DEEP MOONQUAKES ON GANYMEDE? S. H. Kirby, USGS, Menlo Park, CA 94025; W. B. Durham, UCLLNL, Livermore, CA 94550

Our work on the inelastic deformation behavior of H_2O ices has provided the first systematic exploration of the fracture, friction, and plastic flow under outer planetary P-T conditions (pressures up to 0.6 GPa and temperatures from 77 to 256 K (1,2)). In the course of carrying out this experimental program, we discovered an unusual form of faulting (1) that has relevance for deep (360-690 km) earthquakes faulting on Earth. The purpose of this note is to point out the possibility of similar deep faulting on Ganymede and other large icy bodies in the solar system.

The faulting instability we observe in ice has several unusual properties: faulting strength does not increase with increasing pressure, a transition to ductile behavior is not observed with increasing confining pressure, and faults form in the maximum shear stress orientation (45°) to compression. These events are restricted to low temperatures and elevated pressures. Later work (3,4) showed the key role in the faulting process played by the ice I→II transformation and noted that parallels exist between the ice transformation and those that occur in the ferromagnesian phases (olivine and the spinel structures) of the earth's upper mantle. The thermodynamic properties of the phase transformations in the upper mantle are similar to those of ice I→II. The transformation kinetics in both transformations are slow. Thus the faulting instability can occur in the ice II stability field where ice I persists metastably at low temperatures and elevated pressures, and the cold thermal structure of the descending lithospheric slab in some subduction zones may be favorable for the faulting instability to develop in metastable olivine, as explained below.

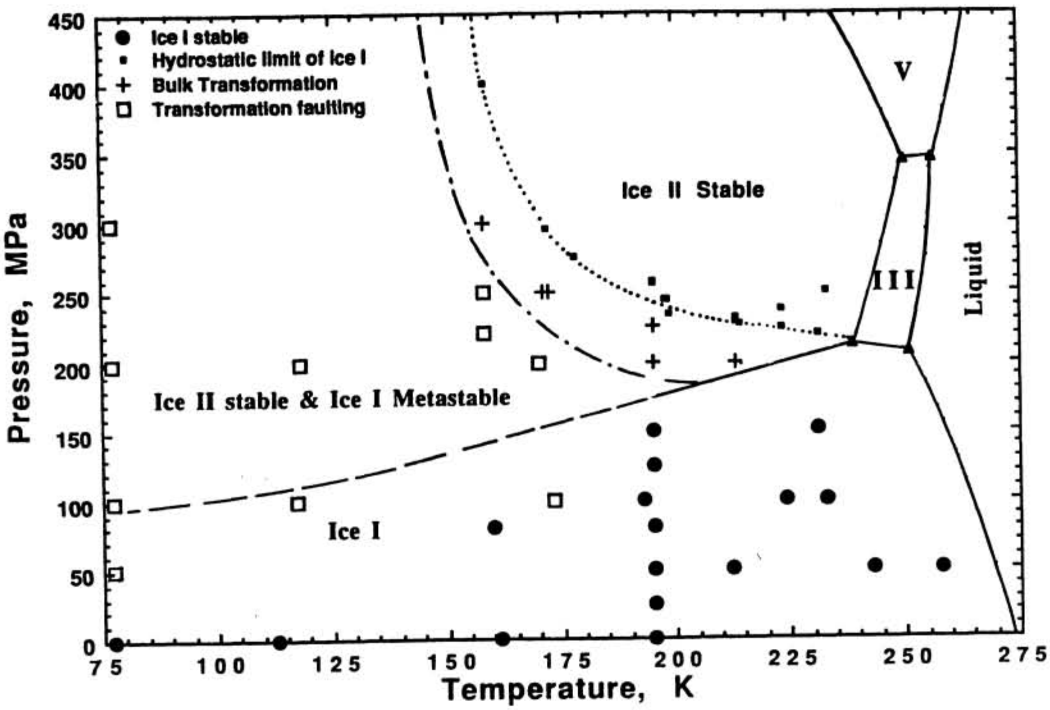

Figure 1. Phase diagram for ice and hydrostatic conditions of the experiments. When ice I is pressurized at constant temperature into the ice II stability field, it does not transform to ice II at the equilibrium boundary. Under hydrostatic conditions (solid boxes), the overpressurization required to cause the transformation to initiate increases sharply as temperature decreases (dotted line). The bulk transformation pressure can be lowered if a differential stress is superimposed on the hydrostatic pressure (crosses). The differential stress required for bulk transformation at any temperature is simply the difference between the actual pressure (crosses) and the hydrostatic limit (dotted line); in other words, the criterion for transformation is a maximum normal stress. At lower temperatures and pressures there seems to be a limit on the maximum differential stress that can be applied, illustrated by the open boxes. Above a shear stress that is weakly temperature sensitive (not shown: about 85 MPa at 77 K, descending to 53 MPa at 170 K) samples fail by macroscopic faulting. The process involves transformation of small amounts of ice I to ice II; hence it is termed transformational faulting, and may be an analog for deep earthquakes in the earth. Such faulting may occur at depths of 40 - 200 km on the large icy moons.

Figure 1 shows the main aspects of the kinetics of the ice I-II transformation as we now understand them. The ice I→II phase transformation is a reconstructive arrangement of molecules accompanied by a ≈ 20% volume decrease. There are two distinct manifestations of the transformation under nonhydrostatic stress (Fig. 1). The first, which we call *transformational faulting*, is the unusual faulting we described above. Xray diffraction reveals small amounts of ice II in such faulted samples, and we have suggested (4) that the large volumetric strain and exothermic character of the ice I→II transformation are the destabilizing factors that cause the faulting. The second manifestation is a *bulk transformation* that occurs at warmer temperatures (above about 175 K) where ice II nucleates at a few points in our 30-cm^3-volume sample and grows in a slow and controlled manner.

Green and colleagues (5,6) have confirmed our hypothesis in observing transformational faulting in olivine-spinel transformations in Mg_2GeO_4 and in silicate olivine and have also identified a possible mechanism by which transformational faults may be nucleated by the interactions of microinclusions of the spinel phase. We recently have followed up on our earlier work on transformational faulting in ice (7), refining the faulting strength data, confirming the fault nucleation hypothesis of Green, and pointing out the importance of earlier work by Goto et al. (8) that the volume changes involved in phase transformations in subducting lithosphere can also give rise to large regional deviatoric stresses that can stimulate transformational faulting.

We think deep earthquakes occur because the reconstructive phase transition olivine→spinel is kinetically retarded for millions of years and hundreds of kilometers depth as a slab of cool lithosphere descends into the mantle. When the transformation finally does occur, and we suggest it occurs progressively from the outer boundaries of the slab inwards as the slab slowly heats up, the negative volume change of the transformation leaves the remaining wedge-shaped core of olivine in a state of slab-parallel compression (8). Stresses eventually rise to the point where transformational faulting, the process we observe in ice in the laboratory, occurs within the olivine wedge, and a deep earthquake is registered seismically.

This unified hypothesis of deep terrestrial earthquakes has implications for deep moonquakes on large, tectonically active icy bodies such as an early Ganymede. A key requirement is that conditions of metastability be present for polymorphic transformations that are strongly exothermic and involve large volume changes (e.g., ice I→II). Earth-style plate tectonics evidently did not occur on Ganymede, but planetary-scale endogenic processes (mostly tensile) certainly did, and some of them could have driven blocks of ice I below its equilibrium boundary. Some downward motion of crust is implied by the extensive resurfacing of Ganymede, for instance by blocks of silicate-laden ice I that have foundered or descended in graben formations. These conditions might also be met during cooling at constant depth and pressure. Transformational faulting may also have had a significant effect on the response at medium depths on the large moons and even on smaller icy moons to large meteoritic impacts. The critical shear stress required for transformational faulting is not strongly sensitive to temperature (varying from about 50 to 85 MPa) and can occur at hydrostatic pressures as low as 50 MPa at 77 K.

References

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