RECENT AND FUTURE VOLCANISM ON DORMANT MARS.

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Summary: Evidence for geologically very recent volcanism on Mars, in some cases within the past 0.1% of Mars' 4.5 Ga history, seems to be at odds with the lack of observation of on-going activity. We suggest that Mars is dormant rather than extinct, in a cycle characterised by ~100 Ma epochs of inactivity, punctuated with ~1 Ma, single-centre, eruptive epochs. Our predictions of erupted volumes and eruption rates are consistent with the volumes and lengths of the youngest lava flows on Olympus Mons, and suggest that, even if an eruptive epoch is on-going, it may be 10s of years before the next ~2 year-long eruption.

Evidence for recent volcanism: With the availability of improved image data over recent years, there have been considerable efforts to refine the methods for dating the Martian surface using crater counts [1,2]. The outcome has been a narrowing of the gap between the results of the leading groups and, despite lingering issues [3], there is a growing consensus in crater isochronological studies. A major result has been increasingly youthful age estimates for late-stage volcanism, most notably at two sites.

Cerberus Planum. The Athabasca Valles channel system in the Cerberus region, to the south-east of the Elysium Rise, has both lava flows and fluvial channels that appear to have been carved by floods initialized by volcanic dyke emplacement [4]. Cratering studies have given ages of <20 Ma [5] and ~3 Ma [6], the youngest of which is <0.1% of the 4.5 Ga age of Mars.

Olympus Mons. Olympus Mons, the largest and youngest giant shield volcano on Mars, exhibits cratering ages as small as a few Ma for some lava flows on the flanks [7,8], and 100-200 Ma for the nested summit calderas [8]. Note, however, that *all* stratigraphic contacts between these calderas suggest age relations contrary to those determined by crater counting [8]. Although many of these might be explicable by quoted statistical errors (~30%) [8], this seems an insufficient explanation for all of the contacts taken together, and so either there have been unusual and unexplained geologic resurfacing events or there are problems with the crater counting method. Until this issue is resolved, these cratering statistics with remain controversial.

Mars meteorite isotopic studies. However, crater counts are not the only indicators of young volcanism. Further support comes from the study of the isotopic signatures of the small but growing collection of Mars meteorites, the youngest of which have crystallisation ages [9] (and hence, presumably, eruption ages) of 173 +/- 3 Ma (EETA79001) and 165 +/- 4 Ma (Shergotty), both of which are <5% of Mars' age.

Evidence for cyclical volcanism: Given these ages, it seems plausible to suggest that Mars may not be volcanically dead, but this appears to be inconsistent with the lack of observation of on-going volcanic activity since fly-bys began >30 yrs ago. An explanation for this may have been provided by *Wilson et al.* [10] who showed that volcanoes tend to be active for epochs of up to ~1 Ma, interspersed with reposes of the order of 100 Ma, based on mean magma supply rates implied by the sizes and ages of martian shields, and times required to freeze magma chambers. If one extrapolates this pattern across all significant volcanic complexes on Mars (of which there are <<100), it follows that, at any one time, there would be no active magmatic system under any of the shield volcanoes. This is consistent with mantle modelling by *Schott et al.* [11] who found that, during late volcanic evolution on Mars, mantle plume activity would be restricted to only a very few provinces, consistent with the presence on Mars of the two major volcanic provinces, Tharsis and Elysium, and that the typical periodicity of activity would be ~100 Ma. Their study suggested that Mars may still be in this cycle. We hypothesise, therefore, that Mars is not volcanically dead, but merely dormant.

Probability of observing activity: The typical volume of a martian magma reservoir is ~7000 km^3, based on caldera diameters [12,13] and modelling of the density structure of the martian crust in areas of mafic volcanism [14]. As a magma reservoir inflates due to the injection of new magma from the mantle beneath it, the internal pressure increases until the stress across the reservoir wall is large enough to initiate dyke propagation [15]. Magma then flows into the dyke, either erupting to the surface, or forming an intrusion, until the stresses are relaxed. [16] showed that the elastic properties of mafic rocks are such that the typical amount of magma discharged from a reservoir during such an episode, irrespective of whether the magma is erupted or only intruded, is ~0.3% of the reservoir volume, i.e. ~20 km^3 in a typical martian case. Given the 100:1 ratio of inactive:active periods proposed earlier, the average mantle magma supply rates to reservoirs during active periods should be about 100 times larger than the mean rate, 0.05 m^3 s^{-1}. This is consistent with the magma supply rates needed to maintain reservoirs against thermal losses, and is similar to terrestrial values [17]. This implies that the interval between magma releases from reservoirs will

typically be $[(20 \text{ km}^3)/(5 \text{ m}^3 \text{ s}^{-1}) =] 4 \times 10^9$ s, ~135 years, for an average magma reservoir. On Earth, magma release events from reservoirs lead to intrusions and eruptions in roughly equal numbers [17] and the factors (subtle variations in crustal structure and magma volatile content) determining this ratio [18] are likely to be similar on Mars and Earth [14]. Thus we infer that observable eruptions onto the surface should happen every ~270 yrs during an active phase of a shield volcano. However, since the volcano is in an active phase for only ~1% of the time, this corresponds to one eruption every 27 ka averaged over its lifetime. There are two major volcanic provinces on Mars that seem likely, based on stratigraphy and crater counts, to be active (Tharsis and Elysium) and so we might expect to see on average on eruption every 13.5 ka. We have observed Mars (intermittently) with spacecraft for ~30 years, and so we have so far stood at best about a 1-in-9 chance of detecting an eruption, *if* one of the volcanoes is in an active phase; otherwise it is more likely to be up to many 10s of Ma.

Eruption durations: In order to estimate a typical eruption duration, we obtain estimates of the magma flow rate out of a typical reservoir in two ways. The first is to note that a common length for the youngest lava flows on the flanks of Olympus Mons is a few 100 km [19]. We assume that this is typical for other volcanoes but such flows are rarely present on other volcanoes, possibly due to them being easily eroded over time [19], and so this is difficult to confirm. Since lava flow length is related via cooling constraints [20] to lava volume effusion rate, these flow lengths on Mars imply magma discharge rates [14] of ~300 $\text{m}^3 \text{ s}^{-1}$. Dividing our earlier estimates of the typical volume that should be released from a martian magma reservoir, ~20 km^3, by this estimated rate implies eruption durations of ~26 months.

A second estimate is obtained by noting that the internal excess pressures in magma reservoirs on Mars are likely to be similar to those on Earth [14], being controlled by rock strength rather than gravity [15], whereas the typical lengths and widths of dikes, which are influenced by the gravitational control on stress variation with depth, are likely to be a factor of 2-3 greater on Mars than Earth [14]. This means that the pressure gradients driving magma though dikes will be 2-3 times less on Mars, and that magma flow speeds, being proportional to the square root of dike width multiplied by pressure gradient, will also be smaller (by the square root of 2-3), but that volume fluxes, being proportional to the product of dike cross-sectional area and flow speed, will be greater by a factor of $[(2\text{-}3)^2/(2\text{-}3)^{1/2} =]$ 2.8-5.1, i.e. ~4. The typical magma release rates during eruptions of Kilauea vol-

cano, a typical terrestrial mafic shield volcano, is ~100 $\text{m}^3 \text{ s}^{-1}$, implying a rate of ~400 $\text{m}^3 \text{ s}^{-1}$ on Mars, and a typical eruption duration of $\sim[(20 \text{ km}^3)/(400 \text{ m}^3 \text{ s}^{-1}) =]$ 5×10^7 s, i.e. ~20 months, similar to the 26 month estimate derived above.

Discussion: There are clearly large uncertainties in our calculations. The concept of a 1 Ma-on, 100 Ma-off cycle is simplistic, and at best an average. The on:off ratio may vary between volcanoes by a factor of a few, or the cycle may be irregular. In fact, a cratering study of volcanic calderas using HRSC and MOC data [8] suggests a possible upsurge in volcanism ~100 Ma ago, and a typical volcanic episodicity at Olympus Mons of ~20 Ma. Note, however, that this is the same study that gave counter-stratigraphic relations for the Olympus Mons caldera, as discussed above. In any case, even a cycle length as short as 20 Ma would still mean that there is a high probability of no activity at any one time. Also, if a dike is emplaced starting from a point other than the top of the magma chamber, which seems likely for flank eruptions on volcanoes in which the magma chamber is above the level of the surrounding plains, as is the case at Olympus Mons [19,21], then the overlying weight of magma within the chamber could increase the typical volume fraction erupted [22]. In addition, the ratio of intrusions to eruptions could differ from that typical of the Earth [16]. Despite these factors, we infer that the combination of these effects is unlikely to affect the odds of observing activity by more than a factor of 10.

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