CALDERAS ON MARS: MODELS OF FORMATION FOR THE ARSIA-TYPE;

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INTRODUCTION. Two fundamental types of caldera have been previously identified on Mars [1] based on their geologic and topographic characteristics: the *Olympus-type* and *Arsia-type.* The *Olympus-type* is similar in morphology and structural development to calderas typically associated with central volcanism over a variety of magmatic compositions and magma replenishment rate regimes on Earth, and can be understood in terms of relatively simple collapse of the surface in response to subsurface volume changes. The *Arsia-type* represents a much larger scale of caldera development, a different structure compared to typical terrestrial calderas, and appears not to have a morphologically or topographically comparable counterpart on Earth. In the following, we focus on the characteristics of the Arsia-type, outline a number of models for their development and begin to assess their significance in terms of general magmatic processes, regional magmatic history, and magma rate regimes of Mars.

CHARACTERISTICS OF ARSIA-TYPE. Calderas on Mars occur on all of the major edifices. Arsia Mons, the type example, shows all of the characteristics defined for the Arsia type. Some of these characteristics also occur in the calderas of Pavonis Mons, Apollonaris Patera, Biblis Patera, Hecates Tholus, Tyrrhenia Patera, and Alba Patera.

The Arsia-type may be distinguished in topographic profile from the *Olympus-type* caldera [1], by (1) a large diameter in relation to the host volcano edifice, (2) broadly concave and sag-like profile (rather than flat-floored profile), (3) generally regional gently-sloping marginal inner walls, and (4) multiple boundary faults (rather than an abrupt bounding inner escarpment). In map view, the Arsia-type is distinguished by the pattern of faults defining the depression boundaries, which are primarily concentric and distributed over a broad radius interval from the center of the depression; and which trace smoothly arcuate scarps, with both inward and outward-facing slopes defining narrow graben along the topographic caldera rim. These map characteristics are in marked contrast to the Olympus-type where boundary faults frequently occur in sets of short, arcuate scarps, the boundaries are sharply defined by a narrow inner slope, and the scarps associated with faulting are inward-facing, scalloped, and responsible for a terraced and chaotic appearance.

The Arsia-type may be characterized as concentric in map pattern and centralized about a common point, in contrast to the more irregular outline of the Olympus-type which occurs frequently in nested sets of several overlapping depressions. This arrangement implies that the Arsia-type is the result of progressive deformations about a central location instead of punctuated or episodic subsidence about different centers as is interpreted to be responsible for the Olympus-type. Detailed geologic mapping of Martian edifice caldera structure [2,3,4] further illustrates that the Olympus-type appears to develope during active edifice construction, but a common aspect of the Arsia-type is its relatively late development, after a protracted period of little or no activity, in each example of its occurrence [5,6]. Although late eruptions occur from the concentric faults and graben in several examples of the Arsia-type, in general the visible concentric faults appear not to be a source of large volumes of late magma. Late eruptions from within the caldera and surrounding flanks may be voluminous, but erupt from a variety of locations and are not always confined to concentric patterns associated with the caldera structure. The most extensive of the late-stage lava outpourings associated with the Arsia-type calderas post-date the caldera subsidence.

Regional Influence. At small radii from the edifice the fault patterns are concentric, reflecting the dominance of stress related to the caldera subsidence over the regional tectonic environment. At large radii from the edifice, they frequently are deflected or rotated [2] in response to their development in the regional tectonic environment. The great lateral extent of the concentric faulting suggests that the development of the Arsia-type caldera influences regional tectonic patterns; we would characterize the scale of this influence as lithospheric in extent. This is in further contrast to the Olympus-type caldera, which must reflect failure of the crust associated with volume changes largely within the shallow crust [3,4]. Whereas Olympus-type calderas occur during variations in high level magma volumes and are largely contemporaneous with the main period of edifice growth [1], the late eruption of large volumes of lava in the Arsia-type, implies a volumetrically large magmatic renewal [1].

INTERPRETATION AND MODELS OF ORIGIN. Caldera formation reflects vertical motion of the surface in response to volume changes at depth. Some calderas may result from volume decreases at depth [7] and others may result from subsurface volume increases [8]. In either case, the primary factor is over-extension, mechanical failure, and downward foundering of a region centered about an area of concentrated magmatic activity. We identify two fundamental sources for volume changes in a central volcano capable of resulting in calderas: *(1) Volume changes in magma reservoirs* and (2) *Loading due to intrusive masses.*

Volume changes in magma reservoirs. There is abundant evidence for changes in magma volume associated with the filling and emptying of subsurface magma reservoirs during volcanic eruptions. Factors that result in volume changes within a magma reservoir include: (a) change in magma density following vesiculation or degassing, and (b) magma movement into or out of reservoir, including draining of reservoir by surface eruption and lateral migration as intrusives (as in Hawaiian rifts[9]). The large lava flows on the flanks of the Martian volcanoes are clear evidence that

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sufficient volumes of magma were removed from subsurface reservoirs; and the formation of calderas in Martian central volcanoes is generally attributed to this mechanism as it is a well known effect associated with central volcanism on Earth.

Relatively large calderas could have formed through collapse of an evacuated magma reservoir. However, this mechanism for caldera formation may not easily accommodate the scale of the Arsia-type caldera, the evidence for its lithospheric-scale influences, and particularly its relatively late development and emplacement prior to the latest eruptions. The scale of the calderas requires a magma reservoir of either great depth (deep lithosphere) and vertical extent, or a shallower reservoir approaching the observed caldera diameter in lateral extent. However, a magma reservoir of these dimensions may be met if it represents an upward deflection of the asthenosphere [10] rather than accumulation of magmas in the crust. Late development in this case might represent continued slow residual warming, partial melting, and accumulation of magma at the base of the lithosphere long after cessation of an earlier more active phase of magma eruption.

Loading due to intrusive masses. Central intrusive loading and subsidence of the core of large central volcanoes has been suggested as an alternative [11] for large scale volume subsidence associated with caldera formation. During magma emplacment, up to ten times the volume of magma erupted at the surface remains at depth [12] as intrusive rocks. Emplacment and accumulation of dense intrusive rocks beneath the central region of large volcanoes that are characterized by long periods of activity might easily represent large mass loads, greater perhaps than the mass of the visible surface edifice. Combined with a lithosphere thermally weakened at the centralized site of volcanism and intrusion, intrusive loads formed in this manner could exceed the strength of the underlying lithosphere [11]. Some structural characteristics of large Martian shield volcanoes may reflect subsidence related to volcanic loading associated with the visible edifice [13]. Considering the potentially greater mass associated with central intrusions and the thermally lowered strength of the immediate lithosphere beneath central Martian shield volcanoes, we suggest that intrusive loading is a viable model for the formation of the Arsia-type calderas. In addition, the creep rate of subsidence associated with intrusive loading might potentially occur over a long time interval, perhaps continuing long after cessation of early central eruptions. Renewed volcanic activity might occur if the subsided intrusive core or underlying lithosphere undergoes remelting and renewed magma emplacements at shallow levels.

CONCLUSIONS. Two types of volcanic caldera have been defined previously for Mars: the Olympus-type and the Arsia-type [1]. The Oympus-type is interpreted to reflect magma volume changes in relatively shallow reservoirs. On the basis of its large size, influence on regional tectonic patterns, and late development relative to the host volcanic edifices, we suggest that the the Arsia-type is not the result of simple magma chamber evacuation, but instead represents either the results of (1) volume changes related to magma removal from a deep asthenospheric-level magma source region, or (2) long-term downward subsidence of the lithosphere beneath volcanoes due to the weight of central intrusive loading.

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