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ASPECTS OF MODELLING THE TECTONICS OF LARGE VOLCANOES ON THE TERRESTRIAL PLANETS; Patrick J. McGovern, Dept. of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, and Sean C. Solomon, Dept. of Terrestial Magnetism, Carnegie Institution of Washington, Washington, D. C. 20015.

Introduction. Analytic solutions for the response of planetary lithospheres to volcanic loads have been used to model faulting and infer elastic plate thicknesses [e.g., 1-4]. Predictions of the distribution of faulting around volcanic loads, based on the application of Anderson's criteria for faulting [5] to the results of the models, do not agree well with observations [6,7]. Such models do not give the stress state in the load itself, but only suggest a state of horizontal compressive stress there. Further, these models have considered only the effect of an instantaneously emplaced load. They do not address the time evolution of stresses, nor do they consider the effect of a load which grows. A finite element approach allows us to assign elements to the load itself, and thus permits calculation of the stress state and stress history within the edifice. The effects of episodic load growth can also be treated. When these effects are included, models give much better agreement with observations.

Method. We use the finite element code TECTON [8,9] to construct axisymmetric models of volcanoes resting on an elastic lithospheric plate overlying a viscoelastic asthenosphere. We have implemented time-dependent material properties in order to simulate incremental volcano growth. The viscoelastic layer was taken to extend to a sufficient depth so that a rigid lower boundary has no significant influence on the results. The code first calculates elastic deformations and stresses and then determines the time-dependent viscous deformations and stresses. Time in the model scales as the Maxwell time τ_m in the asthenosphere.

Results. We consider a volcano 25 km in height and 200 km in radius on an elastic lithosphere 40 km thick (parameters approximately appropriate to Ascraeus Mons). The volcano consists of three load increments applied at intervals of 1000 τ_m. Contours of maximum deviatoric stress in the fully-grown edifice at the conclusion of flexure (t = 3000 τ_m) are shown in Figure 1. Note that the maximum stress occurs in the lower mid-section of the edifice. We adopt the convention that tension is positive.

Discussion. Simple models of plate flexure due to an instantaneous load predict a state of horizontal compressive stress in the plate beneath the load [1,4] with an increasing magnitude of compression from the middle of the plate upward, and a maximum at the surface. Models with a succession of loads emplaced from the bottom up display a different distribution of stress. The maximum horizontal stress occurs in the lowest (first) load increment and decreases upward with each later load increment. Thus, thrust faults (predicted by simpler models) associated with such stresses would be expected to occur only early in the evolution (or not at all) and would be covered by later units which remain unfaulted. Such a distribution of stresses could also affect the locations and dimensions of magma chambers. A zone of horizontal compression within the edifice would inhibit ascending magma from reaching the summit and thus might cause magma to pool beneath it. Since magma will propagate perpendicular to the direction of least compressive stress, radial propagation of magma in sheet dikes or sills might also occur. The effects of adding fault slip along a basal detachment between edifice and lithosphere (as proposed in models of the flank tectonics of Hawaii [10]) was shown to achieve an even greater reduction in horizontal compressive stress in the edifice [11]. Such a structure may control the growth and evolution of tectonic features surrounding volcanoes on both Mars and Earth [11].

Stresses calculated from planetary loading models have been used, in conjunction with Anderson's criteria for faulting [5], to predict types of faulting that should be observed [1,2,4]. Typically, a zone is found surrounding the load with both the least compressive stress σ_1 and the most compressive stress σ_3 horizontal (assuming that near the surface, σ_{zz} is small and compressive). Application of Anderson's criteria yields a prediction of strike-slip faulting. Such a region surrounding a large load has not heretofore been observed [6,7]. Given the complete stress field in an element in this region from the TECTON solutions, we can plot Mohr diagrams, as in Figure 2, and compare them with a Mohr-Coulomb failure envelope. The Mohr circles grow in size as flexure proceeds, until the failure envelope is exceeded at about 70 τ_m after first loading. The largest circle shows stresses at the conclusion of flexure. This stress state corresponds to that given by analytic plate models (in which flexure occurs instantaneously). Simply interpreting this final stress state is seen to be misleading for two reasons. First, σ_1 (= σ_{rr}) is much larger than the tensional strength of any rock. Use of a shear failure criterion (such as Mohr-Coulomb) for such a stress state is improper [7]. Use of a tensile failure criterion will predict the formation of tension joints which may be precursors of graben [7]. Second, consideration of the stress history indicates that at the time of first failure, the shear failure criterion is satisfied, with principal stress directions that predict circumferential normal faulting. Formation of these faults would relieve stresses and provide planes of low resistance along which further faulting with a similar orientation would be expected to develop. Thus, the "prediction" of a zone of strike-slip faulting surrounding a lithospheric load, based on simple instantaneously-loaded plate flexure models, is in error.

Conclusions. Simple interpretations of the results from instantaneous load models lead to predictions of lithospheric stress fields that do not match observations. Consideration of the history of stresses in the lithosphere and within the load itself helps to resolve these discrepancies.

References. [1] R.P. Comer *et al.*, *Rev. Geophys.*, *23*, 61, 1985; [2] H.J. Melosh, *Proc. LPS 9*, 3513, 1978; [3] P.J. McGovern and S.C. Solomon, *Inter. Colloq. on Venus*, LPI , p. 68, 1992; [4] R.P. Comer, *GJRAS*, *72*, 101, 1983; [5] E.M. Anderson, *The Dynamics of Faulting*, 1951; [6] M.P. Golombek, *JGR*, *90*, 3065, 1985; [7] R.A. Schultz and M.T. Zuber, *LPS*, *23*, 1247, 1992; [8] H.J. Melosh and A. Rafesky, *GJRAS*, *60*, 333, 1980; [9] H.J. Melosh and A. Rafesky, *JGR*, *88*, 515, 1983; [10] P.W. Lipman *et al.*, *USGS Prof. Pap. 1276*, 45 pp., 1985; [11] P.J. McGovern and S.C. Solomon, *LPS*, *23*, 885, 1992; [12] J. Handin, in *Handbook of Physical Constants*, ed. S.P. Clark, 223, 1966;

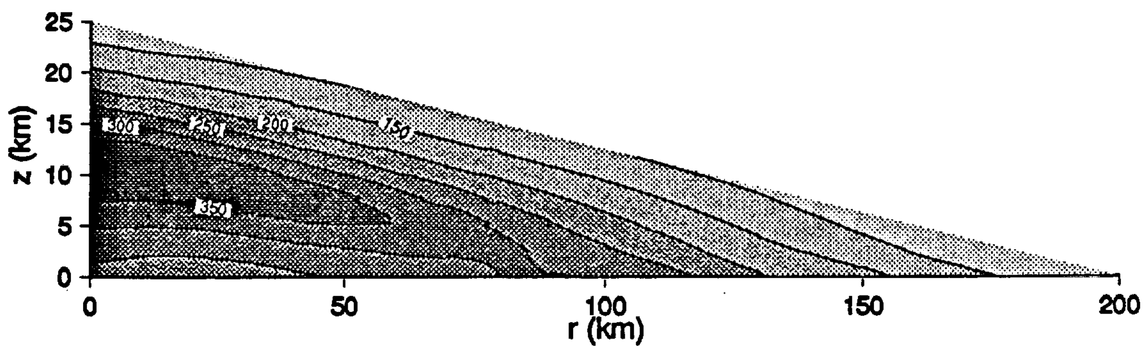

Figure 1. Contours of maximum deviatoric stress (MPa) in the volcanic edifice described above.

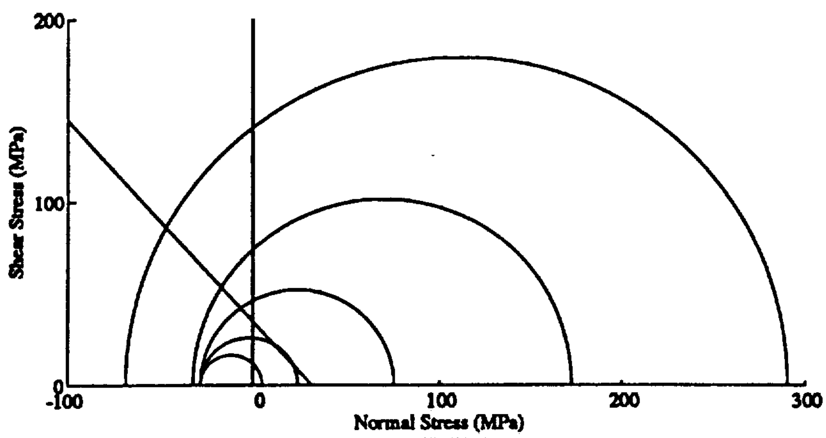

Figure 2. Mohr diagram for element at the top of the lithosphere (stresses calculated at element center: $r = 265$ km, $z = -2.5$ km). Diagonal line is Mohr-Coulomb failure envelope for basalt [12] with angle of internal friction $\phi = 49°$ and cohesion $c = 38$ MPa. In order of increasing radius, the circles represent stress state at $t = 30$, 70, 1000, 2000, and 3000 τ_m . When failure envelope is first exceeded ($t = 70\ \tau_m$), $\sigma_1 = \sigma_{rr}$ and $\sigma_3 = \sigma_{zz}$. At final time shown, $\sigma_1 = \sigma_{rr}$ and $\sigma_3 = \sigma_{\theta\theta}$.