HOW LATERAL DENSITY GRADIENTS AFFECT THE DISTRIBUTION OF MULTIPLE MAGMA CHAMBERS WITHIN MARTIAN SHIELD VOLCANOES.

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Summary: We propose that the reason why certain martian volcanoes produce multiple summit calderas is that the locations of successive underlying magma chambers migrate under the influence of lateral density gradients that form within the edifice.

Introduction: Ascraeus and Olympus Montes have multiple summit calderas, consisting of several small calderas arranged around the periphery of a large central one. It would be difficult to generate these regular caldera shapes by invoking a series of local collapses over different parts of one large chamber, because magma with a near-Newtonian rheology transmits stresses in a linear manner. The overlapping nature of the calderas indicates that these discrete magma chambers were active at different periods in time [1, 2].

This migration of the magma chambers must occur under the influence of an evolving stress regime: the route which magma takes from its deep source region into an edifice is dictated by the relative orientations of the principle stresses [3]. It will therefore always follow the same route and feed the same magma chamber, unless some factor acts to alter the stress regime. We propose that this factor is the development over time of a lateral density gradient within the edifice as a result of:-

1) the cooling of the magma chamber, producing buoyancy changes which lead to subsidence of the chamber through the edifice, and

2) the lateral expulsion of the cumulate body from the region below the magma chamber base.

Neutral buoyancy changes of a cooling magma chamber: Magma will adjust its equilibrium position dependent upon its density contrast with the host rocks making up the volcanic edifice [4, 5]. Buoyant equilibrium is easier to achieve for solids contained in a fluid medium than for fluids, e.g. magma, in a solid medium, although the principles are similar [6, 7].

The supply of magma to martian edifices was intermittent, with repose periods of a few hundred million years, much longer than the 5-10 Ma needed for the contents of a magma chamber to cool [2]. Cooling increases the density of magma from ~2400 to ~2600 kg m^{-3}. Hence, a frozen chamber and its contents are no longer neutrally buoyant. If we assume this magma chamber was originally established at a neutral buoyancy level 11 km beneath the volcano summit [8, 9], subsidence of ~1 km is possible (see Figure 1).

The velocity of subsidence can be calculated using Stokes' Law because the Reynolds number of the motion of the surrounding country rocks is exceedingly small [10]. If typical Martian values are entered into Stokes' equation, $u = (2 \Delta\rho g R^2) / (9 \eta_c)$, then a terminal velocity of 6.65 x 10^{-10} m s^{-1} is calculated, implying it would take ~21 km Ma^{-1} for the magma reservoir to readjust its neutral buoyancy level by 1 km. This is much less than the 200 - 300 Ma rest period between the episodes of high magma supply from the martian mantle [2].

The Expulsion of the cumulate body from below the magma chamber base: A mafic cumulate body with a density of around 2900 kg m^{-3} forms at the base of a magma chamber [11, 12, 13]. We propose that this body will deform plastically as the magma chamber subsides into it and it may even be propelled laterally by the lithostatic load of the magma chamber (see Figure 1), as is thought to have happened at some terrestrial volcanoes [14].

Formation of a lateral density gradient across the edifice: The basalts of the frozen magma chamber or solidified cumulate body are extremely strong plutonic rocks, with a density of between 2600 and 2900 kg m^{-3}. However, the strata which make up a typical basaltic shield volcano are alternating sequences of ‘a’a and pahoehoe lava flows with little bulk strength [15] and a much smaller density of around 2300 kg m^{-3}. This changing lithology produces a lateral density gradient as illustrated in Figure 1. If the cumulate body is propelled into the lava flows, the aggregate density of the two rocks would be around 2500 kg m^{-3}.

Redirection of upwelling magma & the formation of a new magma chamber: Any magma upwelling from the mantle into the shallow reaches of the edifice encountering the situation illustrated in Figure 1 would likely be diverted around the high density solidified rocks of the old magma chamber to its periphery, as demonstrated by the existance of peripheral summit calderas. It does not even need the original chamber to completely solidify for a new overlapping one to form: basalt with a crystallinity of more than ~25% behaves rheologically as a solid [16]. Magma is likely to be transported as dykes in the upper, elastic reaches of the crust [17] following a path perpendicular to the least compressive stress. It is likely that the new chamber begins as a sill-like body: when rising melt reaches a zone of neutral buoyancy, it tends to spread laterally [5]. This entire process would be repeated each time an existing magma chamber freezes.

The relative sizes of the central and peripheral chambers: There is a direct relationship between the sizes of the central and peripheral calderas and, by implication, the underlying magma chambers. Peripheral calderas are approximately half the diameter of the central one; their vertical extents are probably similar, meaning they have only 25% the volume. The central position is probably the optimal one for a magma chamber to attain the largest size: it is the most stable gravitationally, because a peripheral chamber does not have all-round encircling support and the part closest to the flank is the least buttressed. It is possible that an extremely voluminous batch of magma would breach the peripheral chamber wall to produce a flank flow. In this way, the thermal lifespans of the peripheral chambers may be less than that of a centrally located one.

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Figure 1.