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Ancient volcanism and its implication for thermal evolution of Mars

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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

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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 circular raised rims. In contrast, these Nplh are mostly isolated mountain features with random distributions relative to the surrounding topography, making tectonic and impact processes unlikely candidates for their formation. In addition, the mountains in this study are far away from large impact basins and, given their dated age of >3.9 Gya (see below), it seems unlikely that they could have been degraded from impact basin rims to isolated hills in so short time. Other processes for the formation of these isolated mountains can also be ruled out. As indicated by Dohm and Tanaka (1999), the stratigraphic relations between mountains and embayed materials suggest that the mountains are not the oldest rocks of the plateau. Thus they are not the massifs of ancient impact basins or other uplifted ancient crustal materials, e.g. basement complex (Nb).

In summary, based on the detailed morphological and stratigraphic study, we suggest that most of the ancient mountains mapped in this study are of volcanic origin. Their morphology and stratigraphy are described in next section.

2.3. Volcanic features on martian highlands

Viking, THEMIS, HRSC, MOC, and CTX images provide sufficient resolution to examine the details of volcanic morphology and for recognition of volcanoes that have not been previously identified. Based on these data and criteria mentioned above, 75 hills have been identified and interpreted or confirmed as small volcanoes in the Noachian Coprates rise, Thaumasia highlands, Thaumasia Fossae, Icaria Fossae and outside the Thaumasia block (Fig. 1; Table 1, Table S1). Their diameters range from 50 to 100 km with heights above the plains of 2–3 km.

These small volcanic mountains can be divided into three groups based on the degree of modification and degradation. Group 1 includes relatively well-preserved volcanoes with shield-like edifices that are dissected by radial channels with little tectonic deformation (Fig. 2a). There are 36 shield volcanoes characterized as Group 1 (Fig. 2a; Table S1). The large flat-floored crater near the summit of the volcano in Fig. 2a is probably a preserved caldera. Radial channels developed on these volcanoes might be volcanic channels that have been modified by fluvial processes. In general, few of these volcanoes have summit craters because collapse, degradation, and subsequent eruptions may have destroyed the original calderas.

Group 2 includes moderately degraded volcanoes that have experienced extensional tectonic deformation such as rifting (Grott et al., 2005; Hauber and Kronberg, 2001; Kronberg et al., 2007) in addition to impact cratering and channeling (Fig. 2b). There are 14 moderately modified shield volcanoes in the study area. The volcanoes in the Thaumasia highlands were cut by NW-trending faults, mostly expressed as rifts. Volcanoes outside the Thaumasia Highlands were cut by both NW- and NE-trending faults (e.g. Nos. 6, 16, 19, 23, 24, see Fig. 2 and Table S1). The wide rift-like grabens are older than the narrow linear faults.

Group 3 includes 25 heavily degraded volcanoes that have been significantly modified by impact cratering, channeling, and tectonic deformation with only some edifices preserved and recognizable (Fig. 2c). These volcanoes are characterized by domes cut by wide faults with multi-orientations. The faults cut through the volcanic centers or flanks and occupy one-third to one-half of the constructs. There are four heavily degraded volcanoes along NNE-trending faults (e.g. Nos. 8, 9, 13) shown in Fig. 2c and Table S1. These poorly-preserved constructs are 50 to 80 km wide and between 1.5 and 2 km high. It is noted that the unusual fault cuts through the centers of all four volcanoes, which probably controlled the volcanism. This tectono-volcanism is likely a fissure-central eruption along the fault or rift. This kind of rift-volcano assemblage is common in the Thaumasia area and was interpreted as formed by widespread prerift and synrift volcanic activity (Grott, et al., 2007). It suggests that rifting and volcanism were coeval in many places. Some of the Group 3 mountain features are similar to terrestrial continental rift, e.g., at the shield volcano Menengai in the central Kenya rift, and Venus Beta Regio, where the huge Devana Chasma cuts through the centers of Rhea Mons volcano, although there is a large scale difference.

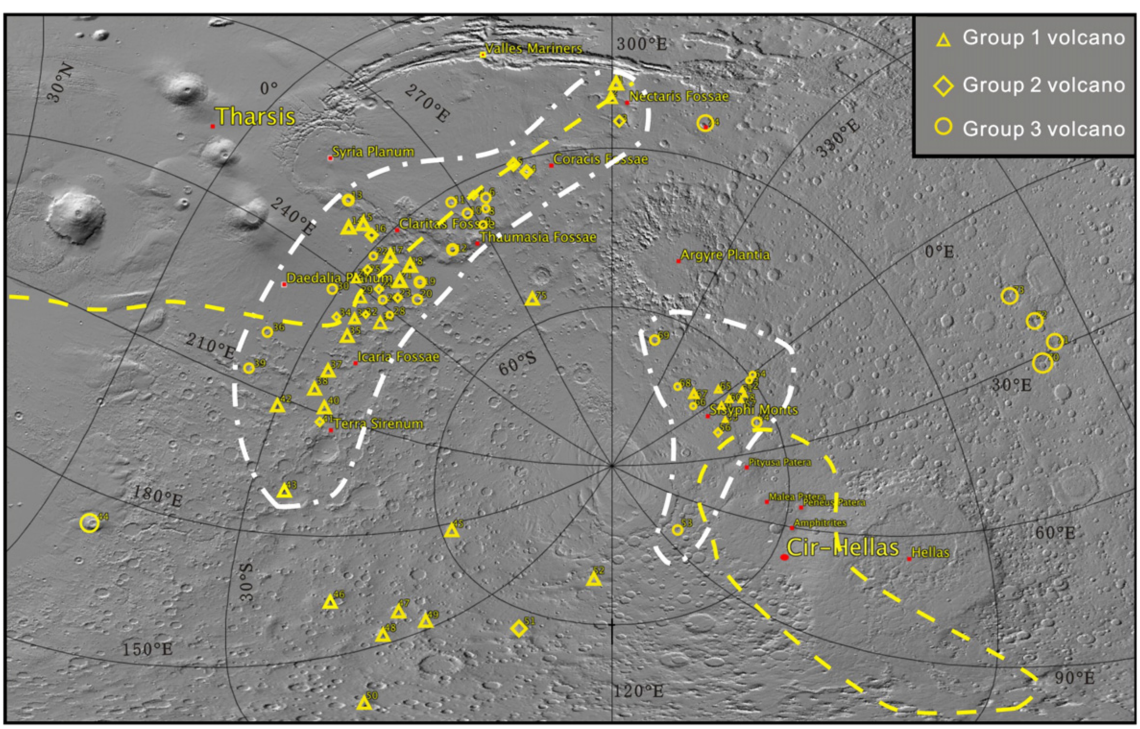

Fig. 1. Location map showing the distribution of old small shields and remnant volcanic constructs (all are numbered and shown in Table 1S). These volcanic edifices are divided into three groups based on their degree of modification, degradation and similarities with shield volcanoes. Base map is MOLA shaded relief. Most of these old volcanoes are situated close to Tharsis and circum-Hellas volcanic provinces, indicated by dot-dashed lines.

Table 1
Crater counting results for ancient volcanoes with locations shown in Fig. 1. The *N(1)* values that are given are calculated for the best-fit Neukum and Hartmann isochrons to the data. The highland volcanoes we examined are mostly Early to Middle Noachian (see also Fig. 4 and Table S1).

No. of volcano	Number of craters	*N(1)* Neukum best fit	Neukun age (Ga)	Neukum period*	Note
1	27	0.0525	4.05	EN	Volcano by Dohm and Tanaka, 1999 Nfc by Dohm et al., 2001a, 2001b
2	29	0.0325	3.98	EN	volcano by Dohm and Tanaka, 1999 HNr by Dohm et al., 2001a, 2001b
3	16	0.0237	3.93	MN	Volcano by Scott and Tanaka, 1981b. HNr by Dohm et al., 2001a, 2001b
4	20	0.0218	3.92	MN	Volcano by Dohm and Tanaka, 1999 c_2 by Dohm et al., 2001a, 2001b
5	40	0.0672	4.09	EN	Volcano by Dohm and Tanaka, 1999 Nb by Dohm et al., 2001a, 2001b
6	39	0.013	3.83	LN	Volcano by Grott et al., 2007
7	20	0.0258	3.94	MN	Volcano by Scott and Tanaka, 1980; Grott et al., 2007 Nfc by Dohm et al., 2001a, 2001b
8	10	0.0247	3.94	MN	Volcano by Scott and Tanaka, 1981a, 1981b; Grott et al., 2007
9	10	0.0548	4.06	EN	Volcano by Scott and Tanaka, 1981a, 1981b; Grott et al., 2007
10	12	0.0549	4.06	EN	Nb by Dohm et al., 2001a, 2001b
11	8	0.048	4.04	EN	Nb by Dohm et al., 2001a, 2001b
12	20	0.0105	3.80	LN	Volcano by Dohm and Tanaka, 1999
13	12	0.0105	3.80	LN	Volcano by Dohm and Tanaka, 1999 Nfc by Dohm et al., 2001a, 2001b
14	11	0.0196	3.90	MN	Volcano by Dohm and Tanaka, 1999; Scott and Tanaka 1980 Nfc by Dohm et al., 2001a, 2001b
15	11	0.0446	4.03	EN	Volcano by Dohm and Tanaka, 1999 Nfc by Dohm et al., 2001a, 2001b
16	45	0.0275	3.95	MN	Volcano by Dohm and Tanaka, 1999 Nfc by Dohm et al., 2001a, 2001b
17	24	0.0657	4.09	EN	Volcano by Dohm and Tanaka, 1999 Nfc by Dohm et al., 2001a, 2001b
18	21	0.0171	3.88	MN	Volcano by Dohm and Tanaka, 1999 HNfc by Dohm et al., 2001a, 2001b
19	12	0.0225	3.92	MN	Volcano by Dohm and Tanaka, 1999 Nfc by Dohm et al., 2001a, 2001b
20	8	0.0825	4.12	EN	c_2 by Dohm et al., 2001a, 2001b
21	11	0.0421	4.02	EN	Volcano by Dohm and Tanaka, 1999 Nfc by Dohm et al., 2001a, 2001b
22	15	0.13	4.19	EN	Nplh by Dohm et al., 2001a, 2001b
23	14	0.0391	4.01	EN	hf by McGill, 1978
24	12	0.0399	4.01	EN	pcm by McGill, 1978
25	33	0.0258	3.94	MN	Volcano by Dohm and Tanaka, 1999
26	9	0.00714	3.73	EH	pcu by McGill, 1978
27	7	0.0393	4.01	EN	pcm by McGill, 1978
28	10	0.0254	3.94	MN	pls by Howard, 1979
29	23	0.0567	4.06	EN	pls by Howard, 1979
30	12	0.0245	3.94	MN	plc by Masursky et al., 1978
31	19	0.00402	3.60	LH	pls by Howard, 1979
32	10	0.0789	4.11	EN	pls by Howard, 1979
33	7	0.0677	4.09	EN	pls by Howard, 1979
34	6	0.0861	4.13	EN	pls by Howard, 1979
35	25	0.0339	3.99	EN	pls by Howard, 1979
36	8	0.0623	4.08	EN	hc by Mutch and Morris, 1979
37	14	0.0327	3.98	EN	pls by Howard, 1979
38	21	0.0347	3.99	EN	pls by Howard, 1979
39	9	0.0949	4.14	EN	hc by Mutch and Morris, 1979
40	14	0.0527	4.05	EN	pls, c_1 by Howard, 1979
41	8	0.0563	4.06	EN	pls by Howard, 1979
42	13	0.067	4.09	EN	pls by Howard, 1979
43	11	0.0234	3.93	MN	m by Howard, 1979
44	48	0.0106	3.80	LN	3.81 Ga, (Werner, 2009)
47	8	0.027	3.95	MN	c_2 by DeHon, 1977
48	19	0.0448	4.03	EN	pr by DeHon, 1977
49	8	0.0565	4.06	EN	pr by DeHon, 1977
50	11	0.037	4.00	EN	hc by DeHon, 1977
51	19	0.0315	3.97	EN	mr by DeHon, 1977
52	5	0.0497	4.04	EN	c_1, pics by Condit and Soderblom, 1978
56	5	0.032	3.98	EN	volcano by Ghatan and Head, 2002
70	17	0.163	4.22	EN	c_1 by Moore, 1980
71	15	0.029	3.96	MN	c_1, hc by Moore, 1980
72	12	0.0378	4.00	EN	c_1, hc by Moore, 1980
73	16	0.0444	4.03	EN	c_1, hc by Moore, 1980
74	17	0.0368	4.00	EN	c_2 by Saunders, 1979
75	25	0.0138	3.84	LN	ps by McGill, 1978

* EN-Early Noachian; MN-Middle Noachian; LN-Late Noachian; EH-Early Hesperian; MH-Middle Hesperian; LH-Late Hesperian.

3. Ages of volcanoes on southern highlands

3.1. Dating methods

Crater size–frequency distributions (CSFDs) for seventy five volcanoes of the Thaumasia region and its surroundings were obtained to derive a general sequence of events and their relation to general martian history. We produced mosaics covering the Icaria Fossae–Thaumasia Highlands region of Mars using the THEMIS daytime-IR data at 100 m/pixel spatial resolution as a standard base. Because of the controversy regarding CSFDs for dating martian surfaces with regard to estimating "absolute" model ages and the use of statistics based on small craters (Hartmann, 2005), our approach in this study was to use craters ≥2 km diameter to avoid the addition of most secondary craters that would yield erroneously old ages and to use the results primarily for age comparisons among the putative volcanic features in this region and other volcanoes on Mars (i.e., even though the "absolute" model ages might not be accurate), the relative ages can be used for such comparisons with earlier studies, e.g., Williams et al. (2009) and Malin et al. (2006) reported impact craters discovered in MOC data produced between 1999 and 2006, which suggests that the cratering rate for Mars extrapolated from the Moon is essentially correct (Hartmann, 2005). Nevertheless, restricting our CSFDs to large craters and using ages for relative comparisons (e.g., to the Tharsis shields or the volcanoes in the circum-Hellas Volcanic Province) should produce more conservative results.

Crater measurements were partitioned into bins of increasing crater diameter based on standard practices. The binned data were used to produce cumulative crater size-frequency distribution plots with corresponding statistical errors (Hartmann, 1966; Neukum, 1983; Neukum and Hiller, 1981; Neukum and Wise, 1976), using the CRATERSTATS software package developed by the Free University, Berlin (Michael and Neukum, 2008). In this technique, the cumulative size-frequency distributions were analyzed to determine crater densities at specific reference diameters and to determine cratering model ages. Cumulative crater densities for 1-, 2-, 5-, 10-, and 16-km diameter craters were used to assess relative ages for martian geologic units and to place units into the martian chronologic system using key units as reference. In general, the lower the crater density (the fewer the craters that formed or have been preserved on the surface) is, the younger the age is. A *cratering model age* (in Ga) is calculated from the cumulative crater density at a reference crater diameter of 1 km using an established cratering chronology model for Mars (Neukum, 1983). The martian model is typically extrapolated from the lunar model (in which crater frequencies are correlated with radiometric ages from *Apollo* samples) and adjusted for the different orbital mechanics, crater scaling, and impact flux for Mars relative to the Moon. The transfer of the lunar cratering chronology model to Mars may introduce a systematic error of up to a factor of 2. This means that the typical uncertainty in cratering model ages could vary by a factor of 2 for ages <3.5 Ga (in the constant flux range), whereas the uncertainty is about ±100 Ma for ages >3.5 Ga (Ivanov, 2001). Extensive testing and application of these techniques, however, have shown that the applied martian cratering chronology model results in ages for basin formation and volcanic surfaces that are in good agreement with martian meteorite crystallization ages with respect to "peak" activity periods (Neukum et al., 2007), which suggests that the chronology model is correct within an uncertainty of less than 20%. We note that all of the surfaces in the Thaumasia region have been highly modified by degradational processes. In most cases, CSFDs show "kinks" in the cumulative distributions that are considered to represent resurfacing events, in which the smaller craters are

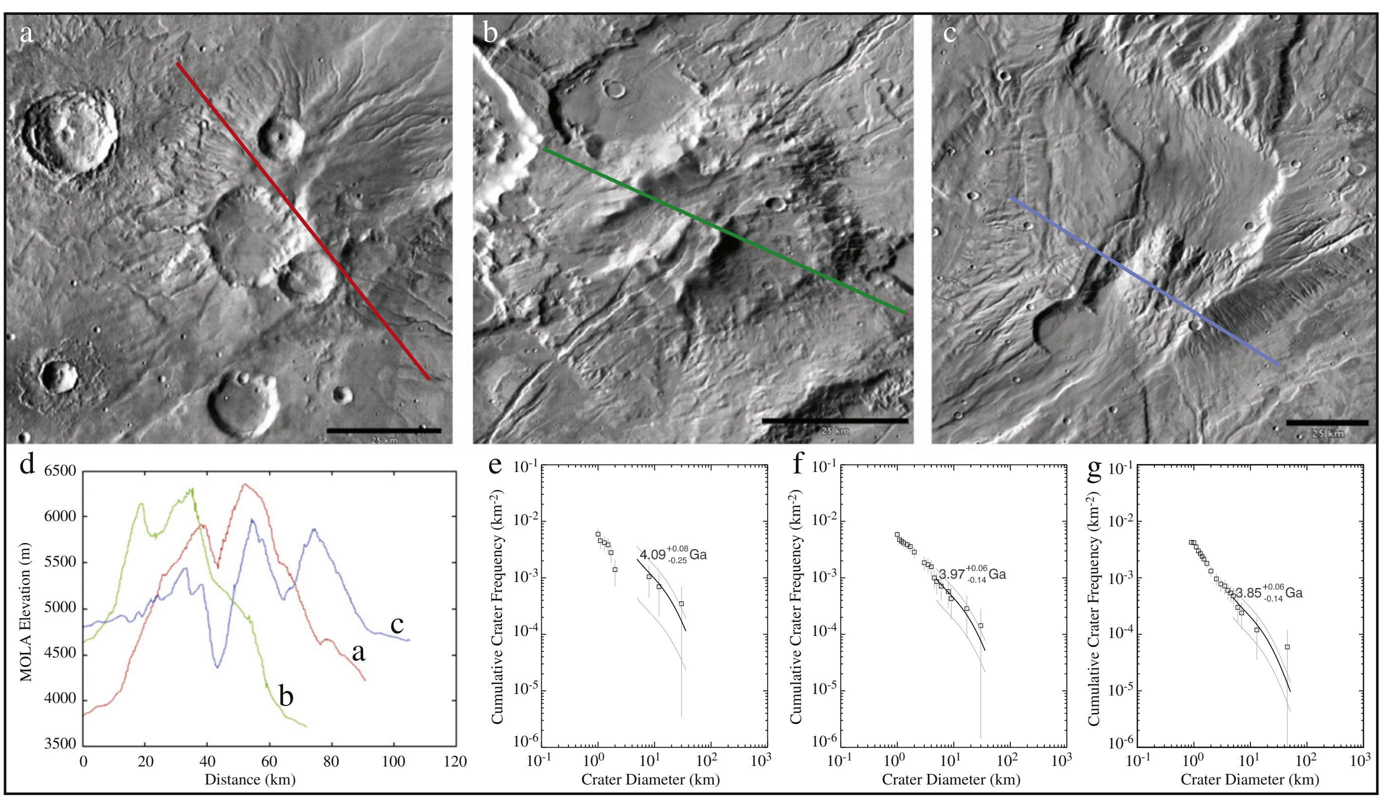

Fig. 2. Selected three group volcanoes and their dating results. (a), (b) and (c) are THEMIS day time IR images with a spatial resolution of 100 m/pixel. (a) Example for a volcano of Group 1, best preserved early Noachian shield volcanoes on the southern cratered highlands. The shield is located to the north of Terra Sirenum, and centered at 215.22E, 34.36S (No. 1 in Fig. 1 and Table 1S). (b) Example for a volcano of Group 2, moderately modified Early Noachian shields. The shield is located to the NE of Terra Sirenum, and centered at 243.36E, 39.53S (No. 23 in Fig. 1 and Table1S); (c) Example for a volcano of Group 3, one of the heavily degraded Early Noachian shields. The shield is located to the SE of Claritas Fossae, and centered at 271.33E, 37.57S (No. 8 in Fig. 1 and Table1S); (d) shows profiles of the three volcanic edifices; (e), (f) and (g) are the results of crater size-frequency distribution measurements for the volcanoes of (a), (b) and (c), respectively.

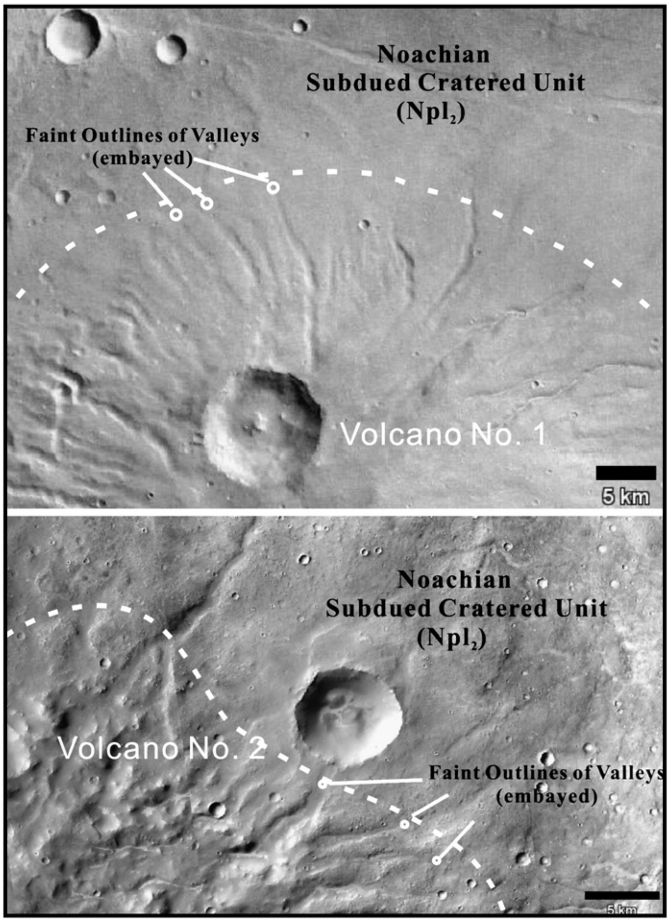

Fig. 3. Examples of stratigraphic boundaries between dissected volcanoes and other highland units. Portions of volcano 1(a) and 2(b) show ancient volcano blanks are covered by Noachian subdued cratered units (Npl, forms highland plains characterized by subdued and partly buried older crater rims; cut in places by grabens; rare flow fronts; locally grades into younger (Hesperian) and older (Hesperian–Noachian) ridged plains materials. It is interpreted as thin layer of lava flows and fluvial and aeolian deposits that partly bury underlying rocks. Dohm et al., 2001a, 2001b). These two volcanoes were mapped as Noachian older flow and construct material (Nfc) by Dohm et al. (2001a, 2001b). The dashed lines are the boundaries between Noachian units, as mapped at the 1:15 million scale by Dohm et al., 2001a, 2001b; Scott and Tanaka (1986) or Greeley and Guest (1987).

obliterated, while the larger craters are still visible and can be counted. Resurfacing events can include mantling by windblown, volcanic, or other deposits, or surface degradation processes, such as mass wasting or periglacial/permafrost activity, which could differentially remove smaller craters. Because of the uncertainty in the process(es) leading to these "kinks," and because the focus of this study is on the major formative, putative volcanic events, this aspect of the CSFDs is not considered.

3.2. Dating results

THEMIS daytime-IR mosaics at 100 m/pixel spatial resolution (Edwards et al., 2011) were used as a consistent image base to perform crater counts on the proposed volcanic edifices, complemented with CTX images at 6 m/pixel (Malin et al., 2007) (Table 1 and Table S1; Fig. 4). The crater counting method follows standard practices. The estimates for the Group 1 volcanoes yield a mean cratering model age of ~4.0 Ga, which falls into the Early Noachian Epoch based on Ivanov (2001) and Hartmann and Neukum (2001). These dating results are generally consist with stratigraphic correlations between dissected volcanoes and other highland units (Fig. 3).

The ages obtained using crater counts for moderately modified (Group 2) and heavily modified (Group 3) domes are mostly between 3.9 Ga and 4.1 Ga (Figs. 2, 4, Table 1 and Table S1). The results demonstrate that for all three groups relatively small domes are very close in age at 4.0 Ga. They formed in late Early Noachian and are the oldest martian volcanoes identified on Mars. Because these ages were estimated from crater counts and the craters are overlapped by erosion features, it is suggested that the ages could also indicate the time of latest surface water flow modification, and that fluid water and snows that covered volcanoes melted before 3.5 Ga in this area between 40°S to 10°S. Old small volcanoes close to Hellas basin (60°S to 80°S) also show similar features (Table S1).

4. Discussion

4.1. Features of Noachian volcanism on Mars

Volcanoes formed in the Noachian as dated by this study have very different surface morphologies and expression than those produced in the Hesperian (Fassett and Head, 2007; Greeley and Spudis, 1981; Werner, 2009). Noachian volcanic materials occur as shields and lava plains and have mostly been modified by impact craters and channels, while Hesperian volcanism is primarily flood lavas and a number of low shields (e.g. Syrtis Major) modified by recent aeolian mantles that fill depressions.

The study of volcanism in the southern highlands is inhibited because of the heavily cratered and degraded land surface. It is generally accepted that flood volcanism occurred, even though most ridged plains of the highlands have Hesperian ages <3.7 Ga (Williams et al., 2009). Noachian volcanic edifices are poorly studied with the exception of larger structures around the Hellas basin (Williams et al., 2008, 2009) and in the Tharsis rise (Werner, 2005, 2009). Our study reveals the presence of Noachian shield-like, putative volcanic structures with 50–100 km diameters and 2–3 km high in the Thaumasia Planum (Dohm and Tanaka, 1999; Xiao et al., 2009), Coracis Fossae, Claritas Fossae, Icaria Fossae, Aonia Terra, Terra Sirenum, Terra Cimmeria, and Sisyphi Montes (Fig. 1, Scott and Tanaka, 1986; Tanaka and Scott, 1987; Ghatan and Head, 2002). We suggest that these well-preserved putative shields (group 1) may represent the remaining examples of a larger population of volcanic edifices formed in early Noachian times, considering their old ages and preservation state in the southern highlands. The origins of the significantly modified shield-like edifices are probably also related to volcanism and/or magmatism. The relatively small volcanoes, along with fissure eruptions, would have generated lava flows and possibly pyroclastic deposits that cover this part of the martian surface.

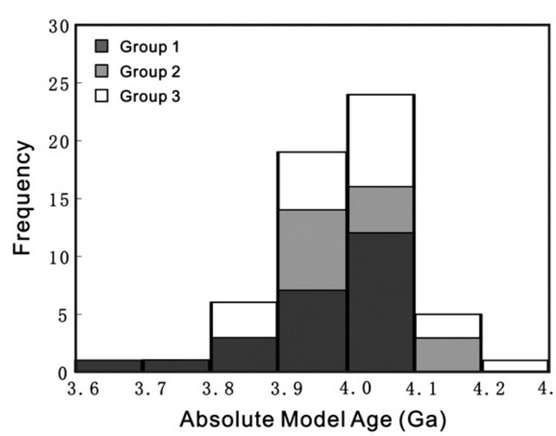

Fig. 4. Histogram diagram showing the ages of ancient volcanoes in south highland of Mars, data from Table 1 and Table S1.

Interestingly, most of the 75 relatively small volcanoes can be grouped into two volcanic provinces: 43 near the Tharsis rise (Numbers 1–43, see Fig.1) and 17 close to circum-Hellas (Williams et al., 2009) volcanic province (Numbers 53–69, see Fig. 1). The remaining 15 volcanoes are also located in the southern heavily cratered highlands. They are distant from the above mentioned two large volcanic provinces and may represent independent localized volcanism (see Fig. 6).

4.2. Relation with Tharsis and circum-Hellas volcanic provinces

The Tharsis rise is the largest volcanic province on Mars; it is usually recognized as composed of several large volcanoes (e.g. Olympus Mons, Pavonis Mons, Arsia Mons, Ascreaus Mons, and Alba Mons) and includes small volcanoes at Syria Planum and elsewhere on the Tharsis rise (Baptista et al., 2008; Hauber et al., 2009). Its boundary is defined by the topographic rise and lava flows erupted from the large volcanoes (to the north of the dot-dashed yellow line in Fig. 1). The volcanic history of Tharsis has been proposed to have lasted from Hesperian to Late Amazonia (<3.8 Ga to less than 0.1 Ga, Werner, 2009; Hauber et al., 2009, 2011; Xiao and Wang, 2009). Here we suggest the existence of 43 small volcanic constructs located just to the southern margin of the Tharsis volcanic province (Fig. 1) that were formed mostly at ~4.0 Ga, to 3.9 Ga, and connect them timewise with the Tharsis large volcanoes. The space and time correlation implies that they could have been generated from the same super-mantle hot field, initiated with numerous small volcanoes covering most of this region and eventually evolving into a long-term volcanic eruption, shifting to fewer but larger volcanoes above the hottest or most massive magma source region. Combining the small volcanoes identified by this study with the large Tharsis volcanoes suggests that the primary Tharsis volcanic province is larger than its present occurrence, and that its activity could be traced to early Noachian time.

The newly identified 17 small volcanoes southwest of the Hellas basin are spatially close to the circum-Hellas Volcanic Province. There are six large volcanic features (Tyrrhena, Hadriaca, Amphitrites, Peneus, Malea, and Pityusa Paterae) located in this province, which formed after the Hellas impact between 3.8 and 3.6 Ga (Williams et al., 2009, 2010). These volcanoes, plus the surrounding putative volcanic ridged plains, are comparable in size to the Elysium volcanic province, and they may have been a dominant source of volcanism early in martian history (Williams et al., 2010). These 17 small volcanic edifices make the circum-Hellas Volcanic Province larger and imply a longer history of volcanism that ceased earlier than in the Tharsis volcanic province. Together with the Elysium volcanic province, there would have been three large volcanic provinces triggered by three super mantle plumes or magma source regions, respectively.

4.3. Implications for Martian thermal evolution history

Many researchers have proposed models to investigate the thermal evolution and crustal growth history of Mars based on geophysical modeling (Breuer and Spohn, 2003, 2006; Fraeman and Korenaga, 2010; Hauck and Phillips, 2002; Keller and Tackley, 2009; Li and Kiefer, 2007; McGovern et al., 2002, 2004; Nimmo and Stevenson, 2001; Schumacher and Breuer, 2007; Spohn, 1991; Wieczorek and Zuber, 2004) and on geochemical analysis of the martian meteorites (Norman, 1999, 2002). It is generally assumed that the bulk of the crust was in place around the end of the Noachian epoch at 4 Gyr b.p. (Nimmo and Tanaka, 2005; Xiao et al., 2008). The volumetrically largest, late stage contribution to the martian crust is marked by the emplacement of the Tharsis rise, which was essentially complete at the end of the Noachian period (Phillips et al., 2002) and changed little thereafter (Banerdt and Golombek, 2000).

The ages of volcanism are summarized in Table 1 and Fig. 4. Previous crater counts (Plescia, 2004; Werner, 2005, 2009; Williams et al., 2009; Robbins et al., 2011) have reported several old volcanoes (>3.9 Ga), and proposed planetwide volcanism in martian early history (>3.5 Ga, Werner, 2009). However the ages of the oldest volcanoes reported in this study provide a piece of evidence that allow us to track visible martian volcanism to as early as Early Noachian (>4.0 Ga). With reported ages of volcanoes of very late Amazonian (<0.1 Ga, Hauber et al., 2009, 2011), volcanism on Mars lasted longer than previously thought. The long time span can be divided into four overlapping phases (Fig. 5): a) phase I included widespread plains volcanism, which is defined as being an intermediate style between flood basalt and the Hawaii shields (Hauber et al., 2009), and globally distributed small constructs, including the Tharsis area before 4.0 Gyr, from pre-Noachian to Early Noachian; b) phase II represents major central volcanism around the Hellas basin, Tharsis paterae and Nili Patera between 4.0 Gyr and 3.7 Gyr, from Middle Noachian to Late Noachian; c) phase III was the major volcanism in the Tharsis and Elysium provinces between 3.7 Gyr and 3.5 Gyr, from Late Noachian to Late Hesperian; d) phase IV had waning volcanism in Tharsis and Elysium volcanic provinces, lasting from 3.5 Gyr to present, Amazonian, which may also occur as local plains volcanism that is related to partial melting in an anomalous warm mantle underneath a thickened crust (Hauber et al., 2009, 2011; Schumacher and Breuer, 2007).

Numerous and randomly distributed fissure and central volcanoes would be expected on the surface of Mars, as most of the geophysical models suggested. With rapid cooling in the Middle Noachian, the magma body solidified and only a few small, isolated chambers were left to produce the volcanoes in the southern highlands. Finally, magmas were produced by mantle plume activity and formed the Tharsis and Elysium volcanoes (Baratoux et al., 2011). This picture is shown in Fig. 6. However, we do not exclude the possibility that

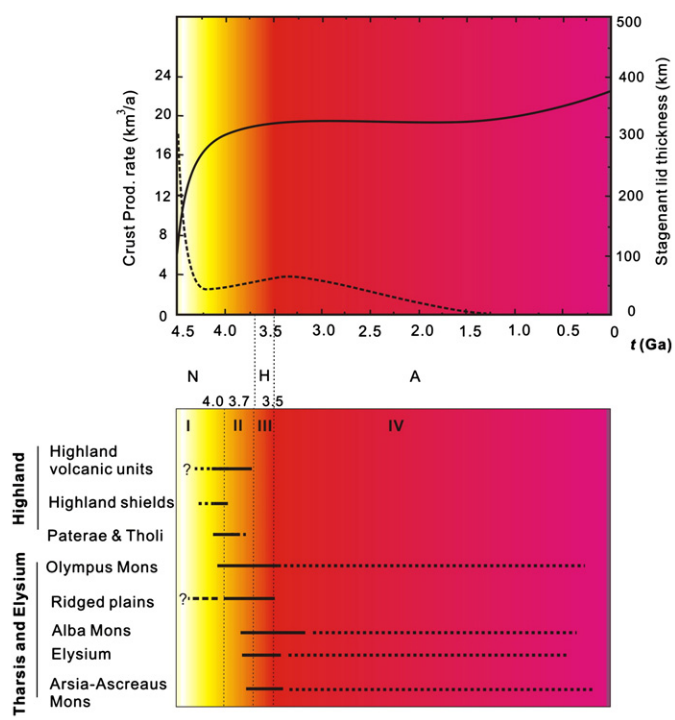

Fig. 5. Integrated model constraints on thermal evolution and volcanism on Mars. Upper: N, Noachian; H, Hesperian; A, Amazonian. Volumetric flux of martian crust production rate (dashed line) and thickening of the martian stagnant lid (solid line) as functions of time *t* (cooling models are after Breuer and Spohn, 2006). The models base on the assumption of a dry martian mantle and without a primordial crust and initial mantle temperature are 1900 K. There are other evolution scenarios with a wet mantle suggesting a different crustal production rate and stagnant lid thickness with time. Lower: Ages of global volcanism. Solid lines indicate recognizable volcanoes with crater counts ages, whereas dotted lines correspond to inferred volcanism. I, II, III and IV represent four volcanic phases. See the text for detailed discussions.

there was a catastrophic volcanic event in the Early Hesperian, which could account for the Hesperian ridged plains materials (Carr and Head, 2010), such as Lunae Planum, Amazonis Planitia, Solis Planum, Syrtis Major Planitia (Saunders et al., 1981), and the circum-Hellas ridged plains (Malea Planum, Promethei Terra, Hesperia Planum, and the eastern Hellas basin floor) that are contemporaneous with the formation of the major volcanic edifices (3.6–3.8 Ga) in the circum-Hellas volcanic province (Williams et al., 2010). Clearly, these ridged plains are parts of Tharsis, circum-Hellas, Elysium and Syrtis Major volcanic provinces, and could be of volcanic origin. This implies that all of the four large volcanic provinces have experienced catastrophic eruption events at Late Noachian to Early Hesperian time.

It is noted that the ancient small volcanoes are mostly located to the south and southeast of the Tharsis rise, which is the largest volcanic province on Mars and which experienced the longest volcanic history (Greeley and Spudis, 1981). The small volcanoes could represent the initial stages of volcanic activity in the Tharsis province. We propose that the Tharsis super-plume initiated and generated a large population of small volcanoes in this region, similar to those located in Venusian volcanic lava plains (Head et al., 1992). Most of these volcanoes ceased activity before and shortly after 4.0 Ga, except for the large volcanoes (such as Olympus Mons and Alba Mons).

5. Summary and concluding remarks

Mars has experienced a long volcanic history and has some of the best preserved early volcanic features among terrestrial planets, which provide unique insight into the thermal history of the inner

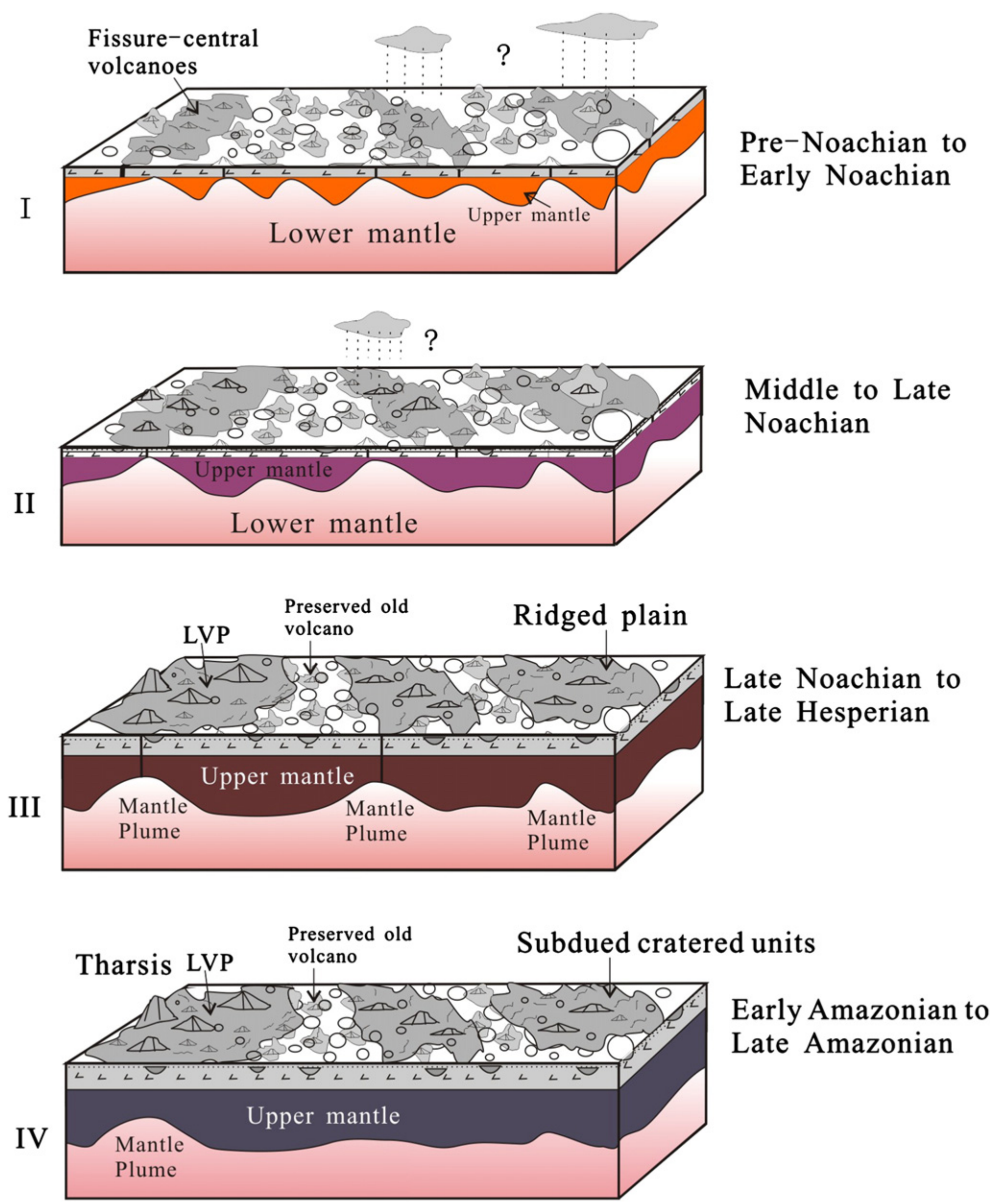

Fig. 6. Volcanic features formed during the early history of Mars. Volcanism in martian early history was changed from initial global distributed central and fissure-central volcanoes, and plain volcanism (I), to regional volcanism (II) then to locally activated and mantle plume controlled volcanism, which formed the predominant large volcanic provinces (LVP) (III, e.g. Tharsis, Elysium, circum-Hellas and Syrtis Major) and ridged plains (e.g. Lunae Planum, Amazonis Planitia, Solis Planum, Syrtis Major Planitia, Malea Planum, Promethei Terra, Hesperia Planum, and the eastern Hellas basin floor),and local recent small shields and plains volcanism (IV, e.g. Tharsis rise). Most of the oldest volcanoes have been modified by impact cratering, channeling, and tectonic deformation, covered by later volcanic materials, and few were preserved. Not to scale. See text for details.

planets. Available high spatial resolution global image data set (e.g. THEMIS, HRSC and CTX) allow us to re-examine heavily-eroded surface features and assess whether they could be some of the oldest volcanoes on Mars, or perhaps even some of the oldest volcanoes of the solar system. The main results of this study are:

1) The identification of 75 relatively small ancient volcanoes in the southern highlands; they are divided into three groups according to their state of degradation and morphological similarities to shield volcanoes. We interpret most of these features as shield-like, central volcanic edifices with diameters ranging from 50 to 100 km, heights of 2–3 km, and which formed during the Early Noachian (>4.0 Ga). These features constitute the oldest volcanoes reported on Mars.
2) Most of these features are spatially adjacent to or partially overlap the Tharsis Province and the circum-Hellas Volcanic Province, and suggest that these ancient volcanoes are part of these two large volcanic provinces, possibly indicating that the volcanic histories of these provinces was longer than previously thought.
3) Volcanic features are closely related to the thermal history of Mars. Volcanism started with globally distributed fissure and small central volcanoes (>4.0 Ga) and then declined to a few locations (<3.5 Ga) because of a decrease in interior heat production, e.g. Tharsis, circum-Hellas, Elysium, and Syrtis Major.

The international Mars exploration programs have brought untold new knowledge about Mars. New small volcanic edifices and their surface modification features provide new evidence to understand early volcanic history and environmental changes from Early Noachian to Late Noachian. However, some important questions related to early martian volcanology and environmental changes remain: 1) where and how old are the oldest volcano(s) on Mars? If the earliest volcanism was globally distributed and constructed numerous small volcanic edifices, most could have been buried and partially buried by later volcanic materials and/or destroyed by impact cratering. Another difficulty is the small sizes of the volcanoes, which challenges dating methods. Some small volcanoes could have survived from large impacts and it could be possible to obtain a younger age relative to those encountered big impact. To solve this problem, we should consider studying the surface features, morphology and the ages of underlying terrains in more detail; 2) moreover, we do not know much about the true composition of these oldest volcanoes. Available CRISM and OMEGA, and TES data have been reviewed for these volcanoes, however, most of these volcanoes are heavily dust-covered and in-situ composition of outcrop rocks is currently impossible to obtain; 3) there is still a debate about early martian atmosphere and environment changes. Radial fluid channels observed on these old volcanoes could be resulted from rain fall, due to a warm and wet environment or local big impact events. These should be evaluated through future studies.

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2012.01.027.

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