MARTIAN ICE AS A RESOURCE FOR EXPLORATION: CURRENT KNOWLEDGE AND RECENT RESULTS.

C. M. Dundas[1], [1]U. S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ, 86001, USA (cdundas@usgs.gov).

Introduction: Mars is an ice-rich world. Shallow ground ice occurs throughout the mid- and high latitudes, and the Polar Layered Deposits constitute massive volumes of ice. This ice has been extensively discussed as a resource for future exploration, as it may be both accessible and abundant. This abstract summarizes current knowledge and recent findings regarding near-surface water and ice on Mars. Such ice has not, to date, been the subject of a formal USGS resource assessment, as has been done for a variety of terrestrial resources [1]; instead, these are science results that could be used for a future USGS assessment of Mars water resources and as information for others investigating the possibility.

Mid-Latitude Ice: *Spatial distribution:* The theoretical basis for the spatial distribution of stable, shallow subsurface ice has been known for over fifty years [2], with improvements in detail from recent work. Latitude is the strongest control, with ice becoming stable in the mid-latitudes [3-5], as well as on lower-latitude pole-facing slopes [6]. Regional properties (albedo, thermal inertia) are also relevant. The spatial distribution predicted by such models is broadly consistent with detections by the Gamma Ray and Neutron Spectrometers on board Mars Odyssey [3, 7], with radar sounding results [8-9], and with the distribution of ice exposures from new impact craters [10-11]. However, in detail each of these methods suggests some differences in ice distribution, likely as a result of different spatial scales and depths probed. The ice may be slightly more extensive than predicted based on current conditions, either because of some additional stabilizing factor or because the spatial distribution takes some time to adjust to variations in Mars' orbit and atmospheric water vapor content [11]; however, the theory is successful overall.

Depth to ice: The same theory that predicts the distribution of ice also predicts the depth to the top of the stable ice. This depth is primarily a function of latitude, varying from a few centimeters at high latitude (such as the Phoenix landing site [12]) to at most a few meters. New impact craters exposing ice confirm this expectation, excavating ice at depths similar to predictions [10-11].

Ice content: Early theoretical predictions were that ice would be frost deposited from atmospheric water vapor and simply fill in the pore space of the regolith, leading to relatively low volumetric ice contents [13]. However, multiple lines of evidence now indicate excess or massive ice, as well as debris-covered glaciers. Most directly, the Phoenix lander excavated some material that was estimated to be ~99 volume percent ice [14], although ice of this type was considered likely to be only a small fraction of the overall near-surface ice volume at the Phoenix landing site [15]. Neutron Spectrometer mapping also reveals high ice contents [7,16]. Radar sounding detected debris-covered glaciers at multiple mid-latitude locations [17-18], and subsequently found evidence of broader ice sheets tens of meters thick in both Utopia and Arcadia Planitiae [19-20]. Sublimation-thermokarst landforms also suggest the widespread occurrence of high volumetric ice contents [21]. Such high ice contents could arise from buried snowpacks [22] or growth of ice lenses or wedges [23-24], which result in different ice table structures. Even ice derived from snowfall is likely to contain some small amount of atmospheric dust and salts incorporated during accumulation.

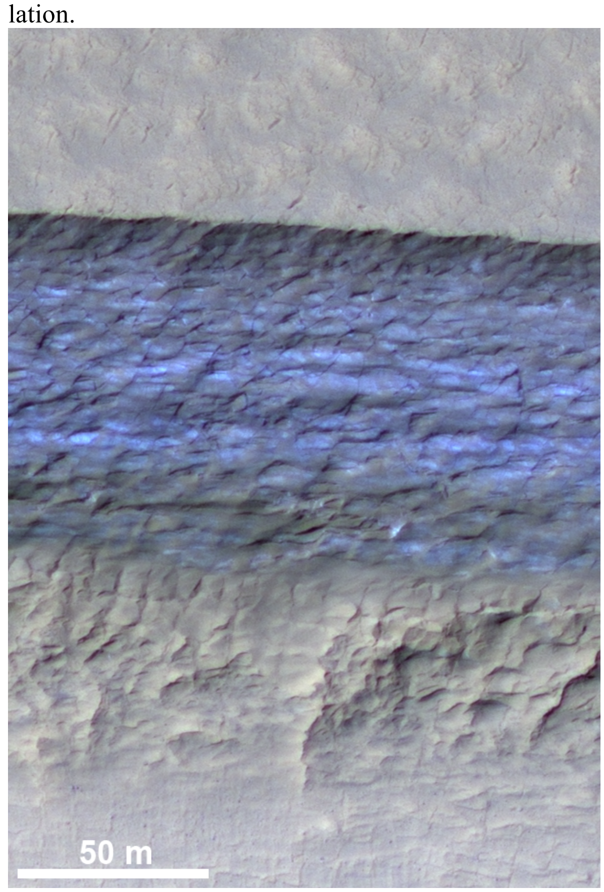

Figure 1: Ice exposed in cross-section in a steep slope (HiRISE image ESP_021954_1230). The ice sheet reaches within 1-2 meters of the surface in places.

Information from local exposures: Recent images revealing ice exposures at latitudes of ~55-60° in each hemisphere (Fig. 1) have provided some new insights into the ice at those locations [25]. First, the local ice content is extremely high throughout a layer tens of meters thick; this ice is likely a compacted snowpack containing some atmospheric dust, although boulders are present on the surface. The deposits at these locations are likely the result of locally thick accumulation or preservation and similar to ice sheets and debris-covered glaciers elsewhere. Second, some of these ice deposits begin within 1-2 meters of the surface. They may be capped by a thin veneer of ice-cemented soil and a surficial ice-free layer. This vertical structure may be similar to that for ice sheets and debris-covered glaciers elsewhere, but latitude (and mass wasting off slopes for glaciers in valleys) may affect the thickness of the covering of dry and ice-cemented materials. Hence, these exposures demonstrate the existence of shallow, relatively-clean ice at particular locations; further study would be needed to fully assess how this structure varies across the planet.

Polar Layered Deposits: The Polar Layered Deposits in both hemispheres are thick, layered reservoirs of water ice with low dust contents; a recent review [26] summarizes current information about them. Different techniques provide different estimates of the dust contents of the deposits, but all estimates are <15 volume percent, probably variable from layer to layer [26]. The principal challenge for using this ice as a resource is the high latitude.

Near-Surface Liquid Water? Features such as gullies and Recurring Slope Lineae (RSL) have been considered possible locations of present-day flowing water or brine [27-28]. However, current activity in gullies appears to be associated with CO_2 frost in winter [29], and it now appears that RSL are likely granular flow features, perhaps with some H_2O involved in their initiation [30]. Their value as sources of water is questionable at best. Present-day surface liquid may be limited to small volumes associated with deliquescent salts [2,31] or unfrozen surface layers on ice [24].

Planetary Protection: Locations with shallow ground ice require attention to planetary protection considerations [32]. Appropriate access scenarios have been given preliminary consideration by a Mars Exploration Program Analysis Group Special Regions study [32].

Summary: Ice on Mars is widespread at middle and high latitudes and occurs at shallow depths. Much (but not all) of this ice occurs in bodies with a high volumetric ice content; in some places, massive ice sheets lie within 1-2 meters of the surface, a favorable scenario for In Situ Resource Utilization. Important uncertainties that could be addressed by further research include: 1) the precise location of the boundaries of ice deposits, and 2) a better understanding of the local vertical structure of the ice table and its variability in different settings. The former is important because lower latitudes are more thermally favorable for possible missions using ice as a resource; new impact craters can provide point indications but not detailed maps. The latter is important because not all locations may be as simple as the ice revealed in cross-section [25], in ways that relate to the geologic history of the ice.

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