

# 1 **Three-dimensional radar imaging of structures and craters in the Martian polar caps**

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## 16 **Highlights:**

- 17 • 3-D radar volumes give clarified views of structures within the Martian polar caps.
- 18 • 3-D map of south polar CO<sub>2</sub> deposits finds 16,500 km<sup>3</sup>, 11% larger than prior estimate.
- 19 • Apparent impact craters at base of northern cap are consistent with a Hesperian age.
- 20 • Radar-derived topography at 86.95–87.45° latitude extends prior laser altimetry data.

## 21 **Keywords:**

22 Mars; Mars, polar caps; Mars, climate; Mars, interior; Ices; Cratering; Radar observations

## 23 Abstract

24 Over the last decade, observations acquired by the Shallow Radar (SHARAD) sounder on  
25 individual passes of the Mars Reconnaissance Orbiter have revealed the internal structure of the  
26 Martian polar caps and provided new insights into the formation of the icy layers within and their  
27 relationship to climate. However, a complete picture of the cap interiors has been hampered by  
28 interfering reflections from off-nadir surface features and signal losses associated with sloping  
29 structures and scattering. Foss *et al.* (2017) addressed these limitations by assembling three-  
30 dimensional data volumes of SHARAD observations from thousands of orbital passes over each  
31 polar region and applying geometric corrections simultaneously. The radar volumes provide  
32 unprecedented views of subsurface features, readily imaging structures previously inferred from  
33 time-intensive manual analysis of single-orbit data (e.g., trough-bounding surfaces, a buried  
34 chasma, and a basal unit in the north, massive carbon-dioxide ice deposits and discontinuous  
35 layered sequences in the south). Our new mapping of the carbon-dioxide deposits yields a  
36 volume of 16,500 km<sup>3</sup>, 11% larger than the prior estimate. In addition, the radar volumes newly  
37 reveal other structures, including what appear to be buried impact craters with no surface  
38 expression. Our first assessment of 21 apparent craters at the base of the north polar layered  
39 deposits suggests a Hesperian age for the substrate, consistent with that of the surrounding plains  
40 as determined from statistics of surface cratering rates. Planned mapping of similar features  
41 throughout both polar volumes may provide new constraints on the age of the icy layered  
42 deposits. The radar volumes also provide new topographic data between the highest latitudes  
43 observed by the Mars Orbiter Laser Altimeter and those observed by SHARAD. In general,  
44 mapping of features in these radar volumes is placing new constraints on the nature and  
45 evolution of the polar deposits and associated climate changes.

## 46 1 Introduction

47 The icy layers of Planum Boreum and Planum Australe, the north and south polar caps of  
48 Mars, have been studied from orbit for decades, but the record of climate change that they  
49 encode is still not fully understood (Byrne, 2009). Two orbiting radar sounders, the Mars  
50 Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) onboard Mars Express and  
51 the Shallow Radar (SHARAD) onboard Mars Reconnaissance Orbiter (MRO), have been  
52 probing the cap interiors since 2005 and 2006, respectively. MARSIS results have established  
53 the gross internal geometries of both polar caps (Plaut *et al.*, 2007; Selvans *et al.*, 2010) whereas  
54 SHARAD results have revealed finer-scale layering and structures (Seu *et al.*, 2007a; Phillips *et al.*,  
55 2008).

56 In Planum Boreum, SHARAD mapping with more extensive coverage (Putzig *et al.*,  
57 2009) showed that the broadly continuous strata, delineated by packets of finely spaced  
58 reflecting layers separated by relatively homogeneous inter-packet zones, is pervasive.  
59 Comparisons to results from climate models (Laskar *et al.*, 2002; Levrard *et al.*, 2007) suggested  
60 that each sequence may correspond to a ~1-Ma orbital cycle (Phillips *et al.*, 2008; Putzig *et al.*,  
61 2009). A low degree of basal deflection (< 100 m) indicated either a transient state of  
62 compensation in the mantle (unlikely) or a much thicker (>~300-km) elastic lithosphere than  
63 had previously been considered (Phillips *et al.*, 2008). Mapping of structures below spiral  
64 troughs showed them to be dune-like, poleward-migrating features that result from a long-lived  
65 interaction of winds with icy surface materials (Smith and Holt, 2010; Smith *et al.*, 2013). In  
66 addition, Holt *et al.* (2010) delineated unconformities and mapped a buried chasma to the east of

67 the topographic saddle that connects Gemina Lingula to the main lobe of the north polar layered  
68 deposits (NPLD), while showing that Chasma Boreale is a long-lived feature and not the result of  
69 erosion into pre-existing layers. Beneath the NPLD, SHARAD data show transitions from nearly  
70 radar-transparent ice to a basal unit yielding diffuse reflections under most of the main lobe  
71 (Brothers et al., 2015; Nerozzi and Holt, 2017) and to a presumably rocky substrate yielding  
72 strong reflections elsewhere. Deeper, strong reflections obtained by MARSIS show that the basal  
73 unit extends down to the same rocky substrate (Selvans et al., 2010), but SHARAD generally  
74 obtains no reflections there, its higher frequencies apparently attenuated within the basal unit.  
75 This radar basal unit corresponds to the sand-rich rupēs and cavi geologic units of Tanaka and  
76 Fortezzo (2012) at the base of the NPLD that were identified previously with surface imagery  
77 (Byrne and Murray, 2002; Fishbaugh and Head, 2005).

78 In Planum Australe, SHARAD data show regionally discontinuous radar layering, with  
79 truncation at or near the surface in some areas (suggesting previous widespread erosion and a  
80 lack of substantial deposition in the current era) (Seu et al., 2007a) and enigmatic low-reflectivity  
81 zones in other areas (Phillips et al., 2011). The low-reflectivity zones atop Australe Mensa  
82 nearest the pole were determined to be composed of CO<sub>2</sub> ice (Phillips et al., 2011) that appears to  
83 have accumulated during three separate episodes of atmospheric collapse (Bierson et al., 2016).  
84 These deposits contain more than enough CO<sub>2</sub> to double the current atmospheric pressure if  
85 sublimated. Elsewhere in the south polar layered deposits (SPLD), regional mapping efforts  
86 combined with surface imagery have gleaned some insight into the deeper interior (e.g.,  
87 Milkovich et al., 2009) and suggest that the layers are more pervasive than seen in the radar data.  
88 However, some combination of signal scattering and attenuation has made it challenging to map  
89 layers more broadly across the southern cap with the available radar observations (Campbell et  
90 al., 2015).

91 While detailed mapping of internal structures in the northern cap has been more  
92 successful than in the south, doing so in either hemisphere with collections of data from  
93 individual radar passes is laborious and hindered by scattering and the interference of off-nadir  
94 surface reflections from spiral troughs and other variable topography. Reflected radar signals that  
95 return to the spacecraft (“returns” hereinafter) are dominated by those coming from the nadir  
96 track (the vertical projection of the spacecraft position to the surface), which usually arrive first.  
97 Returns from off-nadir surface structures, termed “clutter,” usually arrive later and may be  
98 mistaken for or interfere with nadir returns from subsurface interfaces. In areas where surface or  
99 subsurface interfaces are sloped, a common geometry near the spiral troughs of both polar caps,  
100 the first returns may be from off-nadir locations with no returns from nadir, yielding distorted  
101 profiles that are difficult to interpret. Focused processing enabled by along-track Doppler  
102 frequency shifts is typically applied to single-pass observations (i.e., two-dimensional profiles;  
103 see next section). Such processing greatly enhances along-track resolution by constructing a  
104 synthetic aperture (antenna) in that direction and can be effective in suppressing clutter and in  
105 improving positioning along track, but the cross-track components cannot be similarly focused to  
106 improve resolution.

107 One means to address these problems is to gather data from many closely spaced orbital  
108 passes into a single volume and apply a three-dimensional (3-D) image-correction process that  
109 has been best developed in the field of seismic data processing (Yilmaz, 1987; Gray et al., 2001).  
110 This treatment enhances the signal-to-noise ratio (SNR) by combining returns from overlapping  
111 and nearby tracks while placing scattered along-track and cross-track returns into their proper

112 source locations, thereby revealing the true geometry of surface and interior structures. In the  
113 following sections, we discuss SHARAD observations and provide an overview of the methods  
114 used by Foss et al. (2017) to produce SHARAD 3-D volumes encompassing the north and south  
115 polar caps. We then show results from the two polar data volumes and describe our initial  
116 scientific findings stemming from the use of these unique datasets.

## 117 **2 SHARAD Observations**

118 SHARAD is a chirped-pulse sounding radar with a 10-MHz bandwidth centered at 20  
119 MHz. Range ( $\sim$ vertical) resolution (i.e., the radar wavelength) is 15 m in free space and finer in  
120 the subsurface, depending on the material properties (Seu et al., 2007b). For nearly pure water  
121 ice with a real permittivity,  $\epsilon'$ , of 3.15 as is inferred for the NPLD (Picardi et al., 2005; Phillips et  
122 al., 2008; Grima et al., 2009), the range resolution is reduced to  $15/\sqrt{\epsilon'} = \sim 8$  m. A greater  
123 proportion of lithic inclusions, likely the case for Planum Boreum basal units and in portions of  
124 Planum Australe, will increase the real permittivity and thereby yield a finer range resolution.  
125 Increased pore space or a different composition (e.g., CO<sub>2</sub> ice, such as in the low-reflectivity  
126 zones near the south pole) may result in a decrease of real permittivity and a coarser range  
127 resolution. With the MRO orbit at a 250–320 km altitude, the lateral resolution at the surface is  
128  $\sim 3$ –6 km, reducible in the along-track direction to 0.3–1.0 km in focused processing (Seu et al.,  
129 2007b).

130 Each SHARAD record contains reflections from all terrain within a large area illuminated  
131 by the antenna beam, so additional processing is used to narrow the contributing region. Along-  
132 track resolution is greatly improved by focused Doppler processing of a suite of pulses recorded  
133 as the spacecraft moves along track. Returns from several seconds of observation are used to  
134 form a synthetic aperture in which the reflections from the desired region are isolated in time  
135 delay and Doppler frequency shift, then summed to obtain the maximum SNR. Side-by-side  
136 stacking of progressive focused return traces spaced at 300–500 m along track creates a  
137 radargram (i.e., a 2-D profile image of returned radar power with distance along track on the  
138 horizontal axis and range delay time—sometimes converted to depth—along the vertical axis;  
139 see Fig. 1). For more details of 2-D radar processing methods, see the documentation for the U.S.  
140 SHARAD derived data products and references therein (Campbell and Phillips, 2014).

141 Bright returns in a radargram indicate strong contrasts in the dielectric properties of  
142 materials at geologic interfaces while providing geometric information that reveals subsurface  
143 structure. Mineralogical differences may strongly attenuate radar waves, and changes in return  
144 strength along a dipping horizon can be used to characterize the loss properties (e.g., Campbell et  
145 al., 2008; Watters et al., 2007). In the polar terrains of Mars, reflections likely arise from  
146 dielectric contrasts between ice layers with different compositions (H<sub>2</sub>O or CO<sub>2</sub>) or degrees of  
147 dust or lithic loading (e.g., Nunes and Phillips, 2006; Grima et al., 2009; Putzig et al., 2009).

## 148 **3 Methods**

149 Here we provide an overview of the procedures used by (Foss et al., 2017) to take the  
150 SHARAD observations from collections of 2-D profiles to geometrically corrected 3-D volumes  
151 for each polar region. More details are available in the cited references.

152 Crucial to focused processing of orbital radar data is an accurate representation of the  
153 spacecraft velocity and the local surface slope. Horizontal reflectors directly below the spacecraft

154 typically yield the strongest surface and subsurface returns. As an interface dips away from  
155 horizontal, the focusing becomes less effective, and at high slope angles interfaces may  
156 disappear entirely due to the geometric limitation imposed by SHARAD's 135- $\mu$ s range window.  
157 Clutter signals from features off the nadir track of the spacecraft (e.g., crater walls, polar  
158 troughs) are often difficult to uniquely identify in a single radargram since they may focus well  
159 in 2-D (Fig. 1). A useful discriminator between clutter and subsurface returns is their relative  
160 "move-out." Typically, off-nadir surface features will shift much more in time delay between  
161 nearby, parallel ground tracks than near-horizontal reflectors at nadir. This type of analysis was  
162 demonstrated with data from the Apollo Lunar Sounder Experiment (Maxwell and Phillips,  
163 1978; Peeples *et al.*, 1978) using a graphical approach. For SHARAD, Mars elevation data and a  
164 model of the radar have been used to produce synthetic radargrams for identifying clutter  
165 (Choudhary *et al.*, 2016).

166 Over the course of the MRO mission, the coverage density of SHARAD observations in  
167 the polar regions has increased to the point where it has become feasible to treat each polar  
168 dataset as a 3-D volume rather than as a collection of 2-D profiles. This approach provides  
169 several advantages. At orbit crossings, data from multiple observations may be summed to  
170 improve the SNR proportionally to the square root of the number of overlapping data values  
171 (demonstrated with 2-D profiles by Campbell *et al.* (2015)). The 3-D imaging relies on a  
172 technique referred to as "migration" in seismic data processing (which usage differs in  
173 substantive ways from that employed in the field of radar processing) and described in detail  
174 below. Where features are well sampled by the radar, 3-D migration processing can unravel  
175 interfering nadir and off-nadir returns, effectively treating the latter as useful information on the  
176 geometry of off-nadir topography with respect to the nadir ground track.

177 Terrestrial active-source seismic surveys are designed to sample the subsurface in either a  
178 cross-sectional area (2-D acquisition with sources and receivers deployed in a line) or a volume  
179 (3-D acquisition with sources and receivers deployed in a grid). A fraction of the energy emitted  
180 by the sources that passes into the subsurface is reflected upward and recorded at receivers. The  
181 clarity of the recorded image depends on the acquisition parameters and the seismic complexity  
182 of the subsurface. In seismically complex areas, it is often necessary to apply certain processes to  
183 the data to correct geometric effects. To this end, migration has become a routine part of seismic  
184 data processing. Migration is a mathematical inversion process whereby the seismic image  
185 recorded at or near the surface is re-imaged to appear as if it were recorded directly above the  
186 subsurface points sampled by the wave field (French, 1974; Claerbout, 1985; Yilmaz, 1987;  
187 Yilmaz *et al.*, 1987a; Yilmaz *et al.*, 1987b). Migration converts the input seismic image to one in  
188 which subsurface features appear in their proper position laterally and vertically. In addition,  
189 migration improves resolution of the image by collapsing backscattered wave-field energy to the  
190 scattering point. Many migration algorithms have been developed and implemented to account  
191 for subsurface seismic complexity of various degrees (Stolt, 1978; Gazdag, 1978; Gray *et al.*,  
192 2001; Bednar, 2005).

193 Migration algorithms often require zero-offset data, wherein sources and receivers are  
194 nominally co-located. True zero-offset seismic surveys are not typical in practice because  
195 seismic sources (e.g., dynamite, airguns) are destructive, so additional processing steps are taken  
196 to produce pseudo-zero-offset data. For SHARAD, the same antenna transmits and receives the  
197 signals, with the spacecraft typically moving less than 10 m and Doppler processing accounting  
198 for the relative motion between the spacecraft and the surface, so the polar grids of 2-D

199 radargrams are already effective zero-offset 3-D volumes. Thus, it was possible to use zero-  
200 offset seismic processing methods to treat the SHARAD data over each polar region as a single  
201 3-D reflectivity volume (Foss et al., 2017). As implemented, 3-D migration addresses many of  
202 the limitations of interpreting single 2-D radargrams in areas of complex topography. For  
203 example, clutter returns in 2-D are “moved” in the 3-D volume to better align these returns with  
204 the surface topography from which they were reflected. In addition, the 3-D processing further  
205 improves the SNR largely through incoherent stacking of reflectors seen in multiple tracks.

206 Prior to carrying out the 3-D processing, it is necessary to correct ionospheric distortions  
207 and delays of the radar returns that vary in time and space. The dense grid of SHARAD coverage  
208 proved very useful in assessing and removing the relative ionospheric delays between tracks and  
209 along each track, a critical correction aimed at preserving the range resolution of the input data.  
210 As implemented for the standard processing of SHARAD data (Campbell and Phillips, 2014),  
211 these corrections are carried out in an autofocusing process (Campbell et al., 2014). In  
212 preparation for the 3-D imaging, we apply a so-called “demigration” process to each 2-D  
213 radargram that redistributes each sample along a hyperbolic 2-D diffraction curve (Foss et al.,  
214 2017). This step has the effect of repositioning reflectors to their zero-offset positions, resulting  
215 in a product that is similar to an unfocused radargram (e.g., Fig 1a). Next, all 2-D radargrams  
216 (2300 in the north and 2100 in the south for the current volumes) are assembled into a 3-D  
217 binning grid, wherein the grid size (475 m) is chosen close to the input 2-D frame interval. While  
218 spatial aliasing is theoretically possible at these bin sizes (e.g., see p. 191-196 of Liner, 2016),  
219 the data are effectively anti-aliased along-track in the 2-D pre-processing. Subsequent to the 3-D  
220 binning, a spatial interpolation is applied to fill coverage gaps—largest on the polar-cap  
221 periphery where tracks diverge—prior to further processing that culminates in the 3-D migration  
222 step (Foss et al., 2017), which “moves” reflectors from the locations where they were recorded to  
223 their true subsurface positions.

## 224 **4 Results and Discussion**

225 The geometric corrections and improved SNR afforded by these first SHARAD 3-D  
226 volumes are providing an improved understanding of the interior structure and stratigraphy of  
227 Planum Boreum and Planum Australe. Major subsurface structures that required substantial  
228 effort to map with collections of 2-D profiles (e.g., the surface of a basal unit (Brothers et al.,  
229 2015), a buried chasma (Holt et al., 2008), and a widespread shallow sequence providing  
230 evidence of a recent glaciation (Smith et al., 2016) in the north; interior layering and CO<sub>2</sub> ice  
231 deposits in the south (Phillips et al., 2011; Bierson et al., 2016)) are plainly visible in the  
232 volumes (Figs. 2 and 3; see also animations available at <http://sharad.psi.edu/3D>). At the same  
233 time, other features are newly imaged. In Planum Boreum, previously obfuscated unconformities  
234 and layered sequences below trough-rich regions above and within the basal unit (dashed red line  
235 in Fig. 2; Figs. 4a and 4b) provide new clues about the depositional history of the polar cap  
236 (Smith et al., 2016). In Planum Australe, many of the layers that are disrupted on individual  
237 observations can now be followed much further throughout the 3-D data volume, and geometric  
238 corrections provided by the 3-D imaging improve the view of buried structures (e.g., Figs. 4c and  
239 4d). In particular, the improved imaging of CO<sub>2</sub> ice deposits associated with the low reflectivity  
240 zones in Australe Mensa have allowed us to more confidently map their extents (Fig. 5). With  
241 extrapolation to geologic boundaries mapped inside the radar no-data zone surrounding the south  
242 pole, we find that these deposits contain about 16,500 km<sup>3</sup> of CO<sub>2</sub> ice, which is 11% larger than  
243 the previous estimate (Bierson et al., 2016) and corresponds to a mass 6% greater than that of the

244 current Martian atmosphere. Because SHARAD does not have complete coverage over the polar  
245 regions, some artifacts occur within the radar volumes. Specifically, surface and subsurface  
246 returns are not fully corrected in areas where the reflecting features do not have sufficient  
247 coverage for complete 3-D images, such as lower (~30%) coverage areas near the periphery of  
248 Planum Boreum and Planum Australe and locations along the high-latitude no-data zones.  
249 Examples of such artifacts are given in Figs. 4b and 4d.

250 In addition to providing geometric corrections, the 3-D volumes allow examination of the  
251 radar data in orientations not offered by the collection of 2-D profiles, such as constant delay-  
252 time or depth slices and profiles that need not follow the orbit trajectories (e.g., Figs. 2, 3, and 7).  
253 The slice views are especially useful for examining the distinctive radar signatures associated  
254 with known, partially buried craters. We find similar signatures elsewhere in both volumes but  
255 without surface expression (e.g., circled features in Figs. 2 and 3). Presumably fully buried  
256 craters, these features provide a potential means to constrain the ages of both the substrate and  
257 the overlying icy deposits that is independent of climate models. Identification of such apparent  
258 buried craters throughout the radar volumes is ongoing. Because the 3-D imaging process  
259 involves the use of a hyperbolic operator, hyperboloid (bowl-shaped) processing artifacts appear  
260 in the volumes, typically where radar coverage of features is incomplete. Given that craters are  
261 themselves bowl-shaped structures, one must take care to avoid mistaking such artifacts for  
262 buried craters. Since the material properties in the subsurface are assumed to be constant for the  
263 imaging process, the expected shape of isolated processing artifacts is well known, and this fact  
264 can be used to help discriminate artifacts from true structures.

265 For this work, we report our initial efforts to identify apparent craters at the base of the  
266 NPLD in Planum Boreum. We have identified and mapped 21 of these features (see map in Fig.  
267 6, radar examples in Fig. 7, and data in Table 1), ranging in size from 7 to 45 km in diameter.  
268 Smaller craters are difficult to resolve with the 475-m grid size of the 3-D volume. The materials  
269 underlying the NPLD are believed to be either the same as those in the surrounding plains or  
270 consisting of sand-rich basal deposits, which have been interpreted to have a similar age (i.e., the  
271 Hesperian “Vastitas Borealis interior” geologic unit in the surroundings and the Hesperian  
272 “rupēs,” and “cavi” geologic units at the base (Tanaka and Fortezzo, 2012)). Therefore, we  
273 compared our set of apparent craters to surface craters mapped previously in the polar region  
274 (Robbins and Hynek, 2012). In Fig. 8, we present cumulative size-frequency distributions for our  
275 set alone, for our set combined with surface craters in the same area (80°N–87.5°N), and for  
276 surface craters in the surrounding region (70°N–80°N) along with isochrons for various ages  
277 (Hartmann, 2005). In our analysis, we omit six features on Planum Boreum marked as surface  
278 craters by Robbins and Hynek (2012), having found no clear evidence of crater morphology in  
279 current high-resolution imagery. In general, we find a good agreement between the sets of  
280 craters, suggesting that the features we mapped are indeed buried craters present in units of the  
281 same age as that of the surrounding plains. At the smallest size bins, the distribution of apparent  
282 buried crater rolls off quickly, an indication of the lower limit of resolution where we were able  
283 to identify them in the radar volume. This first result lends some confidence to our ongoing  
284 effort to identify and map other buried craters within the overlying NPLD and in the south polar  
285 3-D volume. Given the relatively young age of the NPLD suggested by climate modeling results  
286 (e.g., Levrard *et al.*, 2007) and our limits of feature-size detectability, there may be too few  
287 apparent craters available within the icy layered deposits for a reliable age determination. A  
288 preliminary look at the Planum Australe volume suggests that there are many more apparent

289 buried craters within the SPLD than within the NPLD, likely reflecting a greater age and perhaps  
290 a sufficient number to provide a reliable cratering age.

291 As noted above, the 3-D imaging process correctly positions radar returns from features  
292 that are well sampled, and this applies to surface reflections as well as to subsurface ones.  
293 SHARAD coverage is very dense at the highest latitudes reached in MRO's orbit, and this allows  
294 us to produce maps of surface topography in addition to mapping subsurface features. While the  
295 lateral resolution of SHARAD is inferior to that of the Mars Orbiter Laser Altimeter (MOLA)  
296 onboard Mars Global Surveyor (MGS), MRO reached higher latitudes than MGS. Thus we are  
297 able to derive topographic maps for both polar regions between the maximum latitudes reached  
298 by MGS and MRO. In areas with equator-facing slopes, these maps extend somewhat poleward  
299 of the MRO maximum latitude due to off-nadir sampling by SHARAD that is corrected into  
300 these areas by the 3-D imaging process. In areas with pole-facing slopes, there are gaps where no  
301 returns are obtained by SHARAD. In Fig. 10, we present revised topographic maps of the polar  
302 regions as extensions of the MOLA 128-pixel-per-degree gridded maps (Smith *et al.*, 2003)  
303 using the SHARAD-derived topography. In addition to providing new topographic data in a total  
304 area of 28,500 km<sup>2</sup> for both poles, the improvement in topography will also be of benefit for  
305 creating more accurate clutter simulations (e.g., Choudhary *et al.*, 2016) along the tracks of  
306 individual SHARAD polar observations.

307 In the course of assembling SHARAD observations into a 3-D volume, it was discovered  
308 that the delay to the surface at track intersections differs between observations taken on different  
309 orbits (Foss *et al.*, 2017). The problem was found to pervade the entire SHARAD dataset (polar  
310 and non-polar) and has multiple causes, one of which is variable spacecraft-to-surface delay  
311 times at the same locale due to the constantly changing state of the ionosphere (Campbell *et al.*,  
312 2011). While a means was developed to account for the majority of the delay offsets (Campbell  
313 *et al.*, 2014), residual delays remain in both volumes. These residuals combined with incomplete  
314 coverage in the 475-m × 475-m binning grids impact the quality of the 3-D volumes, most  
315 notably by reducing the effective vertical resolution by a factor of ~2 relative to the input 2-D  
316 radargrams. Specifically, finer shallow layering and smaller structures evident in the input 2-D  
317 observations are not resolved as well in the 3-D volume (see Fig. 4). This loss of resolution  
318 hampers the ability to improve upon prior efforts to correlate radar layering with that seen in  
319 visible imagery (e.g., Milkovich *et al.*, 2009; Phillips *et al.*, 2009; Christian *et al.*, 2013), to map  
320 minor troughs and near-surface undulations linked to climate signals (e.g., Smith and Holt, 2015;  
321 Smith *et al.*, 2016), and to visualize small structures. As noted above, another limitation of the  
322 radar volume is the incomplete correction of clutter in areas with SHARAD coverage that is  
323 coarser than the 3-D grid size. A continuing effort will attempt to reduce the residual delays, and  
324 SHARAD data acquisition is ongoing with a goal of infilling coverage in areas targeted for 3-D  
325 processing. Additional processing improvements are being considered and may enable mapping  
326 of changes in dielectric properties within the volumes, among other improvements (Foss *et al.*,  
327 2017). In the meantime, these first 3-D volumes provide superior imaging of the larger-scale  
328 features and views of the data that are not possible with the collection of 2-D profiles (e.g., slices  
329 and transects through the volumes in any direction). These factors allow refinement of previously  
330 mapped feature boundaries and the discovery of new features, such as the apparent buried  
331 craters.

## 332 5 Conclusions

333 SHARAD observations on thousands of orbital passes by MRO over Planum Boreum and  
334 Planum Australe have enabled the construction of 3-D data volumes encompassing the Martian  
335 polar ice caps. Each volume has undergone 3-D migration processing, an imaging method that  
336 corrects off-nadir returns (clutter) and properly positions internal structures while improving the  
337 overall SNR (Foss et al., 2017). Clutter mitigation and the structural corrections that migration  
338 provides have been particularly effective, supporting the mapping of a shallow unconformity  
339 linked to the most recent retreat of mid-latitude glaciation (Smith et al., 2016) and an improved  
340 volume estimate for buried CO<sub>2</sub> ice discovered with 2-D profiles. In addition, the clarified view  
341 provided by the 3-D volumes reveals what appear to be impact craters fully buried below and  
342 within the icy layered deposits. In a first effort to map them in the radar data, we find 21 of these  
343 features at the base of the NPLD with diameters between 7 km and 45 km, consistent with the  
344 size and distribution of surface craters in the surrounding plains. A more complete assessment of  
345 buried craters within both PLDs may provide new constraints on the ages of these deposits that is  
346 independent of climate models, but detecting a statistically sufficient number for accurate  
347 cratering dates may be challenging due to the expected relatively young age of the deposits. In  
348 general, the clarified views of the polar-cap interiors emerging from the polar SHARAD 3-D  
349 volumes is enhancing our ability to map interior structures and infer the history of their  
350 emplacement. Ongoing work to improve the vertical resolution and coverage for polar SHARAD  
351 volumes is likely to yield more insights and discoveries, allowing more advancement toward the  
352 overarching goal of linking the geologic history of the polar deposits to climate processes and  
353 their history.

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363 available on the Geosciences node of the Planetary Data System (PDS) from the SHARAD  
364 archive page at <http://pds-geosciences.wustl.edu/missions/mro/sharad.htm>. Animations currently  
365 available at <http://sharad.psi.edu/3D> will be included as PDS supplemental products.

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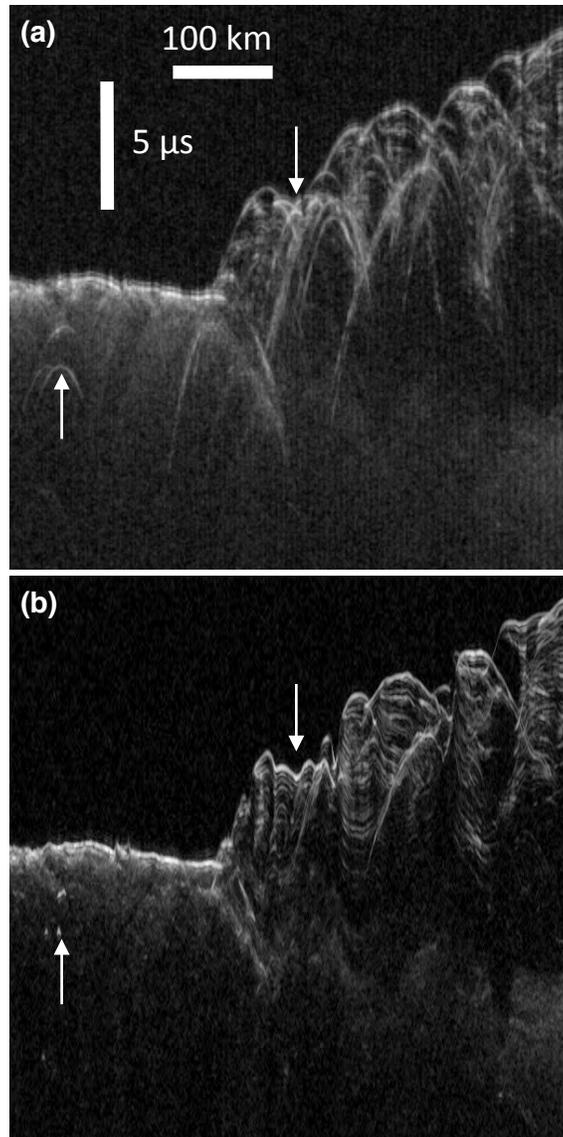
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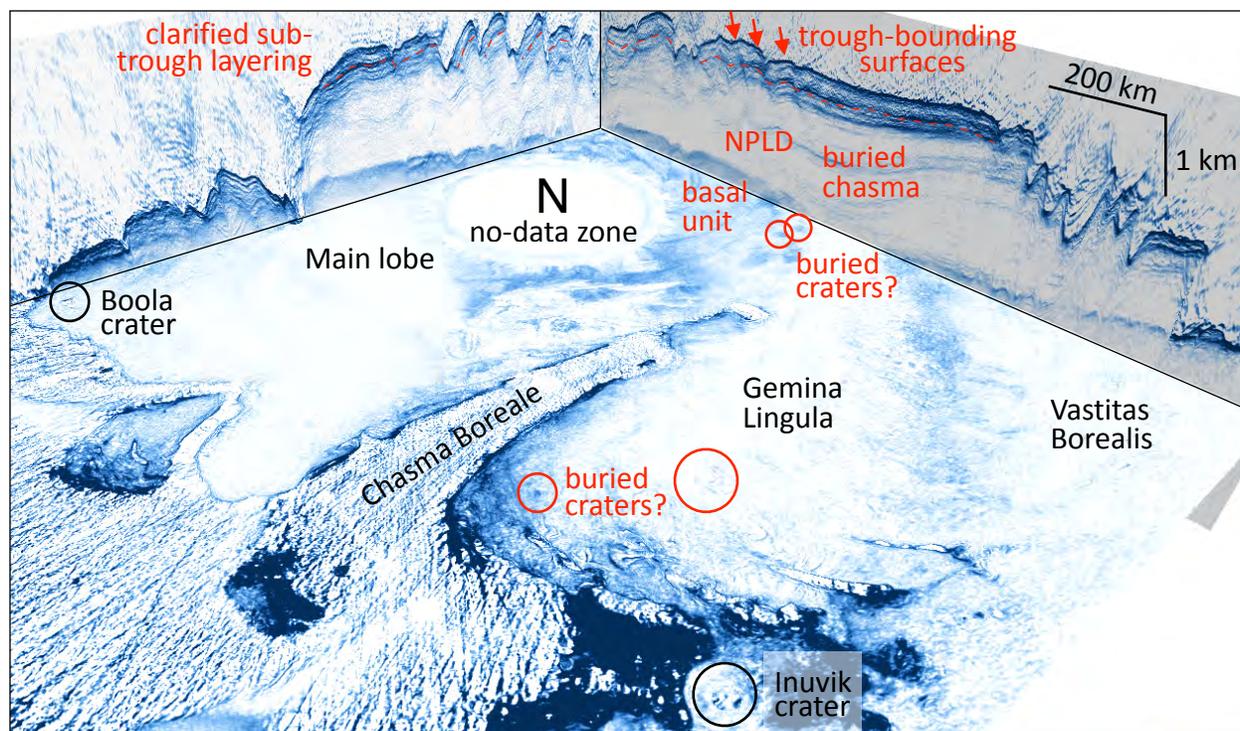
**Table 1.** Sizes and locations of apparent fully buried craters at base of NPLD.

Max. diam. (km)	Min. diam. (km)	Latitude (°N)	Longitude (°E)	Elevation <sup>1</sup> (m)	Depth (m)
45.3	39.0	85.142	94.159	-4621	1671
41.0	35.2	86.872	-130.547	-1011	1571
38.0	24.9	82.241	-124.299	-4237	193
37.5	36.6	81.627	94.746	-3591	589
29.2	28.4	83.024	-99.549	-2932	617
26.0	22.4	84.628	146.064	-4165	145
25.0	23.8	86.246	-111.275	-1657	1159
23.9	22.0	85.303	35.438	-1297	1624
22.8	21.8	82.025	-8.989	-1816	1564
22.7	20.7	80.432	9.181	-2066	1388
21.9	20.9	81.596	-64.877	-3747	144
17.6	17.3	83.316	-31.256	-3550	758
17.3	16.5	81.103	50.096	-3813	431
17.0	11.1	85.800	-78.893	-1816	1070
16.1	15.5	82.603	-23.431	-2376	1350
14.7	14.5	82.990	26.772	-1292	1764
14.1	13.8	81.598	-24.158	-2442	1328
11.8	11.7	83.282	-4.919	-1874	1536
11.5	11.2	81.628	4.810	-1467	1717
11.4	9.4	82.007	-93.365	-3845	186
7.3	6.6	82.939	-3.201	-1684	1624

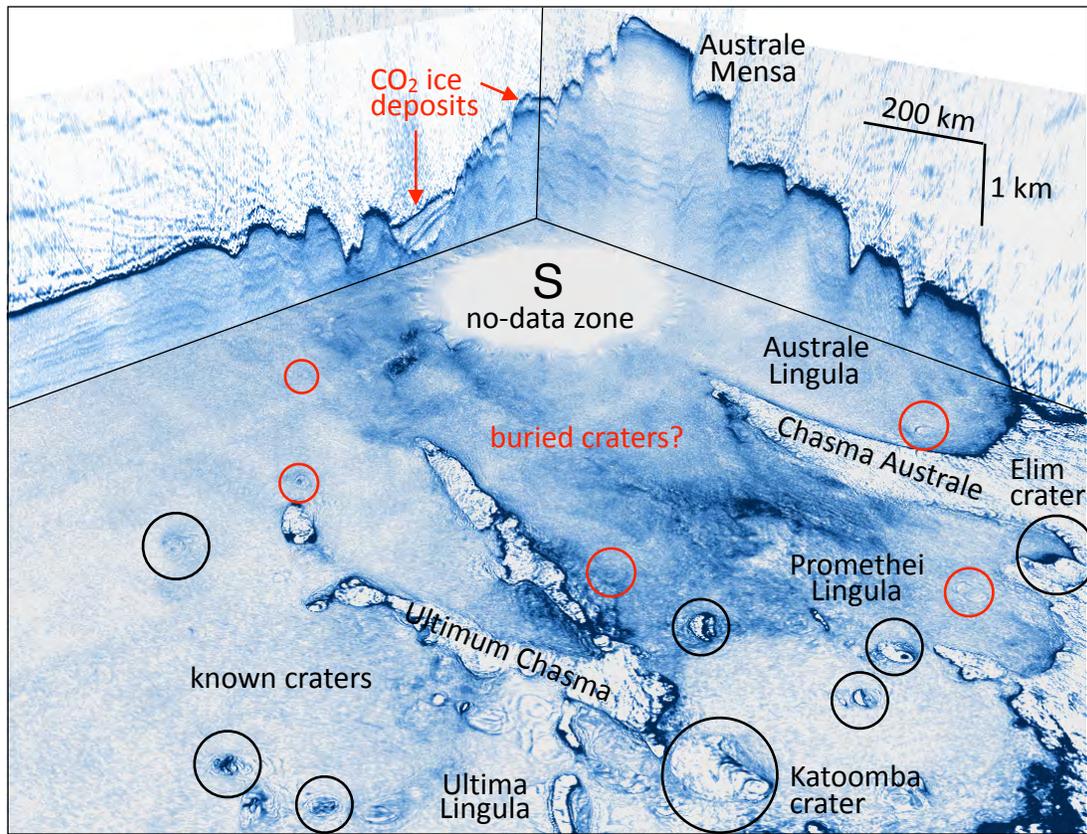
<sup>1</sup> Elevations measured at deepest point near the center of each apparent crater.



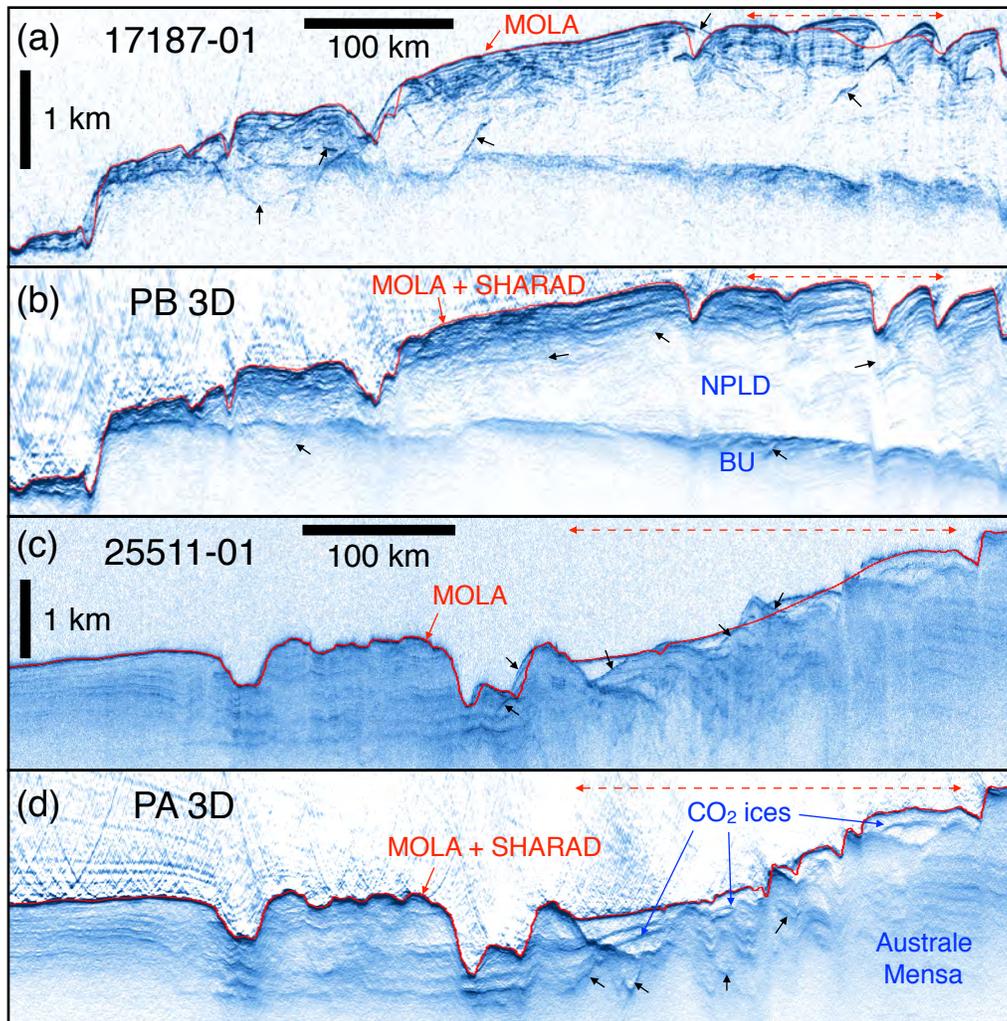
**Figure 1.** Radargrams (profiles of power in delay time vs. along-track distance) for SHARAD observation 19777-01 in a trough-rich area of the NPLD. (a) Echoes in the unfocused image appear as hyperbolic arcs centered on ground features. (b) 2-D focusing combines echoes with appropriate phase and time-delay shifts to produce a view of surface and subsurface reflectors in finer along-track resolution and higher SNR. Arrows show effects of focusing for an off-nadir surface clutter source (left) and for a surface depression (right).



**Figure 2.** Cut-away perspective view (toward 150°E) into the depth-converted Planum Boreum SHARAD 3-D volume, showing radar-return power (blue high, white low) from previously known (black) and buried (red) features within the north polar cap. The SHARAD no-data zone is due to MRO's orbit inclination. Depth conversion assumes pure water ice ( $\epsilon' = 3.15$ ). Scale is approximate (varies in this perspective), with vertical exaggeration of 136:1.

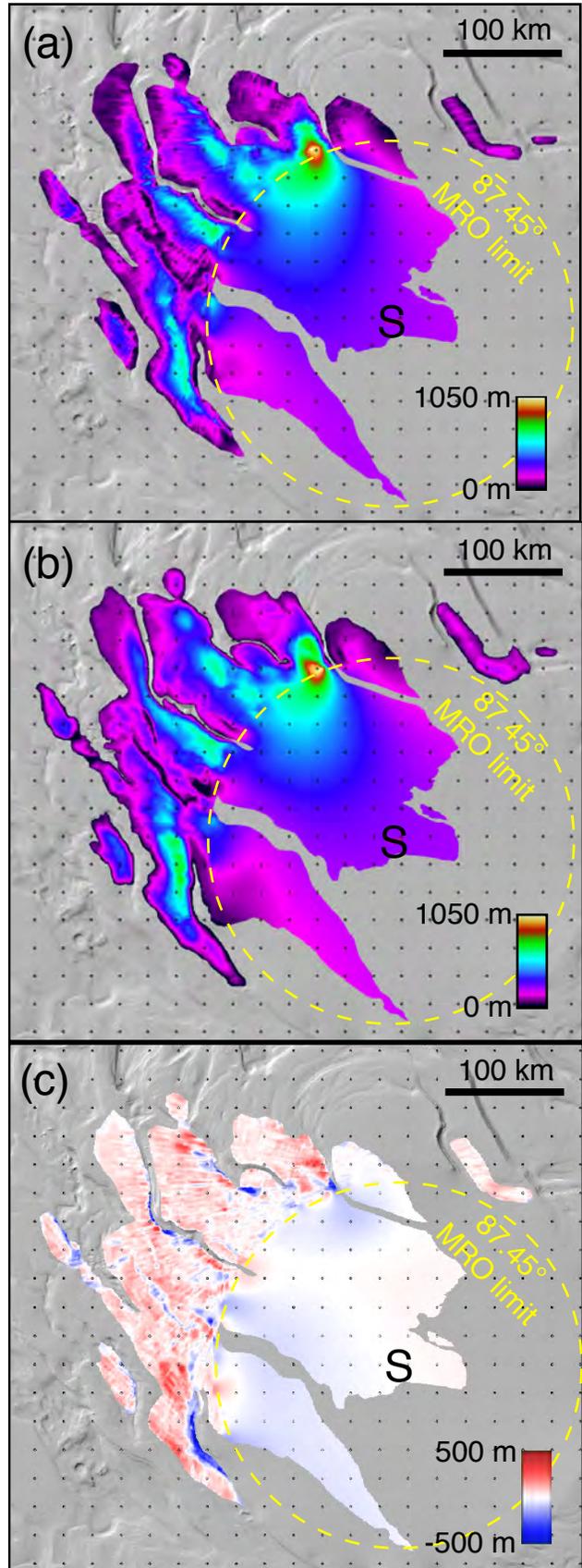


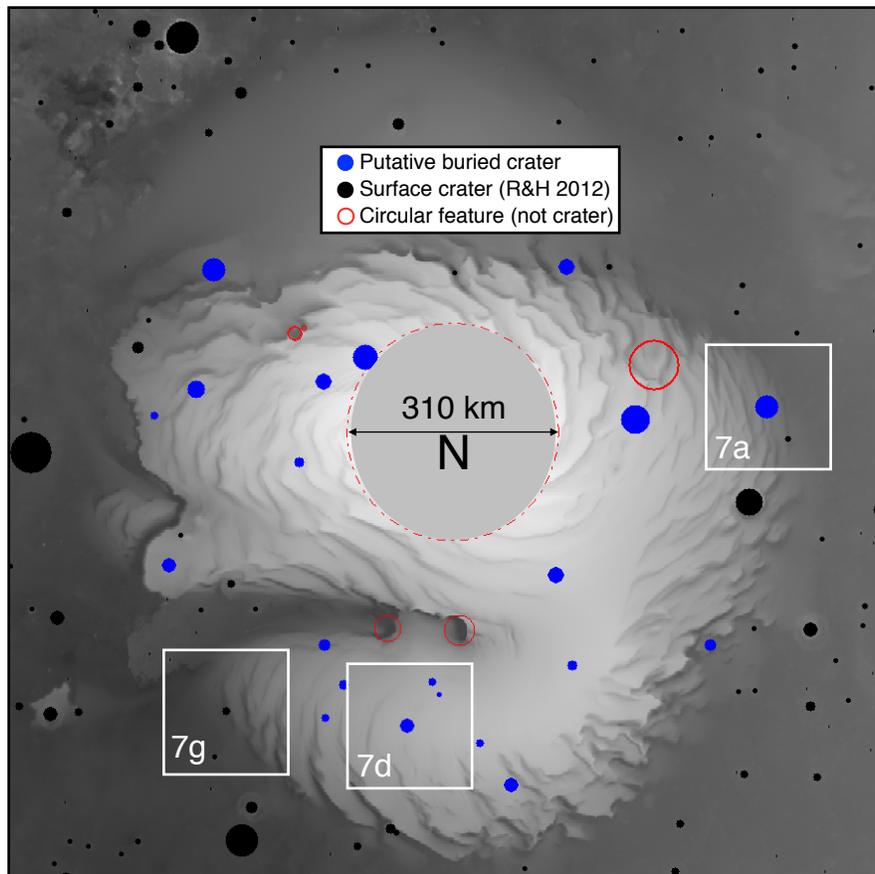
**Figure 3.** Cut-away perspective view (toward 315°E) into the depth-converted Planum Australe SHARAD 3-D volume, showing radar-return power (blue high, white low) from previously known (black) and buried (red) features within the south polar cap. The SHARAD no-data zone is due to MRO's orbit inclination. Depth conversion assumes pure water ice ( $\epsilon' = 3.15$ ). Scale is approximate (varies in this perspective), with vertical exaggeration of 136:1.



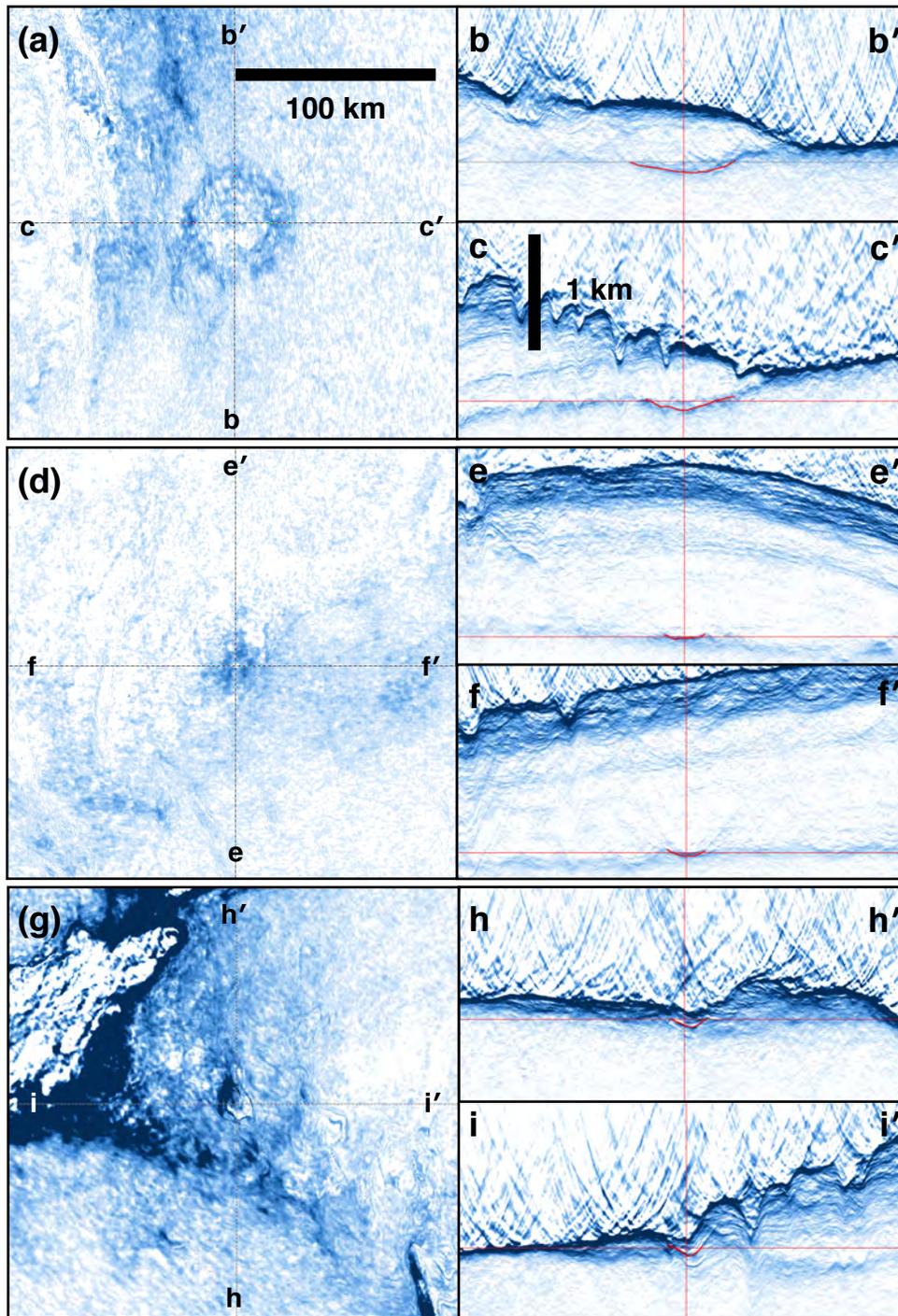
**Figure 4.** (a, c) SHARAD depth profiles for single-orbit crossings compared to (b, d) profiles extracted from the corresponding 3-D volumes along the same ground tracks in Planum Boreum (a, b) and Planum Australe (c, d). 3-D imaging corrects surface and subsurface structures, separating the interfering nadir and off-nadir returns evident in the 2-D profiles, and enhancing SNR at depth but with some loss of vertical resolution. Black arrows in (a, c) indicate examples of clutter signals largely corrected by 3-D processing. Black arrows in (b, d) indicate examples of likely artifacts in the 3-D volumes due to incomplete correction of off-nadir echoes from features with inadequate SHARAD coverage. Red lines are the MOLA-derived surface profile along each ground track, replaced by the SHARAD-derived surface in (b) and (d) in the zones indicated by red dashed arrows where SHARAD observes higher latitudes than MOLA did. Depth conversion assumes pure water ice ( $\epsilon' = 3.15$ ). See Fig. 9 for ground-track locations.

**Figure 5.** Maps of CO<sub>2</sub> ice thickness in Australe Mensa using (a) a collection of 429 SHARAD 2-D profiles (Bierson et al., 2016) and (b) using the SHARAD 3-D volume, and (c) the difference between the 3-D and 2-D thickness maps. Orbit-track-aligned lineations and patchwork in the 2-D thickness map are largely the result of interpolation. The improved 3-D imaging of subsurface structures provides more confidence in locating the deposit and in estimating the volume of CO<sub>2</sub> ice, which we find to be 16,500 km<sup>3</sup> (11% larger than the 2-D-based result).

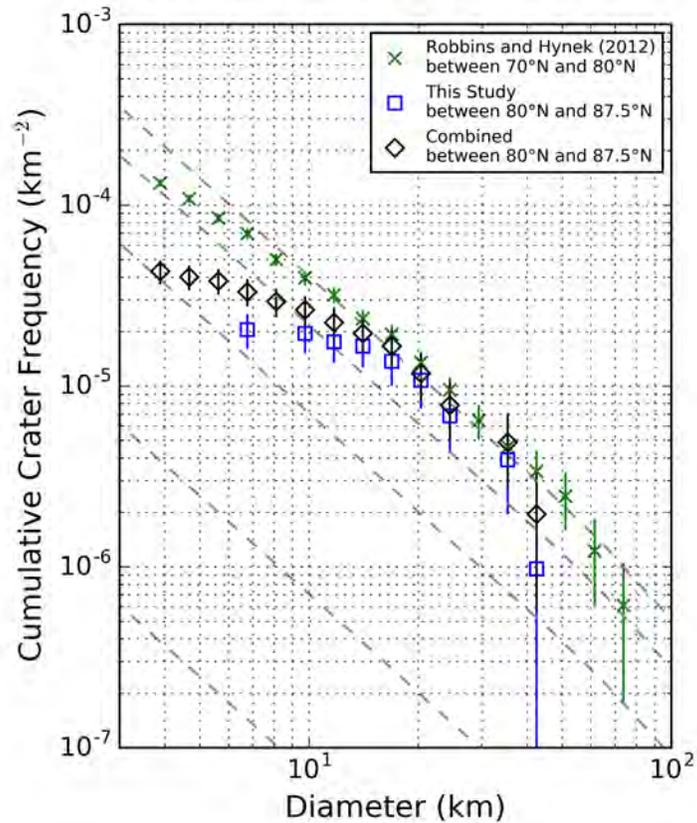




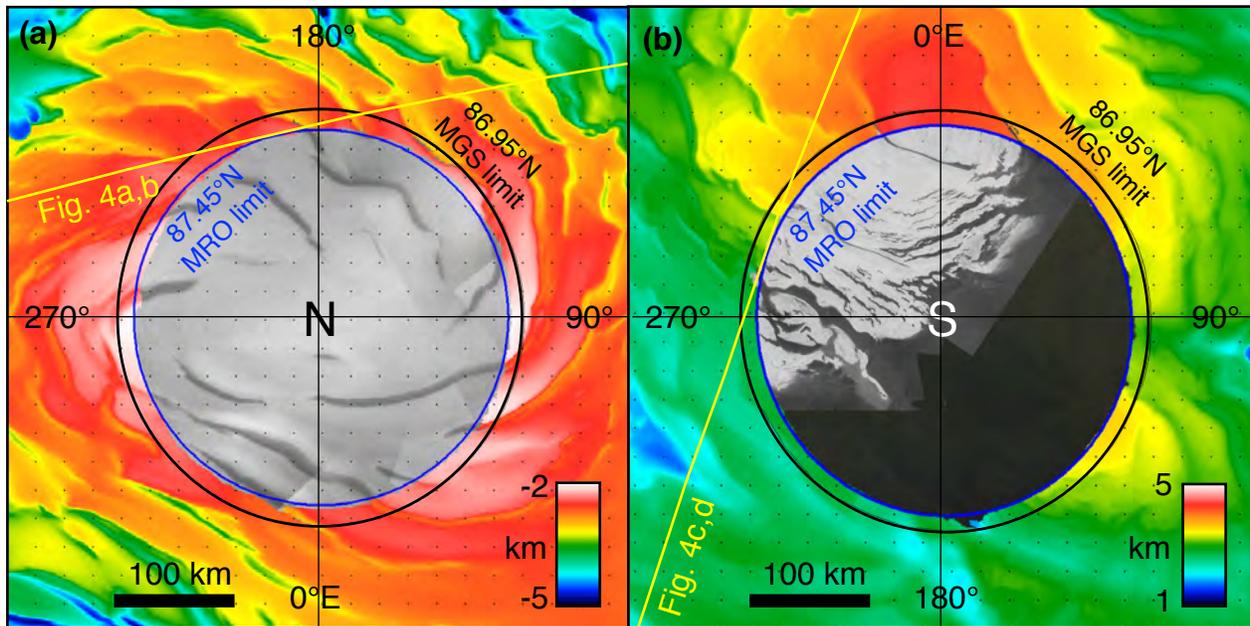
**Figure 6.** Locations of craters larger than 4 km in diameter as previously mapped with surface data (black circles; Robbins and Hynek, 2012) and of apparent buried craters (blue circles) that we mapped in the Planum Boreum 3-D radar volume at the base of the NPLD. We found six Robbins and Hynek (2012) features (red circles) to be questionable as craters and omitted them from our analysis (Fig. 8). Circles are scaled to the maximum diameters of each feature. White boxes show bounds of radar views in Fig. 7 of the apparent or known crater at the center of each box. Base map is MOLA 128-ppd elevation (Smith et al., 2003) (black low, white high).



**Figure 7.** SHARAD 3-D radar views of (a-f) two apparent fully buried craters and (g-i) one partially buried, known crater, showing (a, d, g) constant-depth slices, (b, e, h) inline profiles aligned with 0-180°E, and (c, f, i) crossline profiles aligned with 270-90°E. Bold red lines on each profile show interpreted extents of crater. Traces of orthogonal views align with crosshairs in each panel and scale bars apply to all panels. See Fig. 6 for location of depth slices.



**Figure 8.** The cumulative size-frequency distribution of the apparent fully buried craters at the base of the NPLD (blue squares) matches well with that of previously mapped surface craters (Robbins and Hynek, 2012) in terrains surrounding Planum Boreum (green crosses) for diameters between 15 and 35 km. When the apparent buried craters and known surface craters within Planum Boreum are taken together (black diamonds), the correspondence improves. Isochrons (dashed lines, Hartmann, 2005) from lower left to upper right are for 10, 100, 1000, 3000, and 3500 Ma. Vertical lines show 1- $\sigma$  confidence intervals. See Fig. 6 for crater locations.



**Figure 9.** Topography of (a) Planum Boreum and (b) Planum Australe. At latitudes below the highest reached by MGS (black circles,  $\sim 86.95^\circ$ ), the maps show MOLA 128-pixel-per-degree gridded topography (Smith et al., 2003). At higher latitudes up to the highest reached by MRO (blue circles,  $\sim 87.45^\circ$ ) the maps show SHARAD-derived topography in a total area of 28,500 km<sup>2</sup>. The SHARAD data show fidelity to finer structures (e.g., undulations at  $87^\circ\text{N}$ ,  $265^\circ\text{E}$ ) and data drop-outs or poleward excursions in steeply dipping terrains. Image mosaics inside the MRO circles are from (a) Viking MDIM and (b) MRO CTX (courtesy of Peter Thomas).