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Large-scale deformational systems in the South Polar Layered Deposits (Promethei Lingula, Mars): "Soft-sediment" and Deep-Seated Gravitational Slope Deformations Mechanisms

Luca Guallini [a,*], Francesco Brozzetti [b], Lucia Marinangeli [a]

[a] International Research School of Planetary Sciences, Dipartimento Scienze Umanistiche e della Terra, Università "G. d'Annunzio", Via dei Vestini, 31, 66100 Chieti Scalo, Italy
[b] Geodynamics and Seismogenesis Laboratory, Dipartimento Scienze Umanistiche e della Terra, Università "G. d'Annunzio", Via dei Vestini, 31, 66100 Chieti Scalo, Italy

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ABSTRACT

The present study is the first attempt at a detailed structural and kinematic analysis of large-scale deformational systems observed in the South Polar Layered Deposits (SPLDs) in the Promethei Lingula (PL) margins (Mars). By systematically collecting attitude data referable to previously unknown deformational structures and defining the cross-cut relationships of the structures, we reconstructed a deformational history consisting of two superimposed, well-defined stages. The first stage is dominated by large-scale strike–slip and transtensional faults arranged into conjugate systems and delimiting shear zones that show a wide range of subsidiary structures, including normal and reverse faults, drag folds, boudins, S–C tectonites and sub-horizontal interstratal shear planes marked by sygmoidal boudins. Other typical structures referable to this event are ductile folds (locally true convolute folds) and lobes (ball-and-pillow structures) affecting certain marker beds of the succession. We suggest that the structural assemblage might be the expression of a shallow soft-sediment tectonics that possibly occurred during warm periods of the South Pole climate.

The second stage seems to affect the weaker and in certain cases pre-deformed stratigraphic levels of the SPLD succession. This stage is mainly characterized by extensional deformations caused by gravity. The consequence of the deformations is the nucleation of Deep-Seated Gravitational Slope Deformations (DSGSDs) marked by typical morphostructures, such as scarps, trenches and bulging basal contractant zones. These phenomena were never observed within an ice cap. According to terrestrial modeling, these slow collapses were caused by (1) the presence of detachment levels (i.e., subhorizontal bedding planes) along which the ice-sheet margins can slide and (2) the development of listric faults within the glacial mass, which merge with sub-horizontal shear planes in the subsurface.

The presence of complex deformational systems in the SPLD necessarily implies that a large-scale dynamics of the ice-sheet occurred in the past. The relatively fast internal creep and basal/internal sliding, inferable from the structure assemblage, can be due to partial melting of the ice possibly caused by climatic changes in the Promethei Lingula region. In this manner, we believe that climate heating (which, according to the literature, is likely caused by orbital variations) softened some of the SPLD layers, triggering or accelerating the ice sheet's outward movement.

The evidence of a marked disharmonic deformational style through the SPLD succession suggests the possibility of local periodic compositional variations in the sequence.

1. Introduction

1.1. The geologic and geomorphologic regional setting

The Amazonian South Polar Layered Deposits (SPLDs) represent the older sequence (~10–100 My, Plaut et al., 1988; Herkenhoff and Plaut, 2000; Koutnik et al., 2002) of the Mars Planum Australe ice dome (Fig. 1a) and consist of a kilometers-thick glacial-sedimentary unit (Thomas et al., 1992; Herkenhoff et al., 1998; Kolb and Tanaka, 2001; Plaut et al., 2007) resting upon the Noachian plateau sequence and the Hesperian Dorsa Argentea Formation (DAF) and underlying the Residual Ice Cap (Kolb and Tanaka, 2001).

Remote images at visible wavelengths reveal a cyclical stratigraphic sequence of regionally continuous layers that are affected by erosional events. The erosional events are recorded by several recognized unconformities that interrupt the continuity of the

* Corresponding author.
E-mail addresses: guallini@irsps.unich.it (L. Guallini), f.brozzetti@dst.unich.it (F. Brozzetti), luciam@irsps.unich.it (L. Marinangeli).

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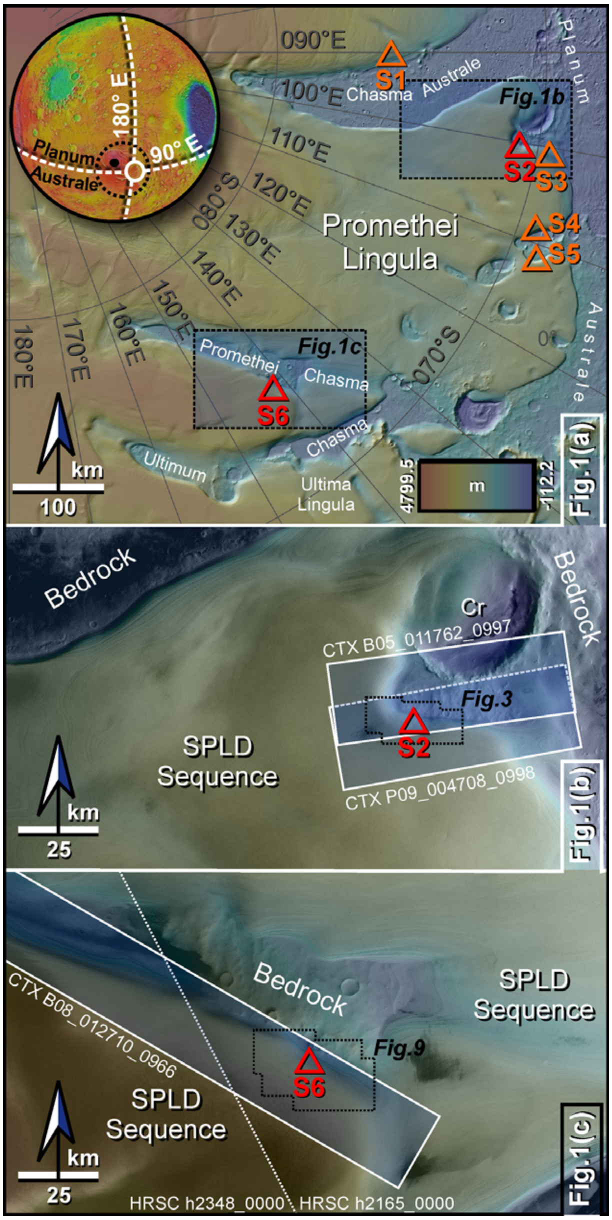

Fig. 1. (a) Geographic context and MOLA topography of the Promethei Lingula (PL) region and location of the deformational systems (S1–S6, orange triangles; in red the S2 and S6); (b) S2 location in the PL margins and analyzed dataset; (c) S6 location in the PL margins (Promethei Chasma) and analyzed dataset. In all the images, the black dashed insets indicate the figures context. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

layers and are possibly related to past climatic changes (Kolb and Tanaka, 2001, 2006; Seu et al., 2007; Milkovich and Plaut, 2008; Milkovich et al., 2009; Guallini et al., 2010).

The SPLD are thought to be mainly composed of a variable alternation of layers of dust and water–ice precipitates (Miller and Smythe, 1970; Cutts, 1973; Kieffer et al., 1976; Thomas et al., 1992; Mellon, 1996; Clifford et al., 2000) with a maximum volume fraction of dust of 10–15% (Nunes and Phillips, 2006; Plaut et al., 2007; Zuber et al., 2007; Wieczorek, 2008).

The occurrence of a variable fraction of CO_2 is a debated issue. Certain authors consider the south polar mound to be mainly composed of water–ice and a small percentage of CO_2 (Nye et al., 2000). Additionally, interbedded layers of CO_2 and CO_2 clathrate hydrate were hypothesized in small quantities by Kolb and Tanaka (2000, 2001) and by Kargel and Tanaka (2002). Phillips et al. (2011) have recently reconsidered this subject and suggest a number of CO_2 deposits are buried in the SPLD.

According to Kolb and Tanaka (2001), long-term variations of CO_2–CO_2 clathrate and sediment changed the rheology of some layers. These variations could have induced partial basal melting of the polar mound (suggested also by morphologic evidences; e.g., Clifford, 1987), causing some of the deformations observed in the SPLD. This hypothesis seems to be supported by the possible lowering of the melting point due to the occurrence of perchlorate salts in the SPLD, as suggested by Fisher et al. (2009).

Other works suggest that previous important ice-sheet flows caused periodic advances and retreats of the ice cap (Winebrenner et al., 2008). These stages would be marked by morphological (e.g., the lobate margins) and structural (e.g., boudinage-related structures) features (Head, 2001; Head and Pratt, 2001; Kargel and Tanaka, 2002).

Regarding the deformations, only local soft-sediment (Edgett and Malin, 2000) and rare post-emplacement small-scale deformations are reported (Kolb and Tanaka, 2001; Kargel, 2001; Herkenhoff et al., 2003, 2008), mostly in the Ultima Lingula (UL) region (Murray et al., 2001; Kolb and Tanaka, 2006; Milkovich and Plaut, 2008; Grima et al., 2011). In this region, normal and reverse faults, thrusts and folds are recognized, although they do not occur in an articulated pattern or regional systems. These observations led certain authors to suggest a concentration of tectonic activity in the UL (Milkovich and Plaut, 2008), likely due to the great thickness of the deposits (Byrne, 2009). However, detailed surveys and structural analyses over the entire SPLD and the bordering Promethei Lingula were lacking before the present work.

Similar to the Ultima Lingula, the PL is part of the south polar ice dome. The PL extends toward the equator from the central ice cap in a broad, flat, low-relief plateau ("tongue-like" ice sheets). The region is separated from the other plateaus by three chasmata (Australe Sulci, Ultimum Chasma and Promethei Chasma) and characterized by the SPLD unit. Based on information on the local sequence thickness derived by Plaut et al. (2007) using the Mars Advanced Radar for Subsurface (MARSIS; Picardi et al., 2005), the PL is thinner than the central dome, which is overlain by the Residual Ice Cap. The PL region shows an average thickness of approximately 1000–1500 m (±200 m of vertical uncertainty) and is characterized by a decrease in the mean elevation of the topography from the region's inland toward its margins (from approximately 3500 m to 1500 m). The basal interface between the SPLD and the bedrock appears to be irregular and characterized by several topographic highs and depressions.

1.2. Objectives

The purpose of the present work is to investigate the complex pattern of previously unrecognized large-scale deformational systems affecting the SPLD in the PL. After noting the existence of the systems in this region (Guallini et al., 2011), we describe them in detail and suggest that in the past, shallow-tectonic activity was significant around the SPLD outer margin. These deformations consist mainly of asymmetric drag folds, boudinages, fractures and brittle–ductile shear planes offsetting the layered deposits. The shear planes are interpreted and defined as faults, taking into account their regional extent.

Even if each analyzed deformational system is not linked to the adjacent ones (the systems are separated by tens to several hundreds of kilometers, Fig. 1a), their frequent occurrence, lateral extent (up to tens of kilometers) and common structural and kinematic characteristics support the hypothesis that an ice flow or basal sliding affected the PL, as proposed by several authors for the north polar dome (Zuber et al., 1998; Fisher, 2000;