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Review article

Structures and fabrics in glacial ice: A review

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ABSTRACT

Glaciers, ice sheets and ice caps represent tectonic systems driven by gravity. Their movement can be studied in real time and the rheological properties and strength of ice determined from laboratory experiments and field measurements. All glacial ice has primary stratification, exhibited by variations in grain size, bubble content and debris content. As it deforms, with deformation dominated by plastic flow and recrystallization, accompanied locally by fracture under tension, a suite of structures develops that reflects the primary fabric of the ice and the anisotropy that develops as a result of cumulative deformation. Initial variations in solid impurity content and strain dependent anisotropy as a result of a crystallographic fabric give rise to effective viscosity increases or decreases compared to isotropic polycrystalline ice of about a factor of ten. Foliation develops from inherited (mostly stratification) or introduced (mostly ice veins or fracture traces) fabric elements and from dynamic recrystallization. It is largely dependent on the accumulated strain, which is highest at the base and near the margins of glaciers, ice sheets and ice streams. Folds develop largely passively due to initial amplification of irregularities in the primary stratification, to variations in flow with time or to inhomogeneous flow associated with shear zones and ductile accommodation around open fractures. Buckle folds and boudinage, mostly on a small scale, occur where viscosity contrast is large, mostly in basal ice. Thrusting and wrench faulting are documented in surging glaciers but theoretically most unlikely and rare or absent elsewhere. Many structures interpreted as faults are not due to shear failure but rather result from shear displacements during opening and closing of tensile fractures.

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1. Introduction

Glaciers have particular appeal to structural geologists, providing natural 'tectonic' systems in which a variety of brittle and ductile structures develops under known driving forces and at rates that can be directly measured. Analogies between structural development in ice and in rocks have been made by many authors (e.g. Wegmann, 1963; Hambrey and Milnes, 1977; Kamb et al., 1985; Hudleston, 1992; Lawson et al., 1994), and have been drawn from the scale of the crystal – ice in some ways being a good analogue for quartz (e.g. Wilson and Russell-Head, 1979; Wilson et al., 2014), to individual structures such as folds (e.g. Hudleston, 1977b) and boudinage (Hambrey and Milnes, 1975), to tectonic systems (e.g. Herbst and Neubauer, 2000).

One benefit of studying structures in ice is that the rheology is relatively well understood, with a well-established flow law for isotropic polycrystalline ice and with recent advances that allow characterization of the rheology at low stresses and with preferred crystallographic orientation (e.g. Pettit et al., 2011; Treverrow et al., 2012; Wilson and Peternell, 2012). Considerable experimental work has also been done on the effect on rheology of solid particles dispersed in ice and behavior of ice-saturated sediment (Moore, 2014). Much recent work has been done on the microstructure of ice and the development of preferred crystallographic orientation with strain (e.g. Duval et al., 2010; Montagnat et al., 2012, 2014), with particular focus on the Greenland and Antarctic ice caps. In those locations, understanding the flow history has important implications for interpreting proxy signals for climate change, since deformation overprints and disrupts stratigraphy deep under ice caps due to the nature of the ice flow.

Geophysical methods are employed to determine ice flow and material properties at depth within and over large areas of ice sheets and glaciers. Radio-echo sounding (e.g. Drews et al., 2009) and ground-penetrating radar (e.g. Vaughan et al., 1999; Holschuh et al., 2014) are used to determine ice thickness and elucidate internal structure. Not only can these techniques pick up internal reflectors representing stratification (isochrones), they may also detect changes in crystallographic fabric (Eisen et al., 2007), as may seismic wave velocity analysis (Diez et al., 2014). Interferometric synthetic aperture radar (InSAR), together with optical-image-tracking methods provided by satellite imagery and GPS, are used to measure surface velocities over large areas and over time frames of from seconds to years (e.g. Joughin et al., 1999, 2010). This is especially useful for studying ice streams in ice sheets.

Hambrey and Lawson (2000) have provided a comprehensive summary of structural studies on glaciers from the 1950s until the turn of the century. Good examples of detailed studies are those of Allen et al. (1960) on the Lower Blue Glacier, Washington; Meier (1960) on the Athabasca Glacier, Alberta; Hambrey (1976a,b) on Charles Rabots Bre, Norway; Hambrey and Milnes (1977) on Griesgletscher, Switzerland; Hambrey and Müller (1978) on White Glacier, Axel Heiberg Island, Canada; Sharp et al. (1994) and Lawson (1996, 1997) on the Variegated Glacier, Alaska; and Goodsell et al. (2005) on Haut Glacier d'Arolla, Switzerland.

The approach taken in this paper is first to provide brief reviews of ice rheology, the kinematics of flow in glaciers and larger ice bodies (Fig. 1) and the crystallographic fabric that develops as a result of this flow. The bulk of the paper is devoted to descriptions of the various structural and fabric elements found and mapped in glacial ice and a discussion of the processes involved in their development. The paper concludes with a brief section discussing the assembly and sequence of structures and fabrics developed in glacial 'tectonic' systems.

2. Rheology

Data from experiments and theoretical considerations suggest

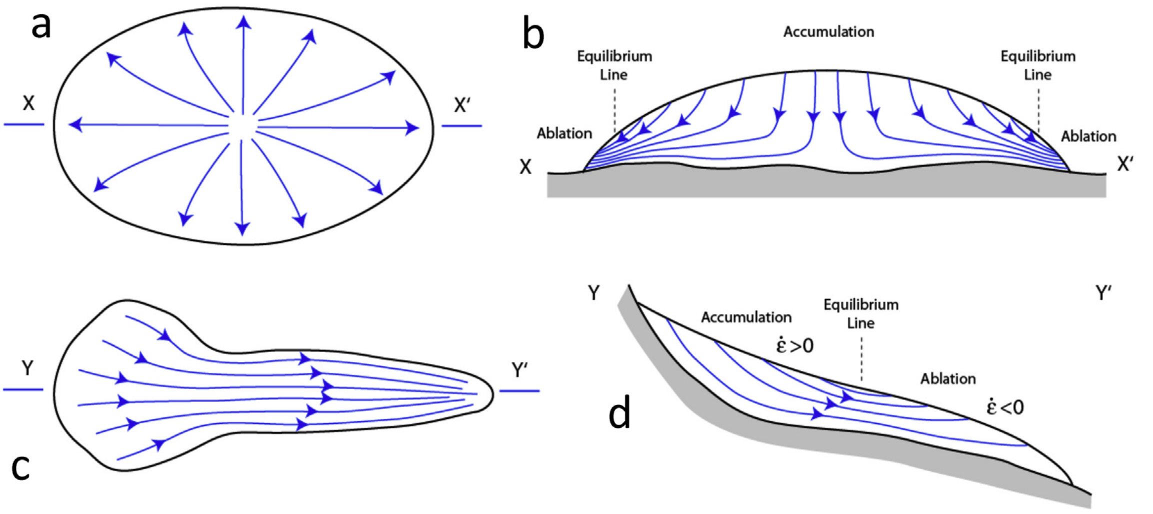

Fig. 1. Schematic diagrams to illustrate the flow patterns in ice caps and valley glaciers in map view (a, c) and in cross section (b, d). Net accumulation exceeds ablation in the accumulation zone (longitudinal strain rate $\dot{\varepsilon} > 0$), and net ablation exceeds accumulation in the ablation zone ($\dot{\varepsilon} < 0$). If basal temperature is at the pressure-melting point there will be a component of basal slip (not shown). Ice sheets (not shown) are much larger than ice caps and possess ice divides separating flow basins; they possess outlet glaciers and ice streams at their margins in which the velocity is much higher than in the surrounding ice (see Rignot et al., 2011). Otherwise, the basic flow pattern in an ice sheet resembles that of an ice cap.