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Morphometric and geometric characterization of normal faults on Mars

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ABSTRACT

Using three different approaches (fault plane fitting, 3D crater rim palinspatic restorations and fault scarps morphometric analysis) we investigate the geometry and degradation history of Martian normal faults in two distinct areas. The three independent methods produce similar results, indicating that the average dip angle of the normal faults on these two locations is probably below the value that is usually assumed for Mars ($\sim 60°$). Our best estimate for this average dip angle is $46.8 \pm 9.8°$, which is a value comparable with the mean dip angle inferred on Earth for seismically active normal faults. This lower average dip angle implies that all the rift strain estimates performed until now might be underestimated. From the comparative analysis of the two faulted regions (Phlegethon Catena and Claritas Fossae), we show that local and regional dip variabilities may exist on Mars. This reinforces the idea that the amount of extension associated with Martian rifts must be reconsidered.
We also demonstrate the advantages of performing a comparative morphometric analysis of fault scarps. This approach enables the reconstruction of the faults scarps degradation history and can be used to evaluate how environmental conditions changed through time. After modeling the degradation of the fault scarps at the two sites we conclude that the observed morphometric variations are mainly due to the different faulting ages in an environment characterized by low scarp degradation rates (4×10^{-3} m^2/kyr) over the last 3 Ga.

1. Introduction

Rifts, extensional zones consisting of normal faulting, are abundant on Mars and they can give us indications about the timing, location and the nature of tectonic processes on the planet. Normal faults can be found in diverse arrangements, from simple long and narrow grabens (Polit et al., 2009) to more complex en-echelon and pull-apart geometries (Bistacchia et al., 2004; Vaz, 2011). At a global scale, the mapping of these features revealed a complex sequence of extension events responsible for the formation of several rift systems (Anderson et al., 2001), which are comparable in dimension and style of deformation to continental rifts on Earth (Hauber et al., 2010).

A simple geometric model is commonly used to estimate the amount of strain associated with Martian rifts. Fault planes are modeled as pure dip–slip non-rotational structures presenting a constant dip angle (α). Extension (e) is computed according with $e = D/\tan\alpha$, where the vertical throw (D) of the faults is directly measured from topographic profiles (Borraccini et al., 2005; Hauber and Kronberg, 2001, 2005; Spagnuolo et al., 2008). More recently, a new set of tools that enable the automatic mapping and morphometric characterization of scarps was used to obtain continuous strain estimates along normal faults traces (Vaz, 2011). The accuracy of this mapping methodology has been assessed using MOLA (Mars Orbiter Laser Altimeter) data (Vaz et al., 2012), but in terms of strain modeling the results obtained are still highly dependent on the assumed faulting dip angle. A better understanding of normal faults geometry on Mars is thus crucial to improving crustal strain estimates, as well as for the preparation of future geophysical and seismic network missions (Harri et al., 1999; Knapmeyer et al., 2006).

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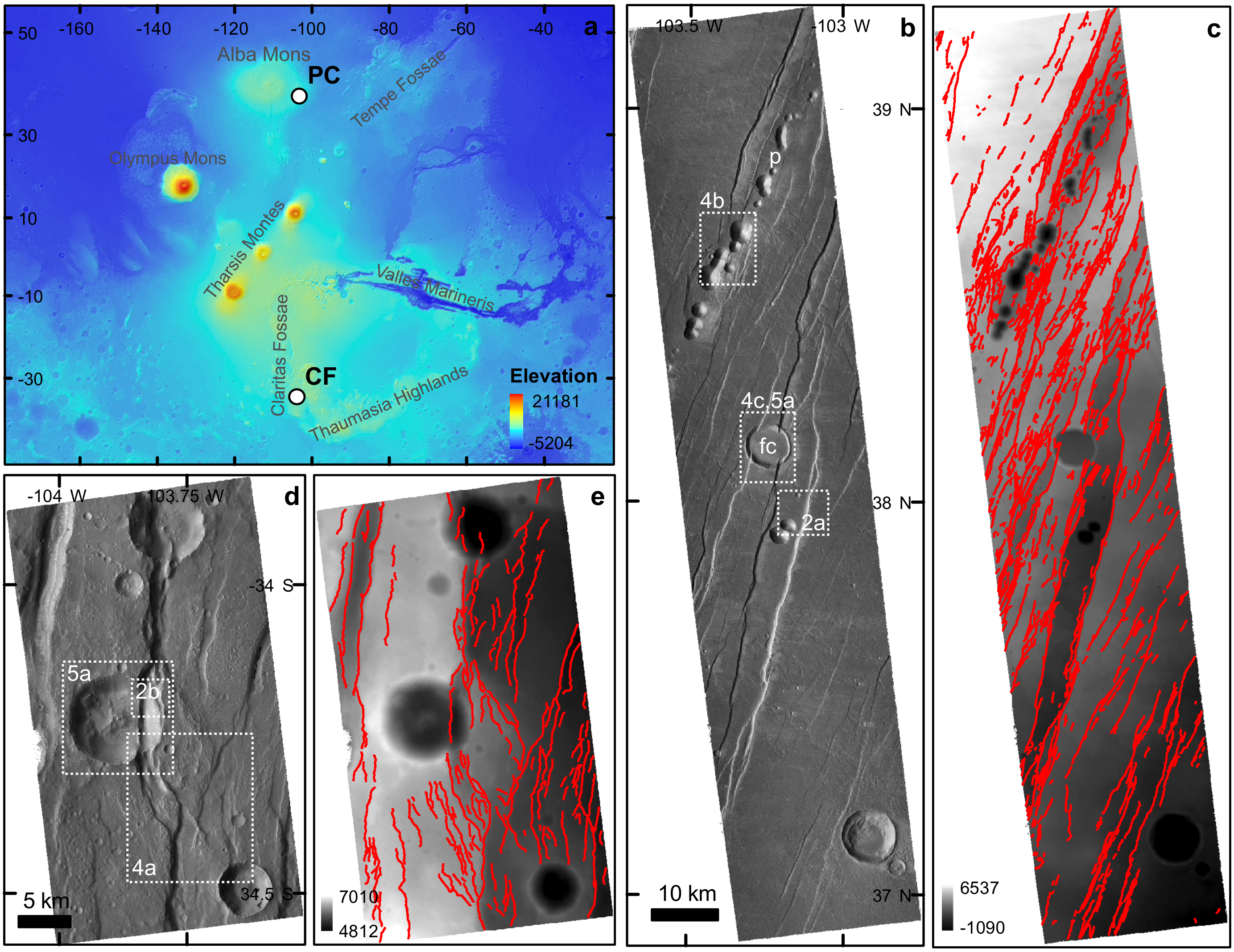

Fig. 1. Regional context and normal faults mapped on the two study areas. a) MOLA topographic map with the location of the study areas (PC – Phlegethon Catena and CF – Claritas Fossae); b) Phlegethon Catena CTX orthoimage, note the existence of pit craters (p) and the location of the faulted crater (fc) which is analyze in this paper; c) normal faults scarps automatically mapped from the topographic data and overlaid on the CTX DTM; d) Claritas Fossae CTX orthoimage; e) normal faults scarps automatically mapped from the topographic data, compare the good agreement between the mapped scarps and the structures identifiable on the image.

Since faults scarps on Mars usually present signs of degradation, direct measurements of normal faults dip angles on Mars are scarce (Chadwick and Lucchitta, 1993; Davis and Golombek, 1990). This drove the scientific community to assume a 60° average dip angle, which corresponds to the angle predicted for the formation of normal faults in a regime where the maximum compressive stress is vertical (Anderson, 1951). This value also agrees with the optimum brittle failure angle given by the Mohr–Coulomb failure criterion (assuming an intermediate coefficient of internal friction of 0.6) (Jaeger et al., 2007; Schultz et al., 2009).

Several studies used topographic data to infer the geometry of normal faults. Using forward mechanical modeling, dip angles of 40–55° and 55–65° were reported for the Valles Marineris trough (Schultz and Lin, 2001) and for the eastern Alba Patera region (Polit et al., 2009), respectively. A detailed structural analysis performed on the Candor Chasma area revealed an average dip angle of $55 \pm 11°$ (Schultz et al., 2010). However, to fulfill the Mohr–Coulomb failure criterion the authors excluded from this statistical analysis ∼14% of the measured faults (since they dipped less than 45°).

Despite these efforts, the theoretical dip angle is still widely used for strain estimation purposes. In this work, we better constrain faulting geometry and scarp degradation processes on Mars using high-resolution imagery and topography. To accomplish this, we use three independent methods to infer fault geometry and we examine and compare fault scarps morphometry.

2. Data and methodologies

Three main criteria were followed for the selection of the study areas: 1) good Context Camera (CTX) coverage to allow the production of high quality digital terrains models (DTMs); 2) the existence of large circular craters cut by major faults; 3) different faulting ages. The selected areas, located in Phlegethon Catena and Claritas Fossae, fulfill all these requirements and represent good examples of the complexity associated with Martian tectonic features (Fig. 1).

One High Resolution Imaging Science Experiment (HiRISE) stereopair was used to generate a 1 m/pixel DTM on Claritas Fossae using SOCET SET (Kirk et al., 2008). Two CTX stereopairs were used to derive DTMs (20 m/pixel) and orthoimages (6 m/pixel) using the NASA Ames Stereo Pipeline stereogrammetry software (Moratto et al., 2010). Bundle adjustment was performed using the ISIS (Integrated Software for Imagers and Spectrometers) soft-