Evidence of bed deformation beneath the Wright Lower Glacier, South Victoria Land, Antarctica

Sean Fitzsimons,[1] Sarah Mager,[1] Regi Lorrain,[2] and Suzanne Sleewaegen[2]

[1]Department of Geography, University of Otago, P.O. Box 56, Dunedin, New Zealand
[2]Laboratoire de Glaciologie, Département des Sciences de la Terre et de l'Environnement, Université Libre de Bruxelles, CP 160/03, Avenue F.D. Roosevelt, 50, B-1050 Bruxelles, Belgium

Summary A tunnel excavated into the margin of Wright Lower Glacier revealed a basal ice sequence dominated by the presence of frozen blocks of sand that contained well-preserved fluvial sedimentary structures. The sedimentary structures, together with the presence of ice between the frozen blocks of sand and ice wedges in the uppermost block of sand, suggest that the material is an overridden proglacial permafrost environment. Velocity and strain measurements made in the tunnel show that the permafrost is being deformed and the glacier has entrained the sediment blocks. The measurements also reveal a compound basal velocity profile that is the result of no or very low internal shear in the sand blocks whereas the relatively clean ice experiences relatively high strain rates. The pattern of strain and displacement strongly resembles the velocity structure associated with the deformation of subglacial sediment. However, the low basal ice temperature of the glacier (-16°C) is inconsistent with previous accounts of subglacial sediment deformation that attribute deformation to elevated pore water pressures. We conclude that subglacial sediment deformation beneath cold-based glaciers can occur the glacier substrate contains ice-rich sediments.

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Introduction

The discovery that sedimentary beds are widespread beneath modern glaciers together with the realization that such beds may experience deformation has led to a reassessment of the behaviour of glacier beds and how glaciers are coupled to their beds (Murray, 1997). For example, observations made near the margin of Breidamerkurjökull demonstrated that deformation of water saturated sediment accounted for 90% of glacier motion (Boulton and Jones, 1979) and seismic surveys conducted on the Whillans Ice Stream in Antarctica suggested that the ice was underlain by porous, saturated sediment (Blankenship et al., 1987) which was subsequently confirmed by drilling (Engelhardt et al., 1990). Such observations and measurements suggest that subglacial sediment deformation occurs because of a reduction in effective normal stress associated with elevated pore water pressures. In glaciers with basal temperatures below the pressure melting point the ice is frozen to the bed and it is widely assumed that sliding and subglacial sediment deformation cannot take place. However, theoretical work by Shereve (1984) together with observations by Echelemyer and Zhongxiang (1987), Cuffey et al. (2000) and Fitzsimons (2006) suggest that low velocity sliding can occur. One of the few studies of sediment deformation beneath a cold ice were made beneath Urumqi Glacier No 1 in China where Echelmeyer and Zhongxiang concluded that 60-80% of surface velocity could be attributed to deformation of a layer of ice laden sediment. Subsequently several studies of formerly glaciated permafrost terrain have concluded that extensive deformation of permafrost occurred beneath glaciers in arctic Canada and northwestern Siberia (Astakhov et al., 1996; Murton et al., 2004). These studies suggest that the beds of cold-based glaciers may have been strongly coupled with ice-rich permafrost. Despite these studies and debates concerning whether the substrate needs to be unfrozen or frozen during detachment and transportation there is no general theory has been advanced to account for the debris transported in front and beneath glaciers in this way (Alley et al., 1997), and there have been very few studies that have attempted to study this problem in modern cold-based glaciers. In this paper we report a study of the structure and deformation processes at the bed of this glacier from measurements made in a tunnel over a period of four years.

Methods

Our observations and measurements were made in a tunnel excavated through the apron using electric chainsaws and demolition hammers. The tunnel was oriented parallel to ice flow and extended 10 m from the foot of the ice cliff and a 4 m-deep vertical shaft was excavated through the main debris-bearing layers. Continuous records of ice deformation were obtained using linear variable displacement transducers (LVDT's) logged every 60 minutes using Campbell Scientific data loggers powered by deep cycle batteries that were charged with a wind generator. Displacement measurements were made using plumb lines that consisted of nylon lines attached to an anchor screwed into the roof of the tunnel and a plumb bob that was set over a brass target attached to the tunnel floor. Strain rates were measured by drilling rectangular arrays of stainless steel bolts into the tunnel walls and resurveying the distances between the bolts episodically with a digital caliper that had a precision of 0.01 mm. The arrays were oriented on parallel to the ice flow direction and located close to the end and floor of the tunnel to minimize the effect of wall bulging on the measurements. Strain rates were calculated from the corners of triangles defined from the strain arrays using a numerical calculation of a Mohr circle based on the method outlined by Ramsey 1967 and used in glaciology by Hambrey and Muller (1978) and Hambrey et al. (1980). We have followed the convention for principal strain rates that $\dot{\varepsilon}_1 \geq \dot{\varepsilon}_3$, that extension is positive and $\dot{\varepsilon}_3$ is always horizontal [Sharp et al., 1988].

Basal ice structure and composition

The tunnel revealed a 4.5 m thick section of debris-bearing basal ice that consists of a layered sequence of stratified debris-bearing ice, frozen blocks of sand and clean ice (Figure 1). The stratified debris-bearing ice occurs in several locations in the basal ice sequence consists of layers of relatively clean ice, bubbly ice interspersed with layers of ice that contain dispersed sand and fine gravel particles and with occasional sand lenses up to 10 mm in diameter (Figure 1). The frozen sediment blocks consist of medium to coarse sand that displays well preserved planar bedding and occasional cross bedding structures (Figure 2). The pore spaces in the sand are completely occupied by ice. The sand and ice layers of the sequence dip in an up-glacier direction at angles between 20 and 27°. Thin algal mats are preserved within several of the sand blocks and the upper boundaries of some of the blocks contain ice-filled wedges about 2 mm wide and 60 mm deep (Figure 2D). Numerous cracks and cavities that have formed in the frozen sand show that the blocks have been strongly deformed. The larger air-filled cracks and cavities have accumulations of dry sand in their floors and are partly intruded by ice that appears to be creeping into the open cavities (Figure 2B). The clean glacier ice mainly occurs in the upper part of the basal ice sequence although thin clean ice layers also occur between some of the frozen sand blocks (Figure 1). This ice is characterized by the absence of debris and numerous bubbles which are oriented parallel to ice flow.

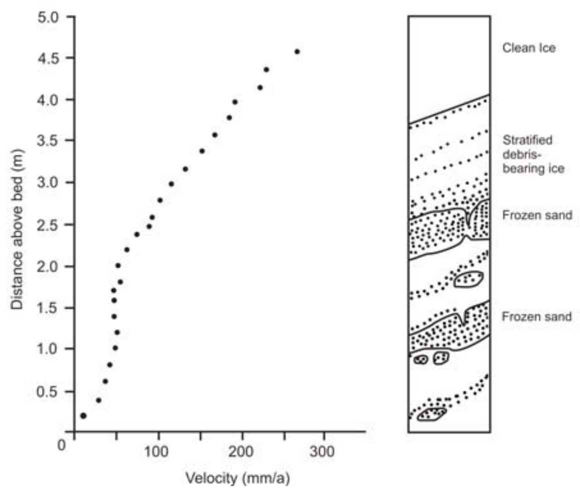

Figure 1. Velocity profile and graphic log

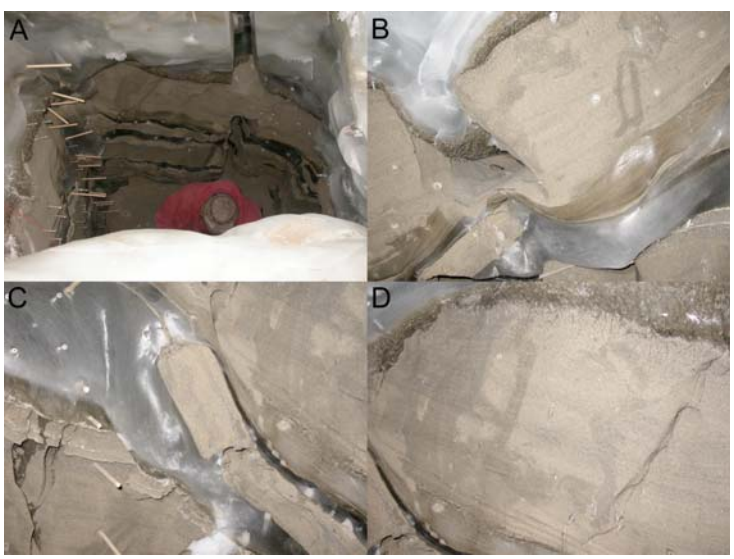

Figure 2. A. 4.5 m-deep excavation throught the basal ice. B Cavity partly filled with ice. C Broken sand blocks with ice flowing around the blocks. D. 200 mm-thick block of bedded sand with small ice wedges on the top surface

Basal ice deformation

The glacier surface velocity adjacent to the tunnel is 1.38 m/a. In the tunnel the velocity profile shows that the entire 4.5 m–thick basal zone is mobile (Figure 1) and the measured displacements constitute 21% of total glacier movement. Below 2.5 m the measured velocities are below 90 mm/a. The near vertical nature of the velocity profile through the sand layers suggests that there the frozen sediment blocks are associated with very low strain rates. In contrast, above the top frozen sand layer at 2.5 m there is a linear increase in velocity.

Strain measurements made in the basal ice sequence show that there are three distinct groups (Figure 3). Low to negligible annual shear strain is associated with material that has high debris concentrations such as the blocks of frozen sand. In contrast, the stratified debris-bearing ice that is characterized by relatively low debris concentrations is characterized by relatively high annual shear strain between 0.05 and 0.09 (Figure 3). However, stratified debris-bearing ice located between the blocks of frozen sand experiences much lower annual shear.

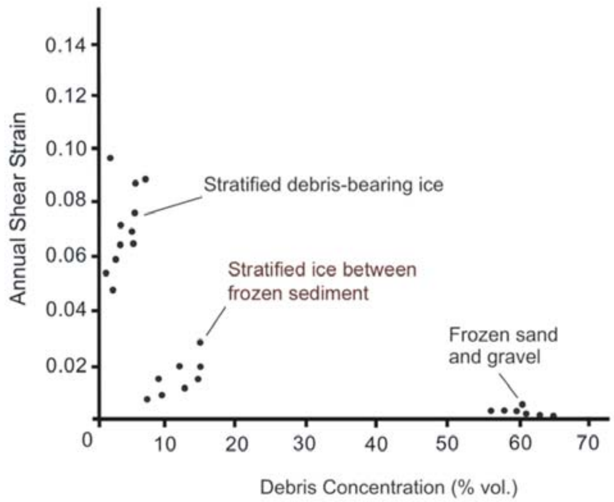

Figure 3. Annual shear strain as a function of debris concentration

Linear variable displacement transducers (LVDT) mounted on the top of the uppermost frozen sand block and attached to a pin drilled into the ice 4 mm above the block recorded no detectable movement which suggests that either there is no sliding or sliding velocities are so low that they were not measurable. In contrast, dial gauges mounted on a boulder about 4.5 m above the bottom of the excavation recorded displacements of 28 mm/a which together with slickenslides preserved in a cavity on the downstream side of the boulder suggests sliding at least in the part of the basal zone associated with higher velocities. Although strain measured within the frozen blocks is negligible, measurements made across cracks in the basal zone of Wright Lower Glacier show that they are actively opening at rates of around 25 mm/a

Discussion

In contemporary sedimentary environments in the McMurdo dry valleys the association of planar bedding, cross bedding and thin layers of algae occurs in small streams and on the surfaces of deltas. Such environments also produce layered sediment and ice because of episodic freezing of streams. Deposition by eolian processes can be excluded because algae do not grow without the presence of liquid water. The presence of small ice wedges that extend into the surface of the sand blocks suggests that at least some of the sand represents a former subaerial surface on which periglacial processes were active. These characteristics suggest the sequence represents sand and refrozen meltwater that has accumulated in either a fluvial or marginal lacustrine environment. The deformation measured within the material show that the glacier is closely coupled to the bed.

The velocity profile through the basal ice sequence can be divided into three sections: below the sediment blocks there appears to be a logarithmic increase in velocity, through the sediment layers where there is no increase in velocity with height above the datum and above the sediment blocks where there is a linear increase in velocity. Such a compound velocity profile bears a striking resemblance to the velocity structure associated with the process of subglacial deformation (Boulton and Jones, 1979). However, in this case the strain rates of the subglacial sediments are not controlled by basal water pressure because there is no liquid water present at bed of the glacier. Thus, the data provide evidence to extend the concept of subglacial deformation to encompass frozen substrates. This interpretation is difficult to resolve with previously work that has concluded that glacial deformation of frozen sediments is hindered by the high shear strength of the materials (eg. van der Wateren, 1985; Hart and Boulton, 1991). Direct shear tests of frozen sand at a displacement rate of 0.1 m/a which is comparable to velocities in the Wright Lower Glacier basal sequence have shown that frozen sand has an average peak shear strength of 2.16 MPa (Fitzsimons et al., 2001). In contrast, clean glacier ice has and average strength of 0.64 MPa, which is consistent with the view that frozen sediments are a high strength material that would resist deformation. However, the same experiments recorded average peak shear strength for stratified debris-bearing ice of 0.71 MPa (Fitzsimons et al., 2000; 2001). Such experiments show that as sediment becomes supersaturated with ice (i.e. the ice occupies more that pore spaces) its shear strength decreases because the increasing ice volume results in a progressive decrease in frictional strength. Such substrates are susceptible to subglacial deformation.

Conclusions

The following conclusions can be made from the observations and measurements made beneath Wright Lower Glacier. Firstly, it appears that the glacier has overridden a proglacial permafrost that consists of layers of fluvial sand together with refrozen meltwater. Secondly, the displacement and strain measurements demonstrate that deformation has penetrated into the glacier substrate and it appears that the deformation is controlled by the volume of ice in the permafrost. Consequently, we conclude that subglacial sediment deformation can occur beneath cold-based glaciers which is consistent with observations of deformed Pleistocene permafrost (Astakhov et al., 1996). Finally, deformation of the permafrost results in mixing of ice and sediment which contributes to the development of the basal ice layer of the glacier.

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