VOLCANISM ON MARS: INTEGRATED CONSTRAINTS AND IMPLICATIONS FOR MARTIAN THERMAL HISTORY. L. Xiao\textsuperscript{1,2}, R. Greeley\textsuperscript{2} and D. Williams\textsuperscript{2}, \textsuperscript{1}Research Center for Space Science & Technology, Faculty of Earth Science, China University of Geosciences, Wuhan, 430074, China (longxiao@cug.edu.cn), \textsuperscript{2}School of Earth and Space Exploration, Arizona State University, Tempe, 85287, AZ.

1. Introduction: Thermal and accretionary models favor initial melting much of the crust early in Mars' history. Volcanism is the most direct expression of thermal evolution and can be linked to other observations, such as crustal dichotomy, global chemical composition and atmosphere. Although martian volcanoes appear to be predominantly basaltic [1-2], other volcanic rocks have been identified by spectroscopy [3-5]. The purpose of this study is to combine morphological analyses, temporal and spatial distributions of volcanoes, and global compositional information with a geophysical model of the evolution of the interior to assess genetic relationships among these factors.

2. Approach: We reappraise spatial distributions, morphologic properties, and relative ages of volcanoes on Mars, based on a) recent mineral mapping from orbiters and landers [4-10], b) information on crustal thickness and dichotomy [11-12], and c) magma production [13] and heat flux [14-16] estimates. To generate integrated model.

3. Results

Time span and spatial distribution of martian volcanoes

The ages of volcanism are summarized in Fig.1. From new crater counts [18, 19], visible volcanism initiated in the Noachian (>3.9 Ga), and included highland ridged plains and shields, and continued to the Late Amazonian (0.1 Ga). This time span can be grouped into three overlapping phases (Fig. 1): a) phase 1 highland volcanic ridged plains and shields constructed before 3.7 Gyr; b) phase 2 major volcanism in Tharsis and Elysium volcanic provinces between 3.7 Gyr and 3.5 Gyr that produced most of the volcanic rocks in these regions; c) phase 3, waning volcanism in Tharsis and Elysium volcanic provinces, lasted from 3.5 Gyr to ~0.1 Gyr.

Diversity of shapes and styles of volcanoes

Martian volcanoes include shields, domes, and various plateaus and plains that lack visible volcanic vents. Relief and slopes of central volcanoes are different and relate to their eruption styles and magma compositions. Generally, the older volcanoes (highland paterae) have lower slopes, ranging from 0.2 to 1˚, and were dominated by explosive eruptions. In contrast, younger shields and domes have high relief, and large slopes, and are were dominated by effusive eruptions. These differences could result from magma properties and environmental conditions, although erosion could also play a role on the older volcanoes.

Fig. 1 Integrated model constraints on volcanism on Mars. N, Noachian; H, Hesperian; A, Amazonian. Volumetric flux of Martian volcanism Vv vs. time t for several values of the crustal fractionation parameter X and thickening of the martian lithosphere with time t (cooling models are after [16]). The models have initial core sulfur concentration x_s of 10 and 25 wt%, respectively. For detailed discussion see text.
Global mineral mapping results and their constraints on magma properties

Primary silicates, such as olivine, pyroxene and plagioclase, have been mapped [4-9]. The spatial distribution of these minerals shows that the surface is compositionally heterogeneous. Olivine is distributed in south highland, particularly in Gusev Crater, Nili Fossae and lower portion of Valles Mariners [4-10]. Olivine is also scattered in other parts of southern highlands [5]. This suggests that olivine occurs only in ancient Noachian-aged materials, with highest content about 25%-30% by volume [7, 8]. Two types of pyroxene have been spectrally confirmed in the southern highlands: high calcium pyroxene or clinopyroxene is present in Hesperian terrains of low-albedo while low calcium pyroxene or orthopyroxene is present mainly in bright Noachian terrains [5, 14]. Concentrations of plagioclase and high-Ca pyroxene are consistent with basaltic surfaces and are located in highland regions north of 45°S. Significant concentrations of plagioclase and sheet silicates/high-Si glass and low concentrations of high-Ca pyroxenes are consistent with andesite surfaces and are concentrated in both southern and northern high-latitude regions. Andesitic materials was found overlapped older basaltic rocks in northern lowland [15]. Interestingly, volcanoes in Tharsis and Elysium provinces have less signatures of olivine and pyroxene in OMEGA data [5, 6] and MGS-TES data [15]; probably suggesting that they are andesitic or andesite-basaltic composition, contrasting to Noachian-aged highland shield volcanoes and volcanic plains.

Thermal history

As modeled by [16,17] and [14] (Fig. 1), the martian interior cooled rapidly in the first 500 Myr followed by a slower cooling rate [17]. Consequently, a magma ocean could have formed early resulting in lunar-like highland crust [21, 22]; later mantle plumes initiated central vent volcanism [23].

4. Discussion and conclusions

Volcanism on Mars can be grouped into three phases. The first phase formed from a magma ocean that was severely cratered to form highlands and subsequent volcanic plains with early-middle Noachian ages. The second phase formed low relief volcanic shields in the southern highland of Hesperian ages. The third phase volcanism constructed high relief shields and domes in the northern lowlands that are Late Hesperian to middle Amazonian in age. These time spans and phases boundaries are generally consistent with chronological epochs. Their genetic correlation is under consideration.

There are different eruption styles for the three phases of volcanism. They may also have distinguishable compositions. In Phase 1 volcanic rocks are mafic and ultra-mafic in composition, forming picritic basalts, suggested by olivine-rich volcanic materials [7, 8], corresponding to high partial melting degrees of whole mantle when the mantle was extremely hot. Phase 2 and 3 volcanism formed more felsic andesite and/or andesite basalts, and resulted from low partial degree melting of the cooling lower mantle by thermal mantle plumes.

Changes in volcanism were controlled by thermal evolution history of the planet. High heat flux of the mantle in early Noachian epoch melted large portions of the martian mantle and formed a magma ocean beneath the southern hemispheric crust. The first-phase plains volcanism was sourced from this magma ocean. With rapid cooling to middle Noachian epoch, the magma ocean was solidified and left only a few small magma chambers to produce shield volcanoes on the southern highland. Finally magmas were produced by mantle plume activity that resulted in low degree partial melting of the mantle and formed andesitic Tharsis and Elysium volcanoes.