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Subglacial bedforms of the Zemgale Ice Lobe, south-eastern Baltic

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ABSTRACT

Presented in this paper are the results of the mapping of ~6600 subglacial bedforms of the Zemgale Ice Lobe (ZIL), their composition and internal structure in the south-eastern Baltic region. Topographic maps at scale 1:10,000 were mainly used to map bedforms in Latvia, while a digital elevation model with cell size of 5 m was used for North Central Lithuania. The ZIL operated during the deglaciation of the Late Weichselian Scandinavian Ice Sheet (SIS), at least in the Middle Lithuanian and North Lithuanian glacial phases, and created a subglacial landform assemblage consisting of glacial lineations such as drumlins, mega-flutings, Mega Scale Glacial Lineations (MSGLs) and transversal morphologies, such as ribbed moraines. It is observed that lineations of different scales co-exist, suggesting subglacial bedform transition and possibly a continuum of bedforms. Highly elongated lineations with a length of up to 24 km and an elongation ratio of up to 1:50, interpreted as MSGLs, are observed in the NE part of the Middle Lithuanian Plain. In the so-called Zemgale drumlin field, 20% of lineations have elongation ratios >10:1, indicating the fastest ice flow in the central part of the main body of the lobe. Based on test surveys and investigated outcrops, the drumlin cores consist of sorted sediments with different levels and depths of glaciotectonic deformation overlain by subglacial till. The main drumlin-forming ice stress was mostly parallel to the crests of drumlins, while some ice stress from inter-drumlin depressions acted during the final episodes of their formation. The observed sediment structures indicate multiple episodes of the basal ice/bed coupling and decoupling, which can best be explained by the mosaic ice-bed deformation model. Ribbed moraines are characterized by a complicated structure of multiple till units interbedded with sorted sediments that have been formed by repeated subglacial overthrusting.

1. Introduction

As cited in Benn and Evans (2010, p. 445) with reference to Rose (1987), Menzies and Rose (1989), and Eyles et al. (1999), "subglacial bedforms are longitudinal, transverse or even non-aligned/hummocky accumulations of sediment formed below active ice". Longitudinal bedforms parallel to ice flow include flutings, drumlins and MSGLs, together termed glacial lineations. Transverse subglacial bedforms are represented by Rogen or ribbed moraines.

Recently, subglacial bedforms, especially MSGLs, have been discovered in Antarctica, not only under paleo-ice streams (summarized by Ó Cofaigh et al., 2008; Davies et al., 2012; Livingstone et al., 2012), but also under modern fast-flowing ice streams (King et al., 2007, 2009; Smith and Murray, 2009), where they are formed in areas of deforming till on decadal timescales. Subglacial bedforms are crucial for understanding the behaviour of ice streams. Subglacial bedforms on paleo-ice stream beds can provide useful information for understanding the dynamics of modern-day ice streams.

In this paper, we report the results of the distribution, morphometry, composition and internal structure of subglacial bedforms of the ZIL. The subglacial bedform assemblage of the ZIL consists of such glacial lineations as drumlins, megaflutes, MSGLs and ribbed moraines. This continuum of subglacial bedforms provides insights into the subglacial processes and dynamics of the ZIL in the territory of the Central Latvian Lowland (CLL) and the Middle Lithuanian Plain (MLP) during the retreat of the Late Weichselian SIS.

2. Study area and previous work

The study area comprises the CLL (Fig. 1), which lies in the central part of Latvia and is characterised by a divergent ice-flow pattern, and the adjoining MLP in North Central Lithuania. The glacial topography mostly consists of subglacial bedforms formed during the oscillatory retreat of the Late Weichselian SIS in the

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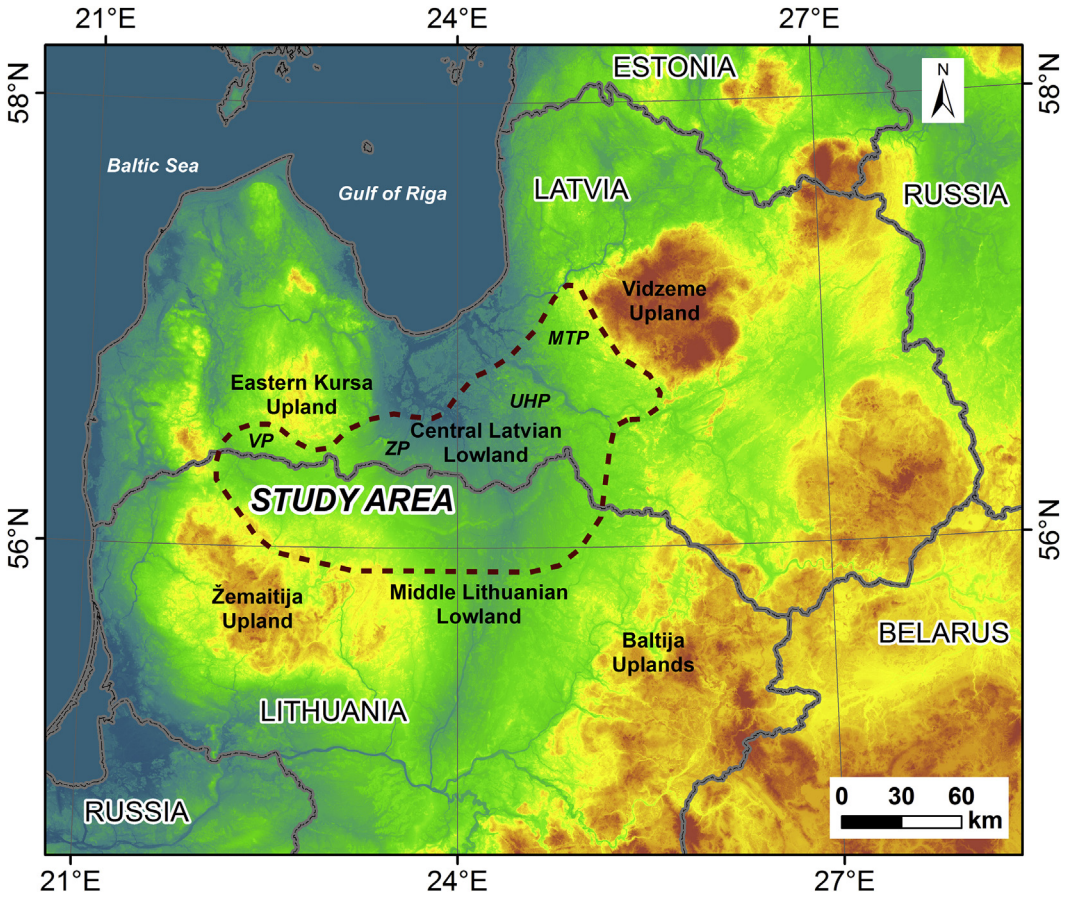

Fig. 1. Location of the study area and glaciomorphological regions referred to in the text. VP: Vadakste Plain; ZP: Zemgale Plain; UHP: Upmale Hummocky Plain; MTP: Madliena Tilted plain. Shuttle Radar Topography Mission (SRTM) digital elevation model in the background.

Middle Lithuanian (locally termed as Gulbene after Meirons et al., 1976) and North Lithuanian (locally termed as Linkuva after Meirons et al., 1976) glacial phases (Zelčs et al., 2011). The extent of ice during the North Lithuanian glacial phase in Latvia and Lithuania (Serebryanny and Raukas, 1966) is clearly marked by the Linkuva end moraine (Āboltiņš, 1970), also called the North Lithuanian marginal ridge (Fig. 7D) by Karmazienė et al. (2013), which developed at the margin of the advancing ZIL. As proposed by Bitinas (2012), this advance or surge occurred asynchronously and locally during deglaciation of the last SIS. The largest pre-Zemgale drumlin field (Zelčs et al., 1990), formed during the North Lithuanian glacial phase, was later disintegrated by the superimposition of ribbed moraines, and only parts of it are preserved as the Zemgale and Iecava drumlin fields. These ribbed moraines are classified as the Zemgale ribbed moraines in Latvia (Zelčs, 1993a; Zelčs and Dreimanis, 1998) due to their particular morphology, which is discussed further. They extend to the Upmale Hummocky Plain between the Iecava drumlin field and Valle ridge, which has been attributed to the marginal formations of the North Lithuanian glacial phase by Āboltiņš (1970). Previously, Straume (1979) considered them to be Labrador-type ribbed moraines in accordance with the terminology of Lavrushin (1976). The Vadakste (Zelčs et al., 1990; Zelčs, 1993a) and Madliena (Zelčs, 1993a, 1993c; Lamsters, 2012) drumlin fields formed during the Middle Lithuanian glacial phase. The Zemgale and Vadakste drumlin fields also extend to the MLP. In the NE part of the MLP, a separate field of very elongated glacial lineations can be recognized. A small convergent drumlin field is also observed on the NE side of the CLL in the vicinity of Limbaži. It was previously called the 'Limbaži uval moraine field' (Zelčs, 1993b), while the Madliena drumlin field was called the 'Middle-Latvian uval moraine area' in Russian terminology (Zelčs, 1993c).

Drumlins and moraine ridges with crests transverse to the latest direction of movement of the glacier in the CLL have been studied since the 1930s (Dreimanis, 1935; Straume, 1968, 1979; Āboltiņš, 1970; Ginters, 1978; Zelčs et al., 1990; Zelčs, 1993a, b; Zelčs and Dreimanis, 1998), and more recently have been investigated by Lamsters (2012), Lamsters and Ošs (2012), and Lamsters and Zelčs (2013).

The Pleistocene sediment sequence in the CLL, similarly as in other glacial lowlands in Latvia, is thin, mainly up to 10 m, and exceeds 20–30 m only at the highest points of the glacial topography (Zelčs and Dreimanis, 1998). Two Weichselian till beds, interbedded with sorted sediments in places, have been recognized in the area up-glacier of the North Lithuanian (Linkuva) end moraine (Savvaitov and Straume, 1963; Āboltiņš, 1963; Dreimanis and Zelčs, 1995; Zelčs and Markots, 2004), formed in the course of oscillatory deglaciation of the last SIS (Zelčs and Markots, 2004; Zelčs et al., 2011). Three till beds, of which the lowermost grey till unit is considered to be a Saalian till, have been confirmed to exist in the local bedrock depressions in the Vadakste drumlin field (Straume, 1968; Ginters, 1978), and locally in the MLP (Guobytė and Satkūnas, 2011; Karmazienė et al., 2013). A tri-layered structure of Weichselian till in North Lithuania has been reported by Baltrūnas et al. (2005). However, as noted by Zelčs and Dreimanis (1998), up-glacier slopes of ribbed moraines in the territory of the Upmale