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Mechanical conditions and modes of paraglacial deep-seated gravitational spreading in Valles Marineris, Mars

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ABSTRACT

Deep-seated gravitational spreading (DSGS) affects the slopes of formerly glaciated mountain ridges. On Mars, DSGS has played a key role in shaping the landforms of the giant Valles Marineris troughs. Though less spectacular, DSGS is common in terrestrial orogens, where understanding its mechanics is critical in the light of the ongoing climate change because it is a potential source of catastrophic landslides in deglaciated valleys. We conducted parametric numerical studies in order to identify important factors responsible for DSGS initiation. DSGS models are computed using an elastoviscoplastic finite element code. Using ADELI's software, we reproduce topographic ridge spreading under the effect of valley unloading. Two types of spreading topographic ridges are investigated, homogeneous or with horizontal rheological layering. We find that gravitational instabilities are enhanced by high slopes, which increase gravitational stress, and low friction and cohesion, which decrease yield stress. In the unlayered ridge, instability is triggered by glacial unloading with plastic strain concentration inside the ridge and at the base of the high slopes. Vertical fractures develop in the upper part of the slope, potentially leading to fault scarps. Ridge homogeneity promotes a deformation mode controlled by uphill-facing normal faulting and basal bulging. In the second case, the ridge encompasses horizontal geological discontinuities that induce rock mass anisotropy. Discontinuity located at the base of the slope accumulates plastic strain, leading to the formation of a sliding plane evolving into a landslide. The presence of a weak layer at ridge base therefore promotes another slope deformation mode ending up with catastrophic failure. Mechanical conditions and slope height being equal, these conclusions can probably be extrapolated to Earth. Compared with Mars, DSGS on Earth is inhibited because terrestrial topographic gradients are lower than in Valles Marineris, an effect counterbalanced by increased gravitational stress, where the intensity of deformation is enhanced because of the Earth gravity potential.

1. Introduction

Deep-seated gravitational spreading (DSGS) of slopes affects mountain ridges usually in postglacial conditions (Ballantyne, 2002; Mège and Bourgeois, 2011). Due to ongoing climate change, glacial retreat in many mountains is anticipated to affect slope instability, enhancing DSGS and potentially huge landslides (Hewitt, 2008). The Valles Marineris troughs on Mars provide excellent examples of such relationships among glaciers, DSGS, and huge landslides (Lucas et al., 2001; Mège and Bourgeois, 2011; Gourronc et al., 2014). The DSGS history in Valles Marineris on Mars is rooted in a specific tectonic context that starts with events presenting similarities with rifting in large igneous provinces on Earth. Emplacement of a sequence of thin (typically 50–100 m) layers of volcanic rocks of contrasting strength (McEwen et al., 1999; Beyer and McEwen, 2005), such as basalts and ash or tuff, occurred in response to plume impingement on the base of the lithosphere of the Tharsis dome with a diameter of ca. 5000 km (Mège and Masson, 1996; Mège, 2001). The crust was then stretched, shaping the primary landforms of Valles Marineris (Fig. 1). Evidence for graben development is observed in the southern chasmata (troughs) including Ius, Melas-Candor, Ophir and Coprates: 1) segmented rhombohedral geometry of the floor of some chasmata (Peulvast et al., 2001); 2) the presence of narrow grabens subparallel to the chasma walls on the surrounding plateaus, the fault population distribution of which follows a scaling law that also matches the Valles Marineris dimensions (Schultz, 1997); 3) the chasma floor cratering record, which testifies to plateau subsidence (Blasius et al., 1977; Schultz,

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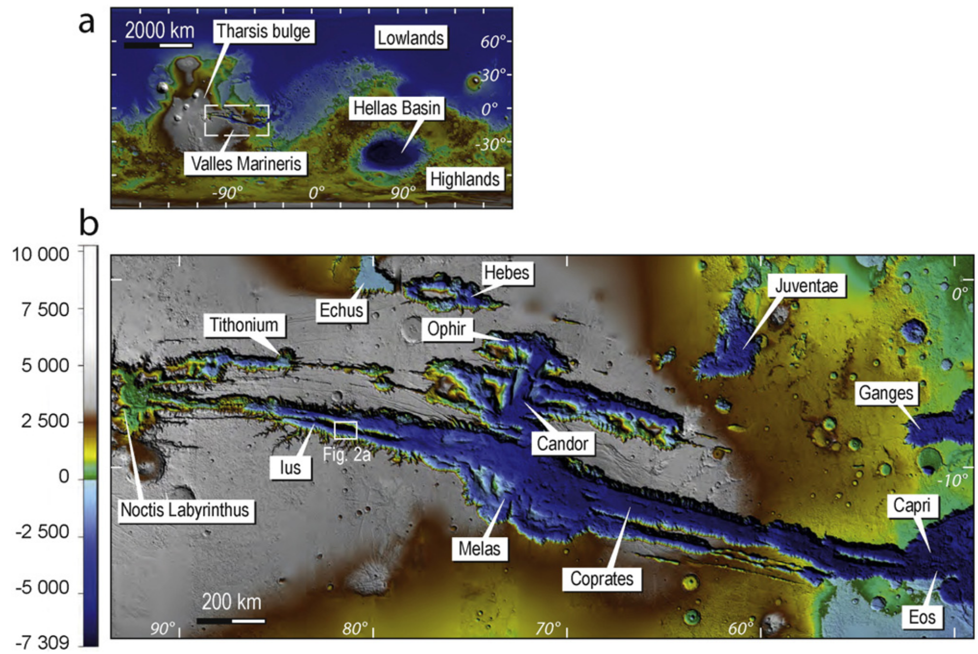

Fig. 1. General setting of Valles Marineris and its troughs (chasmata) on Mars. (a) Location of Valles Marineris. MOLA digital elevation model (NASA/MGS/MOLA), topography varying between −8 km (dark) and 12 km (white). (b) Main chasmata in Valles Marineris. HRSC digital elevation model (ESA/Mars Express/HRSC/DLR/FU Berlin). North is up.

1991); and 4) the presence of triangular faceted spurs (e.g., Hamblin, 1976) on the spur and gully-shaped walls of the chasmata (Peulvast et al., 2001). These indicate that this subsidence was primarily achieved through normal faulting. The Echus, Hebes, and Juventae chasmata do not display such features, suggesting that they have a partly different origin (Schultz, 1998; Jackson et al., 2011). Most observed chasma border fault scarps were removed by further glacial erosion. The fault scarps, located within the inter- and intra-chasma horsts mostly uphill-facing and frequently producing ridge-top grabens, have been interpreted as a result of postglacial deep-seated gravitational spreading (Fig. 2a; Mège and Bourgeois, 2011; Gourronc et al., 2014).

On Earth, from a geomorphological point of view, DSGS refers to movements on high energy hillslopes. These movements affect the whole slope, usually with low displacement rate (Agliardi et al., 2001; Ambrosi and Crosta, 2006). Extension of the upper part of the slope, in the form of tension fractures and uphill-facing normal fault scarps (Jahn, 1964), is balanced by oversteepening of the lower part of the slope (Agliardi et al., 2001; Gutiérrez-Santolalla et al., 2005), sometimes overthrusting the valley (Fig. 2) (Nemcok, 1972).

Nemcok (1972) linked DSGS with post-glacial unloading, which generates fractures parallel to the mountain crest. Forcella and Orombelli (1984) proposed that DSGS faults are a by-product of neotectonic activity. Today, the most commonly accepted interpretation is ridge spreading induced by the release of body forces.

From field observations on the regional context and timing of DSGS, deglaciation appears to play a critical role in DSGS. The loss of lateral ridge buttressing by valley glacier erosion (Agliardi et al., 2001; Cossart et al., 2008; Hippolyte et al., 2009) changes the balance of forces within the ridge, eventually resulting in slope failure. Although most authors have stressed the importance of deglaciation in DSGS; its precise role remains an open question. The major objectives of this study are therefore to constrain i) the role of deglaciation in changing the slope stability, ii) the effect of slope inclination and iii) the influence of weak geological discontinuities on DSGS processes. Besides the

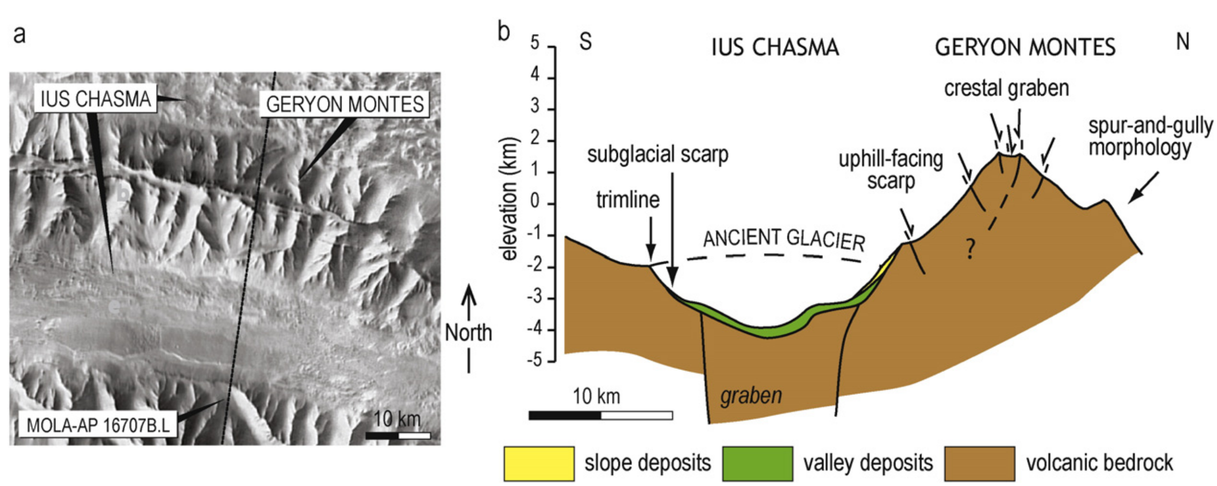

Fig. 2. Deep-seated gravitational spreading on Mars: example at Geryon Montes in Ius Chasma. (a) DSGS affecting the Geryon Montes horst in Valles Marineris with location of MOLA profile MOLA-AP 16707B.L. (b), Geologic interpretation of the MOLA profile (modified from Mège and Bourgeois, 2011).