Journal of Palaeogeography 2016, 5(4): 363—380 (00105)

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.journals.elsevier.com/journal-of-palaeogeography/

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

A.J. (Tom) van Loon [a,*], ***Małgorzata Pisarska-Jamroży*** [b], ***Māris Nartišs*** [c], ***Māris Krievāns*** [c], ***Juris Soms*** [d]

[a] *Geocom Consultants, Valle del Portet 17, 03726 Benitachell, Spain*
[b] *Institute of Geology, Adam Mickiewicz University, Maków Polnych 16, 61-606 Poznań, Poland*
[c] *Faculty of Geography and Earth Sciences, University of Latvia, Rainis Blvd. 19, 1576 Riga, Latvia*
[d] *Department of Geography, Daugavpils University, Parades 1, LV 5401 Daugavpils, Latvia*

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

Received 9 September 2015; accepted 1 February 2016; available online 10 May 2016

* Corresponding author.
E-mail address: geocom.vanloon@gmail.com (A.J. van Loon).
Peer review under responsibility of China University of Petroleum (Beijing).
http://dx.doi.org/10.1016/j.jop.2016.05.002

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