REGIONAL STRESS PATTERNS, MAGMA RESERVOIRS, AND CALDERAS ON MARS;

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INTRODUCTION. Martian calderas are useful from the terrestrial perspective in that they preserve structures associated with their evolution. We have recently completed a compilation of the characteristics of calderas on Mars [1,3] that enable an assessment of the significance of their structures with respect to both regional structure and magma emplacement processes. The influence of regional stress patterns on magma emplacement, dike orientation and shape, and magma chambers is becoming better understood [2]. On Mars, many patterns of regional strain may be adequately modeled as arising from global topography, particularly that associated with the large volcanic rises of Tharsis and Elysium[7,8]. In this study we examine whether patterns of regional stress in the younger volcanic provinces are consistent with these effects or whether other influences might have been important.

OBSERVATIONS. Many of the larger and younger (Tharsis and Elysium) calderas at the summits of large volcanoes and situated within the large volcanic rises are characterized by an axial trend of either fissures or alignments of subsidiary calderas. Several types of alignment are identified in martian summit caldera and flank structures: (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 (Figure 1). These patterns are most prominent in larger edifices or the larger calderas that are indicative of large magma reservoirs. In contrast, 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.

The planimetric shapes of younger calderas appear to have been influenced more by remote stresses than older calderas. In addition, the axial patterns associated with subsidiary calderas and fissures appear more prominent in larger calderas [3]. The apparent tendency for greater influence of regional stress patterns on younger calderas has been noted previously [4]. Many of the younger and larger volcanic centers with these characteristics occur on or near the interior of large rises and late in the history of their development. The observed sample is small enough, however, that this interpretation is by itself insufficient and preliminary discussion of its potential viability is warranted.

ANALYSIS. A dike is propagated from a magma body, resulting in magma being either erupted at the surface or injected laterally, when the wall failure criteria $P_l + P_m \geq |\sigma_3| + T$ [eq.1] is satisfied [5] and magmatic pressure exceeds the sum of remote stress (minimum compressive stress, σ_3) and tensile strength (T) of the country rock. The total magmatic pressure within the chamber is the sum of a lithostatic (P_l) term and a magmatic pressure (P_m) term, the latter arising from either the addition of new magma to the chamber or accumulation of pressure through vesiculation or magma differentiation. A dike may be propagated from a reservoir either by increasing the magma pressure or by decreasing the minimum compressive stress; the first is accomplished within the magmatic system, whereas reduction in σ_3 may occur as a result of changes in external local or regional (remote) tectonic stress arrangements. Once conditions of [eq.1] are satisfied, dike emplacement occurs in a direction perpendicular to the minimum compressive stress orientation. Systematic arrangements of volcanic features associated with dike emplacement are therefore sensitive indicators of the minimum compressive stress orientation [e.g., 6]. The influence of regional stress on magma emplacement, dike orientation and shape, and magma chambers is a relatively well-discussed phenomena [2]. Regional patterns of stress that may influence the orientation of σ_3 can arise from either tectonic or topographic deformation. Regional topographic gradients are predicted to have a significant influence on regional stress arrangements on Mars [7,8]. As a result they may be correspondingly significant during caldera formation and evolution. Topographic stresses are applicable especially to planetary surfaces where large-scale or global topographic relief is significant. For example, 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 [9]. The influence of remote stress induced by regional topography predicts that in general many larger scale features (dikes, fissure patterns, pit crater and caldera chains) associated with propagation of subsurface magmas in large magmatic systems on Mars will tend to be oriented at right angles to maximum compressive stress directions, which, for Mars, generally mimic regional slope directions.

Figure 2 shows a comparison of predicted patterns of minimum stress arising from global topographic relief on Mars [7,8] with orientations of the minimum stress as recorded in overlapping calderas, concentrations of pits and channels on flank sectors, and linear, through-trending fissure patterns. Within adjacent large volcanic edifices and large calderas the relevant σ_3 indicators tend to be characterized by similar orientations.

DISCUSSION. Magma chambers tend to form where the density of the surrounding rocks are similar to the density of the magma [10] 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 [11]. Lateral growth is favored at the expense of vertical growth in large reservoirs [11]. 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

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dimensions, however, stresses are such that lateral propagation will occur almost exclusively [11]. Large magma reservoirs are thus characterized by a tendency to grow laterally, and the orientation will reflect the minimum regional compressive stress. These conditions appear to have occurred within the largest martian magma reservoirs and as a result, growth in the late stages may have occurred by lateral propagation of magmas along the directions of least resistance. Crater ages of events in the Tharsis Montes [12] support the conclusion that lateral propagation of the magma reservoirs in the largest edifices and their calderas occurred late in their evolution.

The observed patterns of strain associated with the larger calderas are consistent in general with the influence of the predicted regional patterns of stress that may have been operating at the time of large caldera emplacement. 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 slip of the edifice on the slopes of Tharsis may have dominated the local stress field. This also appears to be the case for Tharsis Tholus. There is no striking evidence for an influence by remote stresses on the shapes or structure of many smaller calderas individually, including those within summit complexes. The orientations are consistent with the inference that regional topographic stresses significantly influenced the propagation direction of dikes and the subsequent lateral growth of large magma reservoirs.

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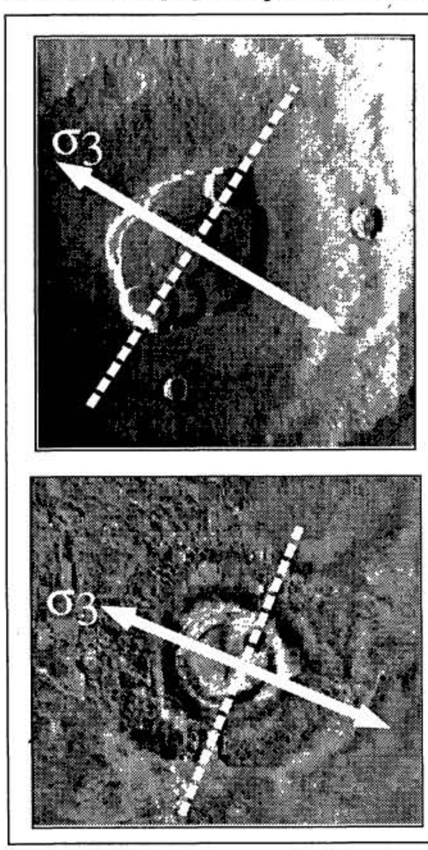

Figure 1. Examples of stress orientation recorded in overalaping and elongated calderas of Olympus Mons and Arsia Mons.

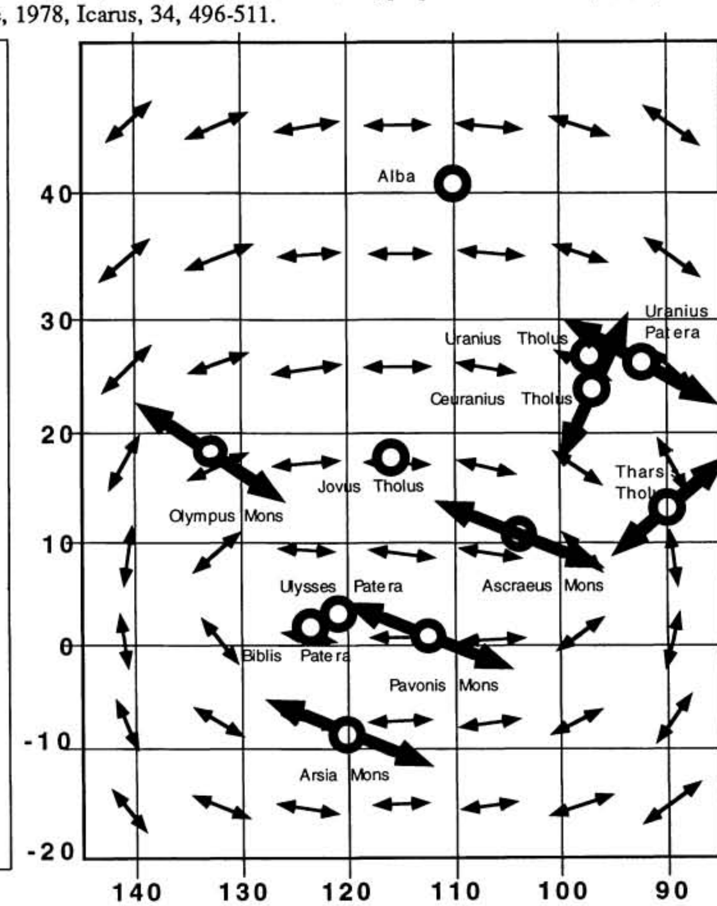

Figure 2. Orientation of minimum principal stress recorded in martain calderas (large arrows). Predicted orientation of minimum principal stress arising flexural load associated with Tharsis relief [7,8] shown as small arrows. The larger and younger calderas may have been influenced by regional strain whereas the calderas of Olympus Mons, Tharsis Tholus, and Ceraunius Tholus appear more influenced by local body stresses associated with their respective edifices.