Imaging the Subsurface Structure of Planum Boreum with the Mars Reconnaissance Orbiter Shallow Radar

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***Abstract*—We review prior mapping of the subsurface structure of Planum Boreum that was conducted with 2-D sounding data from the Shallow Radar (SHARAD) instrument onboard the Mars Reconnaissance Orbiter (MRO) [1]. Widespread reflections from basal and internal interfaces of the north polar layered deposits (NPLD) occur throughout the 1,000,000-km^2 area. A dome-shaped zone of diffuse reflectivity up to ~1 km thick underlies two-thirds of the NPLD. This zone is associated with a basal unit identified in image data as Amazonian sand-rich layered deposits [2,3,4]. In other areas, the NPLD base is remarkably flat-lying and co-planar with the exposed surface of the surrounding Vastitas Borealis materials. Within the NPLD, radar-layer packets [5] that extend throughout the deposits have been mapped as five units with a total volume of 821,000 km^3, exclusive of the basal unit. Application of a 3-D imaging technique commonly used in processing seismic data to the polar grid of 2-D SHARAD observations is expected to yield an improved representation of the subsurface layering geometry and greatly reduce the effects of surface clutter.**

Keywords—Planets, Mars; Radar imaging; Arctic regions; Geophysical measurements; Geology

I. Introduction

The polar regions of Mars contain ~4 km of finely layered materials nearly centered on each pole and cut by large, arcuate chasmata and smaller reentrant and interior troughs. These materials are composed primarily of water ice with a variable amount of lithic inclusions [6,7]. The layered nature of the deposits seen in optical images of surface exposures along the periphery and within chasmata is likely related to such variations (see [8] and references therein), but it has been shown that the apparent brightness of layers is controlled more by topography, texture, and surficial frosts than by internal composition [9]. High-resolution images show a major division between the upper stack of layered deposits (referred to hereinafter as the “NPLD”) and a lower basal unit (BU), where the lower unit is typically darker and its layers less continuous [2,3]. The BU was inferred to extend beneath most of the main lobe of the polar cap but generally not beneath the Gemina Lingula lobe (Fig. 1), leading to the suggestion that the location of Chasma Boreale (Fig. 1) may have been controlled by the position of the BU’s southern edge [3].

The first subsurface profiles of Planum Boreum, from the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) instrument onboard Mars Express, showed a strong radar return from the base of the deposits [6,5,10]. Subsequent SHARAD observations show a weaker, diffuse radar return from the base, but many more internal reflections from overlying layered materials [5]. Taken together, these results exemplify the complementary nature of the two instruments, with MARSIS providing greater depth of penetration and SHARAD finer vertical resolution (~10 m in water ice, vs. ~100 m for MARSIS) [11]. We focus on the SHARAD observations, which provide a more detailed view of internal structures and allow a more direct comparison to image-based geologic interpretations.

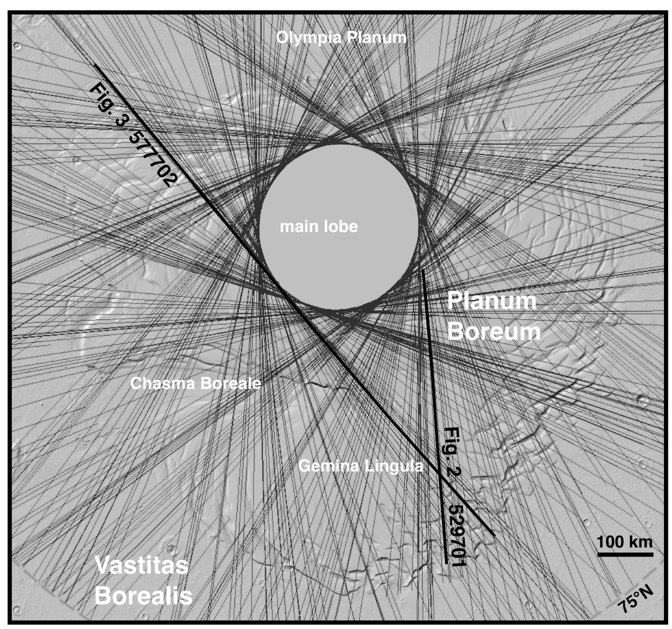

Figure 1. Polar stereographic location map of Mars’ north polar region, showing SHARAD ground tracks (tangent to limit of MRO orbit at ~ 87.4° N) for observations used in the [1] study, overlain on MOLA shaded relief. Bold lines are labeled with observation numbers corresponding to radargrams in Figs. 2 and 3. 0° longitude is at bottom-center of figure.

The Italian Space Agency provided SHARAD to NASA’s MRO mission, and its operations are led by the InfoCom Department, University of Rome “La Sapienza.” Thales Alenia Space Italia is the prime contractor for SHARAD. The MRO mission is managed by the Jet Propulsion Laboratory, California Institute of Technology, for the NASA Science Mission Directorate, Washington, DC. Lockheed Martin Space Systems of Denver, Colorado is the prime contractor for the orbiter. SeisWare International, Inc. provided the subsurface data interpretation software used in this study.

II. OBSERVATIONS

SHARAD is a chirped-pulse sounding radar with a 10-MHz bandwidth centered at 20 MHz, yielding a range resolution of 15 m in free space, or 8.4 m in water ice with a real permittivity of 3.15. The altitude of MRO varies between ~250 and ~320 km, giving a ~3–6-km lateral resolution (1–2 Fresnel zones) at the surface, reducible in azimuth (along-track) to 0.3–1.0 km with synthetic-aperture focusing. A detailed discussion of the SHARAD experiment in provided by [11].

A SHARAD observational campaign has yielded dense coverage in the north polar region, with data acquired on more than 1900 orbits through March 2010. Typical SHARAD observations of the polar region are taken over a 700-second period and span 20° of latitude on either side of the pole (~2000 km). Reference [1] selected 358 observations for their study, providing the coverage shown in Fig. 1. We present representative portions of two observations where they extend across Planum Boreum in Figs. 2 and 3.

Subsurface radar data are typically displayed as radargrams, with distance along track shown horizontally and power vs. delay time shown vertically in an image format (e.g., Figs. 2 and 3, top panel). Where topographic relief is present, delay-time radargrams exhibit an apparent geometric distortion due to the difference in signal speed in free space vs. that in typical geological materials (e.g., regolith or water ice). Furthermore, reflections from off-nadir surface features may arrive at delay times similar to those from the subsurface, and a careful analysis of the sources of such surface clutter is required. To address the geometric distortion, one may convert delay time to depth on a sample-by-sample basis as:

$$\Delta d_i = c\, \Delta t \,/\, 2\, \varepsilon_i^{1/2} \qquad (1)$$

where Δd_i is the depth interval for the i-th sample in delay time, c is the speed of light in free space, Δt is the delay-time sampling interval, and ε_i is the real permittivity of the traversed medium, with the divisor of 2 accounting for two-way travel (radar transmit and receive paths). For the depth conversion, we first identify the samples associated with the surface return and then apply (1), assuming values for ε_i of 1.0 above the surface and 3.15 below, where the latter value is typical of pure water ice under Martian surface conditions [12,13,14]. Where the initial surface return is off-nadir, a distortion in the depth-converted radargram can occur. The assumption of nearly pure water ice in the NPLD is based on estimates of their lithic content derived from the attenuation of radar signals [5,6,14].

Radar signals reflected from spacecraft-facing facets of topographic highs or depressions on either side of the ground track may produce a return that is delayed in time relative to the nadir surface return in proportion to the difference in distance from the spacecraft. Some such surface clutter may be addressed qualitatively by examining a map of surface topography in the vicinity of the radar ground track. For subtle features, a more quantitative approach to characterizing clutter may be taken by producing simulated radargrams, which can be generated from topographic information such as an elevation map of Mars Orbiter Laser Altimeter (MOLA) data. Such synthetic radargrams are used routinely in distinguishing probable subsurface detections from surface clutter in terrestrial studies [15] and in MARSIS and SHARAD data [6,16,17]. Extra caution is advised when interpreting radar observations made in the vicinity of areas with sparse elevation data, such as the regions poleward of 87° latitude, as surface features missing from the elevation maps may yield clutter in the radar data that does not appear in the simulated radargrams.

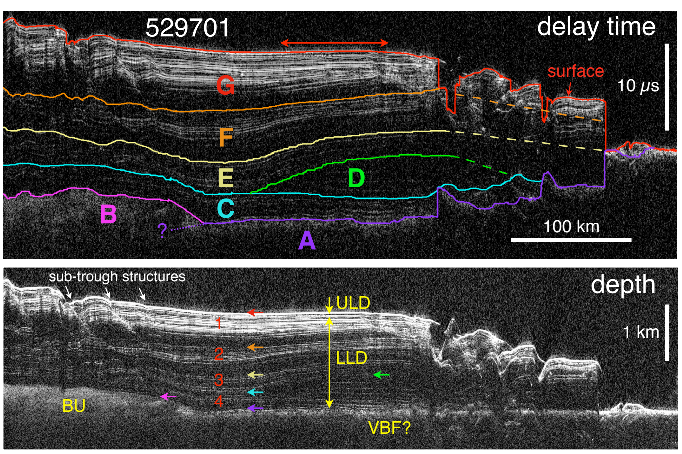

Figure 2. SHARAD observation 529701, crossing topographic saddle between the main lobe and Gemina Lingula. Delay-time radargram (top panel) is overlain with interpreted boundaries for radar units A–G, dashed where extrapolated. Contact where Unit A extends beneath Unit B is not typically evident in SHARAD data. Red arrow shows lateral extent of apparent angular unconformity at ~2.5 μs delay time in Unit G. Depth-converted radargram (bottom panel), which is created by assuming a subsurface real permittivity of 3.15 (nearly pure ice), shows proper geometric relationships at ~45:1 vertical exaggeration, with packets [5] in red and approximate correlations to geological units [4] in yellow (VBF: Vastitas Borealis Formation; BU: basal unit; LLD: lower layered deposits; ULD: upper layered deposits). Colored arrows show reflectors corresponding to unit boundaries in upper panel. Layer discontinuities occur progressively closer to the southern extent of the BU with depth (white arrows). After Fig. 2 of [1].

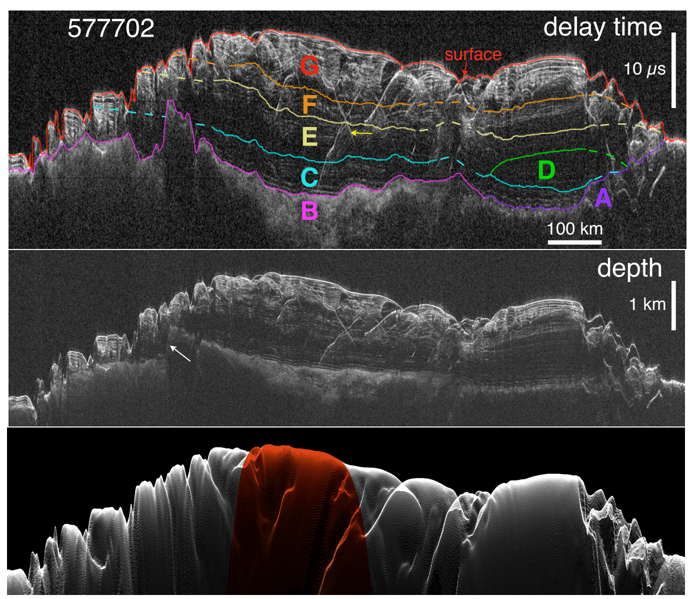

Figure 3. SHARAD observation 577702, extending from Olympia Planum across the main lobe and Gemina Lingula. Radargrams in delay time (top panel) and depth (middle panel; vertical exaggeration ~100:1) show the same units and use the same depth-conversion methods as in Fig. 2. Bottom panel shows simulated delay-time radargram produced from MOLA data, identifying as surface clutter many returns with steep apparent dip. Other returns (e.g., yellow arrow in top panel) do not appear in the simulation but are attributable to troughs poleward of the ~87°N limit of the MOLA data (region affected by the no-data zone is shaded red). White arrow in middle panel identifies a large elevation anomaly at top of Unit B discussed in text. After Fig. 7 of [1].

An example is shown in Fig. 3, where troughs poleward of 87°N seen in Viking images are missing from the MOLA map, leading to surface clutter visible in the SHARAD radargram but not in the MOLA-generated simulation.

III. Radar-Unit Mapping

SHARAD radargrams show a packet of closely spaced, strong reflections to ~5 μs delay time below the surface of Planum Boreum. The packet of strong reflectors is generally underlain by a zone of much weaker or negligible returns ~2–3 μs in round-trip delay time. At later delay times, several similar sequences of packet–inter-packet reflections follow, but the reflectors are typically reduced in number, frequency, and relative backscattered power. Much of this behavior may be attributable to attenuation of the radar signal by transmission and path losses rather than actual increases in layer thickness or reductions in dielectric contrast [18]. The series of reflectors within packets and the repeated packet sequences represent two periodicities, which [5] and [1] related to global climatological cycles of Mars driven by orbital and rotational dynamics [19].

The lowermost of the radar-based geologic units defined by [1] is Unit A (Fig. 2), seen as a relatively thin (1–3 μs), diffusely reflective zone and interpreted as an extension of the Vastitas Borealis Interior Unit (ABvi) [4]—often referred to as the Vastitas Borealis Formation (VBF) [20]—beneath Gemina Lingula, portions of the main lobe in the eastern hemisphere, and the topographic saddle between the two lobes.. A thicker (5–10 μs), diffusely reflective zone extending beneath most of the main lobe and partly under Gemina Lingula that is correlated with the BU is designated Unit B. Although not evident in most of the SHARAD data, Unit A extends beneath Unit B, rarely displaying a weak reflection under the main lobe and below Olympia Undae; this same contact yields the strong basal reflections seen by MARSIS [6,5,10]. Overlying Units A and B is a set of quasi-parallel reflecting horizons ~200–300-m thick that appear to extend throughout the NPLD, designated as Unit C. The upper boundary of this unit is identified by the presence of a 'wedge' of nearly parallel, reflecting interfaces up to ~300-m thick that is confined to the eastern part of Gemina Lingula and defined as Unit D (see Figs. 2 and 3). Another packet of near-parallel reflectors, together with an underlying inter-packet zone of modestly diffuse returns, appears to be 'draped' over Units C and D, and is designated as Unit E. This unit is in turn overlain by a packet–inter-packet sequence identified as Unit F. Finally, Unit F is itself overlain by the uppermost packet–inter-packet sequence that extends to the surface and is designated as Unit G.

Many of the reflector undulations seen in the delay-time radargrams are actually due to the combination of complex topographic relief at the surface and the difference in radar wave speeds of the atmosphere and subsurface materials. The true geometry of the subsurface returns is shown to be much smoother in the depth-converted radargrams (second panels of Figs. 2 and 3)—for example, those returns corresponding to the top of Unit A are nearly flat-lying everywhere and those associated with the top of Unit B appear as a smoothly varying dome, with one notable exception. From right to left across the depth-converted radargram in Fig. 3, one sees the top of Unit B rising gradually before a 'precipitous' drop of ~600 m (actual slope is only ~3–4°). In addition, the character of the radar returns changes in this zone such that the backscattered power at the boundary is greater and the diffuse power normally associated with the underlying Unit B is diminished. MARSIS data also show disruptions in this region [10].

After delineating unit boundaries on the selected delay-time radargrams, subsurface data analysis software was used to map them to a regular grid with cells of 2.7 × 2.7 km [1]. Surface returns were mapped everywhere poleward of 75°N, basal Units A and B were mapped out to their intersections with the surface grid, and the internal boundaries (Units C–F) were extrapolated to their intersections with either the surface grid or the basal grid. Thickness and elevation maps ([1]; Fig 4) were created using (1) and assuming a subsurface real permittivity of 3.15. The total NPLD volume was found to be 821,000 km^3 and the BU volume was estimated at 319,000-km^3. An effort to better constrain the volume of the BU from MARSIS observations is ongoing [10].

The NPLD thickness map in Fig. 4 demonstrates that much of the difference in elevation between Gemina Lingula and the main lobe (see Surface elevation map in Fig. 4) can be attributed to the BU deposits (Unit B), with the stack of NPLD layers in Gemina Lingula approaching the same maximum thickness of ~2 km that it does in the main lobe. At their highest point, the BU deposits stand about 1 km above the surrounding terrain (see Base NPLD map in Fig. 4), which presumably represents their maximum thickness above the flat-lying Vastitas Borealis deposits.

IV. Discussion

SHARAD results provide a detailed view of the internal structure of Planum Boreum, confirming expectations of that structure developed from surface data [8,4] and revealing many new features. Unveiling of the basal unit's true geographic extent and its subsurface topography raises interesting new questions about the history of these deposits and their influence on the subsequent evolution of the NPLD. The Unit D wedge discovered in eastern Gemina Lingula hints at a dramatic shift in the north-polar ice deposition early in NPLD history. Radar mapping of the NPLD base confirms that it is extremely flat beneath Gemina Lingula and the eastern main lobe (Fig. 4), implying an extraordinary lack of significant isostatic compensation as discussed by [5]. This result has far-reaching ramifications for regional and global heat flow and the nature of Martian mantle materials. While the troughs and surface undulations obscure our view of the subsurface in many areas by introducing unwanted clutter into the radar data, they are an integral part of the NPLD and have provided a window into the interior for image-based studies [21]. In some areas, the radar exposes structural features beneath the troughs and surface undulations (e.g., Fig. 2), and mapping of these features promises to impart key information about trough migration and development [22].

V. 3-D Imaging with SHARAD

SHARAD provides for the first time large volumes of closely sampled subsurface sounding data for a body other than the Earth. 3-D subsurface sounding is performed routinely on Earth for industrial and scientific purposes using both radar and seismic techniques, but such orbit-based observations are rare and there is no comparable dataset with the geographic extent and coverage that SHARAD has obtained for the polar regions of Mars. The volumetric nature of this data lends itself to the use of 3-D subsurface imaging technology, best developed in the petroleum exploration industry.

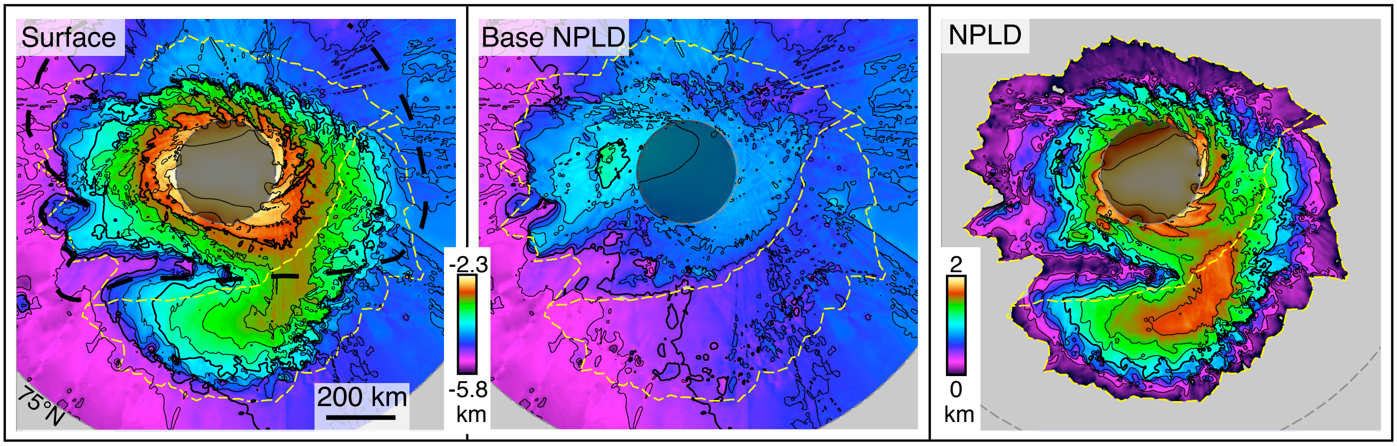

Figure 4. Polar stereographic maps of the elevation (left two panels) of the Planum Boreum surface and the base of NPLD (i.e., top of units A and B) and of the thickness (right panel) of the NPLD, derived from SHARAD data [1]. Subsurface real permittivity of 3.15 (nearly pure water ice) is assumed. Contour intervals are 250 m in elevation and 200 m in thickness. On each map, a dashed yellow outline encompasses basal Units A (lower right section) and B (upper left section). Shaded oval extends to northernmost extent of MRO ground tracks at ~87.4°N. Black dashed line in surface map is limit of basal unit as mapped by [3].

Proper interpretation of surface-penetrating radar data relies on discriminating between nadir returns from subsurface features and signals scattered from off-nadir surface and subsurface features. Additionally, 3-D geometries—such as dipping or folded layering—may result in the mislocation of subsurface features when they are imaged solely with 2-D methods (e.g., SHARAD single-orbit radargrams). Application of the radar process known as focusing (or synthetic-aperture processing) on a series of radar frames tends to compress the response from finite scatterers, but often leaves significant residual errors in the subsurface structural geometry. To address similar geometric issues with active-source seismic data acquired on Earth, imaging techniques somewhat analogous to radar focusing have been developed extensively over the last few decades. 3-D acquisition involving many sources and receivers spread over a large area is routinely employed in seismic exploration work, and 3-D imaging processes often largely correct the geometric distortion effects, placing structures in their correct location in 3-D space. The recently acquired grids of SHARAD observations over the polar regions of Mars have achieved sufficient density to be treated as 3-D data volumes. Since the quality of the imaging results improves with signal-to-noise ratio, SHARAD data from the north polar region—where returns from layering interfaces are much more continuous and typically have higher power relative to any other location, including the south polar region—are ideally suited for a first application of this technique to planetary radar observations. Substantial advancements toward the overarching goal of linking the geologic history of the polar layered deposits to climate processes and their history can be achieved.

References

[1] Putzig, N. E. & 9 co-authors, 2009. Subsurface structure of Planum Boreum from Mars Reconnaissance Orbiter Shallow Radar soundings. Icarus 204, 443-457. Portions of Figs. 2, 7, 9, and 10 reprinted here as Figs. 2, 3, and 4 with permission from Elsevier.

[2] Byrne, S. & Murray, B.C., 2002. North polar stratigraphy and the paleo-erg of Mars. J. Geophys. Res. 107, 5044, 12 pp.

[3] Fishbaugh, K.E. & Head, J.W., 2005. Origin and characteristics of the Mars north polar basal unit and implications for polar geologic history. Icarus 174, 444–474.

[4] Tanaka, K.L., 7 co-authors, 2008. North polar region of Mars: Advances in stratigraphy, structure & erosional modification. Icarus 196, 318–358.

[5] Phillips, R.J. & 26 co-authors, 2008. Mars north polar deposits: stratigraphy, age, and geodynamical response. Science 320, 1182–1185.

[6] Picardi, G. & 33 co-authors, 2005. Radar Soundings of the Subsurface of Mars. Science 310, 1925–1928.

[7] Plaut, J.J. & 23 co-authors, 2007. Subsurface radar sounding of the south polar layered deposits of Mars. Science 316, 92–95.

[8] Clifford, S.M. & 52 co-authors, H.J., 2000. The State and Future of Mars Polar Science and Exploration. Icarus 144, 210–242.

[9] Herkenhoff, K.E., Byrne, S., Russell, P.S., Fishbaugh, K.E. & McEwen, A.S., 2007. Meter-scale morphology of the north polar region of Mars. Science 317, 1711–1715.

[10] Selvans, M.M., Aharonson, O., Plaut, J.J. & Safaeinili, A., 2009. Structure of the Basal Unit of the North Polar Plateau of Mars, from MARSIS. Proc. IEEE Radar Conf., 3206 (abstract).

[11] Seu, R. & 11 co-authors, 2007. SHARAD sounding radar on the Mars Reconnaissance Orbiter. J. Geophys. Res. 112, E05S05,, 18 pp.

[12] Johari, G.P., 1976. The dielectric properties of H2O and D2O ice Ih at MHz frequencies. J. Chem. Phys. 64, 3998–4005.

[13] Mätzler, C. & Wegmüller, U., 1987. Dielectric properties of fresh-water ice at microwave frequencies. J. Phys. D: Appl. Phys. 20, 1623–1630.

[14] Grima, C.& 7 co-authors, 2009. North polar deposits of Mars: Extreme purity of the water ice. Geophys. Res. Lett. 36, L03203, 4 pp.

[15] Holt, J.W., Peters, M.E., Kempf, S.D., Morse, D.L. & Blankenship, D.D., 2006. Echo source discrimination in single-pass airborne radar sounding data from the Dry Valleys, Antarctica: Implications for orbital sounding of Mars. J. Geophys. Res. 111, E06S24, 13 pp.

[16] Holt, J.W. & 9 co-authors, 2008. Radar sounding evidence for buried glaciers in the southern mid-latitudes of Mars. Science 322, 1235–1238.

[17] Plaut, J.J. & 7 co-authors, 2009. Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars. Geophys. Res. Lett. 36, L02203, 4 pp.

[18] Nunes, D.C. & Phillips, R.J., 2006. Radar subsurface mapping of the polar layered deposits on Mars. J. Geophys. Res. 111, E06S21, 16 pp.

[19] Laskar, J., Levrard, B. & Mustard, J.F., 2002. Orbital forcing of the martian polar layered deposits. Nature 419, 375–377.

[20] Tanaka, K.L. & Scott, D.H., 1987. Geologic map of the polar regions of Mars. USGS Miscellaneous Investigations Map I–1802–C.

[21] Rodriguez, J.A.P., Tanaka, K.L. & Berman, D.C., 2009. Depression Systems in Western Planum Boreum, Mars: Distributions, Orientations, and Cross-Cutting Relationships. Lunar Planet. Sci. XL, 2371 (abstract).

[22] Smith, I.B., Holt, J.W., Christian, S.W. & Safaeinili, A., 2009. Evidence for Spiral Trough Migration and Evolution from SHARAD Radar Observations of Stratigraphy within the Northern Polar Layered Deposits, Mars. Lunar Planet. Sci. XL, 1423 (abstract).

REVIEW COMMENTS

On 2010 April 18, the authors received two reviews of the paper "Imaging the Subsurface Structure of Planum Boreum with the Mars Reconnaissance Orbiter Shallow Radar" by Putzig, Phillips, Campbell, and Foss. The reviews are designated here as Review 222 and Review 224.

On the review form, "Scientific interest of the paper," "Scientific rigor of the paper," and "Clarity of the exposition" were rated "Medium," "High," and "Medium" in Review 222 and "High," "High," and "High" in Review 224, respectively. Both reviewers selected "yes" in response to the questions "Are the abstract and the text coherent?", "Are the references adequate and are they all recalled within the text?", and "Is the length of the paper adequate?". In response to the question "Are the figures adequate and properly represented?", Review 222 selected "no" and included the comment "No copyright clearance" while Review 224 selected "yes". In response to the question "Is the English language correct?", Review 222 made no selection while Review 224 selected "yes". Both reviewers selected "no" in response to the question "Does the reviewer want to see the paper again after corrections?". For "Synthetic judgement," Review 222 selected "Acceptable after minor revision" while Review 224 selected "Accepted as it is."

Only Review 222 provided "Specific comments of the Reviewer," which were:

> This paper presents recent progress in understanding of Mar's Planum Boreum with Mar's SHARAD radar. It is never said clearly, but this paper simply reviews previous findings, rather than presenting new results and thus confusing for me. Such review-type papers are acceptable for this conference but it should be clarified. Figures 2 and 3 are from other papers but no copyright issues are cleared. It would be trouble if it is published without copyright permissions from the publishers. Or, does the author own their copyright with them (rather than giving it to the publisher)?

Only Review 224 provided "Specific comments of the Technical Co-chair," which were:

> This paper is very well written and should be accepted as it is.

REVIEW RESPONSES

Review 222 asserts that the paper "simply reviews previous findings" without clearly stating that it does so. While this claim is correct for much of the paper, the final section (V. 3-D IMAGING WITH SHARAD) discusses work that was recently selected for funding and is currently underway. We expect to present some preliminary findings at the GPR 2010 conference. To clarify the nature of the review portion of the paper, we replaced the original first sentence of the abstract, which read:

> **Sounding data from the Shallow Radar (SHARAD) instrument onboard the Mars Reconnaissance Orbiter (MRO) have been used to map the subsurface structure of Planum Boreum [1].**

That sentence now reads:

> **We review prior mapping of the subsurface structure of Planum Boreum that was conducted with 2-D sounding data from the Shallow Radar (SHARAD) instrument onboard the Mars Reconnaissance Orbiter (MRO) [1].**

Review 222 points out that no copyright clearance was indicated for Figures 2 and 3. In addition, Fig. 4 incorporates material from Reference [1] as well. We obtained the necessary license from the publisher, Elsevier. The reference was updated to include an acknowledgement per the license agreement:

> [1] Putzig, N. E. & 9 co-authors, 2009. Subsurface structure of Planum Boreum from Mars Reconnaissance Orbiter Shallow Radar soundings. Icarus 204, 443-457. Portions of Figs. 2, 7, 9, and 10 reprinted here as Figs. 2, 3, and 4 with permission from Elsevier.