RADAR SOUNDING OF EUROPA'S ICY SHELL: THE VIEW AFTER NEW RESULTS FROM MARS AND ANTACTICA.

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Introduction: The recent spectacular results of MARSIS [1] and SHARAD [2] at Mars have validated radar sounding as an effective tool for investigating cold planetary ices. To date, these experiments have not shown evidence for ice near its pressure melting point. However, magnetic studies of the icy moons of Jupiter [3] show evidence for extensive, salty subsurface oceans, and remote sensing data from the Cassini mission may indicate liquid water bodies associated with cryovolcanism at Enceledus and Titan. Terrestrial analogs for subice, compositionally impure water on Earth are Antarctic ice shelves and icebergs, and for water infiltration in warm ice are polythermal ice caps.

Here we review recent radar sounding results from Antarctica, applicable to developing hypotheses for the distribution of water for Jupiter's moon Europa, a high priority target for future exploration.

Radar sounding models for Europa: A primary objective of future Europa studies will be to characterize the distribution of subsurface water. Another objective will be to understand the formation of surface and subsurface features associated with interchange processes between any ocean and the surface. Achieving these objectives will require either direct or inferred knowledge of the position of any ice/water interfaces as well as any brine or layer pockets.

Thermal factors: The thickness of ice that can be sounded on Europa is determined by the absorption of electromagnetic waves in the ice (which is dictated by its temperature and impurity content) and the scattering characteristics of the ice body (including the surface and basal interfaces as well as any volume scatterers). In previous work, three ice formational scenarios have been used to infer both impurity distributions and temperature/depth regimes in Europa's icy shell [4, 5]. The first scenario is a "marine-ice" europan crust formed by processes similar to those for ice that accretes beneath the large ice shelves of Antarctica. This regime is characterized by slow freezing or melting on the lower side of the icy crust. Impurities present in the ocean tend to be rejected from the ice lattice during the slow freezing process. A second scenario is characterized by very rapid freezing of ocean water injected into linear fracture zones caused by "tidal/tectonic" processes. Because large temperature gradients will be present, this process could lead to ice with properties similar to terrestrial sea ice. Both the "marine-ice" and the "tidal/tectonic" scenarios would be characterized by a temperature/depth profile for a simple thermally conducting ice layer modified by any tidally generated deformational heat flux [6]. A third ice formation scenario is based on the idea of convection in an isothermal layer under a thermally conducting rigid ice crust up to a few kilometers in thickness, possibly characterized by diapirism. This convecting ice scenario implies ice very similar to that for the tidal/tectonic scenario although subject to a dramatically different thermal regime.

Compositional factors: Radar sounding models of Europa associated with these ice formation scenarios generally assume a sulfate dominated Europa ocean noting that radar absorption due to impurities at temperatures below any eutectic for the constituent salts is expected to arise primarily from impurities such as "soluble" chlorine or sulfuric acid. In these models, a significant consideration is that insoluble impurities such as sulfate salts at temperatures below the eutectic would have similar impact on absorption as dust at similar concentrations. For temperatures above the eutectic for any salts, brine would form in the ice giving it electromagnetic properties similar to those for terrestrial sea ice.

Water bodies within terrestrial ice volumes: Tension fractures dominate the ice sheet surface where ice streaming (i.e., basal sliding) begins, whereas tension fractures dominate both the surface and base of the ice where grounded ice sheets (or ice streams) transition to floating ice shelves. The process that controls the distribution of these fractures is the balance between the strain rate gradient (i.e., the acceleration of the ice) and the ability to accommodate this strain through annealing (which is a function of temperature). Similarly, pervasive and nearly chaotic shear fractures characterize the lateral boundaries of the ice streams over regions that are many times the ice thickness in width. The ice streaming process that controls the position and width of these zones is dominantly stress concentrations at the boundaries of gravity-driven slab flow. Other characteristics of Earth's ice sheets that are rare but possibly relevant include "collapse structures" and ice "blistering". Collapse structures are circular fracture zones several ice thicknesses in width associated with elevated geothermal flux at the base of the ice. Ice "blisters" are zones of vertical uplift, typically meters in width, that are caused by partial melting and refreezing of exposed sub-ice meltwater.

Application to Europa: Tension-fracture and shear-zone evolution proposed for the hemisphere-scale ridges (with bands) on Europa are a result of tidal flexure and non-synchronous rotation that may have analogs in the onset, shear-margin and grounding-line evolution of the sub-continental scale Antarctic ice streams. Many of the hypotheses for the formation of pits and spots on Europa parallel those for "collapse" and ice "blister" structures on Earth and it may be possible to extend the hypothesized processes for the slab flow of ice streams to the motion of blocks within larger zones of chaos on Europa.

Recent Observations: The HiCARS radar system, an advanced nadir pointing radar sounder, was flown on a Twin Otter aircraft in 2000 and 2004/05. It uses a programmable signal source with a dual-channel coherent down-conversion receiver [7] linked to a 10 kW transmitter. The radar operates in chirped pulse mode at 60 MHz and 15 MHz bandwidth. High and low-gain channels allow for recording both weak bed echoes and strong surface echoes simultaneously and without range-dependent gain control. Coherent data acquisition includes integrations of 16 returned radar signals about every 15 cm along-track. Pulse compression and unfocussed SAR processing using additional along-track integration were significant components of data analysis.

Icebergs: The giant Antarctic iceberg B-15 was surveyed in December 2000 and December 2004 [Figure 1]. The low gain data was analyzed without any migration in order to look at basal diffractors with a range of look angles and identify corner reflectors which we interpreted [8] as the lower edges of basal cracks.

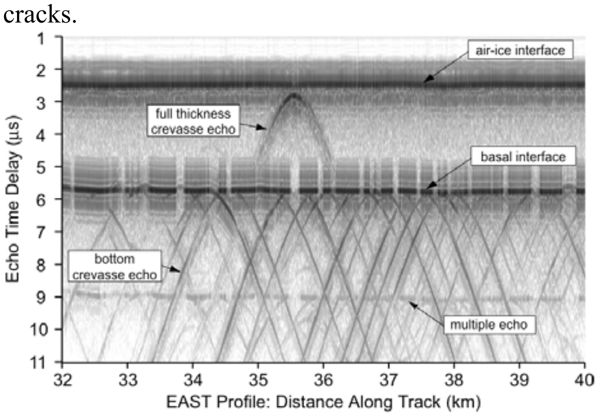

Figure 1. A portion of the EAST radar sounding profile over iceberg B15A showing echoes from bottom crevasses at the ice-ocean interface. Also shown is the echo from a large water-filled crevasse extending through the 275~m thick iceberg. From [8];

The radar echo strengths are consistent with modeled predictions and the combined results were used to classify the identified bottom crevasses.

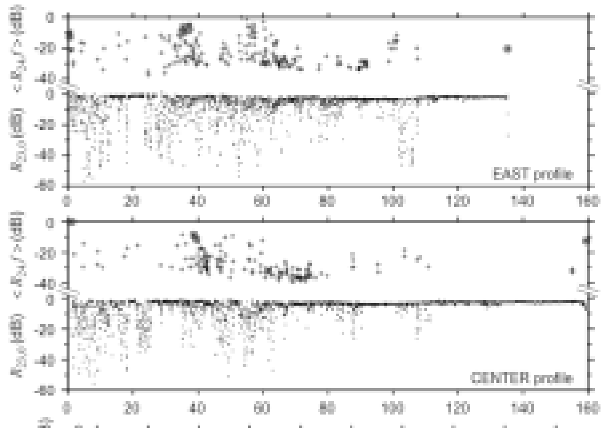

Figure 2. The distribution of bottom crevasses with average crevasse reflection coefficients x *response products,* $\langle R_{24}f \rangle$ *, plotted as crosses (top portion of plots). Also shown are the normal incidence basal reflection coefficients,* $R_{23,0}$*, plotted as dots (bottom portion of plots). Results are shown for two transects. The circled crosses indicate results from either crevasses that are assumed to be water-filled or the iceberg edges. From [8].*

The classification includes major crevasses filled with sea water and incipient/freezing crevasses that are either small with sea water or larger with marine ice accretion [Figure 2].The large water-filled crevasses likely exhibit varying amounts of marine ice accretion with moderate brine inclusions. Crevasse height estimates were obtained under the assumption that all crevasses have interfaces similar to known water-filled crevasses or iceberg edges. These statistics are indicative of the basal dynamics of the seawater/iceberg interface.

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