MAGMA CHAMBERS ASSOCIATED WITH CALDERAS ON MARS: SIGNIFICANCE OF LONG-TERM MAGMA REPLENISHMENT RATES;

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INTRODUCTION. Calderas on Mars are characterized by a wide range of shapes, structural complexity [1,2], and interaction with regional stress fields[3,13]. The presence of calderas implies a fundamental condition influencing their formation on larger planetary bodies. In order to form calderas, the conditions must exist for the formation of relatively shallow magma chambers [4]. Here we show that specific rates are necessary in order to maintain long-lived magma chambers. The observed range of characteristics of the calderas of Mars may reflect these differences in rate.

CALDERA AND MAGMA CHAMBER CHARACTERISTICS. Diameters of calderas on Mars range from ten to over 100 km [1-3; 12]. Many of the smaller calderas are of the "Olympus-type" [1,2] and are similar to calderas on shield volcanoes on Earth. But the larger calderas of the "Arsia-type" [1,2] have no terrestrial counterpart. The calderas of the Arsia-type tend to be simpler in shape (circular), non-overlapping and isolated, and characterized by diffuse marginal deformation. These characteristics are interpreted to reflect a relatively deep magma body, since the magnitude of stresses induced at the surface by deep chambers are more likely to result in diffuse marginal deformation. Existing estimates of depth suggest magma chambers of the Olympus-type may reside in the lower interior of the volcanic edifice [5], but many of the larger calderas of the Arsia-type could arise from magma reservoirs at much greater, perhaps sub-crustal, depths.

THERMAL BUDGET OF SUB-VOLCANIC MAGMA CHAMBER. The thermal state of a subvolcanic (beneath the edifice) magma body depends on the net rate of thermal flux into (Q(+)) and out (Q(-)) of the system. If the influence of magma replenishment (Q_R), thermal conduction to surroundings (Q_{cn}), forced convection by fluids outside the magma chamber (Q_{cv}), eruption (Q_e, $Q_{e'}$), and the latent heat (Q_L) are considered, the net long-term or steady-state heat flux (Q) of a subvolcanic magma chamber or reservoir can be reduced to

$$Q = Q(+) + Q(-) = \{Q_R - Q_{cn} - Q_{cv} - Q_e + Q_L\}. \quad (1)$$

Of these, Q_{cv} is poorly known but depends on the depth distribution of likely fluids, their long-term supply versus depletion, and the overall permiability of the country rocks forming the crust. Exclusion of convective flux results in an upper bound on magma chamber lifetime, but may be appropriate to the possibly dryer mid-crustal environment of late-Tharsis volcanoes as interpreted on the basis of the change in volcano morphology from highland to Tharsis edifices. Heat loss (Q(-)) from the system will depend on the shape of the magma body (here we use a shape factor in the Fourier equation given by thermal shape analysis of a tabular body in isothermal surroundings [7]), the temperature Tc at depth (related to the planetary thermal gradient and volcanic pre-heating), the interior temperature (T_{mc}) of the magma chamber of radius **a**, and the long term loss due to eruption at volumetric replenishment rate Re of magma at temperature Tm with solidus and liquidus temperatures Ts and Tl respectively

$$Q(-) = \{8\, a\, k\, (T_{mc} - T_c) - Re\, c\, p\, (T_m - T_s)\}. \quad (2)$$

Models of the ascent and emplacement of magmas on Mars [11] suggest that lateral dimensions of magma chambers are likely to be greater than their vertical dimension as a result of the relatively greater ease with which lateral dike injection occurs once neutral buoyancy is attained. Great lateral extent of magma bodies is likely therefore to occur at interfaces of significant density contrast (lower volcanic pile or crust-mantle transition) (Fig. 1) under conditions of moderate to low driving pressure from the melt source regions.

Given the above thermal losses, a magma chamber will not occur if the region of magma accumulation does not remain above the solidus; heat additions must exceed the heat loss in order for the magma chamber to remain active or grow. Assuming a tabular geometry consistent with this model, the injection of fresh, hot magma at near-liquidus (assumed typical mafic Martian lava at 1300°C) at a rate Re and the effects of latent heat during crystallization [8] will result in thermal addition (Q(+)) to the magma chamber given by

$$Q(+) = Re\, c\, p\, (T_m - T_{mc}) + L\, p\, [X(T) + \Delta X(V/\Delta T - Re)]. \quad (3)$$

The terms on the right account for latent heat for given crystallinity X(T) as a function of magma chamber temperature. Magmas with crystal contents exceeding 0.5 may be considered 50% solidified. Lavas with crystal fractions greater than 20% are rare terrestrially and, due to the polymerizing effect of crystals on silicate melts, will have rheologies inconsistent with dominantly fluidal basalts; therefore, we may assume relatively low values of X(T) and the temperature of the magma chamber is given accordingly (see inset Fig. 2). As we are assuming long-term steady state thermal conditions, the effects of trends in crystallinity (ΔX) may be excluded for practical purposes. Solving (2) and (3) at various dimensions and depths (subvolcanic magma chamber, mid-crustal and lower crustal) yields the rates necessary to sustain equilibrium thermal conditions (Fig. 2) in magma chambers over the range of observed diameters and at two end members of crystallinity (0.1 and 0.5) of magma. The upper (15 km) and lower (60 km) depth ranges could be postulated to represent the Olympus and Arsia-type calderas respectively. Certain stages of volcanic center growth may approach steady state, but complex accumulation of the observed lava morphologies, caldera structures, and isolated upper magma reservoirs within the edifice will tend to obscure steady-state behavior over the lifetime of the volcanic system. Future analysis will consider the non-steady systems important for deciphering the observed complexity of the geologic record [1] at each caldera. It is also clear that the magmatic rates in sub-volcanic reservoirs may exceed eruption rates by factors of 10 to 20 [9]. For certain high level magma reservoirs, however, the endogenous component may be large, and the contribution of sub-volcanic magma to the overall volume of the edifice could be larger than that resulting from subaerial eruption alone. Thus, rates associated

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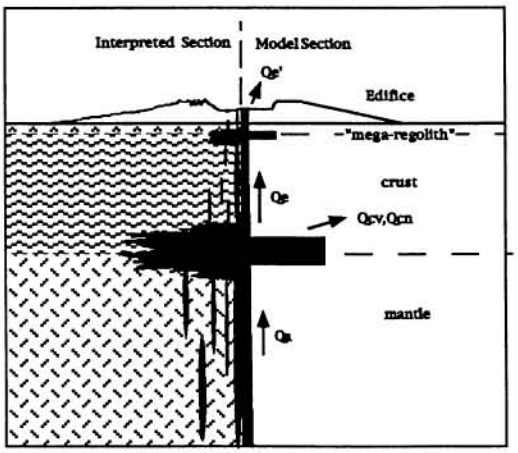

Figure 1. Interpretive section through generalized volcanic system based on detailed mapping of all martian calderas. Model section illustrates characteristics assumed for purposes of thermal calculations.

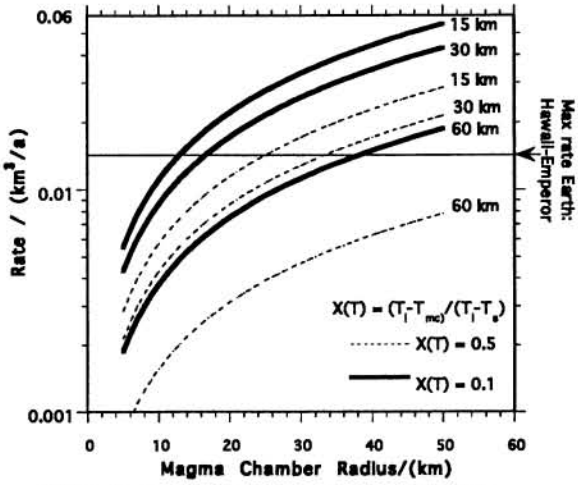

Figure 2. Magma volume replenishment rates necessary to sustain in thermal steady state magma chambers of various depths, crystallinity, and temperature on Mars.

with small high-level magma chambers may be significant for volcano volume growth despite their smaller dimensions relative to deeper magma chambers.

DISCUSSION. Many of the similarities and differences observed with respect to calderas on Earth and the other terrestrial planets, including size, may arise from fundamental differences in ascent and eruption characteristics of magmas as influenced by the planetary environment [6]. By terrestrial standards, the magma volume replenishment rates necessary to attain and to support the inferred large magma bodies beneath most calderas on Mars are high, and approach rates of 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 capable of sustaining magma chambers of the size required to support observed calderas on Mars implies that, unless thermal gradients in the crust were very high compared with current gradients, the formation of the main central edifices of large Martian shield volcanoes, such as Olympus Mons, required a maximum of between 50 to 100 million years to accumulate.

Multiple calderas, each on the order of 10 km or less in diameter, occur at the summits of shield volcanoes of the Olympus-type. These calderas are small and have sharply defined margins. 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, therefore, may reflect periodically higher rate regimes due to short term increases in melt ascent and production that are unlikely to be sustained over extended time intervals. On the other hand, large magma chambers at mid- to sub-crustal depths are more easily sustained, and may account for the great number of large calderas on Mars. Many multiple caldera complexes on Mars show evidence that the largest calderas are among the last to be formed. If the relationship postulated above is correct, then these large late-stage calderas might be a result of the continued life of larger, deeper magma chambers during the waning stages of central volcanism.

Lower replenishment rates sustain deep, low-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. 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.

CONCLUSIONS. Analysis of 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. And (4), multiple or nested calderas at the summits of many Martian volcanoes are probably a result of short-term higher magma replenishment rates. Their formation requires separate, renewed, shallow magma chamber formation in each case, thus accounting for their generally nested distribution.

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