Earth and Planetary Science Letters 323–324 (2012) 9–18

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Ancient volcanism and its implication for thermal evolution of Mars

Long Xiao [a,*], Jun Huang [a], Philip R. Christensen [b], Ronald Greeley [b], David A. Williams [b], Jiannan Zhao [a], Qi He [a]

[a] Planetary Science Institute, Faculty of Earth Sciences, China University of Geosciences, Wuhan, Hubei 430074, China
[b] School of Earth and Space Exploration, Arizona State University, Tempe, AZ, United States

ARTICLE INFO

Article history:
Received 16 April 2011
Received in revised form 16 January 2012
Accepted 22 January 2012
Available online 15 February 2012

Editor: T. Spohn

Keywords:
ancient volcanoes
volcanism
thermal evolution
Mars

ABSTRACT

Volcanism plays an important role in the formation and thermal evolution of the crusts of all terrestrial planets. Martian volcanoes have been extensively studied, and it has been suggested that the volcanism on Mars that created the visible volcanic features was initiated in the Noachian (>3.8 Ga) and continued to the Late Amazonian (<0.1 Ga). However, styles of ancient volcanism, their links with the earliest volcanic constructions, and the thermal evolution of the planet are still not well understood. Here we show that numerous Early Noachian (>4.0 Ga) volcanoes are preserved in the heavily cratered southern highlands. Most of these are central volcanoes with diameters ranging from 50 to 100 km and heights of 2–3 km. Most of them are spatially adjacent to and temporally continuous with the Tharsis and circum-Hellas volcanic provinces, suggesting that these two volcanic provinces have experienced more extensive and longer duration volcanism than previously thought. These edifices are heavily cut by radial channels, suggesting that an early phase of aqueous erosion occurred and ended prior to the emplacement of the encircling Hesperian lava fields.

1. Introduction

Mars experienced long-term volcanism, preserves many large volcanic constructs, and is probably the best planet for studying ancient volcanic processes in the early solar system. Recent studies have led to a general picture of martian volcanism (Carr and Head, 2010; Neukum et al., 2010; Werner, 2005, 2009; Williams et al., 2008, 2009). Noachian volcanoes and volcanic features include highland paterae and mare ridge-like Late Noachian–Hesperian ridged plains (Neukum et al., 2010; Werner, 2009), whereas volcanoes with Hesperian to Amazonian eruptive products are mainly represented by large shield volcanoes on the Tharsis rise and in the Elysium Montes (Carr and Head, 2010; Werner, 2009). Because Noachian volcanoes record valuable information about the earliest thermal evolution and formation of the martian crust, they are important sources of information for martian geologic studies. However, little is known about Noachian volcanism styles (Greeley and Spudis, 1981; Tanaka et al., 1992), especially Early Noachian volcanology (Stewart and Head, 2001), despite the fact that the most extensive magmatism and volcanism are expected in the early stage of martian crust formation (Breuer and Spohn, 2006; Greeley and Schneid, 1991; Grott et al., 2007; Kronberg et al., 2007; Morschhauser et al., 2011; Nimmo and Tanaka, 2005; Schubert et al., 1992).

Long-term and significant geologic modification, heavy degradation, and resurfacing processes complicate the identification and characterization of the volcanoes produced in the Noachian (Scott and Tanaka, 1981a). Highland ridged plains are probably of volcanic origin by analogy with mare-type ridges on lunar flood lavas; the martian ridged plains were produced in Early Hesperian (Greeley and Schneid, 1991). Many of the prominent isolated mountains within the Coprates rise, Thaumasia highlands, Daedalia Planum and Terra Sirenum provinces occur along or near faults and commonly exhibit summit depressions and highly dissected flanks. Some of them have been interpreted as ancient volcanoes or older crustal materials (e.g. Noachian mountain materials (Nm), Noachian highly-deformed terrain materials, basement complex (Nb), Noachian older fractured materials (Nf) and Noachian plains unit-hilly (Nplh): Dohm et al., 1998, 2001a, 2001b; Hodges and Moore, 1994; Saunders et al., 1980; Scott and Tanaka, 1981a, 1981b, 1986; Witbeck et al., 1991). Dohm and Tanaka (1999) mapped fourteen possible volcanoes in the Thaumasia region and proposed that this region preserves some of the best examples of early highland volcanoes and intermediate age plateau lavas on Mars. They also argued that these prominent mountains are not the oldest rocks of the plateau (as interpreted by Scott and King, 1984) and are not likely to be massifs of ancient impact basins as suggested by Craddock et al. (1990). Their stratigraphic study and crater counts for the volcanoes suggest that they formed throughout most of the Noachian and into the Early Hesperian (Dohm and Tanaka, 1999).

Recent crater counts based on High Resolution Stereo Camera (HRSC) and Thermal Emission Imaging System (THEMIS) data yielded

* Corresponding author.
E-mail address: longxiao@cug.edu.cn (L. Xiao).

0012-821X/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2012.01.027

an age of about 3.8–3.9 Ga for the circum-Hellas highland patera volcanoes, suggesting that they are among the oldest central volcanoes on Mars (Williams et al., 2009). However, based on the hypothesis that volcanism generally declines in the planet's history (Carr and Head, 2010; Greeley and Schneid, 1991; Nimmo and Tanaka, 2005; Schubert et al., 1992), it is important to examine whether and where older volcanic structures and products may be located. Fortunately, newly obtained high spatial resolution exploration data allow us to do detailed study about possible older volcanic constructs and to further our understanding of early martian thermal evolution. In this study, we used global THEMIS daytime-IR, HRSC, Mars Orbiter Camera (MOC), and Context Camera (CTX) image data and identified several tens of prominent mountains in the southern highlands, most of which we interpret as old central volcanoes. Some of these features have been previously mapped as older crustal materials, including volcanic structures, as discussed above (Dohm and Tanaka, 1999; Greeley and Guest, 1987; Saunders et al., 1980; Tanaka and Davis, 1988; Tanaka and Scott, 1987). Combined with a study of degradational features on the volcanoes and a previously-published thermal model (Breuer and Spohn, 2006), we discuss the Noachian volcanic history of Mars and how it was influenced by subsequent degradation by water, cratering, younger volcanism, and tectonism. A generally integrated model of ancient martian volcanism is proposed.

2. Prominent mountains/hills in southern highlands

2.1. Mountain building processes on terrestrial planet surfaces

There are a variety of shapes of prominent topographic edifices on Mars, especially in the southern highlands. These include large volcanic constructs (e.g., Olympus Mons, the Tharsis Montes, and Elysium Mons), small circular isolated hills, and irregular prominent edifices of various sizes. On the Earth, mountains may form through geologic processes such as folding, faulting, erosion of larger landforms, deposition of sediment by glaciers (e.g., moraines and drumlins), or by erosion of rock that weathers into hills. It is important to distinguish whether a mountain is formed by volcanism or other geologic processes.

Mountain building on Mars might be simpler as compared to Earth, because Mars is a one-plate planet (Banerdt et al., 1982). Geologic processes on Mars that could form mountains or hills include volcanism, impact, and faulting through compressive deformation. Weathering and erosion usually form valleys, although in some cases, they could also form mesas by deep erosion in a region of channel-developed networks. Other potential mountain-forming mechanisms on Mars are salt tectonism (Adams et al., 2009) and laccolithic structure developed by shallow intrusions. Mountains formed by these different origins can be distinguished on the basis of their morphology and regional setting. Volcanism often forms isolated, generally circular or elliptical outlines, prominent edifices with central pits (i.e., calderas) that differ from elongated mountains or hills formed by folding and faulting. Fault-cut folds can form isolated mountains, but they often occur as clusters or chains of hills. An impact structure is typically a circular or oval depression with a circular raised rim (Carr, 2006; French, 1998; Melosh and Vickery, 1989; Moutsoulas and Preka, 1982) that is distinctive compared with peak or summit depressions of volcanoes. An impact crater floor is lower than the surrounding rim, while the caldera floor of volcanoes is often higher than the surrounding plains, with the exception of maars. Some martian impact craters have been modified by erosion, leaving the crater rim and ejecta field to stand above the surrounding area. Some of these pedestal craters are hundreds of meters above the surrounding area, suggesting that hundreds of meters of material have been eroded (Arvidson et al., 1976). Barlow (2005) proposed models of the latitudinal distribution of ice-rich mantles suggesting that pedestal craters may result from sublimation of the surrounding ice-rich material, with both the crater and its ejecta stand above the surroundings. However, pedestal craters are typically <5 km in diameter and occur in fine-grained deposits which often correlate with the high-H_2O-content regions identified by the Mars Odyssey Gamma Ray Spectrometer (GRS) (Barlow, 2005). It means pedestal craters are small and are mostly distributed in high latitude and ice-rich areas. Finally, cinder cones, rootless cones, pingos, and other pitted cones are also volcano-like in morphology. However, these edifices are generally much smaller in size and show cluster chains, and/or swarms that are different than those volcanoes identified in this study (see next section). Thus, volcanoes on Mars can be distinguished from tectonic and impacts features based on their geologic setting, shape, size, morphology and stratigraphy.

2.2. Reappraisal of the origin of mountains in the southern highlands

Many authors have mapped the southern highlands of Mars and provided fundamental geological information of the region by using Mariner and Viking imagery (e.g. Greeley and Guest, 1987; Saunders et al., 1980; Scott and Tanaka, 1981a, 1981b, 1986; Tanaka and Scott, 1987). Those prominent relief terrains in the southern highlands were named as volcanoes and mountainous material (Nm), highly-deformed terrain materials, basement complex (Nb), flow and construct material (Nfc, HNfc), highly-deformed terrain materials, older fractured material (Nf) and hilly (Nplh). Due to the resolution of Mariner images and lack of high-resolution topography, a definite age and origin for the mountains were not able to be determined. Even with the high-resolution images from the Viking mission, a more detailed assessment of the age and origin of the mountains was not possible (Ghatan and Head, 2002; Tanaka and Scott, 1987). Later geological mapping (e.g., Dohm et al., 2001a, 2001b; Skinner et al., 2006) and other studies (Dohm and Tanaka, 1999; Ghatan and Head, 2002; Grott et al., 2007) using higher resolution data (e.g. MOLA, MOC, THEMIS, HRSC, etc. see next section) provided more detailed descriptions and different interpretation about most of the features. For example, Scott and Tanaka (1981b) mapped the Phaethontis–Thaumasia region and named most of the isolated mountains as volcanoes (about 20 volcanoes in the Thaumasia and surrounding region). Later study by Dohm and Tanaka (1999) mapped thirteen volcanoes in the Thaumasia region, while Scott and Tanaka (1986) and Dohm et al. (2001a, 2001b) classified most of them as Nfc, Nplh, Nf, etc. In these geological maps, Nfc was interpreted as ancient volcanoes and lava flows and (or) eroded high-standing outcrops of plateau material. While it is possible that significant erosion could have occurred to produce these high-standing plateau materials, there is no evidence for the processes that would have produced the original uplift, of which the isolated remnants remain. There are no aligned mountain ranges higher than 2000 m–3000 m on Mars formed by tectonism (see Table S1), and our study of all high relief units suggests that degradational processes could not have eroded edifices of isolated relief that are the heights observed (mostly higher than 2000 m). Other evidence against erosion producing such high-standing outcrops is that these mountains are embayed by Middle–Early Hesperian and Late Noachian materials. To erode several thousand meters of thick materials is unlikely to have happened in such a short period of time for a geologically inactive planet like Mars. Therefore, we conclude that these features are volcanoes rather than uneroded high-standing outcrops of plateau material.

The geologic map unit Nplh (Hilly unit—forms mesas, knobs, and broad areas that rise above surrounding materials) was interpreted to be impact breccia, volcanic materials, and possibly older crustal materials, with its high elevation caused by tectonic uplift and impact-basin formation during the period of heavy bombardment (Dohm and Tanaka, 1999; Tanaka and Scott, 1987). We examined the morphology of most of the isolated Nplh units in our studied region and suggest that their high elevation (2000 m–3000 m higher than surroundings, see next section) could not be formed by tectonic uplift or impact-basin formation. As discussed above, tectonic uplift caused by folding or faulting should produce elongated and aligned depressions or high relief blocks, and impact processes should produce