Do Shallow Radar soundings reveal possible near-surface layering throughout the Northern Lowlands of Mars?

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Introduction

The Shallow Radar (SHARAD) sounder [1] onboard the Mars Reconnaissance Orbiter (MRO) spacecraft has detected clear evidence for subsurface interfaces not only within polar ices [2,3] but also at various locations in the mid-latitudes, where layers of glacial ice [4,5], volcanics [6], or sediments [7] provide a dielectric contrast with underlying materials. More subtle radar returns that potentially originate in the near subsurface occur in other areas, most notably in the Northern Lowlands. This region includes the Phoenix landing site, where SHARAD results show a probable subsurface interface at depths of ~25–45 m [8].

Beyond the Phoenix site, shallow radar returns of similar appearance and delay time occur in many other areas across the Northern Lowlands. Here, we pose the question as to whether these features truly correspond to subsurface interfaces. We consider a range of possible explanations—more than one of which may apply—without drawing any definitive conclusions.

Background

The 15- to 25-MHz chirped pulse transmitted by SHARAD and the nearly circular orbit of MRO yield a horizontal ground resolution of 3–6 km, reducible in processing to 0.3–1 km along track. The vertical resolution is 15 m in free-space or ~6–10 m in the Martian subsurface depending on the dielectric constant [1]. Scattering, path, and interface losses limit the depth of signal penetration in the non-icy subsurface to a few hundred meters. Side lobes of strong surface returns, off-nadir surface clutter, and ionospheric interference may complicate the radar signal, requiring special consideration for targets within a few range resolution cells of the surface.

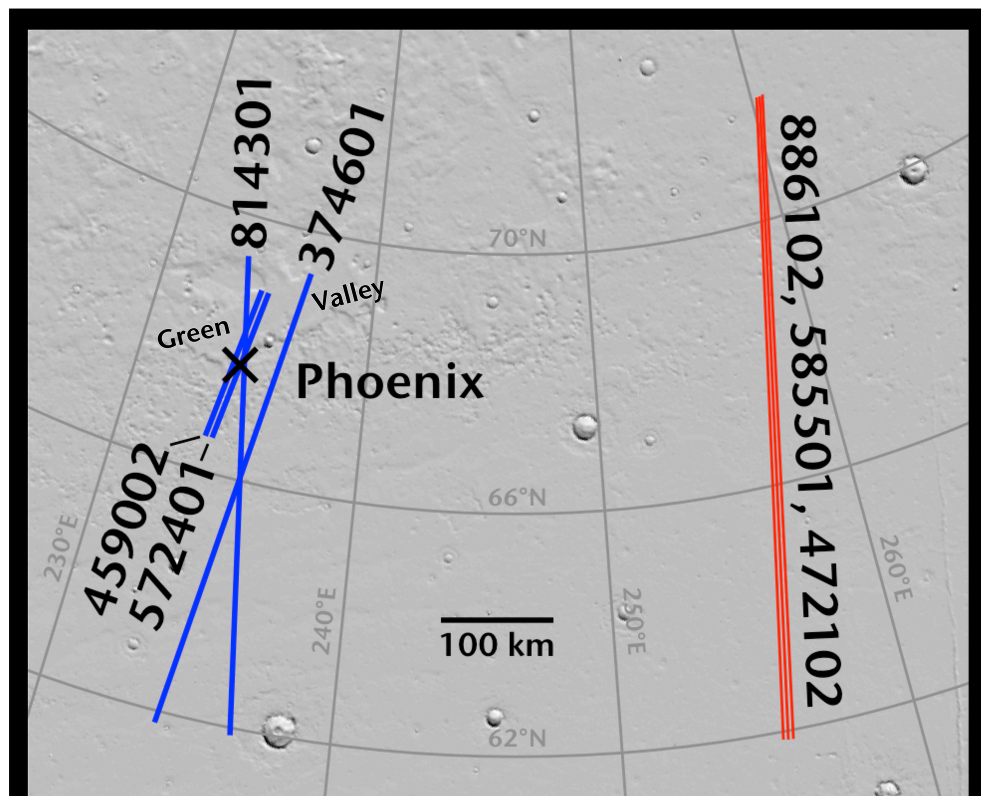

Figure 1: Location map showing SHARAD ground tracks for radargrams near Phoenix landing site at 'x' (Figure 2) and a location ~20° to the east (Figures 3 and 4). Base map is a polar projection of MOLA shaded relief.

In ascending stratigraphic order, the geologic record in the Northern Lowlands contains: remnants of ancient Noachian heavily cratered terrain [9]; possible buried sedimentary deposits from Late Noachian valley-network fluvial activity [10]; Hesperian volcanic ridged plains [11]; Hesperian to Early Amazonian outflow-channel effluent (the Vastitas Borealis Formation, VBF) [12,13]; Late Hesperian and Amazonian volcanic deposits emanating from the Tharsis region [14]; Amazonian polar deposits and mid-latitude glacial deposits [15,16]; Late Amazonian reworking of the VBF by eolian and cold-climate processes, and deposition of volatile mantles represented by pedestal-crater remnants [17]; and a geologically recent, latitude-dependent mantle [18]. The Phoenix spacecraft provided a unique view of the upper surface of this stratigraphic column, which is dominated by near-surface ice [19].

Observations

SHARAD data are typically displayed as radargrams, which are log-scaled signal-power images with distance along track on the horizontal axis and delay time (analogous to depth for a radar sounder) increasing downward on the vertical axis (Figs. 2–5). Focused processing aimed at suppressing surface-return side lobes was employed in this study. Because reflections from off-nadir surface features may appear at delay times similar to those of subsurface returns, we examined synthetic radargrams, generated using MOLA topographic maps.

SHARAD observations of the 'Green Valley,' where the Phoenix lander resides (Fig. 1), typically show a laterally continuous radar return at a delay of ~0.5 μs from the surface reflection (Fig. 2). Synthetic radargrams do not show these returns and measures were taken to reduce side lobes, so we have a high level of confidence that these returns arise from subsurface interfaces. Immediately outside of the Green Valley, the surface is rougher and the radargrams contain many off-nadir returns, with no clear evidence for sub-surface features. Further afield where the surface is again relatively smooth, similar apparent subsurface returns occur, both in the Phoenix region and at similar latitudes all across the Northern Lowlands (Figs. 3 and 5). South of the Phoenix region, these features track to ~61°N on the slopes of Alba Patera; elsewhere, they extend as far south as 45°N (Fig. 5). These latitudes encompass the region where ground ice is inferred to be present on the basis of neutron-spectrometer data [20].

To address potential ionospheric effects, we examined adjacent observations taken with solar zenith angles (SZA) ranging from 50° to 130° at Phoenix and in the region 20° to the east. The apparent subsurface returns persist to the highest SZA—well into the night when ionospheric effects are expected to be small—and we conclude that the returns are unlikely to be caused by the ionosphere.

N ≺ Phoenix region radargrams

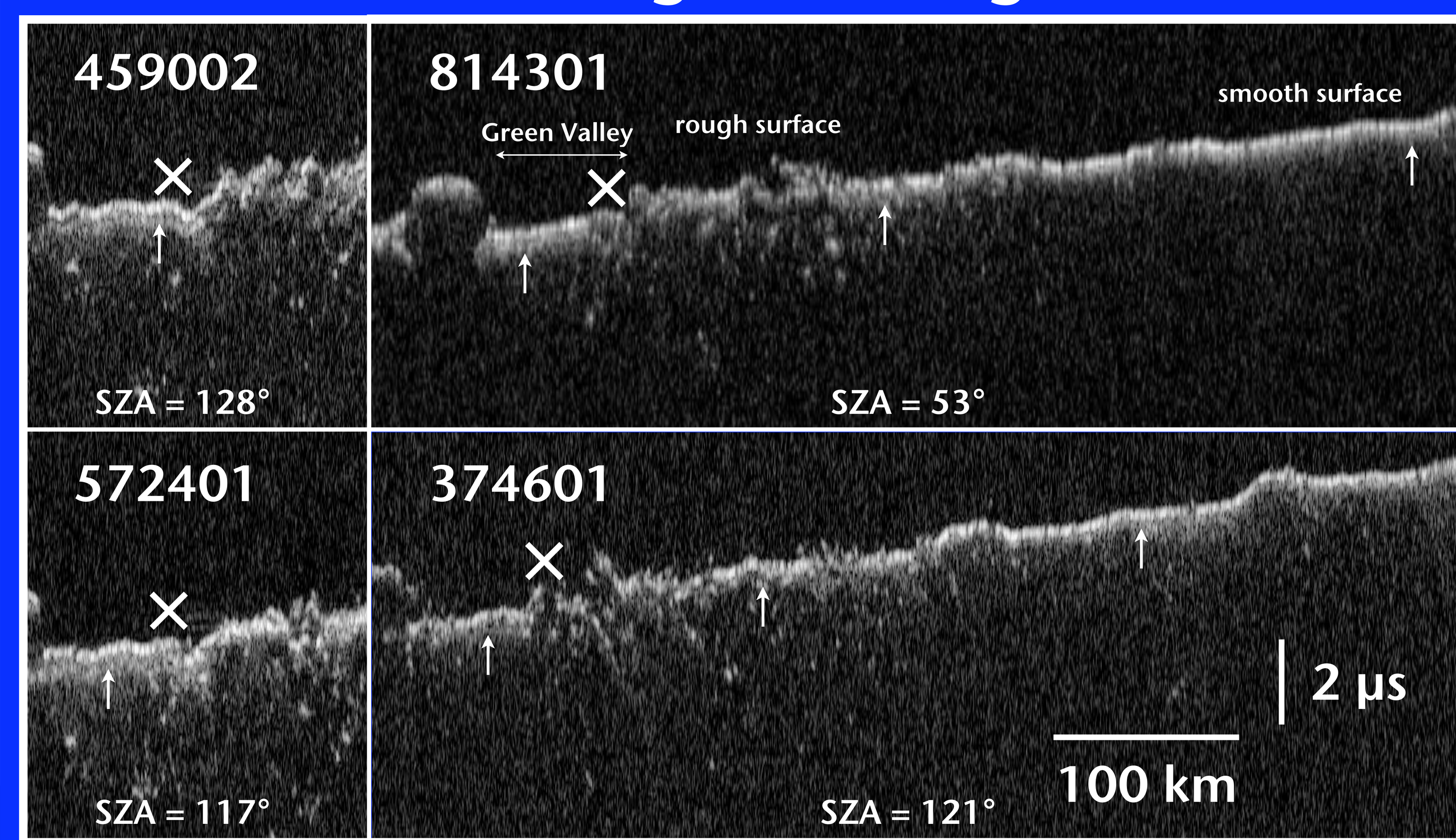

Figure 2: Focused SHARAD radargrams for blue ground tracks in Figure 1, labeled with observation numbers. Each crosses the Green Valley nearest the Phoenix site at the '×'. Longer observations on right extend southward to 62°N. Arrows indicate apparent subsurface detections at ~0.5 μs (~35 m depth, assuming a typical water-ice dielectric of 3.15) both within Green Valley and beyond it. Scale bars apply to all radargrams. SHOC processing.

N ≺ 585501 processing comparisons

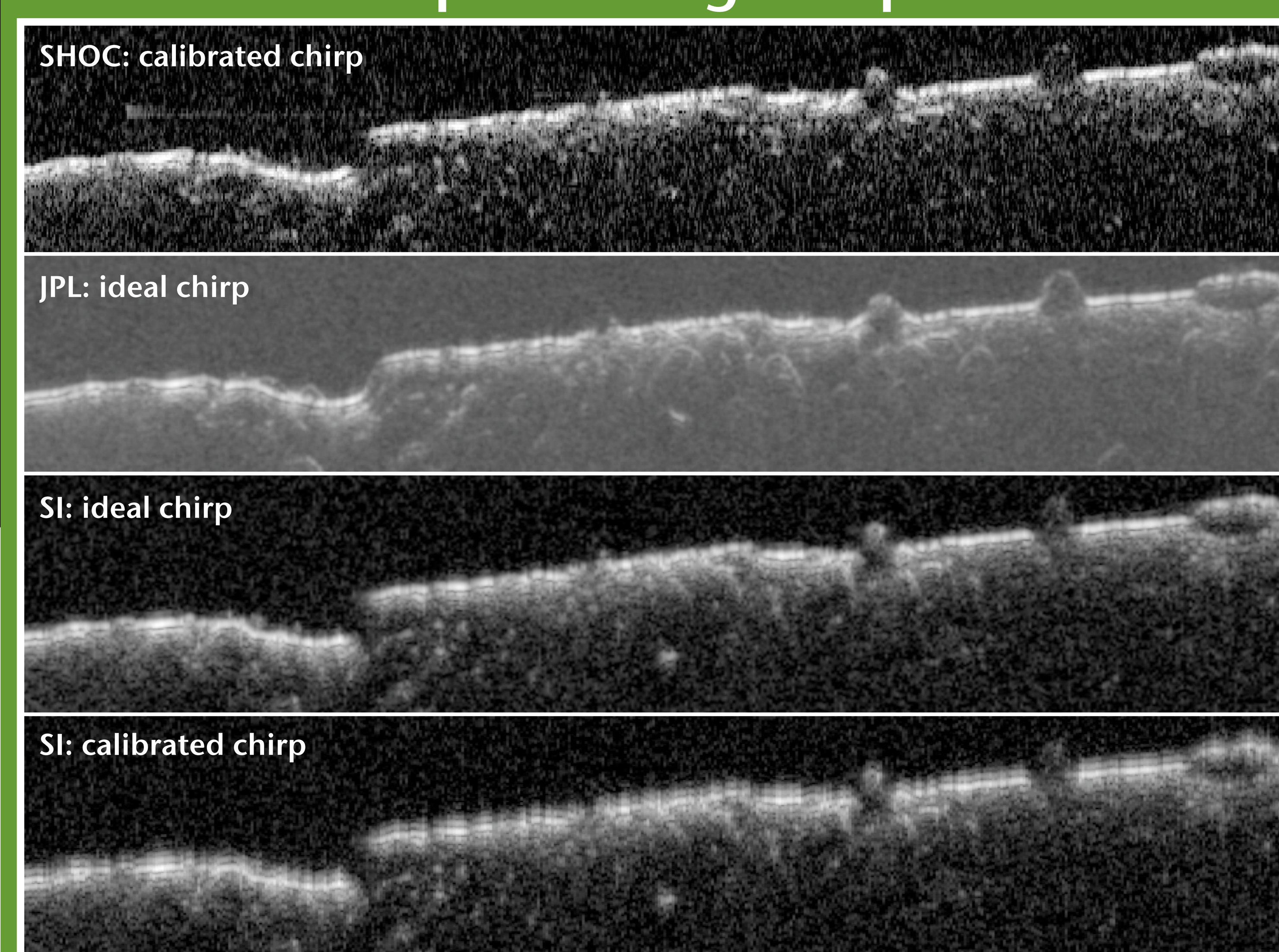

Figure 4: Results from processing algorithms developed at different institutions (SHOC: SHARAD Operations Center; JPL: Jet Propulsion Laboratory; SI: Smithsonian Institution) for a portion of SHARAD radargram 585501 (green box in Fig. 3). Use of an ideal chirp function yields asymmetric side lobes (middle two panels) whereas a calibrated chirp function yields symmetric side lobes (bottom panel), which can be suppressed with a Hanning filter (top panel).

Discussion

Multiple techniques are available for processing radar data, and the parameters used can affect the features seen in radargrams (Fig. 4). Of great importance to evaluating possible returns from near-surface layers is an assessment of the side lobes of the surface return. Proper calibration of the chirped pulse transmitted by the instrument reduces the potential for misinterpreting side-lobe energy as returns from the shallow subsurface. We found the methods of the SHARAD Operations Center to provide the best suppression of side lobes, which raises our confidence that the returns observed are actually coming from subsurface interfaces.

Possible sources of the near-surface detections include elements of the strata discussed in the Background section: 1) ice-rich layers of the VBF [13]; 2) ice-rich lag layers from Late-Amazonian mantles [17,21]; 3) lag-protected dust-rich ice emplaced atmospherically during recent obliquity excursions [18,22-24]; and 4) shallow ice lenses and layers in the upper part of the regolith emplaced by vapor diffusion, subject to time-dependent ice stability factors [25,26]. An equilibrium condition such as the last of these possibilities may be a dominant factor, given the relatively uniform depth of the detections. We explored this idea further with a numerical model (Fig. 6), which suggests that the base of ground ice ought to be at a depth of ~15–30 m, increasing to ~20–40 m (more consistent with the SHARAD observations) if the present geothermal heat flow is 5 mW m^{-2} K^{-1}. The possibility of such low heat flow is supported by the recent finding from SHARAD data of unexpectedly low flexure beneath the North Polar Layered Deposits [2].

Because the signal strength appears relatively weak, an abrupt interface with a large dielectric contrast is unlikely, since SHARAD will typically obtain a strong reflection in such cases [4,5,7]. Rather, either lower ice content in the near surface or a gradual transition from ice-rich to ice-poor at the base may be the cause for the low signal strength.

N ≺ Radargrams from 20°E of Phoenix

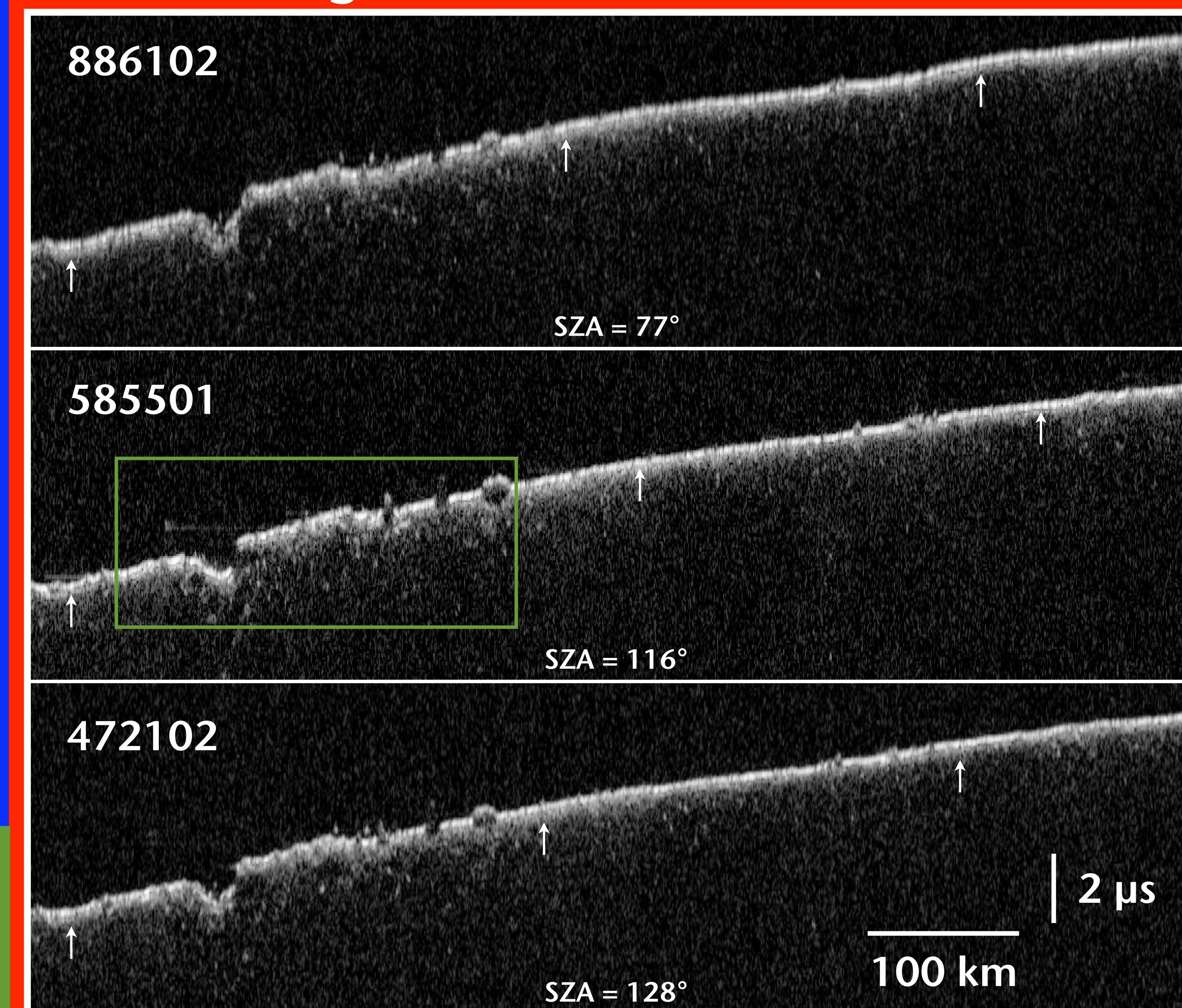

Figure 3: Focused SHARAD radargrams for red ground tracks in Figure 1, labeled with observation numbers. These nearly coincident radargrams show similar surface features despite the range of solar zenith angles (SZA). Arrows indicate apparent subsurface detections at ~0.5 μs (~35 m depth, assuming a typical water-ice dielectric of 3.15). Green box indicates subset used in Figure 4. Scale bars apply to all radargrams. SHOC processing.

N ≺ Other Northern Lowlands radargrams

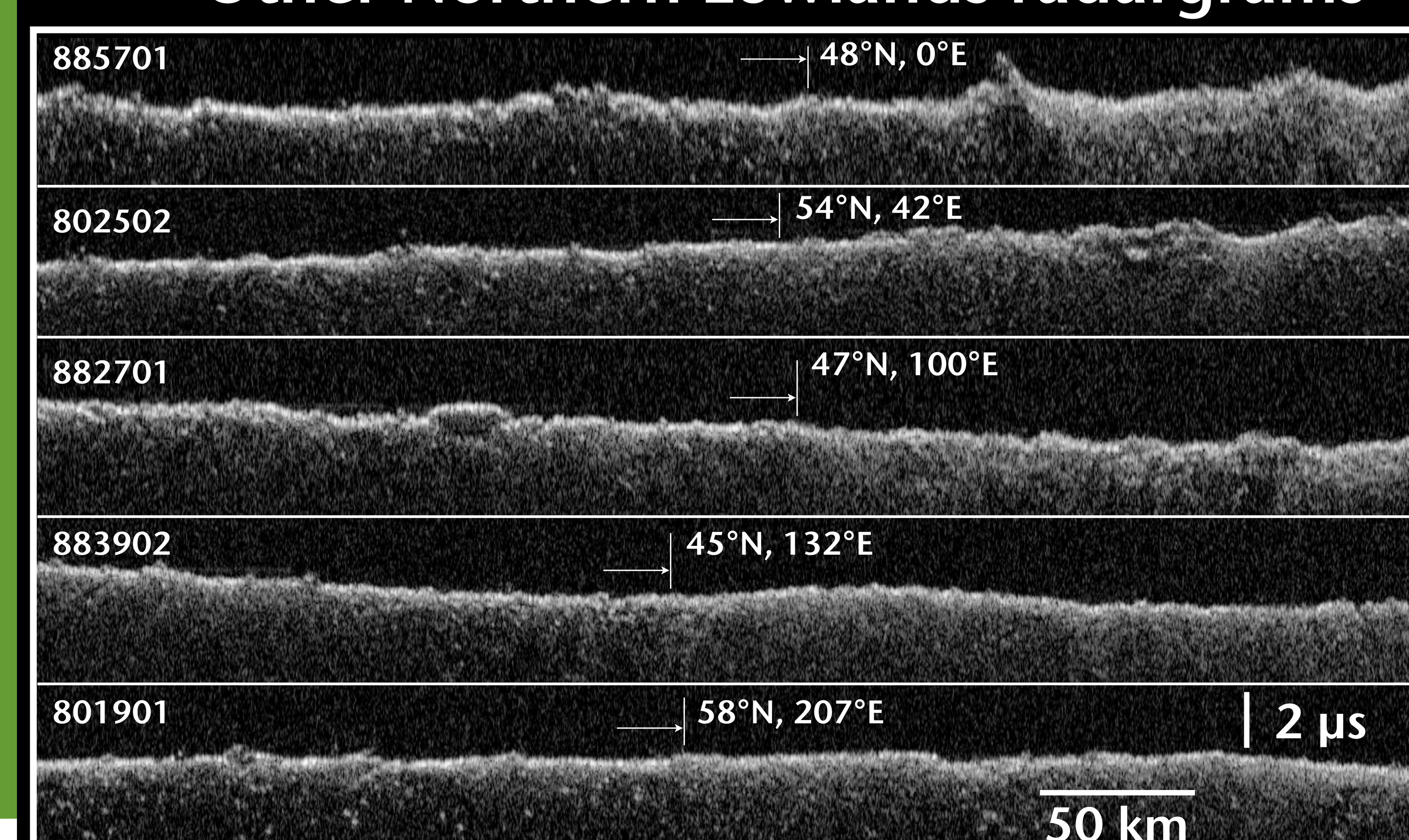

Figure 5: Focused SHARAD radargrams from observations at various longitudes around the Northern Lowlands. Vertical bar is approximate southern extent of putative subsurface feature. Scale bars apply to all radargrams. SHOC processing.

Theoretical base of ground ice

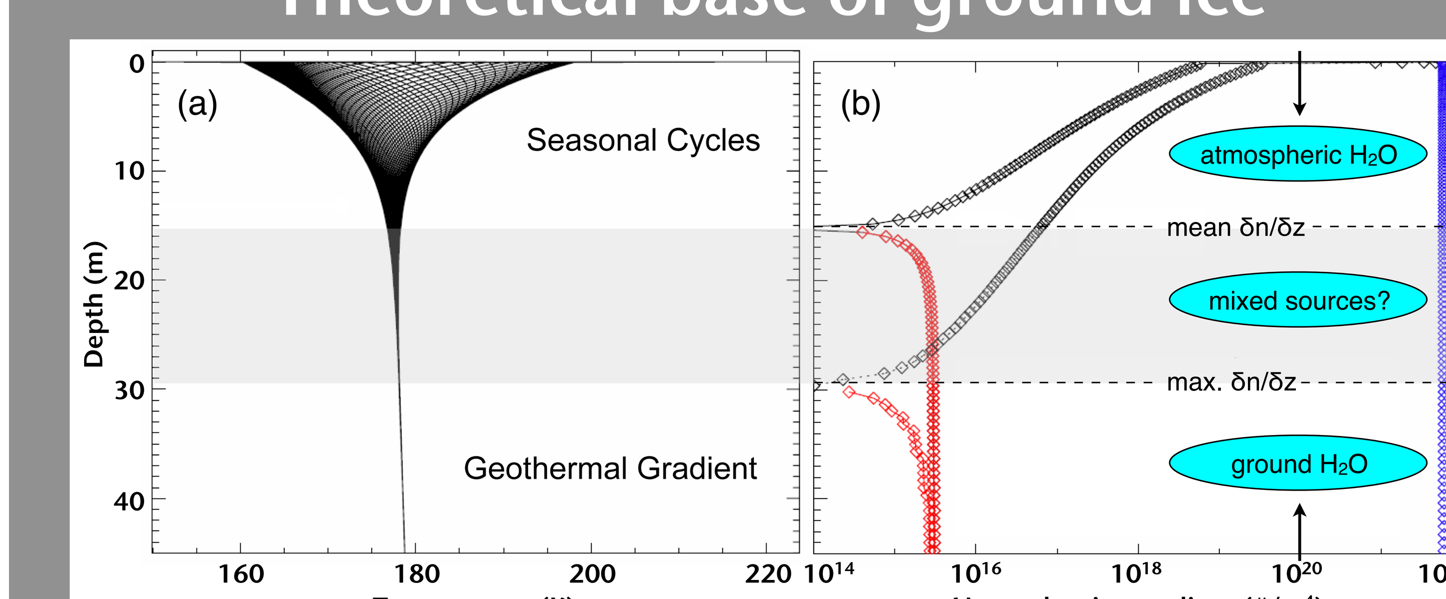

Figure 6: Model of vapor diffusion in Martian near-surface. (a) Temperatures are controlled by the seasonal variation of insolation and the geothermal gradient. (b) Net flux of H_2O vapor diffusing downward from the atmosphere (black diamonds) and upward from a deep ground water system (red diamonds) will converge at a depth that varies with material properties, latitude, obliquity, and season. Graphs shown are for geothermal heat flow of 30 mW m^{-2} K^{-1}, thermal inertia of 200 J m^{-2} K^{-1} s$^{-1/2}$, albedo of 0.2, latitude of 68.2°N (Phoenix site), and the current epoch, with mean and maximum annual vapor-density gradients shown in (b). If ground ice is in equilibrium with the atmosphere, its base will reside in the shaded region. Thickness of model layers increases linearly with depth (blue diamonds).

References: [1] Seu et al. (2007) JGR 112, E05S05. [2] Phillips et al. (2008) Science 320, 1182. [3] Phillips et al. (2009) LPS XL 2007. [4] Holt et al. (2008) Science 322, 1235. [5] Plaut et al. (2009) GRL 36, L02203. [6] Carter et al. (2008) Icarus 199, 295. [7] Campbell et al. (2008) JGR 113, E12010. [8] Safaeinili et al. (2008) AGU Fall Meeting. [9] Tanaka et al. (2005) USGS SIM 2888; [10] Fassett & Head (2008) Icarus 198, 37; [11] Head et al. (2002) JGR 107, 1445; [12] Baker et al. (1992) Mars, Ch. 15, Univ. AZ Press; [13] Kreslavsky & Head (2002) JGR 107, 5121; [14] Carr and Head (2003) JGR 108, 5042; [15] Tanaka (2008) Icarus 196, 318; [16] Head et al. (2006) GRL 33, L08S03; Plaut et al. (2008) GRL 35, 36379; [17] Kadish et al. (2008) LPS XXXIX, 1766; [18] Head et al. (2003) Nature 426, 797; [19] Smith and the Phoenix Science Team (2009) LPS XL 1329; [20] Feldman et al. (2004) JGR 109, 9006; [21] Kadish et al. (2008) GRL 35, L16104. [22] Mustard et al. (2001) Nature 412, 4211; [23] Kostama et al. (2006) GRL 33, L11201; [24] Schorghofer (2007) Nature 449, 192. [25] Mellon et al. (2008) JGR 113, E00A25; [26] Fisher (2005) Icarus 179, 387.