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MARSIS subsurface radar investigations of the South Polar reentrant Chasma Australe

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[1] The Mars Express/Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) has conducted the first-ever subsurface probing of the south polar layered deposits (SPLD) revealing internal structure that is rich in detail. We report on subsurface features detected from a set of orbits that passed over the largest of the south polar reentrants, Chasma Australe, at the edge of the SPLD. We present selected MARSIS overflights to both document the unique observations and gain insight into the possible origin of this feature. We conclude that MARSIS observations clearly reveal new evidence of subsurface structure, such as (1) internal bands, (2) the continuation of the Prometheus basin floor beneath the SPLD to form a prominent basal interface, and (3) the presence of a possible ice-rich layer on the Prometheus basin floor extending to 500-m depth. There is no obvious indication of a present-day aquifer at the head of the chasma and identification of features associated with a past aquifer and water flow is ambiguous. While MARSIS observations may not uniquely solve the chasma origin debate, they do reveal the subsurface region beneath this very interesting feature for the first time.

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1. Introduction

[2] Chasma Australe is a broad (~80 km-wide) erosional reentrant that originates within the south polar layered deposits (SPLD) at 86°S, and extends northward ~500 km along ~90°–95°E longitude. The relief along the sides of the chasma can exceed 1 km. It has been suggested that both Chasma Australe and Chasma Boreale (a similarly sized and oriented feature in the north polar layered deposits) may have resulted from the catastrophic discharge of an underlying reservoir of basal meltwater [*Clifford*, 1987; *Benito et al.*, 1997; *Anguita et al.*, 2000]. Alternatively, *Howard* [2000] has suggested that the chasmata were formed by surficial erosion associated with katabatic winds. A thorough review of the possible formation processes for Chasma Boreale has been presented by *Fishbaugh and Head* [2002], and the mechanisms presented therein may be applicable to Chasma Australe. We examine subsurface sounding data from MARSIS to see whether they can provide any further insights, or offer any constraints, on the origin of this feature – particularly any evidence of a past/present subglacial aquifer that may have acted as an erosion source. We herein document the observations and provide an interpretation of the unique measurements.

[3] Mars Express (MEX) was launched on 2 June 2003 and entered Mars orbit on 24 December 2003. The 86° inclination eccentric orbit ranges from a periapsis of 279 km to an apoapsis of 11634 km. The initial latitude of periapsis was near the equator, but this latitude drifts by about 0.5 degrees per sol. Over the course of the mission, the periapsis location migrates over both poles. MEX periapsis passed over the south polar regions in late 2005/early 2006, during times when the south pole was moderately lit or unlit which allowed signal penetration through the ionosphere [*Gurnett et al.*, 2005] and into the subsurface.

[4] Onboard the MEX spacecraft is the MARSIS instrument that has been in successful operation since June 2005, and made the first-ever ground-penetrating radar soundings of both the northern and southern polar residual ice and layered deposits [*Picardi et al.*, 2005; *Plaut et al.*, 2007a]. For the SPLD returns, the radar signal penetrated a large portion of the south polar ice, revealing interfaces up to 3.7 km in depth. Here we focus on the analysis of data acquired directly over Chasma Australe, the largest reentrant in the SPLD.

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[5] The MARSIS instrument consists of a 40-m antenna, a transmitter/receiver system and a digital electronics system. After some initial concerns regarding antenna deployment, the 40-m tip-to-tip antenna system was successfully unfurled in mid-June 2005. In subsurface sounding mode, the transmitter emits a 1 MHz bandwidth pulse in two of four distinct bands: 1.3–2.3 MHz, 2.5–3.5 MHz, 3.5–4.5 MHz, and 4.5–5.5, MHz. The 40-m antenna has a resonance frequency at $f_{res} \sim 3.75$ MHz, and transmission near this frequency is emitted at peak powers of 5–10 W. The vertical resolution, defined by the bandwidth, is approximately 150-m in free-space, the along-track footprint is ~ 5 km after on-board Doppler processing and the cross-track footprint is 10–30 km. The figures displayed here are derived from the channel centered at 4 MHz, at a frequency well above the local peak ionospheric plasma frequency [*Safaeinili et al.*, 2003; *Gurnett et al.*, 2005].

[6] MARSIS observations near the edges of Chasma Australe were examined for evidence of any attribute potentially indicative of any endogenic activity. An obvious feature to search for is an active basal lake like those that exist below the Antarctic ice sheet [*Robin et al.*, 1977]. If such a feature were present, one might expect that its upper surface would be defined by a bright, flat reflector [*Robin et al.*, 1977]. Clearly, a second target is any feature that may have been associated with a past basal aquifer and catastrophic outflow such as that described by *Anguita et al.* [2000]. This includes any evidence of the disruption of the local SPLD stratigraphy at the head of the chasm by erosion and material collapse, cutting and channeling along the bed, and possible outflow deposits at the mouth of the chasma potentially associated with a massive fluvial discharge [*Anguita et al.*, 2000]. However, unambiguous identification of such features may be compromised by subsequent modification via winds or sublimation [*Fishbaugh and Head*, 2002].

[7] The MARSIS ground penetrating radar provides a first-ever opportunity to probe below the surface to search for a reflection from a basal lake. Should such sub-glacial aquifers be expected below the Martian polar layered deposits? There is substantial circumstantial evidence against their presence including the following: (1) The melting isotherm defining the lower edge of the cryosphere has been calculated to remain at a nominal depth of about 2 km at the equator and > 6 km at the pole [*Clifford and Parker*, 2001]. (2) Recent MARSIS observations of the NPLD [*Picardi et al.*, 2005] indicate that radar signals are passing through a low attenuating medium, consistent with a very cold ice deposit (<240°K) incapable of harboring water liquid. (3) Recent reports [*Plaut et al.*, 2007a, 2007b] also describe a low-attenuating SPLD medium consistent with a cold deposit. While this circumstantial evidence is compelling, the reentrant geomorphology of both Chasma Boreale and Australe has inspired numerous investigations searching for evidence of a fluvial origin [*Clifford*, 1987; *Benito et al.*, 1997; *Anguita et al.*, 2000; *Fishbaugh and Head*, 2002]. Hence given MARSIS' capability to probe deeply into ice, an obvious first investigation is to probe the chasma head and walls for direct evidence of a present basal lake and then search for obvious evidence of a past fluvial event. While circumstantial evidence suggests the likelihood of detection is low, radar probing is a method that has the capability to provide direct evidence to either substantiate or repudiate the possibility.

[8] To examine the basal topography and internal stratigraphy of the SPLD near the chasma, the polar deposits must have low signal attenuation. Previous modeling studies [*Farrell et al.*, 2004, 2005; *Xu et al.*, 2006; *Nunes and Phillips*, 2006] performed before MARSIS deployment suggested that the orbital detection of deep interfaces within the PLD is possible if the ice conductivity remains very low – below 10^{-5} S/m. Surprisingly, in real MARSIS soundings, the signals propagate easily through the north and south PLD with little signal attenuation, consistent with a very low ice conductivity below 10^{-6} S/m (or a loss tangent, $\tan \delta < 0.001$) [*Picardi et al.*, 2005; *Plaut et al.*, 2007a]. Thus for the most part, MARSIS signals can penetrate many kilometers through the PLD to allow a direct examination of basal topography.

[9] *Plaut et al.* [2007a] created a large-scale map of the last detectable subsurface interface, interpreted as the SPLD basal interface, observed by MARSIS. The map of this basal surface is shown in Figure 1. To create this map, the interface was identified in a large set MEX passes. The time delay between the surface and the basal interface at numerous points along each passage was calculated, and this time delay was then converted to a group-delay corrected distance (depth) below the surface assuming an ice permittivity of 3. Mars Orbiter Laser Altimeter (MOLA) measurements [*Smith et al.*, 1998] provided an absolute elevation reference for the surface and the MARSIS-derived basal surface depth was determined relative to this reference surface. *Plaut et al.* [2007a, 2007b] discussed the large-scale implications of this map, including an estimate of SPLD volume of 1.6×10^6 km^3 which corresponds to a equivalent global layer of water of $\sim$11-m depth.

[10] In examining Figure 1, we note that the basal interface in the vicinity of Chasma Australe is relatively flat, and is at the same elevation as the Prometheus basin floor. One exception is the region near the head of the chasma where there is an apparent depression in the basal interface located behind the chasma headwall. This depression is identified in case studies presented here and will be discussed in the context of the subsurface region near the chasma.

[11] We herein present detailed case studies of MEX passes made overtop the chasma with our objective to both document the MARSIS observations and to examine such for any insights provided into the formation of the chasma. This work augments the *Plaut et al.* [2007a] study: They presented the integrated results from many overflights to obtain a set of large-scale maps of the polar basal surface while we analyze individual passes overtop the chasma that show the detailed features that comprise the region. In section II and III, we present the MARSIS observations of subsurface features in the chasma region and we identify new elements of the subsurface morphology. We recognized that the interpretation is preliminary and not necessarily unique given the number of new unknowns. In section IV, we present observational evidence both for and against a fluvial origin in the chasma formation. We note that ambiguities in interpretation of these new observations abound. Whenever possible, we state our assumptions associated with any conclusions, fully recognizing the

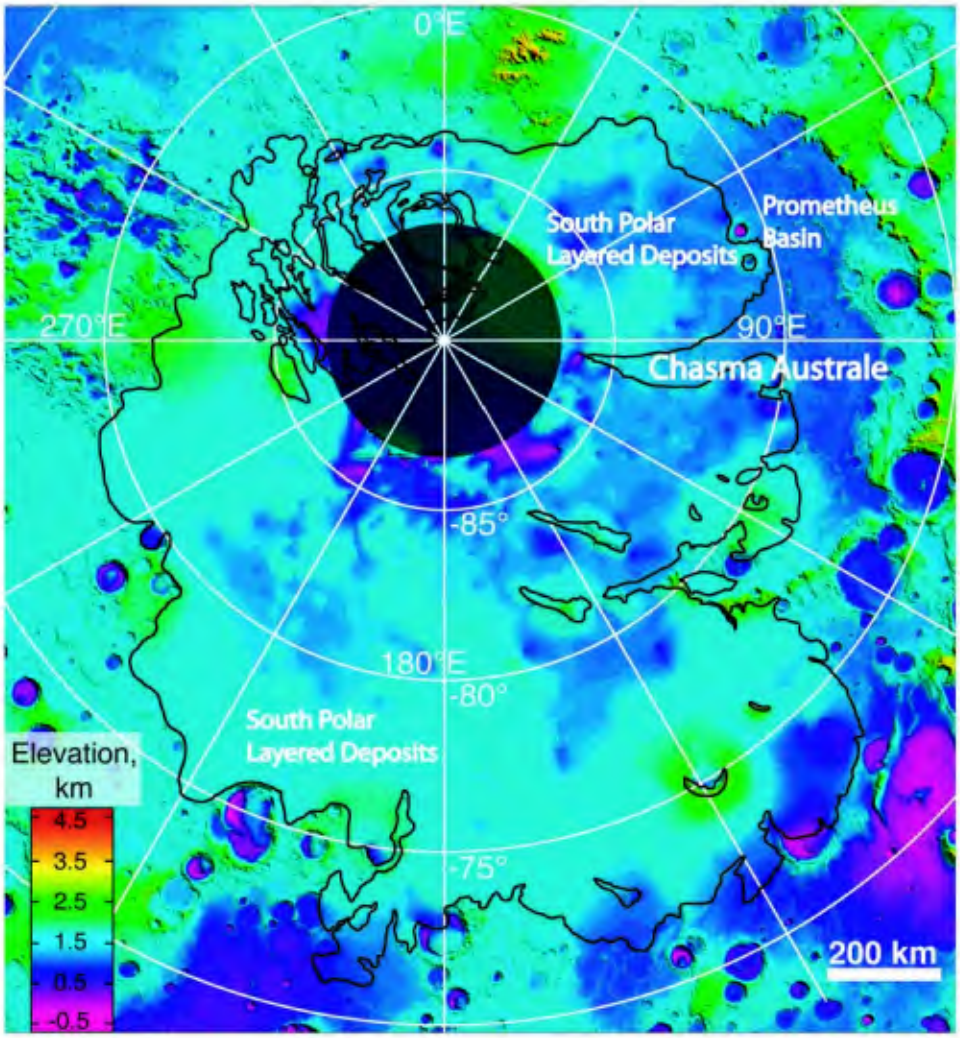

Figure 1. Map of the depth of the basal interface at the bottom of the SPLD as detected via MARSIS basal interface return reflections. Adapted from *Plaut et al.* [2007a]. To create this map, the SPLD basal interface was identified in a large set MEX passes. The time delay between the MOLA-defined surface and the basal interface at numerous points along each passage was calculated, and this time delay was then converted to a group-delay corrected distance (depth) below the surface assuming an ice permittivity of 3. The MARSIS-derived basal surface depth under the SPLD was determined relative to the MOLA-defined surface. Note that the Prometheus basin floor makes a smooth transition to become the SPLD basal interface in the region near Chasma Australe.

non-unique elements of the interpretation lie in these assumptions.

2. Selected MEX Passes Aligned With Chasma Australe

[12] A set of MEX orbits passed longitudinally over the chasma during nightside periods (where radar sounding is optimized due to the low ionospheric density). In these cases, the spacecraft flew over a large portion of the length of the chasma starting from its outer terminus and passing over the SPLD at the chasma's eastern edge. The MEX orbit phasing was such that there were approximately 20 MARSIS ground tracks along this feature. We show a representative selection from these orbits.

[13] Figure 2 shows these measurements obtained by MARSIS when the MEX ground track crossed the chasma longitudinally, just interior to its eastern wall. The insets shows the MARSIS radargrams which present the radar return power (white = strong, black = weak) as a function of echo delay-time plotted vertically downward and ground track position plotted along the horizontal axis. In essence, each set of return echoes (plotted vertically) is stacked along the horizontal axis (the ground track) to build up a two-dimensional picture of both surface scattering and subsurface echo returns. The radargram is presented at the same horizontal scale as the underlying MOLA topographic map of the SPLD. For a constant speed of light, the radargram vertical axis shows subsurface features at an "apparent depth". However, as we discuss below, the light propaga-

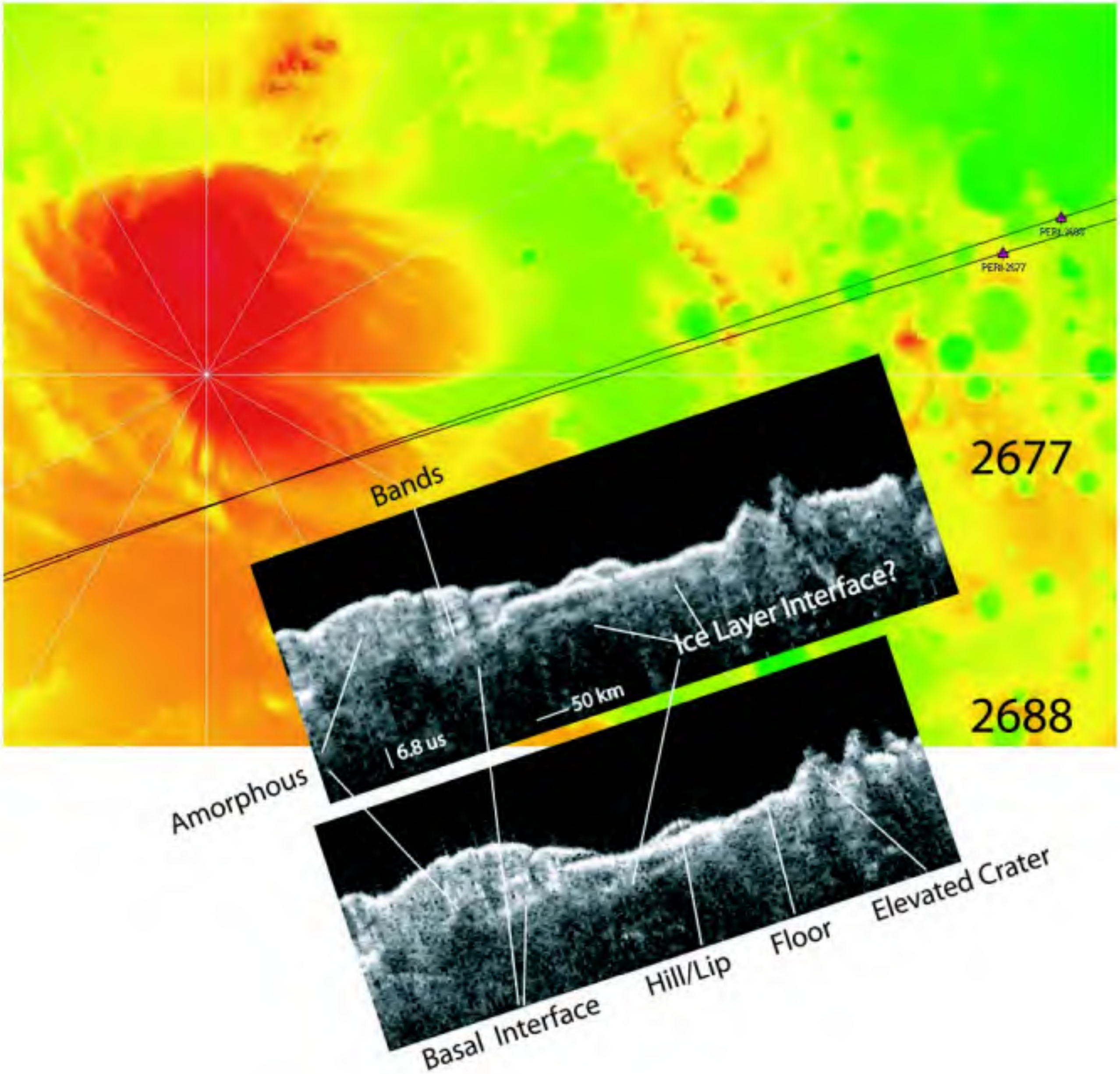

Figure 2. MOLA MAP of the south polar layered deposits and MEX passes over Chasma Australe for orbits 2677 and 2688. The MARSIS radargram for the passes are overlaid to scale.

tion speed in the subsurface differs from free space and this distorts the apparent vertical position of any internal reflector. The MOLA measurements [*Smith et al.*, 1998] provide valuable contextual information for the MARSIS subsurface measurements. The ground track of the spacecraft is indicated in the figure by the solid dark lines, with the spacecraft passing from right-to-left in the figure. The two orbits, 2677 and 2688, track very close to each other, with orbit 2677 lying just slightly east of orbit 2688 along the chasma.

[14] During the passes shown in Figure 2, MARSIS detected five primary features in the surface and subsurface, which we identify relative to the northern (right-hand) side of the trajectory. (1) MARSIS easily detects the raised surface features that define the rim of the Prometheus basin appearing as elevated cratered mountains in the radargram. The apparent subsurface structure below the crater is associated with topographic clutter from off-nadir surface reflections. (2) MARSIS then passes off the rim and detects returns from the floor of the Prometheus basin. We note that the surface radar reflection from this flat plane is relatively bright with little clutter thus suggesting a smooth surface. Also detected is a weaker, somewhat diffuse quasi-horizontal linear feature that appears as a subsurface interface about $\sim$1/2 km beneath the basin floor. We interpret this feature as the possible interface between ice-rich sediment and underlying basement (labeled in Figure 2 as "ice-layer interface?"). *Plaut et al.*

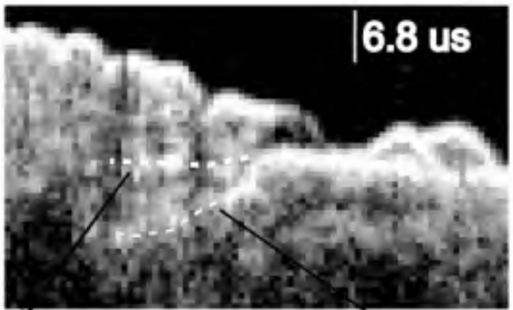

Figure 3. Group velocity delay corrected basal interface for the region at the chasma edge for orbit 2677. The permittiviy of the ice is assumed to be 3.

[2007b] reported that much of the terrain identified as Dorsa Argentea (which includes the Prometheus basin floor) has an upper layer that may be ice-rich and the boundary between it and the substrate could produce a reflection. (3) About 150 km from the rim of the Prometheus basin, MARSIS passes near the margin of the SPLD at the mouth of the chasma identified as "hill/lip" in Figure 2. While the basin floor appears to also extend into the hill as a bright subsurface feature, MOLA-based reflection (Clutter) models like that by *Picardi et al.* [2005] indicate that MARSIS is detecting off-nadir returns from elevated SPLD located slightly to the east of the orbital track, giving rise to the simultaneous appearance of both the hill and basin floor. Once past this region of the SPLD lip, the profile passes back onto the basin floor, but continues to hug the chasma's eastern edge. (4) At the location where the surface reflection of the SPLD sharply rises upward, the external basin floor is seen extending inward to below the SPLD for about 200 km forming the basal interface under the deposit. This basal interface appears as a linear subsurface feature that progressively slopes downward beneath the SPLD as the ground track extends further into the SPLD interior (labeled as "basal interface" on the figure). We note that the point of transit into the SPLD along the chasma's eastern edge is ambiguous on the MARSIS radargram due to off-nadir returns (that can extend 30 km to the sides) that detect the elevated SPLD lying off to the east of the orbital track before the actual transit and the Prometheus basin floor lying off to the west of the orbital track after the actual transit. However, this ambiguity affects only about ± 30 km from MEX's point of transit onto the SPLD. (5) Besides the basal interface, other features in the SPLD are visible as well, including up to five banded layers in the profile obtained during orbit 2677. The bands themselves appear to have a vertical modulation or vertical "lanes" with emission intensity waning and waxing in vertical strips. These vertical lanes may be associated with the polar troughs.

[15] Regarding point (2) above (the interface detected beneath the floor of the Prometheus basin), Mars Odyssey's Gamma Ray Spectrometer (GRS) detected a hydrogen-rich exposed surface interpreted as possible ground ice in regions away from the SPLD [*Boynton et al.*, 2002]. GRS ice detection is limited to the very near surface (less than I-m depth). However, if this ground ice layer is 100s of meters thick at Prometheus, MARSIS would be capable of detecting the bottom edge of a sharp ice-rich boundary layer. In fact, the observed interface beneath the floor of the Prometheus basin (orbit 2677, Figure 2) may represent that lower boundary of the GRS-detected icy top layer [*Plaut et al.*, 2007b]. We note that ice may also extend well into the basement layer, saturating available pore space in that material as well. However, the relative ice concentrations may differ between the two layers.

[16] In Figure 2, we note the presence of reflected bands (point 5 above), appearing like strata, within the SPLD. The exact nature of these linear intensifications is not completely understood [*Plaut et al.*, 2007a]. One interpretation is that they are direct reflections from distinct and sharp ice-ice interfaces of varying impurity content. If true, then the return signals represent reflections from true stratified layers of differing permittivity. However, in some areas of the SPLD, the depth of the layers changes when examining two different MARSIS frequency bands [*Plaut et al.*, 2007a], which suggests the alternate possibility that the linear features are locations where two oppositely directed waves (downward propagating and upward reflected) are constructively interfering to form a standing wave, creating a local brightening. If true, then such an interference pattern will vary in position with varying frequency. An analogous effect has been reported from stratified layers in the ionosphere [*Siefring and Kelley*, 1991]. It should be noted that this second scenario requires highly reflective layers in order to obtain a corresponding highly modulated destructive/constructive interference pattern. Analysis of the features for orbit 2677 and 2688 at two different frequency bands indicates that the bright linear features lie in comparable locations at two different frequencies, suggesting the bands are true reflections from stratified interfaces (or a tight set of unresolved interfaces) rather than standing waves. However, this conclusion may not be applicable across the entire SPLD.

[17] In Figure 2, the apparent downward slope or "warping" of the basal interface is not geologically real, but a result of the slower radio wave group velocity in the thick ice, which for low conductivities is $v_g = c/(n + \omega dn/d\omega) \sim c/K^{1/2}$, where $K = \varepsilon/\varepsilon_o$ (for ice is $\sim$3). The actual depth to the basal interface below the surface is thus $d = cT/2n$ where T is the time delay difference between the surface and basal interface. Correcting for this group velocity delay in ice, the basal interface would actually appear to shift upward by $(1 - n^{-1})$ or 42% compared to the depth of the apparent surface. Figure 3 shows the portion of orbit 2677 at the PLD/basin region along with a line representing the group velocity delay corrected basal interface for an assumed ice permittivity of 3. We note that the corrected surface actually lies at a depth corresponding to the surface of the Prometheus basin floor. In essence, the Prometheus basin floor extends to regions well within the SPLD. The delay-corrected depth of the basal interface at its deepest location in this radargram is $\sim$2 km.

[18] Hence Figure 2 reveals that the basal interface defining the bottom edge of the SPLD is in fact the inward extension of the Prometheus basin floor, with the floor

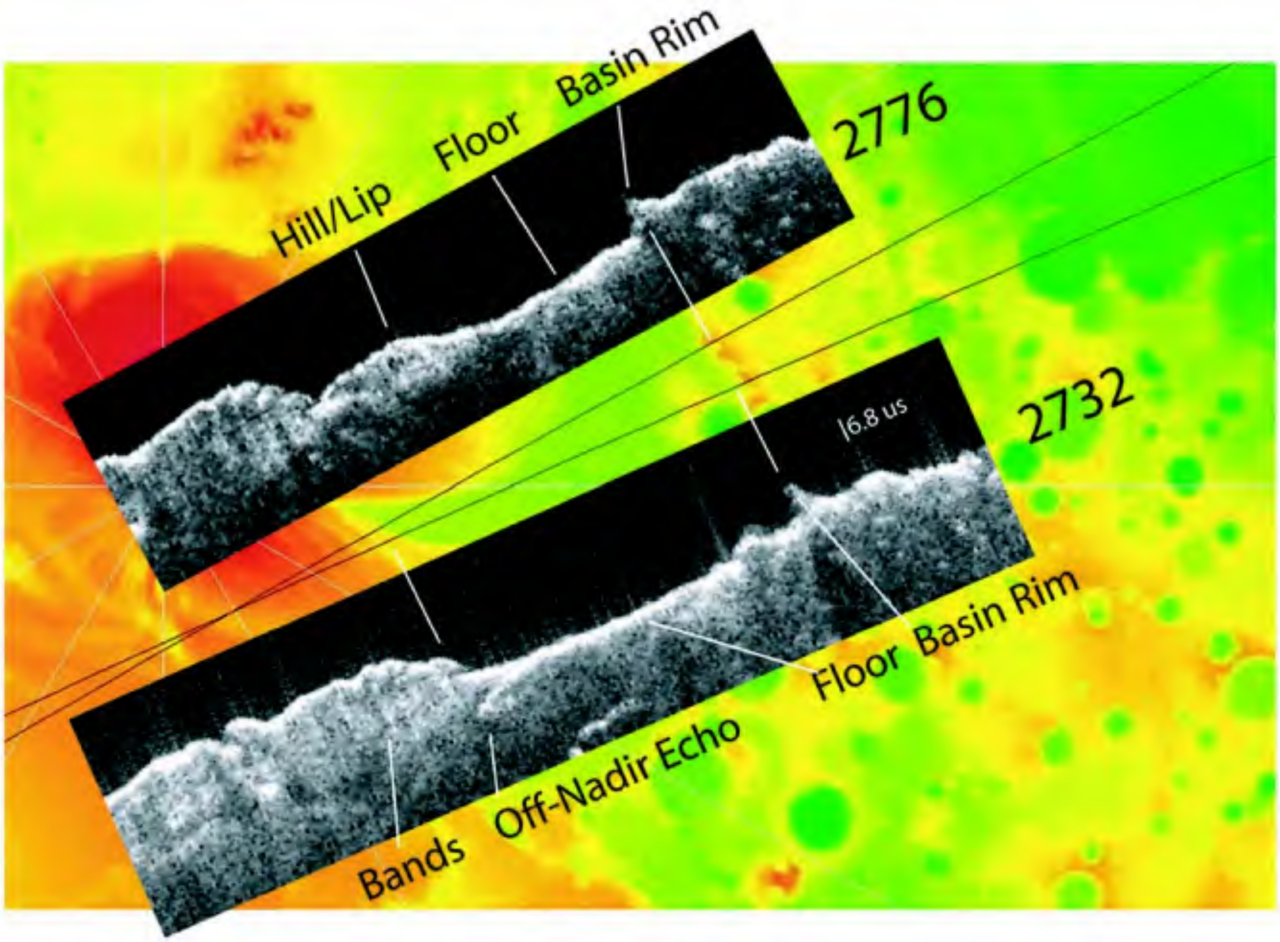

Figure 4. MOLA MAP of the south polar layered deposits and MEX passes over Chasma Australe for orbits 2732 and 2776. The MARSIS radargram for the passes are overlaid to scale.

merging from outside to inside the PLD. While the Amazonian-aged SPLD has generally been considered to be superimposed on the Hesperian-aged Dorsa Argentea Formation in the Prometheus basin [*Tanaka and Scott*, 1987], MARSIS presents the first direct detection of this relationship viewed from beneath the SPLD.

[19] However, an unexpected situation does occur in the interior of the SPLD: the basin floor/interface signature and other bands apparently and abruptly disappear about 200 km into the thicker portion of the SPLD. *Plaut et al.* [2007a] identified similar effects found elsewhere in the SPLD. The apparent loss of return signal from any quasi-linear subsurface bands and interfaces gives rise to an "amorphous" return signal morphology on a radargram in these regions. In such amorphous regions, there is a background "continuum" emission above the noise level possibly associated with wave scattering and/or ray group velocity delay, but also disappearance of clear and distinct stratagraphic bands and the basal interface.

[20] Figure 4 shows two additional passes, one (orbit 2732) being a transit through the chasma central region and the other (orbit 2776) passing near the chasma's western wall. For orbit 2732, the bright Prometheus floor is evident (as it is in Figure 2) that extends from the cratered region at the rim of the Prometheus basin to the SPLD chasma wall. At the chasma wall, there is a bright subsurface feature that dips downward toward the interior of the SPLD which has been identified in reflection/clutter models as an off-nadir reflection. In the SPLD itself, banded structures/strata is again observed, although their signal is relatively weak, just at the limits of detection. At least seven separate (very weak) bands appear to be present.

[21] A similar pattern is found in the profile corresponding to orbit 2776. However, MEX passes over the western lip of

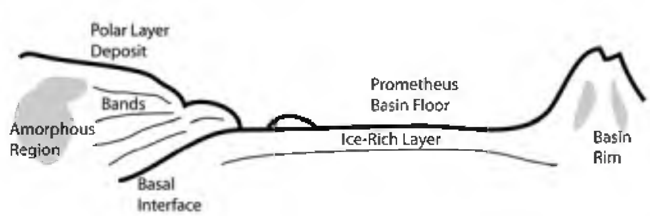

Figure 5. A composite sketch of the typical MEX/MARSIS transit passing longitudinally along Chasma Australe. The sub-spacecraft distance shown is consistent with Figures 2 and 4 of about 1000 km.

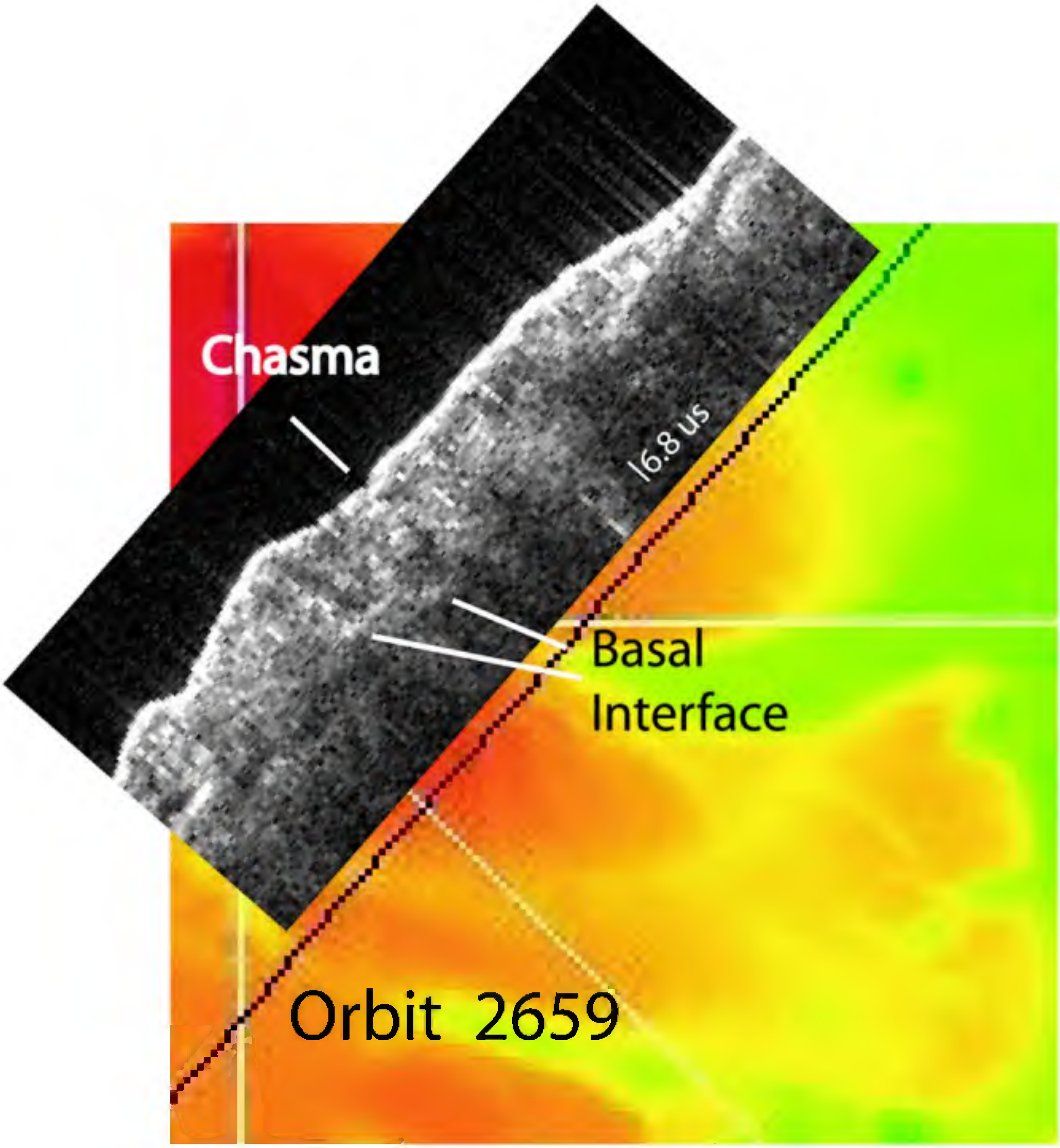

Figure 6. MOLA MAP of the south polar layered deposits and MEX passes over the head region of Chasma Australe for orbit 2659. The MARSIS radargram for the passes are overlaid to scale.

the SPLD, which is evident in the radargram as a relative maximum in the terrain (identified as "hill/lip"). We note in orbit 2776 that the width of the chasma itself is not as wide as the MOLA measurements would suggest, which again is most likely due to the relatively large cross-track resolution of 30 km that detects off-nadir SPLD echoes located to the west and east of the actual MEX track. Because of these off-nadir SPLD returns, the chasma floor appears narrower than suggested by MOLA observations.

[22] MARSIS observations of longitudinal chasma passages reveal the following morphology illustrated as a composite sketch of the actual observations in Figure 5. From outside to inside the deposit, the following are observed: (1) a subsurface interface about 1/2 km below the Prometheus basin floor possibly being the boundary between an ice-rich layer and an underlying basement, (2) the continuation of the Prometheus basin floor beneath the SPLD forming the basal interface at the bottom

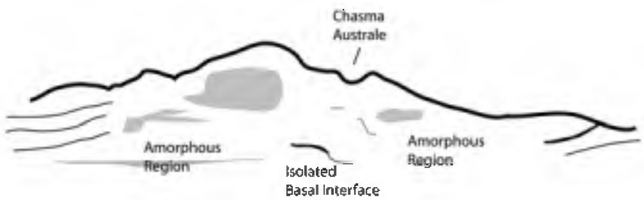

Figure 7. A composite sketch of a typical MEX/MARSIS transit latitudinally across the head of Chasma Australe. The sub-spacecraft distance shown is consistent with Figures 2 and 4 of about 800 km.

of the deposit, (3) large-scale (100s of meters) banded layering within the SPLD interpreted as direct reflections from stratified layers (or sets of narrowly spaced unresolved layers), (4) abrupt cessation of both the basal interface/basin floor and banded structure in the inner deep SPLD, (5) an amorphous radargram signature in the deep central SPLD region.

3. MEX Passes Over the Chasma Head

[23] While the orbits described in section 2 emphasize the longitudinal tracks along the chasma (lengthwise), we now show orbit 2659 that flew latitudinally across the chasma (width-wise). The example shown herein is a representative case for a family of orbits that passed at high latitudes over the region. This overflight is at the head of the chasma, where a source aquifer might be anticipated. The associated radargram is shown in Figure 6.

[24] The most pronounced observation is the lack of any kind of strong reflector or bright region detected by MARSIS in the vicinity of the chasma head. For the most part, the terrain is devoid of structure and consists mostly the amorphous morphology similar to that found in the deeper regions of the SPLD in Figures 2 and 4. While strong quasi-linear reflectors (strata) are typically not observed, there is the presence of a relatively weak, deep basal interface signature located about 2.6 km (delay-corrected) below the overlying surface ice near the chasma. This spatially limited basal segment was repeatedly observed by MARSIS during similar (familial) spacecraft passes and was found to extend northward to eventually connect to the chasma wall/chasma floor.

[25] Assuming that the interface defines the boundary between the icy SPLD and a basaltic regolith basement, we can estimate the top-ice bulk conductivity via a two-layer wave propagation model such as that applied by *Picardi et al.* [2005] to the NPLD. Analyzing the limited data aquired during MARSIS early observing opportunity, radar signals in the NPLD events were found to easily penetrate the deposit which allowed a consistent detection of the basal interface at a depth of $\sim$1.8 km. Two-layer modeling of previously presented NPLD observations [*Picardi et al.*, 2005] suggests that the overlying ice conductivity is below 10^{-6} S/m, (tan $\delta < 0.001$) making the NPLD far more transparent to radar than expected. It was concluded that the medium was behaving as nearly pure water ice.

[26] Consider now the weak basal interface in the SPLD shown in Figure 6. This return appears as a horizontal, spatially limited segment in a region that is surrounded by primarily amorphous terrain. We can use the radar returns from this spatially limited interface to determine the signal loss in the overlying ice via two-layer modeling. The difference between the subsurface interface return power and the surface ice reflection is measured to be about -20 dB and the interface is 2.67 km in depth. Two-layer modeling results suggest that the top-ice conductivity is about 2×10^{-6} S/m (tan $\delta \sim 0.003$) to be consistent with the return power, indicating that the intervening medium is still relatively transparent.

[27] The two-layer model and detection of a deep basal interface at the chasma head raises an important question: What is the cause of the amorphous regions? One obvious cause might be a lossy top-ice that absorbs propagating signals to create amorphous radargram signatures that are mostly devoid of interface reflections. However, the two-layer modeling of the basal interface in Figure 6 suggests otherwise: that the ice is quasi-transparent to depths of $\sim$3 km. Another cause might be that the amorphous regions consist of layered terrain with little dielectric contrast, making the interfaces invisible to (or difficult to detect by) MARSIS. However, it is unclear why dielectric contrasts are more pronounced in the outer regions of the surrounding SPLD in the vicinity of the chasma, but less pronounced in the interior region close to the chasma head. It is especially unclear why the basal interface would disappear in the inner regions about the chasma. Amorphous regions exist elsewhere under the SPLD, including the outer SPLD near 270°E and a region of outer PLD near 120°–150°E. A more formal identification/analysis of these amorphous regions is planned for future work.

[28] As mentioned, the weak interface shown in Figure 6 appears as a spatially limited segment in this figure. However, examining familial passes we find that the upper portion of the limited basal segment (the brighter portion) extends continuously northward under the SPLD, becoming more shallow, and appears to connect to the basin floor at the chasma's eastern wall in a region near 85.6°S, 101°E (within the observational limits provided by the off-track nadir resolution of 30 km). Hence this interface may again be the inward extension of the chasma's floor under the SPLD. Because of the very southerly cross-chasma passage made by MEX, MARSIS then detected only a limited portion of this inward extension appearing as the spatially limited segment.

[29] Figure 7 is a composite sketch representative of the passages over the chasma head. The morphology includes the following: (1) apparent well-defined bands observed clearly and distinctly at the outer edge of the PLD, (2) the presence of an amorphous region in the interior SPLD along the MEX ground track, and (3) weak basal signature under the back wall of the chasma.

4. Search for Present or Past Signatures of Basal Melting

4.1. Present Signatures

[30] *Robin et al.* [1977] defined three criteria for detecting basal lakes under the Antarctic ice caps: (1) that the return signal along the basal interface be 10–20 dB stronger than that from typical ice-rock interfaces, (2) that the return

Table 1. Observational Evidence for and Against a Present Basal Lake at Chasma Australe

Criteria for Identification of Present Basal Lake	Passes	Observations	Ambiguities in Uniqueness of Observations
10–20 dB increase in return signal from basal interface (expected reflectance increase from ice/water interface versus ice/rock interface)	chasma aligned	no bright region observed	Limited viewing of interface: it disappears about 200 km into SPLD. Precludes full examination of the basal interface
	head	a short-segmented basal interface appears above noise level	no other basal interfaces/strata present to derive context
Located at local minimum in basal topography (where water would pool)	chasma aligned	no obvious bright region observed at local minimum in basal topography	Because of group velocity delay in top-ice, local max-mins difficult to uniquely identify. The minima may not be real but associated with top-ice that is more dispersive, slowing the ray relative to other regions
	head	brightest reflection from maximum in topology, not minimum	the observations are very limited in context.
Horizontal flattening of basal reflection	chasma aligned	when dispersion-corrected (Figure 3), the entire interface appears relatively flat	cannot differentiate between actual and apparent interface depth variations because of variations in group velocity delay in overlying top-ice medium
	head	apparently flat	The layers appear flat, but very limited region of observation. No context for comparison.

signal lies at a local depth maxima in stratigraphy/basal interface (a local topographic minimum in strata where water would collect) as identified in a radargram and (3) that the bright signature of the lake appears flat (i.e., horizontally even) in a radargram. Note that points (2) and (3) are contextual in nature and require relatively clear viewing into the full volume to surmise relative maxima/minima contained in surrounding stratigraphy and the flatness of a given feature. We apply a similar criteria to test for the present occurrence of a basal lake along the perceived ice-rock interface for Chasma Australe. Table 1 shows the criteria along with a summary of the MARSIS observations made both along the chasma and over the head region. We also include the ambiguities associated with the observations.

[31] We note that the spatially limited basal interface detected in the head region of the chasma (Figures 6 and 7) is relatively bright, standing out as a coherent quasi-linear feature in a region of amorphous terrain. However, there is a lack of surrounding stratigraphy and as a consequence we cannot uniquely determine the context of this interface, especially to determine if the signature lies at a local topographic minimum. We also note that this interface is relatively flat, but has a clear and distinct shift in depth midway through its signature. One might expect any water layer to pool at the lower of the two interfaces, and hence give rise to a stronger returned signal. However, the lower interface is the weaker signal of the two sections. Consequently, criteria (2) for this interface cannot be determined and the return signature apparently fails criteria (3). We thus conclude that a clear and obvious signature of a present-day aquifer is not found in the head region. As describe by *Robin et al.* [1977], stratigraphic context is critical for a unique identification and context cannot be derived within the amorphous regions around the spatially limited basal interface shown in Figure 6.

4.2. Past Aquifers

[32] While *Robin et al.* [1977] provided a clear and concise test for the detection of present basal lakes, testing for their past occurrence or the possibility that the chasma originated from a massive fluvial discharge is considerably more difficult and subjective. For this application, we consider the effect a catastrophic discharge might have upon its source, along its path, and at its outlet. As indicated in Table 2, a catastrophic discharge might disrupt the stratigraphic layering near its source, as faults or fractures develop due to material collapse associated with the discharge. Along the chasm floor, a large fluvial discharge should have resulted in significant erosion along its path, including the formation of channels as the discharged waned [*Anguita et al.*, 2000]. However, such water-carved features may lose their prominence due to subsequent erosion by winds and/or sublimation [*Fishbaugh and Head*, 2002]. Finally, one might anticipate some signature of deposition, such as a delta, where floodwaters discharged to the surrounding plains. As an analogy, *Fishbaugh and Head* [2002] suggest that a lobate

Table 2. Evidence for and Against a Fluvial Origin of Chasma Australe

Expected Signature of Past Catastrophic Flow	Passes	Observations	Ambiguities in Uniqueness of observations
Disrupted PLD stratigraphy near source	chasma aligned	none apparent	Detection of faults, fractures and fissures limited by MARSIS resolution of ~150-m.
	head	none Apparent	Detection of faults, fractures and fissures limited by MARSIS resolution of ~150-m.
Channels, plung-pools and other water-eroding signatures along path	chasma aligned	no obvious channels, plung pools observed	Winds or sublimation may have erased/eroded evidence of a clear and obvious water-carved features.
	head	N/A	
Outflow deposit onto basin floor	chasma aligned	the layer of 1/2-km depth on top of Prometheus basin floor may be an outflow channel deposit	More than one possible source for the ice-rich top layer, including aeolian process and alternate source from lower latitude meltbacks.
	head	N/A	

deposit at the mouth of Chasma Boreale is evidence for material outflow from a channel.

[33] As described in Table 2, MARSIS observations do not show a highly disrupted stratigraphy, as one might expect from a material collapse associated with a catastrophic discharge. It could be argued that the shift in depth of the deep interface is a manifestation of a collapse, but there simply is not enough contextual information to support anything other than a mere suggestion. The disruption in the form of small-scale sized faults and fractures might be possible, but would be difficult to resolve by MARSIS if they are too small (< 150 m).

[34] At MARSIS resolution, the presence of water-erosion features is not obvious in Figures 2 and 4. Along the chasma's eastern edge, the Prometheus basin floor and its extension inward as the basal interface appear relatively smooth and without a deep water-bearing channel. There is also clearly no evidence for increased clutter levels at the edge of the chasma, suggesting that the surface is smooth at scales of 10s to 100s of meters. Water-formed features may have existed, but may also have been eroded by winds over time to form a smoother surface.

[35] Evidence of a past aquifer may be the overlying ice-rich material found in the top layer of the Prometheus basin floor (see Figures 2 and 5). If a catastrophic discharge occurred, then this basin floor top-layer may be a resulting deposit formed at the mouth of the chasma. We note that the origin of the deposit is not unique and can also be formed via aeolian erosion that also deposited material onto the basin floor.

[36] Consider the case of material removed from the chasma and consequently deposited onto the Prometheus basin floor (at the mouth of the chasma). Using a chasma dimension of ~300 km length, 50 km width and 1 km depth, the volume of material to be removed is ~15,000 km^3. If we assume this volume is displaced to the chasma mouth in a 200 km by 200 km area extending outward from the chasma mouth to the Prometheus basin rim, then the resulting deposit should be ~ 1/2 km deep to be consistent with the displaced volume. In fact, the overlying layer on the Prometheus basin discovered by MARSIS is approximately this depth (and in a comparable or larger area) and is thus consistent with the movement of the chasma mass. Also, the detection of a clear interface between the top and bottom layer material indicates that there is a distinct compositional difference between the top and bottom layers. We presume that if the deposit originated from the SPLD, then its material would be different from that occupying the basement.

[37] While this scenario is interesting, we note that there is also evidence against the ice-rich layer being a chasma-originating outflow deposit, based on the sequencing of layering near the chasma wall. Specifically, examining the order of layers near the chasma wall in Figure 2, the vertical order from top to bottom is the following: the SPLD surface, 5–7 bands of strata, the basal interface (which is the inward extension of the Prometheus basin floor) and a very faint reflection from the bottom of the ice-rich layer that extends below the SPLD. This sequence indicates that the ice-rich layer was present before the SPLD deposition, ruling it out as a layer formed later via SPLD discharge. In this case, the ice-rich layer may be part of the original Dorsa Argentea terrain [*Milkovich et al.*, 2002].

5. Conclusion

[38] We present new observations of the subsurface features in the vicinity of Chasma Australe detailing both the subsurface morphology around the chasma and examining the observational evidence for the origin of the chasma (especially emphasizing a fluvial discharge). The observations are new and we present interpretations of the morphological features, fully recognizing that these interpretations rely on assumptions that are not necessarily unique.

[39] The new MARSIS observations from chasma-aligned passages find the following morphology illustrated as a composite of the actual observations in Figure 5. From outside to inside the SPLD, the following is observed: (1) a consistent subsurface interface about 500-m below the Prometheus basin floor, which is possibly the boundary between ice-rich and basement regolith, (2) the smooth extension of Prometheus basin floor into the SPLD, this floor forming the basal interface at the bottom of the SPLD, (3) large-scale (100s of meters) banded/stratified layering within the SPLD, (4) abrupt cessation of both the basal interface/basin floor and bands in the inner deep SPLD, (5) an amorphous radargram signature in the deep central SPLD region.

[40] In passages over the chasma head an amorphous signature devoid of structure was mostly observed, with the exception of a relatively weak, deep basal interface detected

2.67 km under the chasma headwall (Figures 6 and 7) which appears to be the inward extension of the chasma floor. On the basis of two layer modeling, we find that the overlying top-ice in the region was relatively transparent with the conductivity approaching 6×10^{-6} S/m ($\tan \delta \sim 0.003$). Despite the transparency of the ice, there are no other surrounding stratigraphic features, making it difficult to place the interface feature in proper context. Signal strengths are found to decease along this interface where there is a topographic minimum, most likely ruling out this interface as a signature of a basal lake.

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