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Integrating radar stratigraphy with high resolution visible stratigraphy of the north polar layered deposits, Mars

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ABSTRACT

Shallow Radar (SHARAD) on board NASA's Mars Reconnaissance Orbiter has successfully detected tens of reflectors in the subsurface of the north polar layered deposits (NPLD) of Mars. Radar reflections are hypothesized to originate from the same material interfaces that result in visible layering. As a first step towards verifying this assumption, this study uses signal analyses and geometric comparisons to quantitatively examine the relationship between reflectors and visible layers exposed in an NPLD outcrop. To understand subsurface structures and reflector geometry, reflector surfaces have been gridded in three dimensions, taking into account the influence of surface slopes to obtain accurate subsurface geometries. These geometries reveal reflector dips that are consistent with optical layer slopes. Distance–elevation profiling of subsurface reflectors and visible layer boundaries reveals that reflectors and layers demonstrate similar topography, verifying that reflectors represent paleosurfaces of the deposit. Statistical and frequency-domain analyses of the separation distances between successive layers and successive reflectors confirms the agreement of radar reflector spacing with characteristic spacing of certain visible layers. Direct elevation comparisons between individual reflectors and discrete optical layers, while necessary for a one-to-one correlation, are complicated by variations in subsurface structure that exist between the outcrop and the SHARAD observations, as inferred from subsurface mapping. Although these complications have prevented a unique correlation, a genetic link between radar reflectors and visible layers has been confirmed, validating the assumption that radar reflectors can be used as geometric proxies for visible stratigraphy. Furthermore, the techniques for conducting a stratigraphic integration have been generalized and improved so that the integration can be undertaken at additional locations.

1. Introduction

Investigation of the astronomical theory of climate change prompted a revolution in the detection (Emiliani, 1955), correlation (Hays et al., 1969; Shackleton and Opdyke, 1973) and analysis (Hays et al., 1976; Imbrie and Imbrie, 1980) of periodic signals in Earth's geologic record. Testing the hypothesis of orbital climate forcing required an enormous effort in pioneering new techniques for the quantification of geological data. New paleoclimate proxies had to be discovered (Emiliani, 1955), and accepted methods and interpretations had to be reevaluated and altered (Shackleton, 1967) or even abandoned entirely (Kukla, 1977). The hypothesis was ultimately confirmed by synthesizing multiple records, including sedimentary, geochemical and paleomagnetic, that when integrated provided a comprehensive history of Earth's climate cycles (Imbrie, 1982).

Concurrent with rapid advances occurring in terrestrial climate science, the discovery of layering in the polar deposits of Mars (Murray et al., 1972; Figs. 1b and 2) provided the only empirical evidence for periodic climate change on a planet other than Earth (Cutts et al., 1976) and excited the prospect of a robust martian climate record (Cutts, 1973). The expectation of discovering such a record in the stratigraphy of the polar layered deposits (PLD) has persisted (Fishbaugh et al., 2008), leading to a sustained effort to fully characterize layering (Fishbaugh et al., 2010a). As a result, determining the optical (Blasius et al., 1982; Fishbaugh and Hvidberg, 2006), spectral (Milkovich and Head, 2005; Perron and Huybers, 2009), and radar (Picardi et al., 2005; Phillips et al., 2008) characteristics of the PLD remains an active area of research (Fishbaugh et al., 2008).

Two leading perspectives of PLD stratigraphy have emerged from the resultant studies. High resolution images from Mars Reconnaissance Orbiter's (MRO) High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007) and Context Camera (CTX) (Malin et al., 2007) have prompted spatially-isolated,

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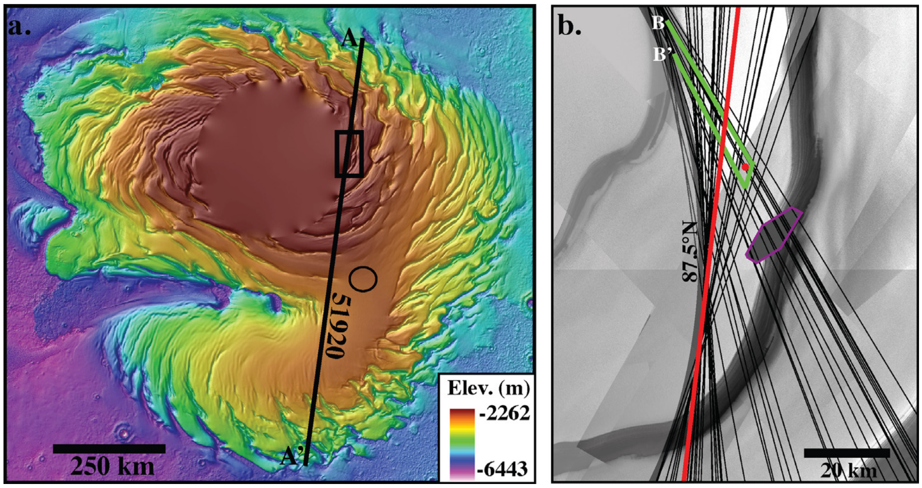

Fig. 1. (a) Mars Orbiter Laser Altimeter (MOLA) topography of Planum Boreum overlain by a hillshade. Context box shows location of Fig. 1b. SHARAD observation 51920 is shown in Fig. 3. Circle denotes area containing line intersections used in the crossover analysis. (b) Study site of data set integration. Black lines show SHARAD observations used to construct subsurface interfaces. Observation 51920 is shown in red, and transect B–B′ (shown in green) gives the location of Fig. 4. The location of a model radar trace is denoted by a red circle. The DEM footprint is shown in gray, outlined in purple.

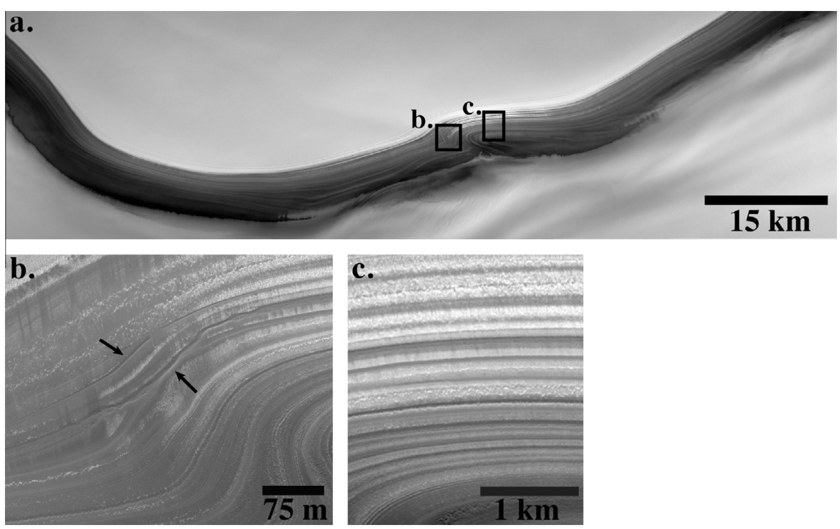

Fig. 2. (a) CTX image P02_001738_2671 shows layering at the study site at a resolution of 6 m/pixel. (b and c) are subimages of HiRISE image PSP_001871_2670 and show layers in high resolution (25 cm/pixel). An angular truncation surfaces, denoted by arrows, are visible in (b).

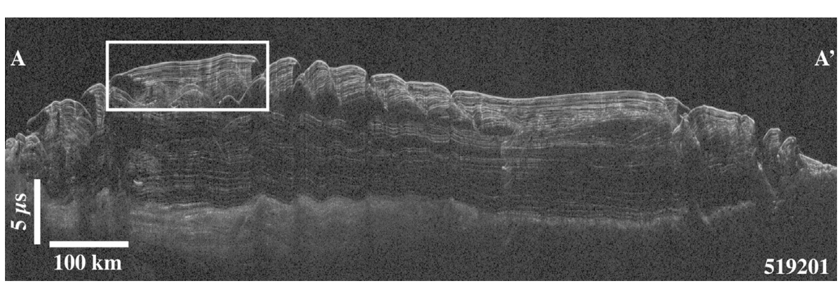

Fig. 3. SHARAD observation 519201. The location of the subsurface study site is outlined by the white box. Transect location is shown in Fig. 1a.

morphologically- and topographically-detailed descriptions of the north PLD (NPLD) surface (Fishbaugh et al., 2010a, 2010b). In contrast to the meter-scale description and delineation of surficial expressions of layering, MRO's Shallow Radar (SHARAD) (Seu et al., 2007) has resolved material changes in the NPLD subsurface (Phillips et al., 2008; Fig. 3). As a result, the definition of an internal radar stratigraphy over 100s of kilometers is possible (Putzig et al., 2009; Holt et al., 2010), albeit at an order of magnitude lower resolution than is common in surface studies (McEwen et al., 2007; Seu et al., 2007).

Apparent repetitions in both visible (Laskar et al., 2002; Milkovich and Head, 2005; Fig. 2) and radar (Phillips et al., 2008;