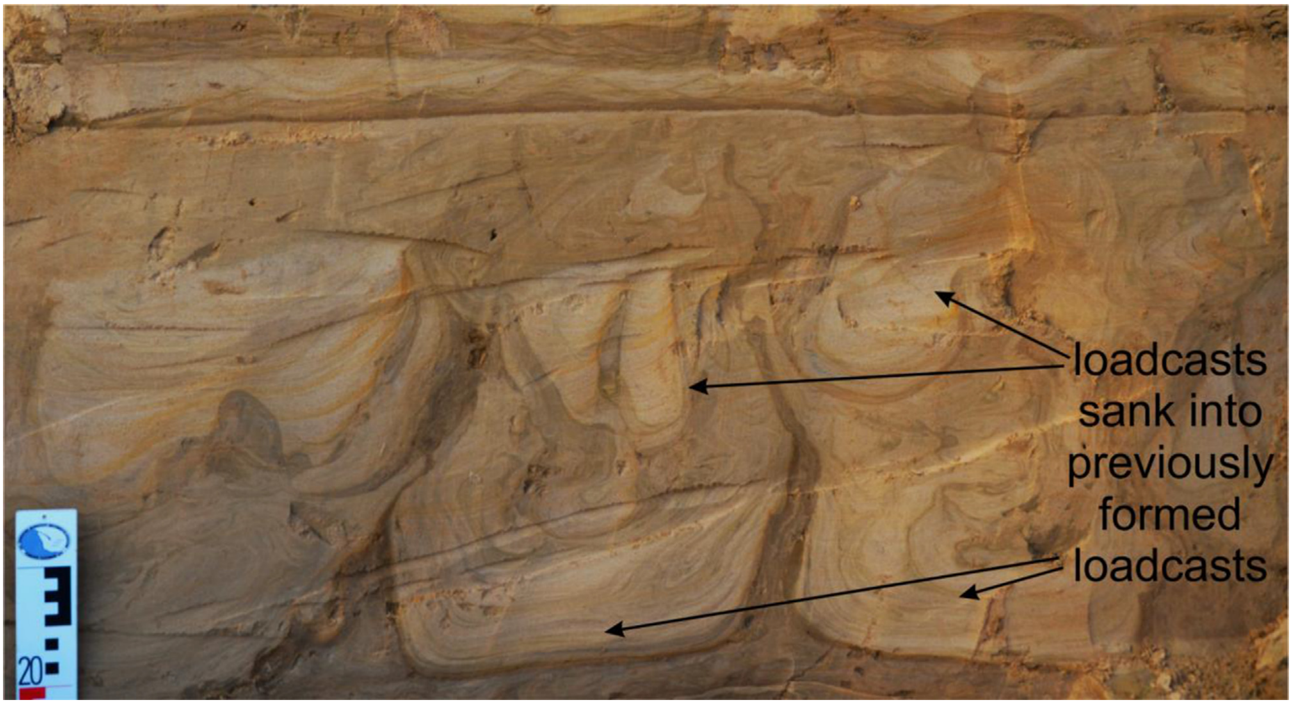

Fig. 7 Details of a deformed layer in the Valmiera section, showing load casts that sank into previously formed load casts. Because the sediment of the 'later' load casts is not coarser than the sediment of the 'earlier' load casts, the loading cannot be attributed to reversed density gradients but must be ascribed to repeated non-sedimentary processes that caused a sudden change (in the form of liquefaction) in the nature of the sediment. The deformed layer has been truncated by a thin current-deposited layer that has itself also been truncated, possibly after a phase of relatively slight deformation (see the truncated load cast at the right-hand top). Scale in centimeters.

The following criteria to recognize seismites were proposed by Owen and Moretti (2011), based on both literature and field examples: (1) a large areal extent; (2) lateral continuity of deformed sediment; (3) vertical repetition; (4) SSDS with a morphology comparable with structures described from earthquake-affected layers; (5) proximity to active faults; and (6) dependence of complexity or frequency with distance from the triggering fault.

The above works thus differ slightly in their criteria for the recognition of seismites, but it seems that those proposed by Owen and Moretti (2011) cover all relevant criteria. The Latvian SSDS will consequently be dealt with in the following sub-sections within the context of the 6 criteria established by them.

3.1. Extent

Seismic shocks with a magnitude of M >5 result commonly in liquefaction processes (Ambraseys, 1988). The effects are mainly located within

Fig. 8 Overview of part of the best exposed wall in the quarry near Rakuti, showing twelve seismite levels (see also Fig. 9).

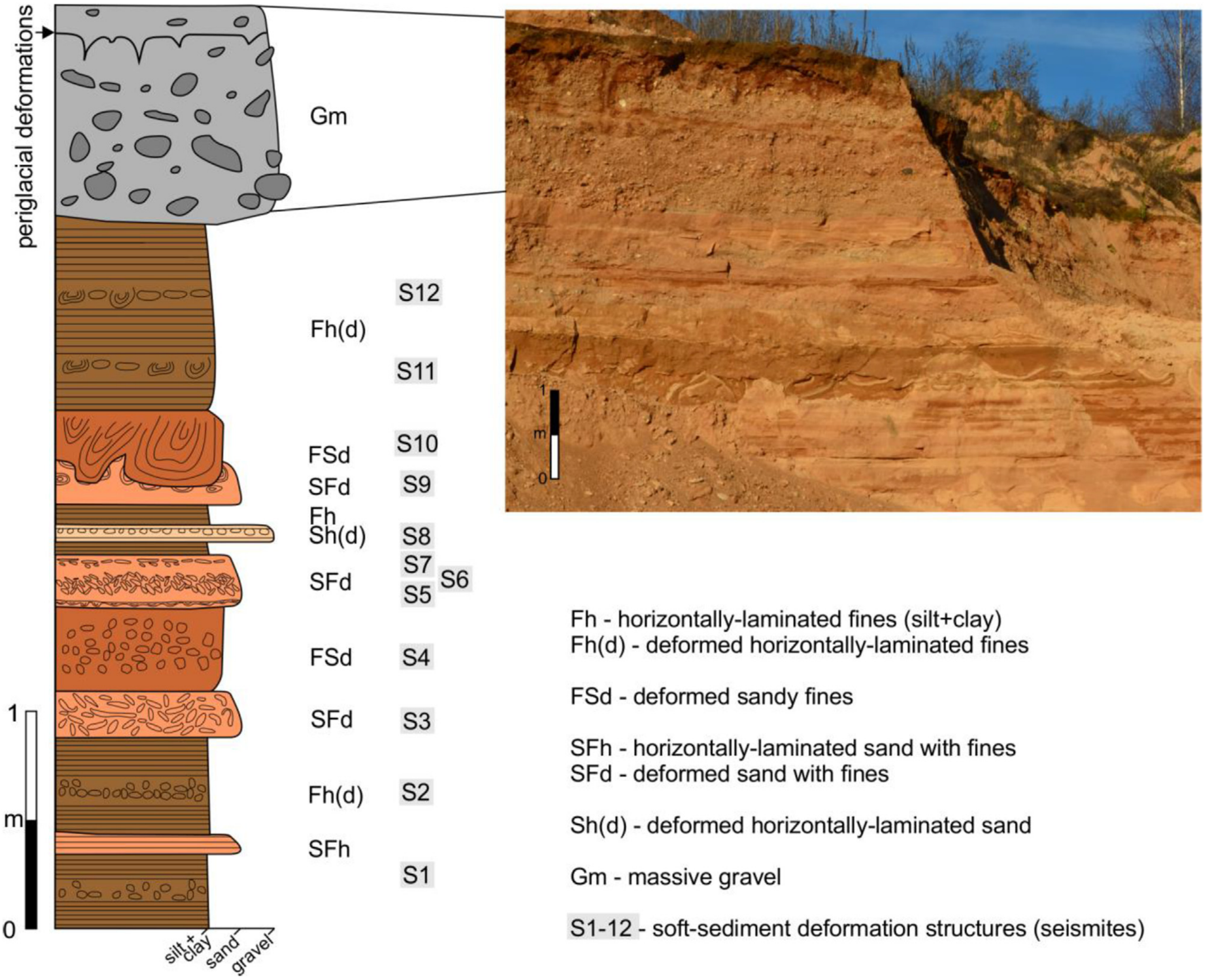

Fig. 9 Schematic sedimentary log of a main wall (see Fig. 8) under study at Rakuti, showing twelve strongly deformed levels (S1–S12) in its lower part, and a coarse part with a level of periglacial deformation structures at the top.

maximum distances from the epicenter of 40 km (more than 90% of recent seismic events: Galli, 2000) though this distance depends on the nature of the affected sediments. Moreover, earthquakes with a lower magnitude may also trigger liquefaction, but only in an area close to the epicenter. According to Papadopoulos and Lefkopoulos (1993), most of the SSDS related to earthquakes with a magnitude of 5–7 occur within a distance of less than 20 km away from the epicenter. Moretti (2000) even mentions that 90% of the seismically affected sites where liquefaction took place are situated closer than 40 km from the epicenter. Thus, the type and dimension of seismites are a function of the magnitude of the responsible earthquakes (Guiraud and Plaziat, 1993; Rodríguez-Pascua *et al.*, 2000). Their spatial distribution and lateral changes can consequently be used to locate main active faults (Alfaro *et al.*, 2010; Rodríguez-Lopez *et al.*, 2007). However, the logical criterion of a large areal extent is, as a rule, hardly applicable in practice because it may be impossible to trace a seismite over a long distance: it may have been locally eroded away or it may have become tectonically disturbed to such a degree that the original sedimentary deformations are no longer well recognizable as such.

The deformed levels in the Valmiera and Rakuti deposits are, unfortunately, not exposed outside the exposures under study. Small isolated outcrops spread over a distance of a few hundreds of meters from the large Valmiera exposure, and the extent over some hundreds of meters in the Rakuti quarry indicate, however, that the completely deformed levels are not

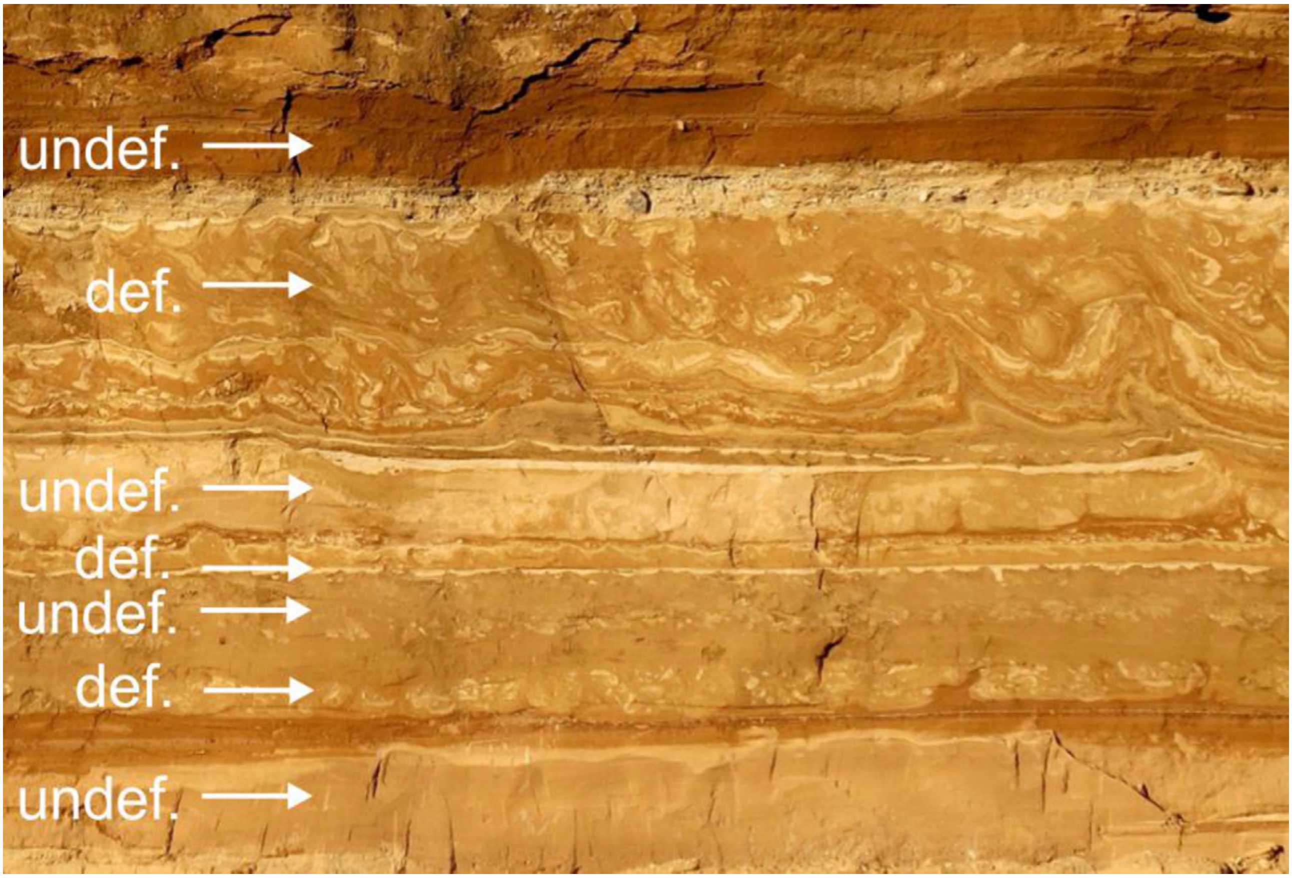

Fig. 10 Details of the wall in the quarry near Rakuti, where several strongly deformed layers are present, separated by undeformed layers. The section shown is about 1.5 m high.

a local phenomenon. As a consequence, this criterion does not exclude an origin of the deformed levels at Valmiera and Rakuti as seismites.

3.2. Lateral continuity

The exposures at Valmiera and Rakuti show several deformed levels, interbedded between similar sediments that do not show any significant SSDS (Figs. 4 and 10). However, the deformed levels show SSDS over their entire length (Fig. 14). This criterion for seismites is thus met.

3.3. Vertical repetition of horizons with SSDS

The occurrence of several deformed levels in each of the two study sites indicates itself already a repetition. Several of these levels have, however, also been deformed during several phases (Figs. 6 and 11). This indicates that liquefaction was most probably induced by a trigger that acted repeatedly so frequently that no distinguishable layers could accumulate in between. This commonly resulted in fairly complex structures (see Figs. 12 and 13). Then some time might pass, long enough to allow accumulation of a bed that would remain undeformed when the trigger became active again, affecting only the uppermost new layer by liquefaction. This is a most important criterion for the recognition of seismites.

3.4. Morphology of the SSDS

A direct relationship between the type and intensity of seismites and the magnitude of the responsible seismic shocks has been established by numerous studies. Rodríguez-Pascua *et al.* (2000) interpret each single kind of SSDS as induced by variable seismic intensity. However, this cannot be true, as it turns out that almost all types of liquefaction-induced SSDS can occur closely together; only their average complexity and intensity change laterally, depending on the

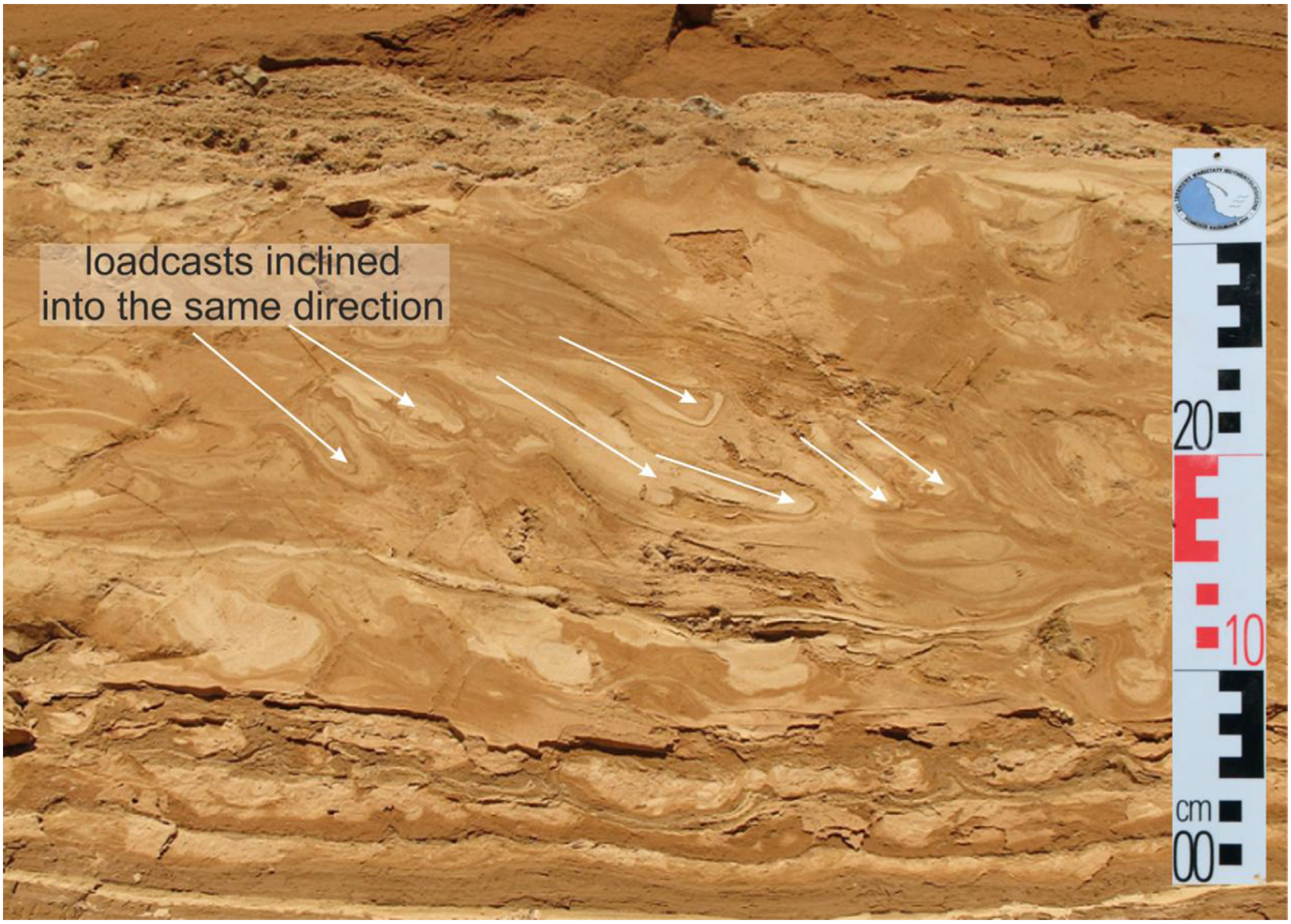

Fig. 11 Stacked strongly deformed layers in the quarry near Rakuti, with levels of SSDS mainly consisting of load casts, which points at repeated deformational activity. Note that almost all load casts are inclined into the same direction. As nowhere else signs of shearing due to currents are present at this site, it must be deduced that some slightly inclined sedimentary surface existed. When a trigger caused deformation resulting in liquefaction, the load casts that formed during the successive deformational phases became directed in their liquefied state following the inclination of the sedimentary surface. Scale in centimeters.

distance to the epicenter and the sediment properties. Also this type/distance relationship can, unfortunately, be difficult to establish, as all studies on SSDS show that the final morphologies are strongly related to the characteristics of the initial sediment, the driving force acting during deformation, and the duration of a deformable state.

Experiments producing 'seismically-induced' SSDS (Moretti *et al.*, 1999) show that the final morphologies are independent of the acceleration (and magnitude) of the earthquakes. The thickness of the sedimentary unit(s) involved in seismically induced liquefaction also seems to be unrelated to the magnitude of seismic shocks. This was detailed by Alfaro *et al.* (2010), who described large seismites from an area in southern Spain that was affected by earthquakes of moderate magnitude; these seismites show clearly that the thickness of the seismically deformed sedimentary unit(s) is related only to the thickness of the sedimentary unit(s) susceptible to liquefaction.

Which types of SSDS are formed as a result of shocks has been investigated in several experiments (*e.g.*, Moretti *et al.*, 1999; Owen, 1992). These experiments showed that particularly load casts and associated structures are easily formed. This is understandable, as the seismically induced shock waves that are responsible for the development of SSDS in water-saturated, unconsolidated sediments in the uppermost decimeters of the sedimentary succession are S-waves, which result in alternations of lateral pressure and tension within the sediment, thus allowing material to sink into the underlying layer, even if there is hardly any difference in density (see Rossetti, 1999). The criterion of a morphology that resembles 'artificial' SSDS caused by shocks is thus well met by the deformed layers at Valmiera and Rakuti.

Fig. 12 Two deformed levels in the quarry near Rakuti which underwent deformation by successive phases of deformation that occurred soon after each other. The deformations in the upper level seem to consist of fragments of a broken-up layer that presumably first formed load casts and subsequently pseudonodules, as discernable in the right-hand part. Beginning fluidization occurred in the left-hand part, where original lamination is hardly visible or even invisible in the sandy fragments. The lower deformed level has probably a similar origin, but underwent longer fluidization so that hardly any primary lamination has been left in the sandy fragments. The black '3' of the scale represents 5 cm.

3.5. *Proximity to faults*

Owen and Moretti's (2011) fifth criterion, *viz*. proximity to an active fault, is an interesting point. The criterion must have been established with the wording 'an active fault' because the great majority of seismites occur under tectonically active conditions. This is confirmed by the monitoring of recent earthquakes and (occasional) analysis of deformations that they have triggered (Moretti and Van Loon, 2014; and references therein).

As mentioned above, no endogenic tectonic activity is known from historical times in northern Latvia, but the Valmiera site is located in a potentially seismically active zone with several faults in Caledonian and Hercynian structural complexes (Nikulin, 2011). In the case of the Rakuti sediments, some faults have been detected in southern Latvia (Lukševičs *et al*., 2012; Popovs *et al*., 2015). It may well be that these old faults became reactivated by the moving zone of differential pressure, due to local changes in the thickness and thus the weight of the retreating ice cap.

There is no reason, however, to invoke reactivation of old faults, as it is well known from many places in the Baltic area that the strong uplift (of the order of many tens of meters) of the Earth crust after retreat of Pleistocene glaciers resulted in earthquakes (see, among others, Mörner, 1990, 1991). Earthquake activity probably triggered by glacio-isostatic adjustment was also noted in northwestern Germany (Brandes and Winsemann, 2013; Brandes *et al*., 2012), and in northern Ireland (Knight, 1999). These earthquakes took roughly place at the front of, mostly retreating, ice caps, where the rapid change in ice thickness caused large local differential glacio-isostatic pressures. This implies that also this criterion for the interpretation of the deformed layers under study as seismites is fulfilled.

3.6. *Laterally changing deformations*

The frequency, size and/or complexity of seismically-induced SSDS should diminish with increasing distance from the epicenter (cf., Rodríguez-Lopez *et al*., 2007). Whether this is the case at the Valmiera site, is difficult to check because the main exposure is small, and the other (still smaller) exposures are only maximally a few

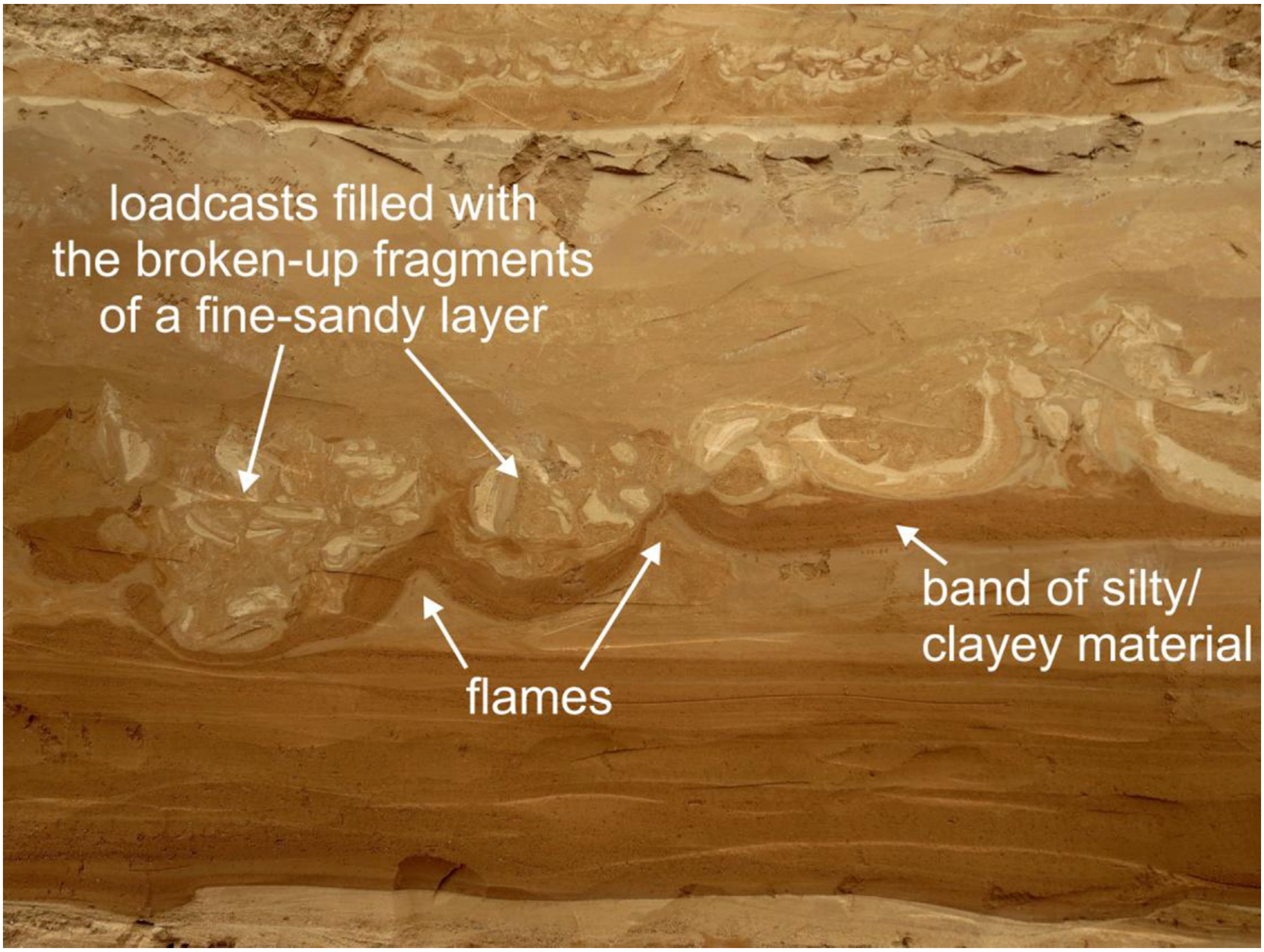

Fig. 13 One of the most interesting deformed levels at Rakuti. The deformed layer as a whole seems to be built of load casts. The loaded material consists not only of broken-up fragments of a fine sandy layer (light colored), but also of the underlying band of silty/clayey material (dark brown). This band sank into the somewhat coarser (silty) light-colored material that forms flames in the central part. The underlying silty/clayey layer (darker brown) has not been affected, proving that a reversed density gradient cannot be held responsible for the loading process. The two leftmost load casts are filled with the broken up fragments of a fine-sandy layer, but the load cast at their right side (and the half load cast visible at the very right) do not have such an infilling. Instead, it seems that the fragments of the broken-up sandy layer are concentrated on top of the flame structure between the load casts. This indicates that the deformation cannot be explained as simple loading, but that successive phases of deformation must have occurred. Height of the photo is about 10 cm.

hundreds of meters away. The Rakuti layers, in contrast, can be traced over several hundreds of meters, but even this is not far enough to detect a significant average change in the complexity or the intensity of deformations. Yet, some answers may be given to the question, posed by the frequent occurrence of seismites at Rakuti, where the epicenter of the triggering fault was located.

As a magnitude of at least M = 4.5—5.0 is required for the formation of seismites with liquefaction features, and because the power of the shock waves diminishes with distance from the epicenter (the energy of the shocks becomes laterally ever more absorbed by the deformation of the sediments), it seems that the faults cannot have had their epicenter in Scandinavia: the faulting must have been more nearby. In 1908 an earthquake occurred near Daugavpils (SE Latvia), but as mentioned above, this was most probably due to neotectonics, not to glacial rebound (Šliaupa *et al.*, 2006). However, it cannot be excluded that this fault existed already for a long time and became reactivated by glacio-isostatic rebound during the Late Glacial, and more recently by tectonic re-activation. The Rakuti site is, however, also located almost right above another fault in the Earth crust that has not affected the sedimentary cover (Nikulin, 2011).

A sufficiently strong earthquake caused by activity of this fault might result in brecciation (cf., Gruszka

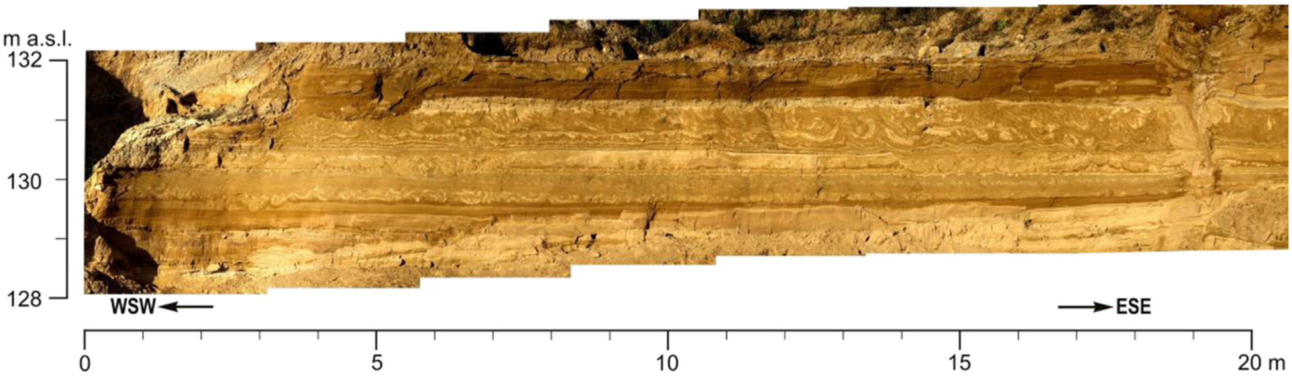

Fig. 14 Composite photo of part of the wall at Rakuti, showing that the deformed layers do not contain individual, isolated SSDS, but are deformed over their entire lateral extent.

and Van Loon, 2007). Although such brecciation in the Rakuti seismites is scarce, some brecciated parts are present, indeed. Accordingly, it cannot be excluded that the fault under the study site is responsible for the seismite formation, particularly because lateral changes in lithology affect the properties of the passing shock waves and thus the nature of the deformations in a seismite (Alfaro *et al.*, 2010; Moretti and Van Loon, 2014; Rodríguez-Lopez *et al.*, 2007). Moreover, earthquake-induced shock waves cannot propagate across shear planes (Mazumder *et al.*, 2006; Schwab and Lee, 1988). In principle, one might reconstruct the direction in which the epicenter was situated by analyzing lateral changes in the nature of the SSDS; by lack of other outcrops with seismites in the vicinity, this is, however, impossible for the Rakuti area. The fault (or faults) responsible for the origination of these seismites therefore remains a problem that might be solved by more focused future fieldwork.

4. Earthquake recurrence time

As mentioned above, the sediments that build the section at Valmiera were deposited most probably not later than 14,500 years ago. Consequently, the oldest of the Valmiera seismites cannot be older. Nartišs (2014) deduced, on the basis of palaeogeographic reconstructions, that the accumulation of the sediments at the Valmiera site cannot have lasted longer than some hundreds of years. The succession under study forms rhythms that might represent seasonal changes; this would imply that the sediments were formed in only 44 years (Krievāns, 2015; Krievāns and Rečs, 2014), but neither a non-seasonally-controlled sedimentation, nor the absence of eroded cycles can be excluded, so that 44 years is an absolute minimum. As 7 seismites formed in this time-span, the earthquakes that triggered the deformations had an average recurrence time of maximally some 150 and minimally 6—7 years.

The section at Rakuti, in which 12 seismites occur, can be dated rather precisely: the sediments were deposited between 17,000 and 16,000 years ago, so within about a thousand years. This implies that the average recurrence time of the responsible earthquakes was less than 100 years. One earthquake in southern Latvia can be ascribed to neotectonics, but it was not strong enough to cause seismites; as no other endogenic activity is known from the Quaternary in this part of Latvia, it is highly unlikely that the seismites near Rakuti can have resulted from endogenic tectonics. Moreover, the frequency of these seismites suggests that glacio-isostatic rebound was the trigger, as was also deduced for several other places around the Baltic (Brandes and Winsemann, 2013; Brandes *et al.*, 2012; Hoffman and Reicherter, 2012; Mörner, 1990, 1991; Van Loon and Pisarska-Jamroży, 2014). The occurrence of two earthquakes (M = 5.0 and M = 5.2) in Kaliningrad on September 21st, 2004 with an interval of only two hours and a half (Gregersen *et al.*, 2007) confirms the possibility of multiple successive seismic events within the Baltic sedimentary basin of the Eastern European Craton.

5. Conclusions

Sections near Valmiera and Rakuti, of about 7 m and 4.5 m high, respectively, contain a relatively large number of deformed layers: 7 and 12, respectively. These deformed layers occur sandwiched between undeformed layers, in some cases at Rakuti stacked upon each other. The layers cannot represent slumps or other forms of mass transport, considering the type of deformations, their lateral extent, their constant thickness, and their granulometric similarity with the under- and overlying sediments. Neither can the deformations be ascribed to endogenic tectonics, considering the fact that most of the layers have not been deformed. Considering that the deposits were formed during retreat of the ice at the end of the last ice age, and considering that such a retreat implies glacial rebound of the Earth crust and that this rebound has resulted in earthquake-triggered seismites in other countries around the Baltic Sea, it must be deduced that the deformed layers under study represent seismites formed by shock-wise rebound of the Earth crust.

The frequency of earthquakes triggered by the glacial rebound was high: the average recurrence time was at most a few hundred years, most likely 100—150 years at Valmiera (possibly much less), and less than 100 years at Rakuti. Considering the fact that the deposits at Valmiera were deposited only some 1500—2500 years after the deposits at Rakuti, it is likely that the seismites at both sites were formed as a result of ongoing glacio-isostatic rebound.

It should be mentioned in this context that seismites are formed only if the magnitude of the earthquakes is high enough ($M \geq 4.5$—5.0). This implies that, during deposition of the two successions, many more earthquakes can have occurred. These earthquakes must have had a lower magnitude, which may, however, have been still considerable.

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