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ScienceDirect
Palaeoworld 24 (2015) 16–35
Palaeoworld
www.elsevier.com/locate/palwor

Soft-sediment deformation structures in the Cambrian (Series 2) tidal deposits (NW Estonia): Implications for identifying endogenic triggering mechanisms in ancient sedimentary record

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Received 15 September 2014; received in revised form 9 December 2014; accepted 19 December 2014
Available online 26 December 2014

Abstract

Soft-sediment deformation structures (SSDS) are documented in several horizons within silt- and sandstones of the Cambrian Series 2 (Dominopolian Stage) Tiskre Formation, and some in the underlying argillaceous deposits of the Lükati Formation in NW Estonia, northern part of the Baltoscandian Palaeobasin. The aim of this study was to map, describe, and analyze these deformation features, and discuss their deformation mechanism and possible triggers. Load structures (simple load casts, pillows, flame structures, and convoluted lamination) with varying shapes and sizes occur in the Tiskre Formation in sedimentary interfaces within medium-bedded peritidal rhythmites (siltstone-argillaceous material) as well as within up to 3 m thick slightly seaward inclined stacked sandstone sequences. Homogenized beds, dish-and-pillar structures, and severely deformed bedding are also found within these stacked silt- and sandstone units and within a large tidal runoff channel infill. Autoclastic breccias and water-escape channels are rare and occur only in small-scale — always related to thin, horizontal tidal laminae. Profound sedimentary dykes, sand volcanoes, and thrust faults, which are often related to earthquake-triggered soft sediment deformation, were not observed within the studied intervals. Deformation horizon or horizons with large flat-topped pillows often with elongated morphologies occur at or near the boundary between the Tiskre and Lükati formations. Deformation mechanisms identified in this study for the various deformation types are gravitationally unstable reversed density gradient (especially in case of load features that are related to profound sedimentary interfaces) and lateral shear stress due to sediment current drag (in case of deformation structures that are not related to loading at any apparent sedimentary interface). Synsedimentary liquefaction was identified as the primary driving force in most of the observed deformation horizons. Clay thixotropy may have contributed to the formation of large sandstone pillows within the Tiskre–Lükati boundary interval at some localities. It is discussed here that the formation of the observed SSDS is genetically related to the restless dynamics of the storm-influenced open marine tidal depositional environment. The most obvious causes of deformation were storm-wave loading, rapid-deposition and shear and slumping caused by tidal surges.

Keywords: Soft-sediment deformation structures; Liquefaction; Tides; Storm-wave loading; Cambrian; Estonia

1. Introduction

Soft-sediment deformation structures (SSDS) preserved in the geological record can provide insights into sedimentary history and geodynamic evolution of a sedimentary basin. These structures form due to the application of shock, as for example ground motion would cause during earthquakes. Soft-sediment deformations can also form due to stress applied by cyclic storm-waves or loading due to rapid deposition of sediments among many other triggers. Whatever the trigger, the gradual built-up of hydrostatic pressure within the water saturated sediments can ultimately lead to a rapid loss of shear resistance and collapse of grain framework (Chaney and Fang, 1991). As a result, sediments become liquefied and prone to deformation until granular strength is regained (Ambraseys and Sarma, 1969). The mechanism and physics of sediment liquefaction have been demonstrated in laboratory tests and discussed in many excellent works by the pioneering researchers in this field (Terzaghi and Peck, 1948; Kuenen, 1958; Seed and Lee, 1966, 1971; Anketell and Dzulynski, 1968; Anketell et al., 1969, 1970;

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http://dx.doi.org/10.1016/j.palwor.2014.12.003
1871-174X/

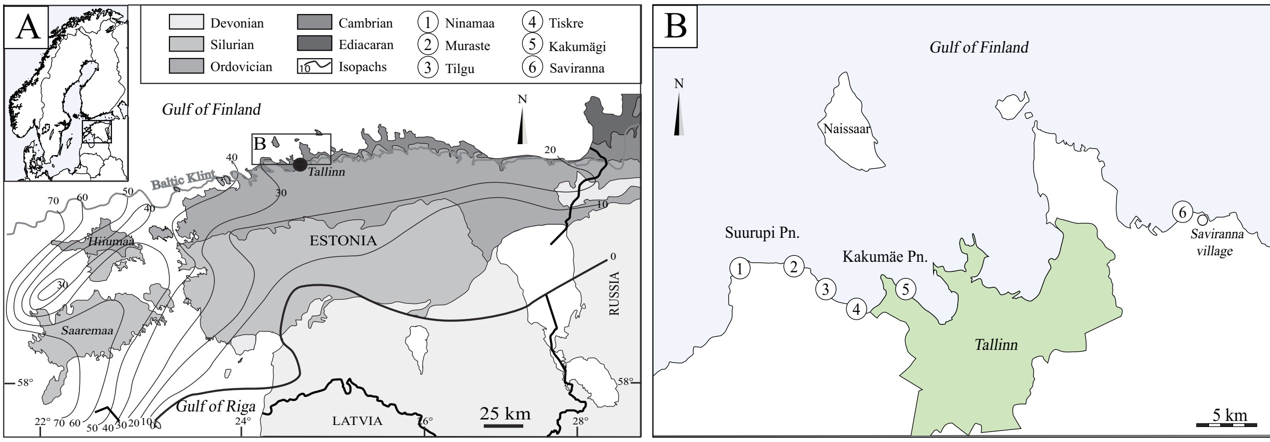

Fig. 1. Location and schematic geological maps of the study region. (A) Distribution and thickness of the Cambrian Dominopolian Stage deposits in Estonia are indicated with isopachs (modified from Mens and Pirrus, 1997b). (B) Sketch-map showing the locations of the studied Cambrian outcrops.

Ishihara and Li, 1972; Stewart, 1975; Youd and Hoose, 1977, and many others).

Many natural processes can induce soil liquefaction in various geological environments. Studies of recent shallow-marine environments have effectively related the formation of SSDS with common geological processes such as storm-wave loading (e.g., Clukey et al., 1985; Foda et al., 1993), tidal waves (e.g., Greb and Archer, 2007; Greb et al., 2011; Fan, 2013), breaking waves (Dalrymple, 1979), rapid deposition and loading (e.g., Owen and Moretti, 2008), and slope processes (e.g., Postma, 1983; Martinsen, 1989; Davies, 2003; Green, 2009). Only a limited number of studies have related such endogenic triggers (Owen et al., 2011) with SSDS horizons in ancient rock record (e.g., Owen, 1995; Molina et al., 1998; Moretti et al., 2001; Alfaro et al., 2002; Chen and Lee, 2013). The most frequently reported SSDS trigger in any ancient sedimentary environment is inevitably — seismicity (Alfaro et al., 1997; Jewell and Ettensohn, 2004; Bachmann and Aref, 2005; Zhang et al., 2007; Ghosh et al., 2010, 2012; Berra and Felletti, 2011; KoçTaşgin, 2011; Kundu et al., 2011; Martin-Chivelet et al., 2011; Moretti and Ronchi, 2011; van Loon and Pisarska-Jamrozy, 2014 among numerous others). Differentiation between exogenic (e.g., seismic) and endogenic soft-sediment deformation trigger is not always straightforward. Identification of the triggering mechanism is especially complex in ancient deposits (see also Owen et al., 2011 for discussion), because the morphologies of soft-sediment deformation structures are not trigger-dependent. Nevertheless, a careful facies analysis should unfold a clear link between the sedimentary facies and the trigger of deformations in case of endogenic processes. Such link should not be well developed or is completely absent in case of exogenic ones (Owen et al., 2011).

In this study we use the three-stage process (facies-trigger-criteria assessment) suggested by Owen et al. (2011) in order to identify the triggers of extensive SSDS that occur in the Cambrian Series 2 (Dominopolian Stage) tidal sediments in northwestern Estonia. These deformations can be observed in the Tiskre and Lükati formations along several outcrops of more than 60 km long coastal cliff section (Figs. 1, 2). Some deformation types (the so-called "flow-rolls" sensu Mens and Pirrus, 1977) in this section have been mapped and measured before (Mens and Pirrus, 1977; Pirrus, 1977, 1978). Our primary goal was to determine whether the formation of soft-sediment deformation horizons within these sediments is genetically related to the dynamics of the depositional environment or they represent series of single event beds describing, for example, a potential tectonic history of the region. According to our preliminary hypothesis, the observed soft-sediment deformation horizons were induced by recurrent high-energy hydrodynamic processes acting within the depositional environment.

This study was conducted in six outcrop localities situated along the northwestern seaboard of Estonia. The outcrop sections are part of extensive series of cliffs (the Baltic Klint) between Öland Island in Sweden and the Lake Ladoga in Russia (shown in Fig. 1A). The Cambrian succession of interest is outcropping best in the outskirts of Tallinn settlement. The study locations included the following outcrop sections: (1) Ninamaa Peninsula location (~2 km long single section); (2) Muraste location (several outcrops, together ~5 km long); (3) Tilgu location (~1 km long single section); (4) Tiskre location (~1 km long single section); (5) Kakumägi Peninsula location (two outcrops, together ~4 km long); and (6) Saviranna location (~3.5 km long single section). Locations of the studied outcrops are shown in Fig. 1B; sedimentary logs of selected study locations are shown in Fig. 3.

2. Geological setting and stratigraphy

After Baltica became detached from Gondwana mainland at the end of the Neoproterozoic and started its epic drift from southerly high latitudes towards the equator (Torsvik et al., 1992; Cocks and Torsvik, 2005), a shallow intracratonic basin started to form within its interior. The precursor of the latter mid-Cambrian Baltic Basin (Nikishin et al., 1996; Mens and Pirrus, 1997a) formed on the East European Platform, on the southern flank of the Fennoscandian Shield (Nikishin et al., 1996; Mens and Pirrus, 1997a; Poprawa et al., 1999; Nielsen and Schovsbo, 2011). During the Cambrian, this palaeobasin covered partially present Belorussia, the Baltic States, and much of NW Russia (Nikishin et al., 1996). Sediments of the palaeobasin represent