VOLCANISM ON MARS: VOLCANOLOGICAL AND GLOBAL SIGNIFICANCE OF ITS CALDERAS.

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INTRODUCTION. Advances in magma ascent and emplacement theory and quantitative analysis of martian volcanic landforms over the past decade enable new constraints on the magma budget associated with volcanism. These yield additional insights into the magmatic history of Mars. Calderas represent records of magmatic processes associated with magma ascent, emplacement, storage, and evolution in planetary lithospheres. Differences in their morphology and structure are functions of differing conditions of crustal density, structure, stress state, volume rates of magma emplacement, and changing conditions associated with magmatic evolution. These factors are recorded in the existing record of Martian calderas, but poorly resolved. Based on current understanding of magma rate regimes and detailed mapping of martian calderas, previous estimates of global magma budgets for Mars appear insufficient to sustain the observed calderas.

STRUCTURE Several types of structure alignment can be distinguished in the summit calderas of the larger martian volcanoes: (1) overlapping calderas, (2) concentrations of pits and channels on flank sectors, and (3) linear, through-trending fissure patterns. Overlapping and elongated calderas characterize the summits of Olympus Mons and the Tharsis Montes. These patterns are most prominent in larger edifices or the larger calderas that are indicative of large magma reservoirs. Calderas associated with smaller volcanoes, such as Biblis Patera, Ulysses Patera, Ceraunius Tholus, and Albor Tholus are either circular or consist of randomly overlapping caldera segments.

Magma chambers tend to form where the density of the surrounding rocks are similar to the density of the magma [1] and where the rate of magma replenishment is such that the supply of heat enables the interior of the magma chamber to remain above the liquidus despite thermal losses from conduction and magma withdrawal. During injection of magma into the magma chamber stress concentration around the walls of a magma chamber are such that a reservoir will tend to grow laterally by dike propagation . Lateral growth is favored at the expense of vertical growth in large reservoirs [2]. Vertical growth will occur only if a lower density cap within the upper parts of
the chamber can result in renewed stress concentration in the upper parts of the reservoir. At certain large

RELATIONSHIP TO LOCAL AND REMOTE STRESSES. Caldera structures preserve regional stress patterns because dikes develop along directions of maximum principal stress. Systematic alignments therefore tend to develop in successive magma reservoirs within an evolving magmatic system [3]. Regional patterns of stress that may influence the orientation of dike emplacement can arise from either tectonic processes, local and regional relief, or pre-existing, directional variations in the value of T (i.e., pre-existing structural fabrics)[4]. All of these are predicted to have a significant influence on regional stress arrangements on Mars [5, 6,7]. The influence of regional topography and its associated stress patterns on dike orientation has been used previously in assessing the orientations of possible dike-related graben sets on Venus [8]. On Mars, basins and basin structures are likely to be important.

Patterns of strain associated with the larger calderas follow stresses predicted from global isostatic flexure patterns particularly within the large volcanic rises of Tharsis. Notable exceptions in Tharsis include Olympus Mons, Tharsis Tholus, Alba Patera, and Ceraunius Tholus. Fractures obeying the predicted pattern of strain occur around Alba Patera, but do not appear to have operated at the time of magma emplacement. At Olympus Mons, large gravity stresses associated with regional slopes of Tharsis may have dominated the local stress field [9]. This appears to be the case for Tharsis Tholus.

ORIGIN OF MAGMA CHAMBERS Relatively high magma volume replenishment rates, by terrestrial standards, tare necessary to develop and to sustain the large magma bodies inferred to occur beneath most calderas on Mars. Estimated rates approach 10 km^3/1000a. This value exceeds the long-term rates of the Hawaii-Emperor magmatic system, the closest terrestrial analog to large shield-building magmatism on Mars in terms of volume. Analysis of the thermal budget required to sustain magma chambers beneath calderas on Mars implies that magma rates were sufficient that central edifices of large Martian shield volcanoes, such as Olympus Mons, still required a maximum of between 50 to 100 million years to accumulate.

The magnitude of stresses induced at the surface by a shallow magma chamber, within the volcano edifice or near its base, is most likely to result in a sharply defined caldera equivalent in size to the horizontal dimension of the chamber. The formation of multiple calderas over the lifetime of the volcano implies the occurrence of many, relatively small, magma chambers. The corresponding shallow magma chambers within the main volcanic edifice, with lateral dimensions of the order of ten km, are difficult to sustain other than at the highest replenishment rates. Multiple calderas reflect periodically higher flux due to short term increases in melt ascent and production. Large magma chambers that are deeper are more easily sustained, and may account for the great number of large calderas on Mars. The largest calderas within multiple and nested caldera complexes are among the last to be formed. Lower replenishment rates sustain deep, low-

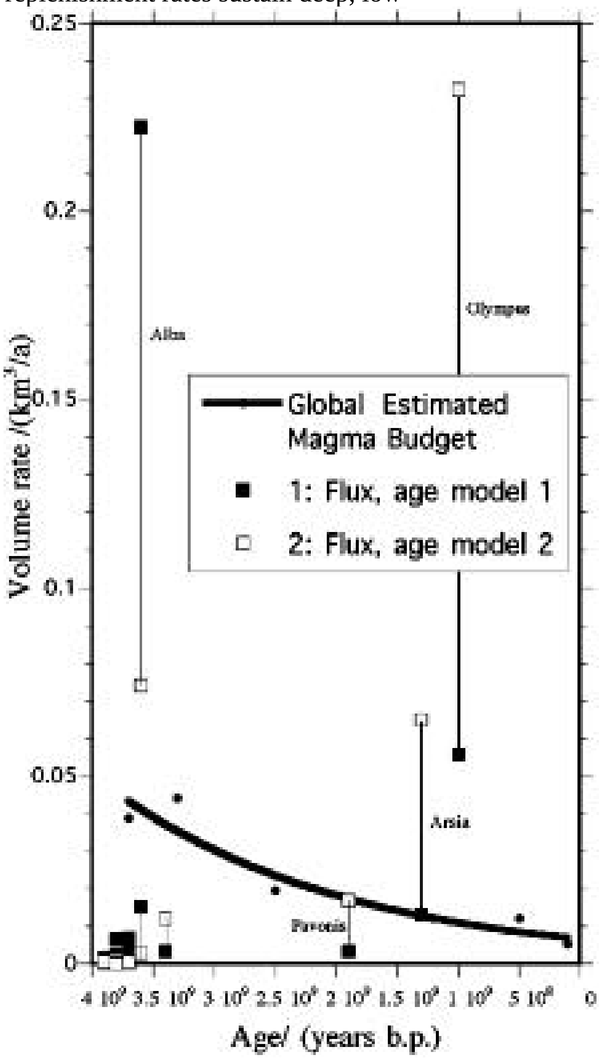

Figure 1. Estimated magma budgets necessary to sustain martian calderas compared with global magma budgets estimated from geologic mapping of calderas.

temperature reservoirs and produce long-lived magma systems. Accordingly, broadly distributed deformation of the type accompanying deep reservoirs is predicted to be among the most common, late-stage structural activity at each volcano. Based on the above results, then large late-stage calderas might be a result of the continued life of larger, deeper magma chambers during the waning stages of central volcanism. Under conditions of declining rates, crystal-rich magmas would be available for eruption from deep chambers for longer periods. The inferred “andesitic” rheologies of certain lava flows on Martian shield volcanoes [10] could be the result of crystal-rich mafic lavas rather than petrologic differentiation.

RELATION TO GLOBAL MAGMA BUDGET. Estimates of the global magamtic history of Mars have been made [ref] based on the results of global compilation of geologic mapping. When compared with the rates estimated here from basic thermal arguments and volcanological theory, it is clear that a single caldera could consumed the entire global magmatic budget. Likewise estimates of rates regimes from known volumes using two end-member model ages yield similar disparities (Figure 1). The origin of this disparity is unclear. The estimates of global magmatism may be too low.

SUMMARY. Simple models of the steady state thermal conditions for magma chambers associated with Martian calderas imply: (1) Relatively high, long-term magma supply rates must occur to support the presence of calderas. In addition to other factors [4], the absence of calderas on the smaller terrestrial planets may be a consequence of magma production and ascent rates that are too low for magma chamber formation. (2) The latest volcanic events in each shield volcano and on Mars as a whole are likely to be a result of deformation or magma transport associated with large deep magma chambers. (3) Deep, low temperature magma chambers are easier to maintain at subliquidus temperatures. Increasing crystallinity of subliquidus magmas from deep chambers may account for variations in lava flow morphology without postulating chemical fractionation. (4) Estimates of the volume flux associated with the average martian caldera exceed the estimates of global flux at anytime in martian geologic history. Current volume estimates, surfaces ages, and details of individual caldera histories require detailed mapping, preferably through extreme resolution geotraveres in order to more precisely determine the timing of geologic events associated with each caldera.

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