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Sedimentological evidence of Pleistocene earthquakes in NW Poland induced by glacio-isostatic rebound

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ABSTRACT

Soft-sediment deformation structures are abundantly present in two levels within Warthanian/Eemian lacustrine sediments at Siekierki, near the Polish/German border. The two 'event horizons' show intense folding, collapse, sag and load structures, indicative of liquidization and fluidization. The structures must have been caused by sudden shocks, most probably resulting from earthquakes that were induced by glacio-isostatic rebound, probably after the Warthanian deglaciation. Such seismites have not been previously recognized in Polish Quaternary sediments. They provide supporting evidence for glacio-isostatic movements that were interpreted up till now based on drilling, lithostratigraphic, geophysical and geodetic data. The recognition of seismites in NW Poland may help recognize other deformed 'event horizons' in Pleistocene sediments as glacio-isostatic or neotectonic seismites.

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1. Introduction

The northern and western parts of Poland were affected during the Middle and Late Pleistocene by three glaciations: Elsterian, Saalian and Weichselian. Lacustrine sediments in Siekierki were deposited at the end of Warthanian ice sheet (second ice advance of the Saalian glaciation) and at the beginning of Eemian interglacial ~120 ka BP, and sandur sediments were deposited at this site during the Pomeranian phase of the Weichselian glaciation around 16–17 ka BP.

The northern and western parts of Poland are not presently affected by significant tectonic activity, and thus far all soft-sediment deformation structures (SSDS) within Pleistocene deposits have been interpreted as a result of glaciotectonics, gravity-induced sliding or slumping, permafrost-induced processes, cryoturbation processes or fluidization or liquefaction due to instabilities resulting from reversed density gradients (Pisarska-Jamroży and Zieliński, 2012; Pisarska-Jamroży, 2013; Pisarska-Jamroży and Weckwerth, 2013).

It is well known from other areas, however, that disturbances of the Earth's crust can be induced by ice-sheet loading/unloading cycles (cf., Mörner, 1990), and this is also known from NE Poland (Morawski, 2009a, 2009b). The link between deglaciation and neotectonics was described by Mörner (1991), Muir-Wood (2000), Kaufmann et al. (2005), Hampel et al. (2009), and Brandes et al. (2012). Neotectonics in NW Poland have been discussed by, among others, Baraniecka (1979), Piotrowski (1991, 1999) and Kurzawa (2001, 2002). According to Kurzawa (2003), the most intensive vertical displacements in NW Poland must be ascribed to isostatic rebound that occurred during the Cromerian, Holsteinian and Eemian interglacials following deglaciation of preceding ice sheets.

Deglaciation can also trigger induced seismicity and earthquakes (see Thorson, 1996; Stewart et al., 2000). The isostatic rebound may well have led to earthquakes which could have left traces in the form of SSDS in the uppermost unconsolidated sediments that were present at the time (Van Loon, 2009; Van Loon and Maulik, 2011; Brandes et al., 2012; Brandes and Winsemann, 2013).

Here we describe two 'event horizons' with SSDS in a succession at Siekierki (NW Poland; (52°48′32″N and 14°14′40″E) that were probably caused by earthquakes triggered by isostatic rebound after retreat of the Warthanian ice sheet (120 ± 1.8 ka). A Warthanian age of the sedimentary succession with the two event horizons was, as will be detailed further on, determined by Piotrowski et al. (2012); these authors found an Eemian age for the overlying lacustrine sediments. This implies that the deformations in the event horizons must have originated within the Warthanian. Lagerbäck (1992) showed that deglaciation-induced seismicity in Scandinavia occurred shortly after the decay of the ice sheet under the highest rate of unloading stress change. This fits well in the regional deglaciation framework, as SSDS in Late Pleistocene deposits caused by postglacial isostatic crustal rebound have been described from northern Germany (Sirocko et al.,

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2002; Reicherter et al., 2005; Brandes et al., 2012; Hoffmann and Reicherter, 2012). Evidence of comparable neotectonic activity was also mentioned from Sweden by Mörner (2003), who interpreted this feature also as being associated with postglacial isostatic rebound, from Ireland (Knight, 1999), and from North America (Thorson, 1996; Wu, 1998; Wu and Johnston, 2000). Earthquakes related to the complex seismic strain-release patterns, modified during the melting and retreat of the ice sheets, have been termed 'deglaciation seismotectonics' by Muir-Wood (2000).

The main objective of the present contribution is to unravel the trigger that led to the formation of the SSDS in two levels, sandwiched between comparable sediments without SSDS.

2. Geological setting

The study site at Siekierki is situated close to the Toruń-Eberswalde ice-marginal valley in NW Poland (Fig. 1), which is incised into a Weichselian sandur and till plain. The ice-marginal valley drained the water from both proglacial streams which ran from the ice sheet in the North, and extraglacial rivers coming from the South. The valley took advantage of the already existing Kostrzyn-Freienwalde Basin, which is generally 12 km wide and is orientated NW–SE. In the North, the Kostrzyn-Freienwalde Basin meets a moraine ridge formed during the Pomeranian phase of the Weichselian glaciation ~16–17 ka ago (Marks, 2012). The study site at Siekierki, which is situated in the Kostrzyn-Freienwalde Basin, is located south of the maximum extent of the Pomeranian phase (Fig. 1). Nowadays, the Kostrzyn-Freienwalde Basin is occupied by the Odra River, peat areas, and fluvial sediments.

The Siekierki exposure is present in a wall of ~3.5 m high (Fig. 2), which runs roughly from NNW to SSE; its lateral extent is some 250 m (Fig. 3), with a few small interruptions (due to vegetation, a small construction and talus cover). The exposure shows a fine-grained lower part and a coarser upper part.

The lower part (Fig. 2) is about 3 m thick; it consists of fine-grained lacustrine sediments, in which some developments in time can be distinguished. The lowermost 2 m is dominated by sand with fines (= silt and clay) with flaser laminations (Fig. 2). In the upper 1 m of the lower part, wavy-laminated lithofacies of sand with fines occur. The 3-m thick lower part has been interpreted by Piotrowski et al. (2012) as accumulated in a shallowing lake; according to them, the basal part of the sediments was deposited in a cold lake during the Warthanian deglaciation, whereas the upper part was deposited in a warm, eutrophic lake during the Eemian interglacial. Piotrowski et al. (2012) based the amelioration of the climate during sedimentation on 72 diatom species in the upper part of the lake sediments, dominated by four species, viz. *Cyclotella fottii*, (a species that is indicative of warm conditions such as at the present-day Balkan Peninsula), *Amphora ovalis*, *Cymbella proxima* and *Gyrosigma acuminatum*.

The about half a meter thick upper part of the Siekierki profile consists of sandur sediments of the Pomeranian phase (horizontally-laminated sand and fines; Fig. 2). The till which would be expected to occur between the lacustrine and the sandur sediments, is absent; it was probably locally eroded during the Late Glacial by proglacial and/or extraglacial rivers and later by the Odra river.

The 'cold' lacustrine sediments contain two levels (units S1 and S2) consisting largely of deformed sediments, interbedded between unconsolidated sediments that show little to no deformation (Fig. 3).

3. Description of the SSDS

The two levels with SSDS are present over the entire length of the outcrop (Figs. 2, 3). They range from millimeter to decimeter-sized features. Both deformed layers (S1 and S2) have a similar granulometry: fine-grained sand (125–500 μm) and very fine-grained sand (62.5–125 μm) with admixtures of fines (<62.5 μm), commonly in the form of alternating laminae or thin layers. No distinction in grain size could be made between the deformed levels and the undeformed material immediately below, and immediately above the deformed layers. In spite

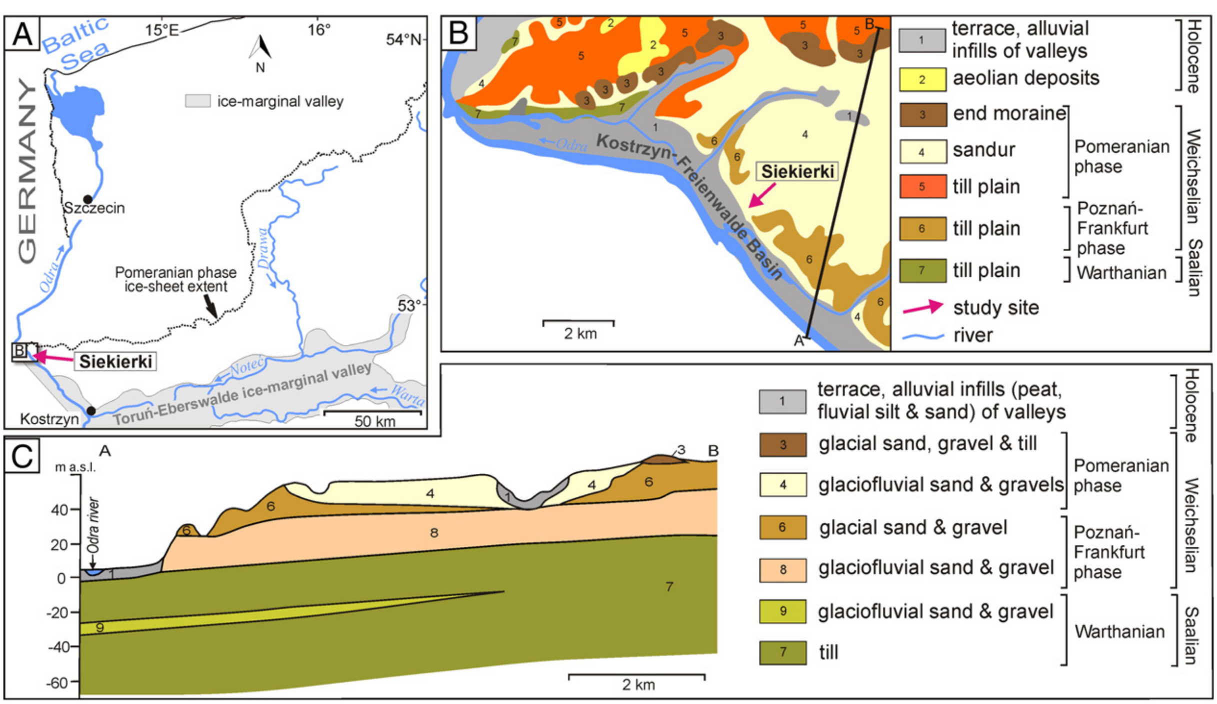

Fig. 1. Location of the study area. A: Location (lower left) within the Toruń-Eberswalde ice-marginal valley. B: Simplified geological map, modified from Kawecka and Pawlak (1974). C: Simplified cross-section A–B. For location, see Fig. 1-B).

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