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Microscale evidence of liquefaction and its potential triggers during soft-bed deformation within subglacial traction tills

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A B S T R A C T

Published conceptual models argue that much of the forward motion of modern and ancient glaciers is accommodated by deformation of soft-sediments within the underlying bed. At a microscale this deformation results in the development of a range of ductile and brittle structures in water-saturated sediments as they accommodate the stresses being applied by the overriding glacier. Detailed micromorphological studies of subglacial traction tills reveal that these polydeformed sediments may also contain evidence of having undergone repeated phases of liquefaction followed by solid-state shear deformation. This spatially and temporally restricted liquefaction of subglacial traction tills lowers the shear strength of the sediment and promotes the formation of "transient mobile zones" within the bed, which accommodate the shear imposed by the overriding ice. This process of soft-bed sliding, alternating with bed deformation, facilitates glacier movement by way of 'stick-slip' events. The various controls on the slip events have previously been identified as: (i) the introduction of pressurised meltwater into the bed, a process limited by the porosity and permeability of the till; and (ii) pressurisation of porewater as a result of subglacial deformation; to which we include (iii) episodic liquefaction of water-saturated subglacial traction tills in response to glacier seismic activity (icequakes), which are increasingly being recognized as significant processes in modern glaciers and ice sheets. As liquefaction operates only in materials already at very low values of effective stress, its process-form signatures are likely indicative of glacier sub-marginal tills.

1. Introduction

Deformation of the soft, unconsolidated sediments occurring beneath many glaciers is thought to account for a substantial component of their forward motion (e.g. Alley et al., 1986, 1987a; Boulton and Hindmarsh, 1987; Clarke, 1987, b; Alley, 1989a, b; Humphrey et al., 1993; Boulton et al., 2001). This concept of a "deforming bed" was first proposed following experiments carried out upon the till beneath the margin of Breiðamerkurjökull in SE Iceland (Boulton, 1979; Boulton and Hindmarsh, 1987; Boulton and Dobbie, 1998) and further supported by high resolution seismic surveys beneath Ice Stream B in Antarctica (Blankenship et al., 1986, 1987). Subsequent field studies and geotechnical experiments have identified a range of possible subglacial deformation responses to glacier basal shear stresses which give rise to increasing cumulative shear strain upwards through the till profile towards the ice base (Boulton et al., 1974; Boulton and Jones, 1979; Boulton, 1986; Hindmarsh, 1997; Tulaczyk et al., 2000a, b; Kavanaugh and Clarke, 2006). The water content, lithological composition and thickness of the tills, along with temporal and spatial changes in the porewater pressures that occur within the subglacial environment, are all considered to exert a strong control on the style and intensity of deformation (see Evans et al., 2006 and references therein). However, the exact nature of the response of tills during subglacial deformation remains a subject of significant debate (cf. Boulton and Hindmarsh, 1987; Benn and Evans, 1996; Boulton, 1996a,b; Hindmarsh, 1997; Murray, 1997; Piotrowski and Kraus, 1997; Piotrowski et al., 1997; Tulaczyk, 1999; Fuller and Murray,

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2000; Tulaczyk et al., 2000a, b; van der Meer et al., 2003; Piotrowski et al., 2004, 2006; Kavanaugh and Clarke, 2006; Evans et al., 2006; Damsgaard et al., 2016), especially the responses that are likely to arise through changing water pressures. For example a number of studies of marine terminating ice streams in West Antarctic have suggested that tidal movements effecting the floating part of the glacier can influence the upstream distribution of pore water pressure leading to variations in the velocity of ice flow (e.g. Winberry et al., 2011; Walker et al., 2013; Thompson et al., 2014; Rosier et al., 2015).

Boreholes through the Trapridge Glacier (NW Canada) indicate that subglacial deformation is driven by changes in shear stress due to the variation in ice-bed coupling and water pressure as well as possible changes in deforming layer thickness (Blake, 1992; Blake et al., 1992; Kavanaugh and Clarke, 2006). Iverson et al. (1994, 1995) used investigations at Storglaciären in northern Sweden to emphasize the complexity of subglacial deformation, concluding that the till acts as a "lubricant" with forward motion being dominated by basal sliding and ploughing of large clasts embedded in the base of the ice. Some subglacial experiments have revealed that, instead of increasing coupling at the ice-bed interface, ploughing clasts actually weaken sediment by elevating porewater pressures (PWP) in sediment prows (Iverson et al., 1994; Iverson, 1999, 2010; Fischer et al., 2001). Hindmarsh (1996) suggested that the till itself may slide over an underlying hard substrate, giving rise to polished/striated bedrock surfaces. Similarly Truffer et al. (2000) and Kjær et al. (2006) have also argued for deformation having occurred deep within or beneath subglacial tills as a potential mechanism for rapid ice flow. Alternatively, Fuller and Murray (2000) recorded basal sliding over soft-sediments at the base of Hagafellsjökull in Iceland, associated with only a very thin (<16 cm) layer of deformed sediment.

Reconciling these process studies with interpretations of the subglacial conditions recorded in ancient sedimentary sequences is particularly challenging, because palaeo-ice sheets and glaciers have left a legacy that comprises complex assemblages of deposits whose sedimentological and structural signatures are ambiguous. Consequently, our current understanding of the conditions encountered within the subglacial environment relies heavily upon theoretical models stemming from a modest number of glaciological process case studies and laboratory experiments. From this comes an understanding that increased porewater pressure (PWP) within the glacier bed, when it is at steady state consolidation, results in the "dilation" of the sediment and a fall in its shear strength (Fig. 1). Fluctuations in PWP will lead to repeated phases of "dilation" followed by "collapse" as the water pressure falls, the latter leading to an increase in the shear strength of the sediment (also see Damsgaard et al., 2016; Winberry et al., 2011); this response may be dampened by materials with lower diffusivity (Iverson, 2010). The computer simulations of the deformation of subglacial tills by Damsgaard et al. (2016) have demonstrated that creep in these modelled simple granular materials keeps porosities somewhat elevated between failure events. At the highest values of PWP the ice may become decoupled from its bed and there may be a significant fall in the shear stress translated to the underlying sediments, effectively switching off subglacial deformation and promoting basal sliding as the dominant mechanism of glacier forward motion. This stick-slip style of motion operating in soft glacier beds has been reported by Fischer and Clarke (1997) and Fischer et al. (1999) for the Trapridge Glacier, where decoupling of the ice takes place during periods of high water pressure. Boulton et al. (2001) also propose a stick-slip motion, operating diurnally, to explain their observations at Breiðamerkurjökull, Iceland, where rising water pressures initiate till dilation, followed by the

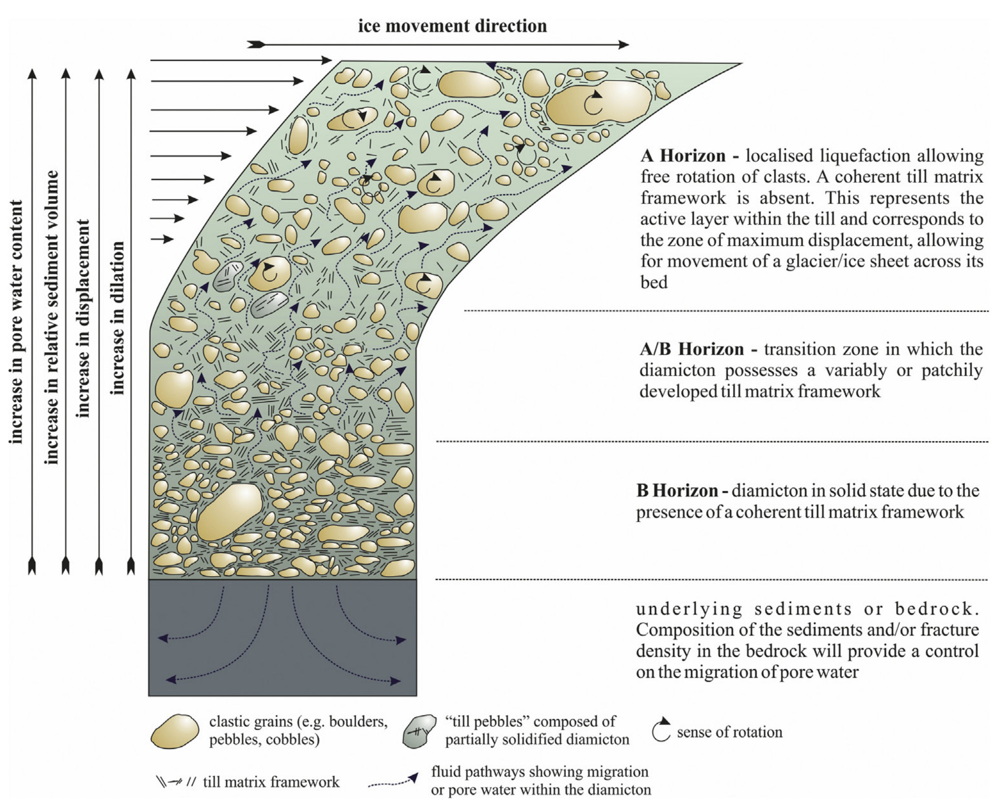

Fig. 1. Diagram showing the zonation of a relatively homogeneous subglacially deforming till and its relationship to "dilation", displacement, sediment volume, shear strength, connectivity and pore water pressure (after Evans et al., 2006).