REMOTE AND LOCAL STRESSES AND CALDERAS ON MARS;

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INTRODUCTION. The detailed structure of calderas is a sensitive indicator of the stress environment existing at the time of caldera formation. Unlike regional patterns of strain, such as wrinkle ridges, graben, and fractures, calderas, however, have short time scales for formation and record local stress at essentially point sources. Strain associated with caldera formation and evolution may also be tied stratigraphically to a relatively well-defined geologic unit and well-constrained times. In the following, we have compiled the structural characteristics of calderas on Mars [1] and compared the deduced orientation of remote stress with predicted patterns of global strain, patterns attributable to regional slopes, and patterns attributable to relict or pre-existing substrate structure.

OBSERVATIONS. 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 (Figure 1). 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.

ANALYSIS. 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 [2]. The principles of dike emplacement were reviewed previously [3] and are here briefly re-iterated. 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 $P_l + P_m \geq |\sigma_3| + T$ is satisfied [4] and magmatic pressure exceeds the sum of remote stress (minimum compressive stress, σ_3) and tensile strength (T) of the country rock. Regional patterns of stress that may influence the orientation of σ_3 can arise from strains resulting from either tectonic processes, local and regional relief, or pre-existing, directional variations in the value of T (i.e., pre-existing structural fabrics)[5]. All of these are predicted to have a significant influence on regional stress arrangements on Mars [6,7,8]. 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]. On Mars, basins and basin structures are also likely to be important.

Figure 1 is a comparison of predicted patterns of minimum stress from global topographic relief [8] with orientations of the minimum stress determined from the relevant σ_3 indicators (overlapping calderas, concentrations of pits and channels on flank sectors, and linear, through-trending fissure patterns).

DISCUSSION. Calderas are limited in absolute number , so the results of a comparison between observed and predicted patterns are of limited quantitative value. However, logical geologic inferences of regional interest can be made based on observed structure and local/regional associations. The salient points are reviewed in Table 1 which summarizes the principal inferences.

Table 1. Three caldera strain/remote stress associations:

Volcanoes	Timing	Origin of Stress
[AM, PM, AM, Uranius Patera, Hecates, Elysium]	mid-age volcanoes	regional dynamic lithospheric flexural stress
OM, Tharsis Tholus, Ceraunius Tholus	mid and young age	local crustal gravity stress (regional slope and edifice effect)
Tyrrhena, Nili, Meroe, Hadriaca, Peneus, Amphitrites]	old to mid age	regional inheritance from pre-existing structure
[Biblis, Albor, Jovus, Apollonaris, Alba(?)]	old	No (or little) apparent local or regional

Patterns of strain associated with the larger calderas follow stresses predicted from global isostatic flexure patterns [6,7,8] 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 slip of the edifice on the slopes of Tharsis may have dominated the local stress field [9]. This also appears to be the case for Tharsis Tholus.

Patterns of deformation in older calderas may relate to regional and local slope effects. The oldest, and lowest, calderas appear to have been influenced by pre-existing structural fabrics associated with basins.

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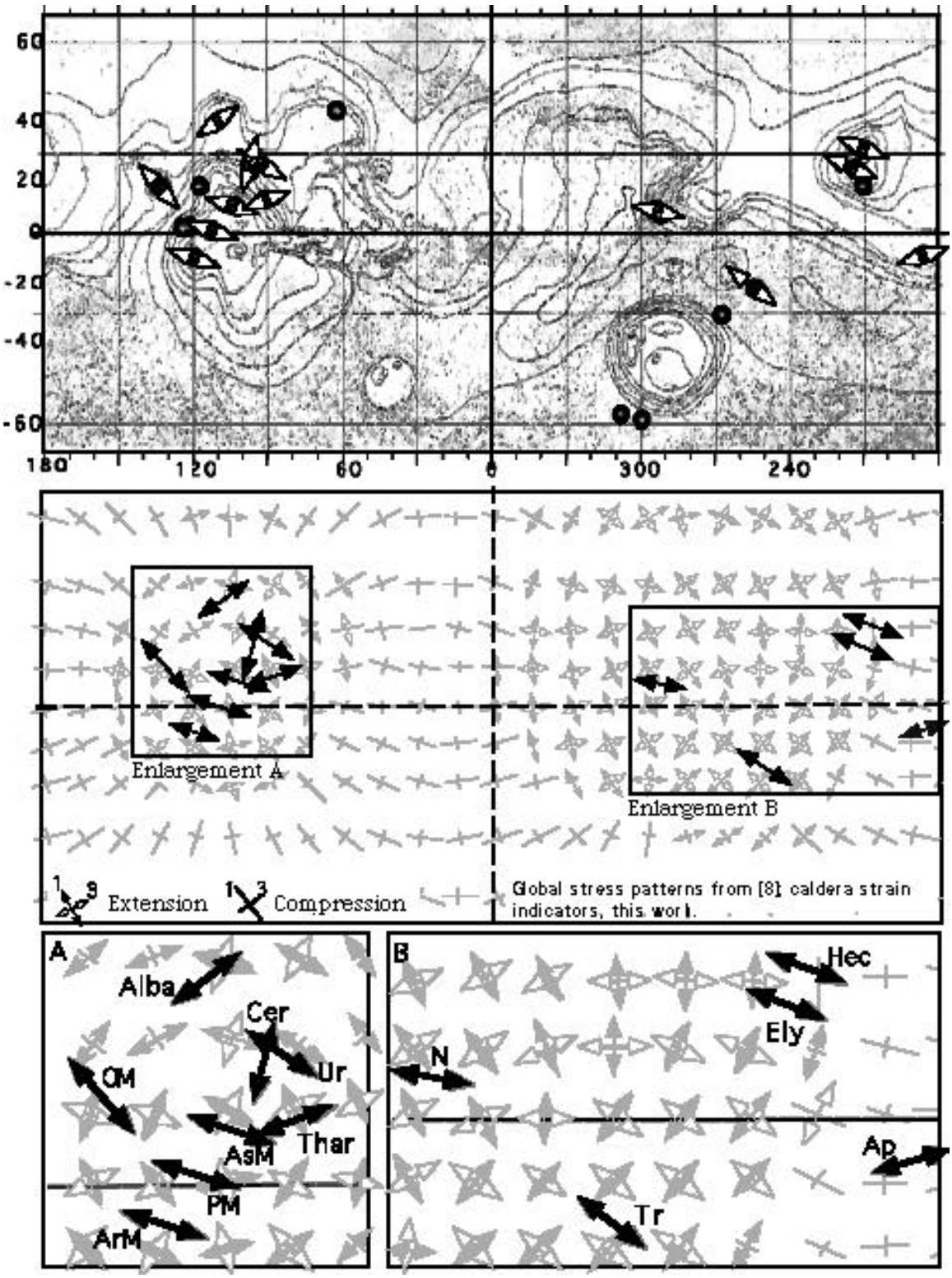

Figure 1. Top: Minimum compressive stress orientations determined from mapped structure of large calderas on Mars [1]. Center: Stress orientations superimposed on global stress field predicted from topography [8]; bottom: Enlargement of main volcanic regions. Observed orientations are consistent with remote stresses predicted from isostatic flexure in many cases, but some calderas appear to have been strongly influenced by stresses within the crust due to slope and azimuthal variations in crustal strength.