IP12B MC: 121 Monday 1515h

Ice: From Molecules to Ice Sheets (A Special Session in Honor of W. Barclay Kamb) I *(joint with NG, H, T, MR, HG)*

Presiding: **S Tulaczyk,** University of California, Santa Cruz**; C F Raymond,** University of Washington

IP12B-01 1520h

Crystal Structure, Dielectric Relaxation and Rheology of the High Pressure Phases of Ice

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Knowledge of the rheological properties of the high pressure polymorphs of ice is important for discussing the tectonic and cratering histories of the icy satellites, and their internal structure. Several research groups have made measurements of the viscous flow properties of these ices. There are striking rheological contrasts between the different ice phases, with some phases being notably stiffer or softer than others. Here we discuss these rheological contrasts in relation to dislocation motion in the different ice phases. The mobility of dislocations is related to the dielectric properties of the different phases, and these are ultimately related to crystal structure, the bending of hydrogen bonds and the presence of proton disorder in some of the ice phases. Special note will be made of the important contributions Barclay Kamb to these studies - from the details of crystal structure to ice flow.

IP12B-02 1535h INVITED

Ice Rheology Beyond Planet Earth

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Barclay Kamb is well known for his seminal work on the motions and internal flow of glaciers, but he was also a pioneer in research on the crystal structures, chemical bonding, and rheologies of the high-pressure phases of ice. In the flow and fracture of terrestrial materials, no rock is more studied than ice. Water ice also has an important presence on other solar system bodies, in particular the moons of the outer solar system, where its flow may extend to deep interiors. Most of these low-density (< 2 Mg/m^3) moons have volume fractions of ice well above 0.5, and the largest moons, for example Ganymede, Callisto, and Titan, have sufficient internal pressures to stabilize the high-pressure phases II, III, V, VI, VII, and, possibly in early satellite history, ice VIII. The rheology of ice I has important influence on the surface morphologies of the moons, and the rheologies of all these phases (including ice I) can affect the thermal evolution of the moons by governing the rates of advection of internal radiogenic heat.

Polycrystalline ice I under terrestrial conditions is far warmer than ice I in most planetary settings. The phenomenon of "premelting" in ice at $T > 255$ K leads to high grain-boundary mobility and much higher activation energy in warm ice than in cold ice under the same stress, so the flow of terrestrial ice may not be a good analog for that in the outer solar system. Phenomena from the rheological law itself to the development of lattice preferred orientation may be affected.

Of the high-pressure phases through ice VI (all whose rheologies have been explored to date), ices III and VI are the weakest, an effect that, as Kamb has pointed out, parallels and draws explanation from the high rate of dielectric relaxation in those phases. Ice III is exceptionally weak and is stable over a very small part of the (P, T) phase diagram that is situated very close to possible planetary temperature profiles. This could lead to either self-regulation or instability in convective flow depending on the assumptions of the model. Experimental investigation of the transformation of metastable ice I to ice II under nonhydrostatic stress has led to the discovery of transformational faulting (a mechanically unstable transformation under shear with possible applications to deep earthquake faulting in Earths mantle) and a stable stress-induced ice I to ice II transformation mechanism involving anisotropic growth of ice II inclusions, producing a simple form of metamorphic foliation.

IP12B-03 1555h

Deformation of ice at low Stresses; Application to the Mechanical Behavior of ice in Polar ice Sheets

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The creep behavior of polycrystalline ice under the conditions prevailing in polar ice sheets, namely at stresses lower than 0.1 MPa, is characterized by a stress exponent lower than 2. The deformation of polar ice is associated with the occurrence of grain growth and recrystallization. The formation of grain boundaries and grain boundary migration appear to be efficient processes to reduce internal stresses and minimize deformation gradients or intragranular misorientations induced by the plastic anisotropy of the ice crystal. The accommodation of basal slip by grain boundary migration could explain the transition from a stress exponent of 3 to a value lower than 2 with decreasing stress.

Measurements on several deep ice cores show that grains orientations evolve quite continuously from randomly oriented crystals at the ice-sheet surface to marked preferred orientations with increasing depth as the result of lattice rotation by dislocation glide. The respective role of slip and recrystallization in the formation of fabrics is discussed by using a micro-macro approach, which permits to simulate fabric development and predict the mechanical behavior of anisotropic ices. It appears that simulated fabrics are in close agreement with those observed in ice sheets as long as migration recrystallization is not occurring. Fabrics associated with migration recrystallization can be considered as stress-controlled as shown by Kamb (1972) and are observed in deep layers of ice sheets when temperature is near the melting point and in temperate glaciers.

IP12B-04 1610h

The Constitutive Relationship of a Glacial-Scale Block of Temperate Ice.

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The specifics of the constitutive equation relating deformation rates to stress in glacier ice remain uncertain. Appropriate values for the flow law exponent n are undecided, with field and experimental evidence suggesting values ranging from 1 to more than 4. A transition in dominant deformation mechanism from grain boundary sliding at low deviatoric stress to intragranular slip at high deviatoric stress has been proposed as the cause of a transition from low-n to high-n flow, but has not been extensively confirmed experimentally or observationally.

We use deformation measurements made in 31 closely-spaced boreholes to examine the rheology of a 6 million cubic meter block of Worthington Glacier, Alaska. Analysis of the three-dimensional stresses and strains within the block indicate that below a depth of about 70 m, the deformation is correctly described by the conventionally accepted flow law with $n \sim 3$. In this region shear stress dominates and the deviatoric stress level is estimated to be greater than about 0.6 bar. Above a depth of 70 m, however, deformation does not form a power law relationship with stress. Rather, the ice in the upper third of the temperate glacier deforms following a linear viscous flow law. A sharp transition between the two flow regimes is observed, suggesting a sudden change from grain boundary sliding or diffusional flow in the upper layers to dislocation and intra-granular deformation at depth. :

IP12B-05 1625h INVITED

Inferences of Ice Processes From Properties

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Barclay Kamb's pioneering work on the physics and mineralogy of laboratory and natural ices has guided glaciological research spanning 40 years. Much of that research required extremely tedious use of optical universal stages to study thin sections of ice. Recent advances in digital systems have revolutionized data collection and offer great opportunities to use ice properties to infer processes that operate too slowly for proper laboratory investigation, leading toward a greatly improved understanding of the history of ice and its softness for further deformation (Wilen, 1999; Hansen and Wilen, in review; Wilen et al., this meeting). Patterns of nearest-neighbor c-axis orientations reveal the influence of nucleation-and-growth recrystallization (typically indicative of steady-state deformation) or polygonization. Combining these results with correlations between grain sizes and dust and chemical loadings reveals impurity effects on active processes. The relations between mean grain size and c-axis-fabric strength may show the importance of grain-boundary processes in deformation. Bubble sizes reveal climate conditions during firnification, and bubble shapes can provide information on in situ strain rates. These and many other possibilities should enhance our understanding of ice flow and of the paleoclimatic records archived in ice.

IP12B-06 1645h

The History of the Glacier Facies Concept

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The concept of glacier facies developed as a result of physical measurements made in Greenland on repeated traverses that went inland from the west coast at two latitudes (77 N and 70 N) and north to south along the crest of the ice sheet. Snow pits and shallow cores showed discontinuities in physical characteristics that defined the facies boundaries. Some refinement have resulted from research in Antarctica and on Alaskan mountain glaciers. Thirty years after the facies were defined, based on field measurements, it was found that radar data (SAR) from satellites show the boundary between the percolation and dry snow facies in Greenland. They also show the percolation facies of the Greenland ice sheet to be the brightest radar reflector on earth. The dry snow facies is rare except on the major ice sheets (Greenland and Antarctica), but it is present on mountains that exceed 4000 m in Alaska and the Yukon. In particular, Mt. Wrangell, Alaska was selected for continued study of glacier facies because it has a large and accessible area above 4000 m. Mt. Wrangell has proven to have the full spectrum of glacier facies, and these can be seen on the SAR map of Alaska. Refinements in the definition of the lower end of the wet snow facies, to deal with a slush zone and a superimposed ice zone, resulted from Fritz Muellers research on Axel Heiberg Island and from studies on the McCall Glacier of Alaska. Minor refinements in defining the dry snow facies resulted from comparing Antarctica and Greenland in places where mean annual temperature and accumulation rates were essentially equal. The glacier facies concept also provides a way of comparing the two polar regions and of speculating on the glacier facies that existed on the Pleistocene continental ice sheets.