Quaternary Science Reviews 146 (2016) 300–321

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Sedimentary and structural evolution of a Pleistocene small-scale push moraine in eastern Poland: New insight into paleoenvironmental conditions at the margin of an advancing ice lobe

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ARTICLE INFO

Article history:
Received 26 March 2016
Received in revised form
15 June 2016
Accepted 20 June 2016
Available online 9 July 2016

Keywords:
Push moraine
Progradational fan
Detachment folds
Fold-accommodation faults
Ice-front sustained advance
Pleistocene

ABSTRACT

Recent studies of push moraines have focused on the interplay between the dynamics of ice margins and the environmental variables of the foreland into which they advance. These studies showed that the spatial distribution, geometry and style of the glaciotectonic deformation of push moraines are controlled by ice-induced stresses, the strain rate, the rheology of the deposits and hydraulic conductivity. In this work, we provide new insight into this interplay at a small spatio-temporal scale, specifically, the ancient glacial system of the Liwiec ice lobe within the younger Saalian ice sheet in eastern Poland. The paleoenvironmental variables that are analysed here refer to the dynamics of the hydrological processes that affected the patterns and sediment deposition rate on the terminoglacial fan and the resulting mechanical stratigraphy and hydraulic conductivity of the foreland. We document the progradational sequence of the fan deposits that developed as a result of the ice lobe thickening and the steepening of its stationary front. The sedimentary features of the fan, the lithology of its basement and the hydraulic conductivity of the foreland strongly influenced the geometry and kinematics of fold growth during the advance of the ice lobe. The predominance of flexural slip and the development of fractures, including fold-accommodation faults, were interpreted to be an effect of buckle folding due to horizontal shortening induced by ice advance. The partial overriding of the push moraine by the ice lobe and, thus, the submarginal conditions for deformation were inferred from the significant hinge migration and internal deformation of the strata under undrained conditions in one of the folds. The synfolding deposition pattern of the fan growth strata allowed us to suggest that the push moraine was probably formed by a sustained advance rather than surge.

1. Introduction

Push moraines are important glaciogenic features that are mainly controlled by the locations of ice margins. In general, these features form arc-shaped trains of ridges that are perpendicular or oblique to the ice flow direction (e.g., Boulton, 1986). The formation of push moraines is related to the frontal dynamics of ice streams or valley glaciers during surges (Croot, 1987; Hart and Watts, 1997; Boulton et al., 1999; Benediktsson et al., 2009; Lee et al., 2013) or sustained advances (Humlum, 1985; Boulton, 1986; Powell et al., 2000; Motyka and Echelmeyer, 2003; Dobrowolski and Terpiłowski, 2006; Thomas and Chiverell, 2007; Krüger et al., 2010).

Push moraines can be produced by the thrusting and/or folding of ice-marginal and proglacial deposits due to ice pushing (marginal bulldozing) (Boulton et al., 1999; Bennett, 2001; Bennett et al., 2004a,b) and/or as an effect of gravity spreading (Croot, 1987; Pedersen, 1987; Hart, 1990; Andersen et al., 2005). Ice pushing relies on the forward advance of the ice front into the foreland and the horizontal compression of the substrate in front of or beneath the glacier. Gravity spreading implies that the differential vertical loading of underlying deposits by an advancing ice margins can be responsible for deformation (Rotnicki, 1976; Aber et al., 1989; Jaroszewski, 1991; van der Wateren, 1995; Bennett, 2001; Andersen et al., 2005). Different opinions exist regarding the

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http://dx.doi.org/10.1016/j.quascirev.2016.06.014
0277-3791/

dominant mechanism of glaciotectonic forces. Geological observations have shown that it is difficult to unambiguously separate structures related to ice-pushing and gravity spreading (Andersen et al., 2005). In both cases, folding and thrusting have been widely reported. Nevertheless, diapiric folding is regarded as a diagnostic structure of gravity spreading because of significant contribution of bending in this deformation where the main folding forces act across layers (Pedersen, 1987; Bennett et al., 2004a; Fossen, 2010).

Push moraines provide valuable information on the interaction between the dynamics of ice margins and the foreland into which they advanced (Bennett, 2001; Lee et al., 2013). Generally, the spatial distribution, geometry and style of glaciotectonic deformation are controlled by ice-induced stresses, the strain rate, the rheology of the substrate and pore-water pressure (e.g., Feeser, 1988; Fernlund, 1988; Van der Wateren, 1995; Boulton et al., 1999; Bennett, 2001; McCarroll and Rijsdijk, 2003; Burke et al., 2009; Benediktsson et al., 2009; Lee et al., 2013, 2016). For example, thrusting can predominate in zones of low pore-water pressure, where deposits are "dry", while folding can be typical of "wet" deposits that are located in poorly drained areas, where higher pore-water pressure can be expected (Ingólfsson, 1988; Benediktsson et al., 2008; Benediktsson 2012; Lee et al., 2013). This example is clearly simplified if we consider the kinematics of fault-related folding, where folds and faults may develop synchronously and thus should not be interpreted as an effect of different rheological conditions or two separate deformation phases (Brandes and Le Heron, 2010). On the other hand, local spatio-temporal changes in ductility/brittleness between different deformed strata can be expected where permafrost or porewater overpressure affected Quaternary deposits (Mackay, 1959; Boulton and Caban, 1995; Phillips et al., 2007; Waller et al., 2012; Vaughan et al., 2014; Lee et al., 2016).

A glacitectonized foreland can be described as a wedge that is composed of proglacial and subglacial deposits (Bennett, 2001). Its geometry can be defined in terms of the thickness, lateral extension and mechanical properties of the ice-foreland contact at or close to the ice margin. The critical-taper wedge theory by Davis et al. (1983) and Dahlen et al. (1984) has been used to describe the dynamic evolution of the wedge's geometry (Van der Wateren, 1995; Kuriger et al., 2006).

The intensity and style of glaciotectonic deformation can be influenced by the shortening degree of the involved strata and thus can differ from the ice margin or subglacial zone to the outer proglacial zone (e.g., Boulton et al., 1999; Phillips et al., 2008). Two general groups of push moraines can be distinguished according to the spatial scale at which the deformation can be transmitted horizontally through the foreland (Bennett, 2001): 1) narrow multi-crested push moraines that display the horizontal transmission of deformation up to 300 m, and 2) wide multi-crested push moraines that are related to the horizontal transmission of deformation over more than 300 m. The latter push moraines have been widely recognized within Pleistocene glacial environments (Pedersen, 1987; Van der Wateren, 1987; Klint and Pedersen, 1995; Aber and Ber, 2007; Thomas and Chiverell, 2007; Lee et al., 2013; Włodarski, 2014), while narrow Pleistocene push moraines have been described by only a few authors (Alexanderson et al., 2002; Dobrowolski and Terpiłowski, 2006; Roman, 2010).

Most studies of narrow push moraines have focused on the interplay between the dynamics of ice margins and the foreland into which they advanced. Meanwhile, less focus has been given to the sedimentary sequences of ice-marginal deposits that are associated with these landforms. Progradational sequences can be expected because of the increasing proximity of the ice margin and higher sediment supply to the foreland during the ice-margin advance (Pedersen, 2012). Such sequences have been described in large-scale push moraines, where proglacial outwash fan deposits have been deformed (Boulton et al., 1999; Benediktsson et al., 2010; Pedersen, 2012), and in small-scale push moraines that involve ice-marginal subaqueous fans (Lønne, 2001; Evans et al., 2013). Interestingly, no evidence indicates that progradational sequences have developed in terminoglacial or hochsander fans despite the spatially different subenvironments within them, which are characterized by the downstream transition of structures, grain size and depositional processes that are controlled by the energy of streams flowing from the supraglacial source area (Brodzikowski and Van Loon, 1991; Krüger, 1997; Krzyszkowski and Zieliński, 2002; Krüger et al., 2002; Kjær et al., 2004).

The aim of this study is to provide new insight into the paleoenvironmental conditions at the margin of the younger Saalian ice lobe in eastern Poland during a major ice advance. The resulting narrow push moraine is analysed at two levels of detail: first, a meticulous interpretation of the sedimentary evolution of the terminoglacial fan deposits and their glaciotectonic deformation; and second, a conceptual model for the more generalized spatio-temporal development of the push moraine. Notably, this model provides an opportunity to discuss the interplay between the ice-lobe margin dynamics and the hydrological processes that affected the patterns and rates of sediment deposition in the glacier foreland and, hence, its mechanical stratigraphy and hydraulic conductivity during glaciotectonic deformation. These phenomena have been discussed in detail for recent advancing glaciers or ice streams (Humlum, 1985; Eybergen, 1987; Boulton et al., 1999; Motyka and Echelmeyer, 2003; Bennett et al., 2004a,b; Kuriger et al., 2006; Benediktsson et al., 2008, 2009; Truffer et al., 2009, 2010; Krüger et al., 2010; Flowers et al., 2011; Benediktsson et al., 2015), but studies of Pleistocene examples are rare.

To understand this interplay, the crucial questions addressed in this work are as follows: (1) How did the dynamics of the ice lobe influence deposition on the terminoglacial fan in terms of the vertical sequence, lateral extent, and primary geometry of lithofacies units? (2) How are the geometry and kinematics of deformation structures controlled by the sedimentary properties of the fan, the lithology of its basement, the hydraulic conductivity of the foreland and the dynamics of the ice lobe? (3) What is the deformation mechanism of the fan deposits, and how did the ice lobe affect its foreland in terms of ice pushing or gravity spreading? (4) What was the amount of horizontal shortening of the deformed fan deposits, and what was the lateral extent of the ice lobe advance? (5) To what degree did the advancing ice lobe override the deformed fan deposits? (6) What is the possible time range within which deposition and deformation might have occurred, and did the ice lobe experience surging or sustained advance?

2. Morphology and geological setting of the push moraine

The push moraine has previously been recognized as an ice-marginal landform associated with the activity of the Liwiec lobe during the younger Saalian glaciation in eastern Poland (Fig. 1) (Godlewska, 2014). The maximum extent of the Liwiec lobe is marked by two landforms that are composed of glacifluvial sediments (Fig. 1): a large outwash fan at 160–163.75 m a.s.l. to the SE (near the villages of Łuniew and Łukowisko) and the ice-marginal valley of the Kratówka River at approximately 155 m a.s.l. near the village of Maciejowice. These landforms are located above a topographic high on top of the pre-Saalian substrate, which rises from NW to SE (Fig. 2; Brzezina, 2000).

Three areas with different geomorphological and geological features occur in the inner zone of the Liwiec lobe: western, central and eastern (Fig. 1). The western area is located above a flat pre-