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Vertical and lateral collapse of Tharsis Tholus, Mars

T. Platz [a,*], S. Münn [b], T.R. Walter [c], J.N. Procter [d], P.C. McGuire [a,e,1], A. Dumke [a], G. Neukum [a]

[a] Freie Universität Berlin, Institute of Geosciences, Planetary Sciences and Remote Sensing, Malteserstr. 74-100, 12249 Berlin, Germany
[b] Leibniz Institute of Marine Sciences, IFM-GEOMAR, Wischhofstr. 1–3, 24148 Kiel, Germany
[c] Deutsches GeoForschungsZentrum (GFZ), Telegrafenberg, Potsdam 14473, Germany
[d] Massey University, Volcanic Risk Solutions, Institute of Natural Resources, Private Bag 11222, Palmerston North, New Zealand
[e] Washington University in St. Louis, McDonnell Center for the Space Sciences, Campus Box 1169, One Brookings Drive, St. Louis, MO 63130-4899, United States

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A B S T R A C T

Tharsis Tholus, a more than 3.9 Ga old composite shield volcano to the east of the major Tharsis Montes, has experienced a complex history of growth and destruction. On the basis of new high resolution images we analysed the morphology as well as the tectonic structures of the Tharsis Tholus volcano in detail. From morphological data, cross-cutting relations of the surface structures, and crater modelling ages we propose a chronostratigraphy for the volcano-tectonic history of Tharsis Tholus.

The strongly faulted volcano reveals two large-scale landslide events followed by two subsequent shield regrowth phases between 3.8 and 1.7 Ga and two caldera collapses. Tharsis Tholus was also affected by regional extensional tectonics between 1.7 Ga and 0.4 Ga recorded by sub-parallel sets of NE trending graben structures. The steep and up to 5.4 km high landslide scarps on Tharsis Tholus suggest deep faulting of the edifice. In order to confirm this hypothesis we used analogue sand box models in which we demonstrated that gravitational flank movement on top of weak basal substrata may have produced the deformation structures as observed on Tharsis Tholus.

1. Introduction

Large volcanoes often display central depressions as well as sectors of flank instability (Walter and Troll, 2003). Due to erosion and tectonic overprinting on Earth, these structures and their causative processes often remain hidden and poorly understood (Shea and van Wyk de Vries, 2010; Walter et al., 2006). On Mars, however, erosion is less and thus some of the largest volcanoes known within the solar system may serve as archetpye examples of combined vertical and lateral deformation processes.

The Tharsis region is the most dominant locus of volcanic activity on Mars extending more than 6000 km (NNE–SSW) by 3500 km (E–W). This region has been mainly formed by five large volcanoes (Alba Mons, and the Montes of Olympus, Ascraeus, Pavonis, and Arsia) and several smaller volcanoes known as paterae and tholi. Among those volcanoes Tharsis Tholus stands out as an isolated edifice in the eastern Tharsis region, approx. 600 km east of Ascraeus Mons (Fig. 1). It was first observed in Mariner 9 images and interpreted as a volcanic dome (McCauley et al., 1972) due to its convex upward, partially faulted flanks, central crater with steep walls and multiple terraces, and the abrupt change in slope (edifice to surrounding plain). Greeley and Spudis (1981) noted that Tharsis Tholus could represent a buried shield. Carr (1973) first described tectonic structures on the edifice in more detail noting a complex summit pit comprising several nested craters with steep walls as well as large circular depressions on the flanks close to the summit region.

Tharsis Tholus was first mapped as cratered shield material, a unit assigned to all volcanic tholi and paterae in the Tharsis quadrangle (Carr, 1975). The same structures were later mapped as volcano of unknown relative age possibly containing a caldera and radial channels (Scott and Tanaka, 1986). Later, Tharsis Tholus was proposed to be a basaltic shield (Hodges and Moore, 1994). The first study focussing on the volcano-tectonic evolution of Tharsis Tholus was carried out by Maciejak et al. (1995), who concluded that Tharsis Tholus initially consisted of two separate edifices which later coalesced. The main edifice was affected by two large sector collapses on the western and eastern flanks which were later modified by caldera subsidence (Maciejak et al., 1995). In addition, a regional tectonic phase, syn- or post-Amazonian in age, has been recognised which also had an effect on the edifice (Maciejak et al., 1995). A more recent study using higher resolution imagery revealed better morphometric data of the edifice and more detailed observations of surface morphology and tectonic structures (Plescia, 2003). Small-scale structures of the regional extensional phase was analysed and its centre localised at Pavonis Mons (Plescia, 2003).

With this study we provide further details into the complex volcano-tectonic history of Tharsis Tholus. Based on new high resolution images we reanalysed morphologic and tectonic structures in detail. Cross-

* Corresponding author.
E-mail address: thomas.platz@fu-berlin.de (T. Platz).
[1] Currently at University of Chicago, Department of Geophysical Sciences, 5734 S. Ellis Ave., Chicago, Il 606370.

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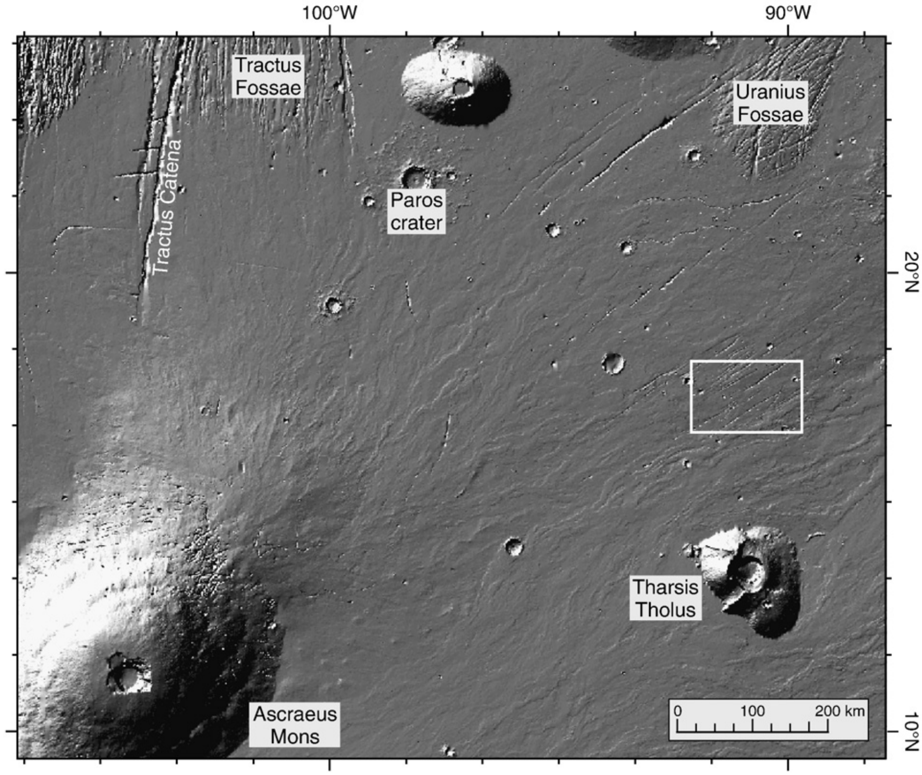

Fig. 1. Portion of the Tharsis region shown on MOLA hillshade with Ascraeus Mons (lower left), Ceraunius Tholus (top), and Tharsis Tholus (lower right). Large lava flows circumventing Tharsis Tholus and abundant fractures and faults are observed. White box indicates the approximate location of Fig. 4b.

correlations of the surface structures as well as crater modelling ages then were combined for reconstructing a chronostratigraphy for the volcano-tectonic evolution of Tharsis Tholus. In order to identify the mechanics of the large-scale volcano deformation of the volcano we used laboratory analogue models. Our model results support the hypothesis that gravitational basal spreading as known from Earth's volcanoes (cf. Borgia et al., 2000; Le Corvec and Walter, 2009; Kervyn et al., 2010) could have produced the deformation structures observed at Tharsis Tholus.

1.1. Data processing

High Resolution Stereo Camera (HRSC) imagery onboard Mars Express is used as the primary source for mapping and crater counting. HRSC orbits 1019_0000, 1041_0000, and 1052_0000 were used to create an ortho-image mosaic with a ground resolution of 12.5 m/pixel. The Digital Terrain Model (DTM) mosaic was derived from five HRSC orbits at approximately 11.5° to 14.8° N and 267.2 to 270.9° E with a ground resolution of 100 m per pixel. For the derivation of high-resolution DTM and ortho-image mosaics, the use of improved orientation data is essential and is based on a bundle block adjustment. The mean intersection accuracy of all object points used for the DTM mosaic is approximately 9.9 m.

For detailed surface studies and assistance in mapping and crater counting, image data of the Context Camera (CTX, commonly 5–6 m/pixel, Mars Reconnaissance Orbiter; Malin et al., 2007), Mars Orbiter Camera (MOC, 1.5–20 m/pixel, Mars Global Surveyor; Malin and Edgett, 2001), and the High Resolution Imaging Science Experiment (HiRISE, 0.3 m/pixel, Mars Reconnaissance Orbiter; McEwen et al., 2007) were employed.

All elevation data refer to values above Martian datum. For volume calculations of Tharsis Tholus a triangular irregular network (TIN) of its visible outline was converted to a raster dataset with a cell size of 100 m × 100 m and subtracted from the HRSC-DTM. Volumes of individual sectors were calculated in the same way by clipping the TIN and HRSC-DTM to the mapped area. The sum of volumes and area sizes of individual sectors/areas deviate from the total values by up to 1.5%. Determining the volcano's volume using the 500 m horizontal baseline, the area of interest was selected and the volume between DTM and the constant base value of 500 m was calculated.

2. The shape and structure of Tharsis Tholus

2.1. Morphometry and morphology

The edifice of Tharsis Tholus has a planar extension of 155 km (NW–SE) by 125 km (NE–SW) and rises up to 8000 m above the surrounding lava plain (Fig. 2).

The volcano surface, primarily formed by basaltic lavas, is mainly characterised by impact craters (up to 9 km in diameter) and large scarps. These scarps allow subdividing the edifice into six major sectors: north flank (sector 1), west flank (2), southwest flank (3), southeast flank (4), east flank (5), and the central caldera (6).

Viewed from the north and the west, the edifice has a convex shape (Plescia, 2004) where flanks arise initially at slope angles of around 16° up to 27° and then continuously flatten with increasing altitude to 3° to <1° (Fig. 3a). Sector 4 has a semi-circular outline and is also characterised by a convex shape. However, the flank does not arise as steeply as on the N, W and SW flanks, also forming a gently outward-dipping plateau region.

The eastern part of Tharsis Tholus exhibits a different flank morphology. The flank has a broader extension and rises only to about 4300 m above the lava plain where it originally may have formed a central plateau (now the central caldera). The slope of the east sector gradually rises at angles <5°, then steepens only to about 10° and flattens towards the plateau at <2°. At its base, an arcuate cliff section, up to 300 m high in places, is exposed which runs approximately parallel to the large partially buried impact crater c.10 km off the flank