TERRESTRIAL ANALOGS FOR RADAR SOUNDING OF EUROPA'S ICY SHELL: THE VIEW FROM ANTARCTICA. D. D. Blankenship[1], M. E. Peters[1], and D. A. Young[1], [1]University of Texas Institute for Geophysics, JJ Pickle Research Campus, RM2200, 10100 Burnet Road, Austin TX 78758 (blank@ig.utexas.edu)

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 ice. 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 active subice water systems on Earth include Antarctic ice streams, ice shelves and icebergs. Here we review recent radar sounding results from Antarctica applicable to 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 shallow subsurface water as well as to identify any ice-ocean interface. 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.

Structure and water within and beneath the Antarctic Ice Sheet: Tension fractures dominate the surface of the Antarctic the ice sheet 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.

Geothermal flux and frictional heating from ice streaming contribute to melting at the base of the ice sheet. This water collects in areas of sufficiently low hydraulic gradient and is known to migrate in response to changes in the surface slope of the ice.

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. Similarly, the migration of brines resulting from thermal or compositional diapirism on Europa may have analogs in the hydraulic evolution of the water systems beneath these ice streams. In addition, tension fracturing of the ice shelves and icebergs that form over the ocean downstream of the ice streams should provide an excellent analog for characterizing the ice–ocean interface of a tidal/tectonic Europan ice shell.

Recent Antarctic Observations: Begining in 2000, we have flown an advanced nadir pointing radar sounder on a Twin Otter aircraft over many of the Antarctic analogs described above. This fully coherent radar [7] 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 our data analysis.

Ice Streams: Figure 1A [8] shows an unprocessed subsurface profile across Kamb Ice Stream in West Antarctica. The figure also shows low- [Figure 1B] and high-resolution [Figure 1C] imaging obtained from synthetic aperture radar techniques for both reflecting interfaces and scattering centers.

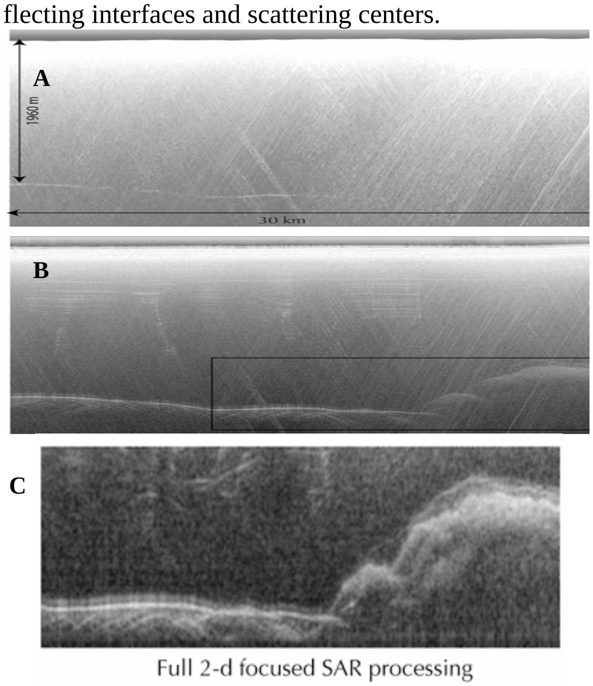

Figure 1: Radar sounding of Kamb Ice Stream, Antarctica.

Analysis methods applied to these data include using echo amplitudes to compute reflection coefficients for inferring the dielectric properties of subglacial materials. In addition, echo phase analysis provides the location of dominant scattering centers as well as interface roughness estimates. Combining the results from these independent analysis allows us to study in detail the evolution of both tensional and shear dominated ice stream margins, as well as the migration of sub-ice water associated with ice sheet evolution.

Icebergs: Figure 2 is profile across Antarctic iceberg B-15 which was surveyed in December 2004. The low gain data was analyzed to evaluate basal diffractors over a range of look angles and identify corner reflectors which were interpreted as the lower edges of basal cracks [9].

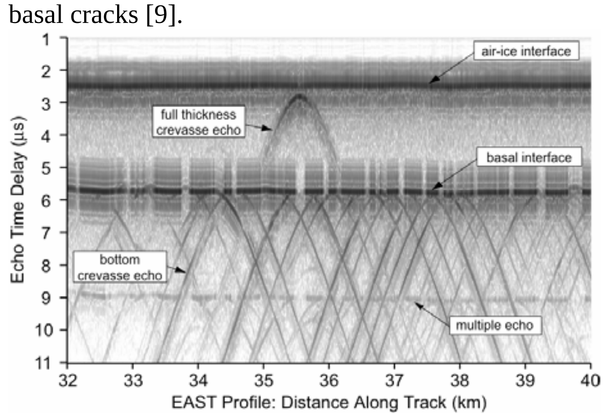

Figure 2. A radar sounding profile over iceberg B15A showing echoes from bottom crevasses at the ice-ocean interface. Also shown is the echo from a large water-filled crevasse extending through the 275~m thick iceberg. From [9]

The radar echo strengths are consistent with modeled predictions and the combined results were used to classify the crevasses. The classification includes major crevasses filled with sea water and incipient/freezing crevasses subject to marine ice accretion.

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