LARGEST THARSIS VOLCANOES KEEP GROWING AND MARK >4-GA-LASTING MARTIAN HOT SPOTS.

J. Ciazela[1], D. Mège[1], B. Pieterek[2], M. Ciazela[1], J. Gurgurewicz[1], A. Lagain[3], and P.-A. Tesson[1], [1]Space Research Centre, Polish Academy of Sciences, ul. Bartycka 18A, 00-716 Warsaw, Poland (jc@cbk.pan.wroc.pl), [2]Institute of Geology, Adam Mickiewicz University, ul. Bogumila Krygowskiego 12, 60-680 Poznan, Poland, [3]Space Science and Technology Centre, Curtin University, Kent Street, Bentley, Perth, Western Australia 6102, Australia.

Introduction: Due to the lack of plate tectonics and magnetic field, the Martian core was long interpreted to be entirely solid and volcanism on Mars extinct. This has been recently questioned by several works suggesting existence of a liquid outermost layer at the Martian core [1–3]. The liquid core would explain the growing body of evidence for recent (2-250 Ma) Martian volcanism [4–10], and volcanic gases (i.e., CH_4, H_2S, SO_2, and HCl) are currently tracked down by the ExoMars Trace Gas Orbiter (TGO) [11, 12]. Two million years make up <0.1% of the Mars age (4567 myr) indicating timespan of volcano eruptions over >99.9% of the Martian history. Four decades of orbital data without observing volcano eruptions are not sufficient to ascertain that volcanism is already extinct. In this study, we take advantage of absent plate tectonics and limited erosion on Mars to track the intensity of volcanism in major volcanic provinces over Martian history and provide more evidence for the dormant character of Martian volcanism.

Geological Setting: We mainly focused on Tharsis, which is the largest volcanic province on Mars, extending from 15°S to 45°N, and from 90° to 140°W. The well-known 21.3-km-high Olympus Mons is accompanied by Alba Mons, Tharsis Montes (>10 km-high Arsia Mons, Pavonis Mons, and Ascraeus Mons), seven other large volcanoes (Uranius Mons, Tharsis Tholus, Biblis Tholus, Ceraunius Tholus, Ulysses Tholus, Uranius Tholus, and Jovis Tholus), and at least 302 much smaller volcanic cones (>1 km in diameter) mapped by us [13] using combined datasets from Mars Orbiter Laser Altimeter (MOLA) of Mars Global Surveyor (MGS), Thermal Emission Imaging System (THEMIS) of Mars Odyssey (MO), and Context Camera (CTX) of Mars Reconnaissance Orbiter (MRO).

Method: We estimated the ages of last activity and volumes of the 12 largest Tharsis volcanic edifices. The ages of the last activity are always based on the summit calderas. Where possible, we identified the youngest calderas using cross-cutting relationships. Otherwise, we dated several calderas and reported the age of the youngest. The calderas were dated by counting >100-m craters with ArcGIS extension CraterTools [14] on the CTX imagery. Crater statistics and derivation of crater model ages with the age errors (Fig. 1) were carried out with Craterstats II [15] by applying the Hartmann's [2005] chronology system [16].

The volumes were calculated with ArcMap using the digital elevation model (DEM) from MOLA/MGS (128 pixels/degree). In order to estimate a realistic error on the method, we have also computed simplified volumes from the right conical frustums approximating volcano shapes. The error bars in Fig. 1 represent the average relative volume difference between the DEM-derived and simplified volumes.

Results and Discussion: Our results indicate a significant inverse correlation ($R^2 = 0.83$) between volcano volume and youngest summit caldera age, consistent with earlier studies [4, 6] (Fig. 1a). Importantly, we do not see such an inverse correlation ($R^2 = 0.03$,

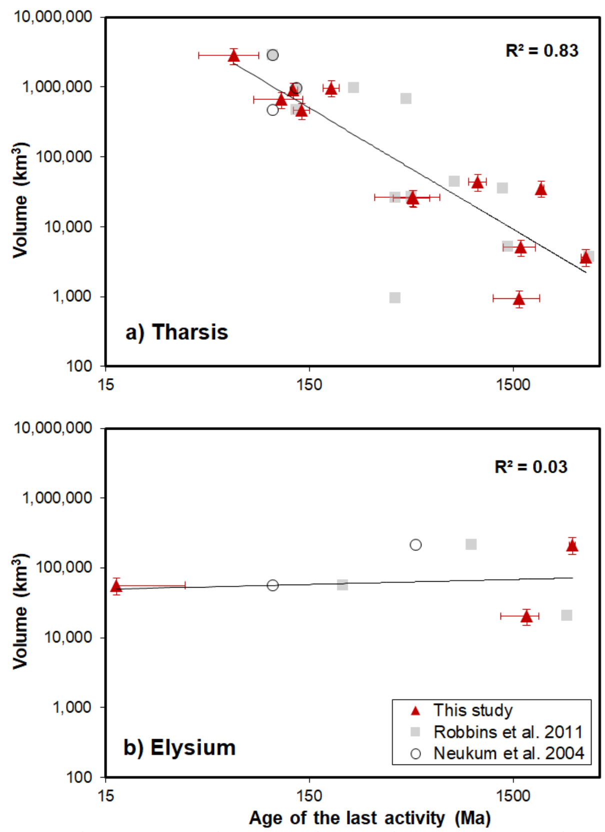

Figure 1. Volcano volume vs. age of the last activity at the summit calderas in the Tharsis (a) and Elysium (b) provinces. Note the high correlation coefficient for the Tharsis province interpreted in the Results and Discussion section. The volume error bars represent the average relative difference between volcano volumes calculated using two different methods (see the Method section). The age error bars are derived from the number of craters used to fit an isochron to the determined Crater Size Frequency Distribution.

Fig. 1b) in the second largest volcanic province on Mars, Elysium. The Elysium province is, however, characterized by a relatively thin crust (40-50 km) [17] and short-lasting volcanism mostly limited to Noachian and Hesperian [18]. The Tharsis crust, on the other hand, is thought to be thicker (70-90 km) [17] and shows a prolonged tectonic activity of nearly constant intensity throughout the Martian history [19]. Our results support this indicating prolonged magmatic activity in Tharsis. After a coeval beginning of volcanic activity in the entire Tharsis province in Early Noachian (~4.5 Ga), small magma reservoirs would have stopped working early, yielding smaller volcanoes, whereas larger magma reservoirs underneath the largest volcanoes lasted longer and might be still active.

Although the high R^2 coefficient for Tharsis is consistent with shield volcano volumes being principally controlled by the times of their emplacement [20], the duration is unlikely the only factor. Such a simplistic interpretation of our correlations would imply that magma flux would gradually increase over the Martian history. This would be though unrealistic considering small size and consequently fast cooling of Mars [21].

Instead, we propose that volcano volume (V) is controlled by a function of age (A) and initial magma reservoir volume (V_0). The shape of this is likely similar to a function of crustal production for Mars. Approximating the function of crustal production for the 4.5-0.0 Ga time interval from Kiefer et al. [22] (the red curve on their Fig. 5), calculated based on the thermal and magmatic evolution model of Sandu and Kiefer [23], we obtain $V \approx 0.3083V_0 \cdot \log(4500 - A) - 210 \cdot (2120 - A)^2$. V is expressed in km^3 and A in Ma. We then performed iteration of the Kiefer function using the 12 edifice volumes and the 12 ages (Fig. 1a) as a set of 24 constraints, and obtained the final function $V = 0.2742V_0 \cdot \log(4500 - A) - 370$. This function predicts the volume evolution of all 12 volcanoes over time. Using derivatives (dV/dAge), magma flux over time is obtained for a given volcano, and ΣdV/dAge predicts eruptive magma flux over time in the Tharsis area (Fig. 2) under the assumption that the whole erupted material would be enclosed in the 12 volcanic cones. In reality this is not the case, and if we assume that the 12 volcanoes comprise only 80% of the erupted material in Tharsis, then the total magma flux for the Tharsis province would be by 125% larger. For example, our model indicates the Tharsis magma flux decreases exponentially with time from >800 km^3/myr in Noachian to ~80-120 km^3/myr today (Fig. 2). However, with the aforementioned 80%, the corresponding fluxes will become yet larger with >1000 km^3/myr and 100-150 km^3/myr, respectively.

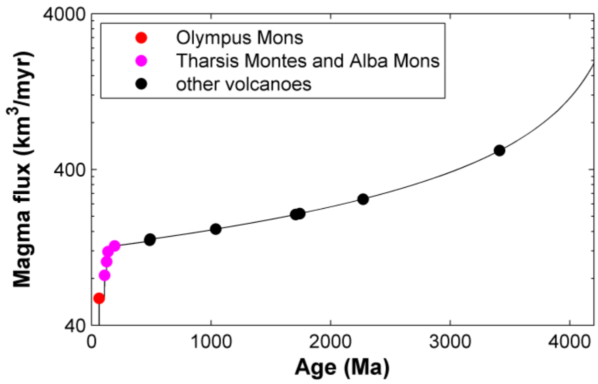

Figure 2. Modelled magma flux in the Tharsis province vs. age. The dots represent the 12 largest Tharsis volcanoes. Dot age represents the last volcano activity. The corresponding magma flux rate is the total flux in Tharsis at this time. Note that Olympus Mons and some other giant volcanoes (the pink dots) do not go in line with the rest of the model and are possibly still active. The model predicts a decrease of the total Tharsis eruptive flux from 164 to 129 km^3/myr between 1000 and 200 Ma. This implies that an ongoing average flux of ~80-120 km^3/myr would be more realistic than the assumption of a completely extinct volcanism. This is in line with the current global Martian flux of 8-400 km^3/myr estimated by Kiefer [24]. See the Results and Discussion section for further details on the model.

Conclusions and perspectives: In any scenario, the >4-Ga-lasting Tharsis volcanism is more likely to be dormant rather than extinct. The eruptive magma flux may be in a range of 80-150 km^3/myr. The best candidates for active magma reservoirs are associated with Olympus Mons, Tharsis Montes, and perhaps Alba Mons. Even though the ExoMars TGO has not yet detected gases of volcanic or hydrothermal origin, future detections in the proximity of large Tharsis volcanoes would not be a surprise.

References: [1] Yoder C. et al. (2003) *Science*, *300*, 299–303. [2] Métivier L. et al. (2008) *Icarus*, *194*, 476–486. [3] Fei Y. and Bertka C. (2005) *Science*, *308,* 1120–1121. [4] Neukum G. et al. (2004) *Nature*, *432*, 971–979. [5] Hauber E. et al. (2005) *Nature*, *434*, 356–361. [6] Robbins S. J. et al. (2011) *Icarus*, *211*, 1179–1203. [7] Jaumann R. et al. (2015) *Planet. Space Sci.*, *112*, 53–97. [8] Richardson J. et al. (2017) *EPSL*, *458*, 170–178. [9] Voigt J. R. C. and Hamilton C. W. (2018) *Icarus*, *309*, 389–410. [10] Head J. W. and Wilson L. (2007) *Ann. Glaciol.*, *45*, 1–13. [11] Korablev O. et al. (2018) *Space Sci. Rev.*, *214*, 7. [12] Vandaele A. C. et al. (2018) *Space Sci. Rev*., *214*, 80. [13] Pieterek B. et al. (2019) *LPSC*, *50*, 1369. [14] Kneissl T. Ã. et al. (2011) *Planet. Space Sci.*, *59*, 1243–1254. [15] Michael G. G. and Neukum G. (2010) *EPSL*, *294*, 223–229. [16] Hartmann W. K. (2005) *Icarus 174*, 294–320. [17] Tenzer R. et al. (2015) *EPSL*, *425*, 84–92. [18] Platz T. and Michael G. (2011) *EPSL*, *312*, 140–151. [19] Bouley S. et al. (2018) *EPSL*, *488*, 126–133. [20] Baratoux D. et al. (2009) *JVGR*, *185*, 47-68. [21] Ruiz J. (2014) *Sci. Rep.*, *4*, 4338. [22] Kiefer W. S. et al. (2015) *GCA*, *162*, 247–258. [23] Sandu C. and Kiefer W. (2012) *Geophys. Res. Lett.*, *39*, L03201. [24] Kiefer W. S. (2003) *Meteorit. Planet. Sci.*, *38*, 1815–1832.