INTERIOR OF MARS' PLANUM BOREUM FULLY IMAGED IN A 3-D VOLUME OF SHARAD DATA.

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Introduction: We will present a three-dimensional (3-D) volume of radar data from observations taken by the Shallow Radar (SHARAD) instrument on 1579 orbits of the Mars Reconnaissance Orbiter (MRO). This volume encompasses the entirety of Planum Boreum, the dome of ice-rich deposits that forms the north polar cap of Mars, and will provide a greatly improved view of the internal structure from the surface to the base of the deposits at depths of ~2–3 km. Major features of the Planum Boreum interior that required painstaking effort to identify and map with 2-D radargrams (images of power along track vs. delay time) are readily identified in a 3-D data volume [1], even with a preliminary sparse volume that has no geometric corrections applied (Fig. 1). Prior to this conference, we expect to have applied those corrections to a fully populated 3-D volume using an imaging process known as migration. We anticipate the discovery of new features below large regions of Planum Boreum that are largely undecipherable in 2-D radargrams due to interference from off-nadir surface returns from polar troughs.

SHARAD Observations: SHARAD operates with a 10-MHz bandwidth centered at 20 MHz. Range resolution is 15 m in free space, ~8 m in nearly pure water ice (expected for the Planum Boreum layered deposits [2-4]), and still finer in ice with a greater proportion of lithic inclusions (likely in the Planum Boreum basal deposits). With the MRO orbit altitude of 250–320 km, the lateral resolution at the surface is ~3–6 km (1–2 Fresnel zones), reducible along track to 0.3–1.0 km in processing [5]. High-power returns indicate a strong contrast in the dielectric properties of materials at a geologic interface. In the polar terrains of Mars, the reflections likely arise from different degrees of dust or lithic loading between adjacent ice layers [3, 4, 6].

Off-nadir returns. Surface features (e.g., hills, crater walls, polar troughs) off of the spacecraft's nadir track often yield reflections, termed *clutter*, that can be difficult to distinguish from nadir returns. Internal structure—such as dipping or folded layering—may result in the mislocation of features with 2-D methods. The use of synthetic-aperture focusing in creating 2-D radargrams compresses the response from along-track scatterers but not from cross-track scatterers, leaving a structural blur in the data. In addition, the signal-to-noise ratio (SNR) can be quite low when material properties lead to substantial scattering or absorption.

SHARAD studies typically have used elevation data to produce synthetic radargrams for identifying surface clutter [e.g., 4, 7], but this technique does not address clutter obfuscation of nadir subsurface returns, mispositioning of internal structures, and signal losses. Fortunately, dense radar coverage allows treating the data collectively in a volume and applying migration processing that will largely correct structural distortion effects by placing signals in their correct locations in 3-D space while improving their SNR.

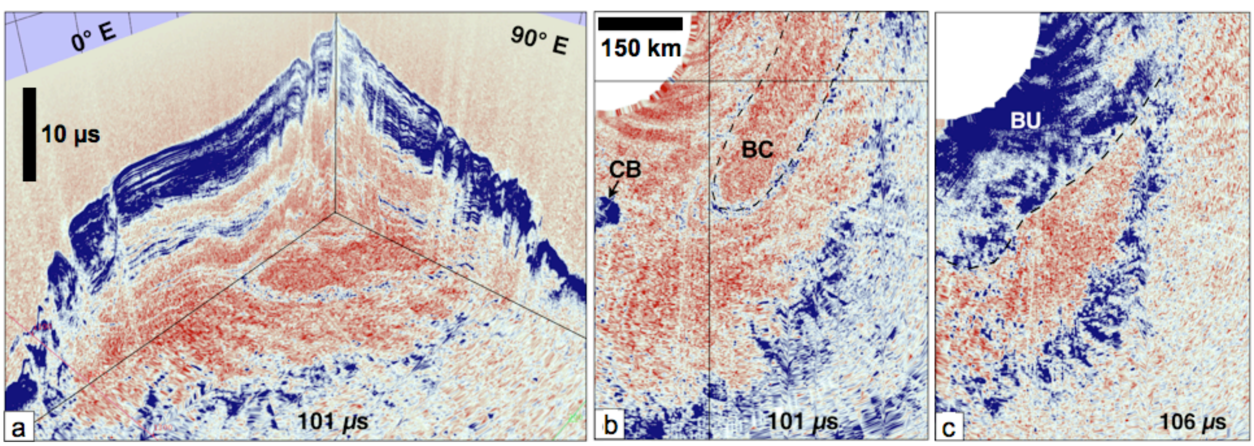

Figure 1. Cut-away view (a) *and timeslices at constant delay* (b,c) *taken from an unmigrated 3-D volume produced with 540 SHARAD tracks. Views show the radar return power (blue high, red low) from the interior of Planum Boreum. A buried chasma* (BC) *first identified by Holt et al. (2010) appears in the 101-µs timeslice* (a,b) *as a horseshoe feature (dashed line in* b*) to the east of Chasma Boreale* (CB)*; adjacent timeslices (not shown) confirm its synclinal structure. Near the base of the layered deposits, the timeslice at 106 µs* (c) *shows in unprecedented detail the boundary (dashed line) of the basal unit* (BU) *at depth. After Putzig et al.* [1].

Time delays. Prior to applying the migration process, the along-track data must be corrected for any relative time delay introduced by the variable orbit altitude and the Martian ionosphere. While accurate ephemeris data enables a straightforward altitude correction, we found that the ionospheric delay varies substantially along track and from one orbit to another. A substantial effort successfully produced an accurate method for estimating those delays [8].

Migration Processing: The occurrence in seismic data of the geometric and loss concerns discussed above led to the development of migration, a mathematical inversion process that converts the recorded seismic image to one in which subsurface features appear in their proper position both laterally and vertically (in time or depth) [9, 10]. Migration also improves resolution by collapsing backscattered wavefield energy to the scattering point. Many migration algorithms have been developed to account for various degrees of subsurface seismic complexity [11-14]. Applied to orbital radar data, 3-D migration will address many limitations of 2-D radargrams. For example, clutter returns treated as noise in 2-D become useful signals in 3-D, enhancing the resulting image upon being repositioned to their source locations. Interfering returns are unraveled and internal structures are properly positioned. In addition, SNR improves by a combination of band-limited, spatial-domain processing and incoherent summation of reflectors seen in adjacent and crossing orbit tracks.

Previous Work: Analysis of SHARAD data from Planum Boreum has revealed a pervasive, broadly continuous stack of layers, with packets of finely spaced layers overlying relatively homogeneous inter-packet zones, where each sequence may correspond to obliquity cycles of ~1 Ma [3, 4]. Holt et al. [15] delineated unconformities and mapped a buried chasma to the east of the topographic saddle that separates Gemina Lingula from the main lobe of Planum Boreum. Beneath the finely layered deposits, diffuse returns extend down to the level where the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) obtained a strong return from a basal unit [16]. The diffuse zone corresponds to geologic units at the base of the finely layered deposits identified previously from image data [17-19].

Preliminary Results: We created a 3-D volume from 540 SHARAD ground tracks crossing the topographic saddle between Gemina Lingula and the main lobe of Planum Boreum [1]. Coverage fold in the 500×500-m bins ranges from 0 to 33 tracks per bin, highest at the orbital tangent latitudes near 87°N. Figure 1 presents some views of the volume, with empty bins infilled for clarity. Even with this sparsely populated, unmigrated 3-D volume, features such as the internal trough-migration paths mapped by Smith and Holt [20], the buried chasma mapped by Holt et al. [15], and the basal-unit boundary mapped by Putzig et al. [4] are revealed in detail. Migration processing will sharpen these and other previously mapped structures, and inclusion of the full data set in this process will allow the delineation of many new features throughout Planum Boreum.

Discussion: Efforts to fully correlate radar reflections in polar layered deposits to layering seen in image data [e.g., 21, 22, 23] have been hampered by loss of signal due to overlap with clutter returns, scattering, and attenuation. While synthetic radargrams are useful to avoid mistaking clutter as subsurface returns, 3-D migration will largely unravel the interfering signals, allowing more confident interpretation of subsurface structure and greater ability to follow reflection events to their terminations in regions where jumbled signals are currently indecipherable. Clarifying these features will allow major advancements toward the overarching goal of linking the geologic history of the polar layered deposits to climate processes and their history.

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