Sedimentary Geology 221 (2009) 71–86

Contents lists available at ScienceDirect

Sedimentary Geology

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

Fluid-pressure controlled soft-bed deformation sequence beneath the surging Breiðamerkurjökull (Iceland, Little Ice Age)

Michaël Denis *, Jean-François Buoncristiani, Michel Guiraud

UMR CNRS 5561-Biogéosciences Dijon, UFR Sciences de la Terre et de l'Environnement, Université de Bourgogne, 6, boulevard Gabriel, 21000 Dijon, France

ARTICLE INFO

Article history:
Received 10 July 2008
Received in revised form 7 July 2009
Accepted 31 July 2009

Keywords:
Subglacial deformation
Fluid pressure
Breiðamerkurjökull
Iceland
Clast-fabric analysis

ABSTRACT

The general subject of this paper is subglacial deformation beneath Breiðamerkurjökull, a surging Icelandic glacier. More specifically it discusses the evolution and the role of fluid pressure on the behaviour of subglacial sediments during deformation. During Little Ice Age maximum, the two outcrops studied, North Jökulsarlon (N-Jk) and Brennhola-Alda (BA), were located at 2550 m and 550 m respectively from the front of the Breiðamerkurjökull. Sedimentological analysis at the forefield of the glacier shows thick, coarse glaciofluvial deposits interbedded with thin, fine-grained shallow lacustrine/swamp deposits, overlain by a deformed till unit at N-Jk. BA outcrop shows fine-grained shallow lacustrine/swamp deposits overlain by a deformed till unit. The sequence of deformation events from one outcrop to the other is similar. First, major thrust planes, which were rooted in shallow lacustrine/swamp deposits developed by glacially induced simple shear. Next, the thrusts were folded, indicating the deformation of hydroplastic sediment assisted by moderate fluid pressure. Then clastic dyke swarms crosscut the sedimentary succession, proving that fluid overpressure caused hydrofracturing associated with fluidisation. Finally, as water escaped from the glacier bed, fluid pressure dropped, and normal faulting occurred in brittle-state subglacial sediments. Fluid-pressure variations are related to glacier dynamics. They control the deformation sequence by modifying subglacial rheological behaviour and the nature of the subglacial tectonism.

1. Introduction

The mechanisms for fast glacier moving (ice streams, surging glaciers) still remain of major interest in the context of global warming and ice-sheet decline. Such fast glacier dynamics often require soft-bed deformation, and numerous studies are focused on this aspect concerning the recent glacial depositional record (Boulton and Jones, 1979; Hart, 1995; Boulton, 1996; Benn and Evans, 1996; Hindmarsh, 1997; Hart and Smith, 1997; van der Wateren, F.M., 1999; Van der Wateren et al., 2000; Fuller and Murray, 2002; van der Meer et al., 2003; Phillips et al., 2007). For warm-based ice flowing on soft beds, subglacial deformation by shearing, folding and faulting can account for the bulk of glacial motion (e.g.: 87% for Breiðamerkurjökull in Iceland: Boulton and Hindmarsh, 1987). In addition to basal sliding, decoupling at the interface between the impermeable bedrock and overlying substrate has been inferred for Icelandic glaciers (Kjaer et al., 2006). Structural approach to subglacial deformation provides information on deformation kinematics and glaciodynamics (Eyles and Boyce, 1998; Van der Wateren et al., 2000). A coupled approach using both concepts in sedimentology, glaciology and structural geology applied to former glacier beds at different scales of investigation is an efficient way to understand glacier motion, to reconstruct physical processes acting at the base of glaciers, and to explain the associated terrestrial glacial landsystem (Evans and Rea, 2003). This integrated approach permits to better understand the role of the hydraulic system on subglacial deformation, particularly with relation to fluid-pressure fluctuations.

For this study, two outcrops located in southeastern Iceland are studied to investigate the role of different types of subglacial sediments in surging-glacier dynamics: mostly gravel for the first and mostly sand for the second. A high-quality outcrop exposes a glacially deformed gravel bed situated relatively close to the Breiðamerkurjökull front. Here, various subglacial deformation structures are described and interpreted; they allow deformation chronology to be reconstructed, and to discuss about the role of the fluid pressure for subglacial deformation.

2. Geological setting

Vatnajökull is located in southeastern Iceland (Fig. 1a). It is the biggest European ice cap (8100 km², max. thickness: 1000 m, average thickness: 400–500 m, Björnsson, 1996). The second largest outlet glacier of Vatnajökull is Breiðamerkurjökull. It is located in the southern part of the ice cap and flows south east, in an inactive rift zone. This actively receding glacier is exposed to a maritime, cold-temperate climate (Evans and Twigg, 2002). It is 13 km wide at the snout and large medial moraines divide it into four lobes (Evans and Twigg, 2002). The study area is located in the forefield of the east lobe (Fig. 1b). This

* Corresponding author. TOTAL CST-JF, 18, Avenue Larribau, 64018 Pau Cedex, France. Tel.: +33 5 59 83 44 03.
E-mail address: michael.denis@total.com (M. Denis).

0037-0738/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.sedgeo.2009.07.013

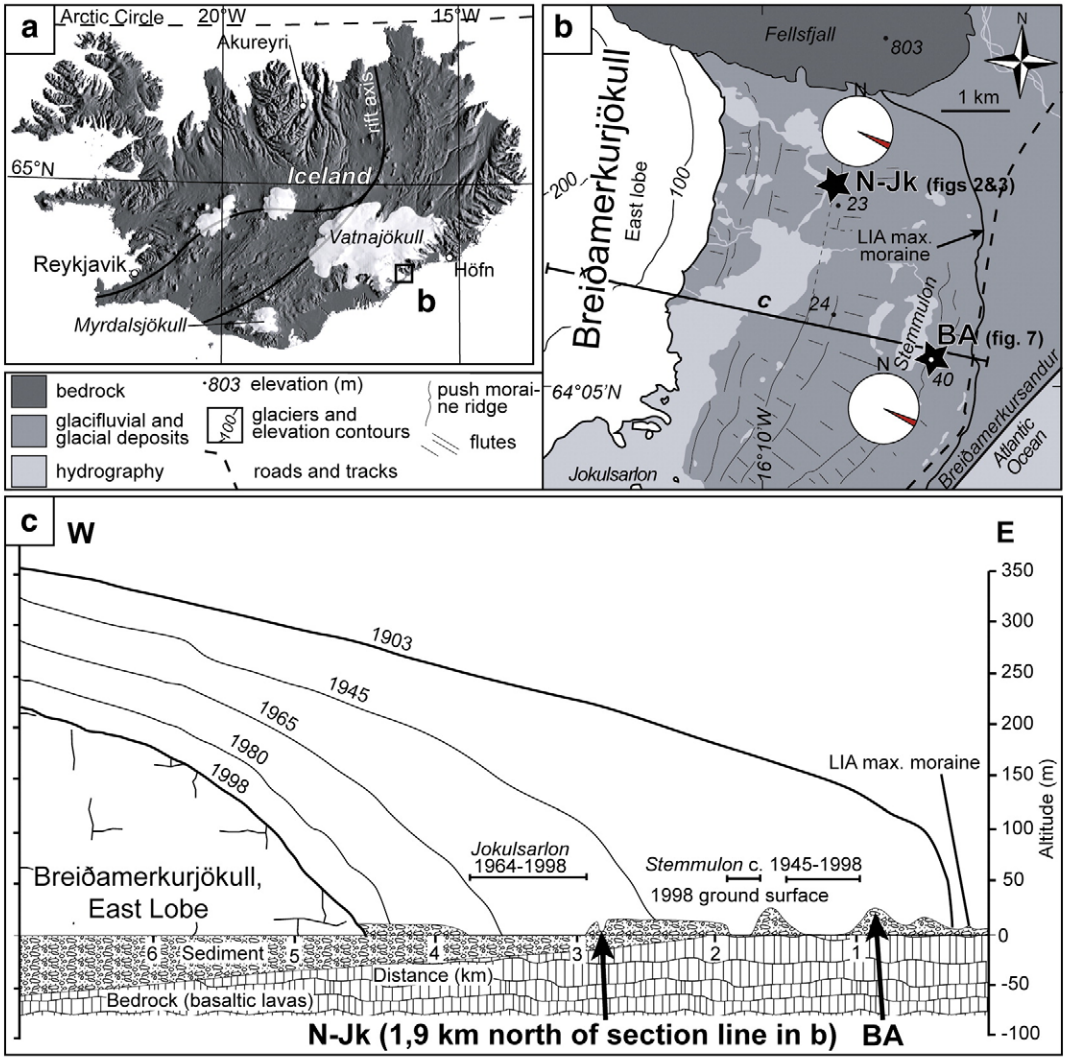

Fig. 1. (a) Location of the Breiðamerkurjökull outlet glacier. (b) Location of study areas (N-Jk and BA) in the deglaciated forefield of Breiðamerkurjökull (simplified from the 1998 map of Evans and Twigg, 2002). Rose diagrams correspond indicate ice flow orientation calculated using macrofabric data (see Figs. 4 and 8). (c) Profile of the surface of the East Lobe of Breiðamerkurjökull from the LIA to 1998, and 1998 ground surface with location of N-Jk and BA (modified from Evans and Twigg, 2002).

forefield is bounded southwards by the Atlantic Ocean and consists of glacial and fluvioglacial deposits (Breiðamerkursandur) exposed by rapid glacier retreat since the Little Ice Age (LIA: ca. 1780–1900, Bradwell et al., 2006). The forefield has been well-studied and precisely mapped. The most distal moraine attests to the maximal glacier advance, up to a few hundred metres from the ocean (Fig. 1c), during the LIA surge of the glacier in 1890 (Björnsson, 1996; Gudmundsson, 1997; Evans and Twigg, 2002). The glacier margin is now located more than 4 km landwards. In the forefield, sediments are 0 to 40 m thick and are composed of glaciolacustrine deposits (proglacial lakes), fluted tills, numerous small push-moraine ridges and a few large ridges resulting from overridden push-moraines. The two outcrops studied, North Jökulsárlón and Brennhola-Alda (N-Jk and BA) are located respectively at 2550 and 550 m from the LIA maximum glacier front (Fig. 1b and c).

The North-Jökulsárlón outcrop (N-Jk, Figs. 2 and 3) is mapped as an area of fluted tills and corresponds to a glacially overridden ice-contact sandur (outwash) fan deposited in front of an earlier glacier margin (Evans and Twigg, 2002). N-Jk is a 15 m-high vertical cliff, continuous over 200 m, formed by proglacial stream incision discharging into the Jökulsárlón proglacial lake. The outcrop shows a good quality south-to-southwest-facing section, oriented highly oblique to perpendicular to the LIA palaeo-ice flow.

The largest moraine of the forefield, Brennhola-Alda (BA), results from glacial overriding of a pre-existing large moraine during the LIA. BA is described as a glaciotectonic thrust moraine. It was formed by the surging activity of the eastern lobe of Breiðamerkurjökull during the LIA (Evans and Twigg, 2002; Evans and Rea, 2003; Björnsson et al., 2003). This outcrop is located in the upper part of a c. 35 m high, more than 100 m-wide and 1700 m long, discontinuous, gullied ridge. The outcrop is southwest-facing and was oriented parallel to ice flow during the LIA. It is partly covered with slope deposits but has been easily accessible and prepared so that detailed sedimentological logging was possible for the uppermost 4–5 metres (Fig. 8a).

3. North Jökulsárlón outcrop

3.1. N-Jk sedimentological description and fabric analysis

Accessibility restrictions only allowed for direct and detailed observations on N-Jk at the basal part of the cliff. However a synthesis of different observations made at various distances was completed and presented in the sedimentological log of Fig. 4a. Twelve lithofacies have been identified (Table 1), from which three lithofacies associations (LFA) have been established.

The basal part of the outcrop displays a gravel-dominated lithofacies association (LFA 1) and a fine-grained sand/silt/clay/peat lithofacies association (LFA 2N). LFA 1 is made up of clast-supported massive conglomerate in fining-upward metre-thick