MOUNTAIN BUILDING ON IO: VARIABLE VOLCANISM AND THERMAL STRESSES. M. R. Kirchoff and W. B. McKinnon, Dept. of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130 (oakes@levee.wustl.edu and mckinnon@levee.wustl.edu)

Introduction: Mountain formation on Io is likely tectonic in nature as almost none of the ~100 mountains discovered so far appear to have classic volcanic mountain features [1]. However, volcanism may still perform an important role in mountain building. Io's heat is advected through the crust by magma. Therefore, when the eruption rate changes, the crust's thermal profile adjusts producing thermal stress. Previous work [2] has shown that for a complete regional cessation of volcanism, thermal stresses are generated that will exceed Byerlee's rule in compression in ~ 0.5 Myr for a crust 25 km thick. Here, to further solve for if and when thermal stresses reach failure, we extend this model to include various rate decreases/increases, an initial thermal stress state, and crustal thickness changes.

Two different (end-member) scenarios of the asthenospheric heat budget as related to eruption (and hence subsidence) rate changes are considered. The first assumes that they are directly coupled, implying a fixed crustal thickness as rate changes occur. The coupling assures that the rate of heat input into the crust's base will equal the rate of heat removal by advection, which is equivalent to the eruption rate. The second scenario assumes the heat supply to (or within) the asthenosphere is not affected by eruption rate changes. Therefore, when the rate decreases, extra heat will remain at the crust's base, melting and thinning it. In addition, when the subsidence rate increases, heat is removed from the base such that new layers will "freeze out" producing a thicker crust.

Some Sources of Stress on Io: When a layer of crust cools off, tensional *thermal stresses* are produced for zero horizontal strain. Conversely, raising a layer's temperature will generate compressional stresses, as in the case of the initial thermal stress state (Fig. 1). In the steady state, continual volcanic burial transports surface material to depth, precipitously heating, and consequently compressing, the material as it is brought to the base of the crust. As a result, the material is stressed to failure deep in the crust. This thin layer of deep failure will likely not by itself lead to surface tectonics, but the failed/relaxed layer effectively mechanically decouples the crust/lithosphere from the asthenosphere below.

Global subsidence stresses are caused by the shrinking of the radius of a layer due to burial, producing large compressional stresses that are important in building mountains [1,2]. Subsidence stresses may be less than Byerlee's rule in compression, as these stresses may be relieved globally or regionally by faulting [2], and in principle could be extensional [3]. In addition, deep layers support overlying ones elastically, producing a modest tensional *overburden stress* that grows linearly with depth.

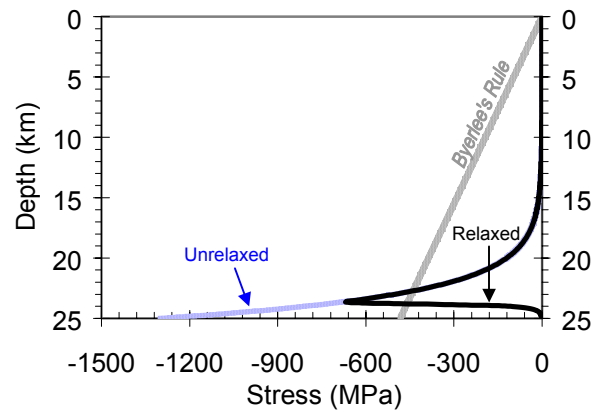

Figure 1. The viscously relaxed (black) and unrelaxed (blue) initial (steady state) thermal stress profile. Note that this stress state already exceeds Byerlee's rule in compression.

Method: To determine the amount of thermal stresses created due to temperature changes as a result of a volcanism rate increase or decrease, we solve for temperature as a function of both depth (z) and time. A finite difference code with a time variable mesh is used to model the time dependent heat diffusion and advection [4]:

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial z^2}\right) - \upsilon\left(\frac{\partial T}{\partial z}\right) \qquad (1)$$

Radiogenic internal heating is not included because this source is negligible compared to the tidal dissipation [5]. The model of the crust is a one-dimensional stack of uniform layers, initially 25 km thick (for definiteness). The boundary conditions are $T_{surface}$=100 K and $T_{base/melt}$=1600 K. All initial eruption velocities (υ) were 1.5 cm/yr, which corresponds with current estimates of the heat flow [2,4,6]. The initial stress conditions range from thermal stresses alone to combinations with either overburden or subsidence stresses.

The eruption rate is varied to ± 25%, 50%, 75%, and 100% of the initial, and resulting temperature and stress profiles are calculated. Stresses at the lithosphere's base are viscously relaxed according to the flow law of anhydrous Maryland diabase [2,7]. When the asthenospheric heat budget is not directly coupled to the lithosphere, the crust thins/thickens. The rate of melting/freezing is equal to the eruption rate change. This rate is multiplied by the appropriate time step to obtain the amount of crust removed/added. The ad-

justment is made and the code continues with a new crustal thickness.

Results: The results in Fig. 2 are for a fixed crustal depth. If volcanism ceases, then large compressional stresses that exceed the failure limit move up into the lower mid-crust. Mountains may then develop from these compressive stresses, if the faults breech the surface. For partial eruption rate decreases, failure and faulting will still occur; however, it will be deeper in the crust (Fig. 2a). Moreover, when subsidence stresses are combined with thermal stresses, the region of failure widens resulting in potentially powerful conditions for mountain building. For eruption rate increases, the deep crust cools and extensional thermal stresses produced. At first the large initial compressional thermal stresses are reduced and the crust is tectonically stabilized. When the eruption rate is doubled (+100%), very deep extensional stresses that exceed Byerlee's rule eventually develop (Fig. 2b), but are unlikely of tectonic consequence.

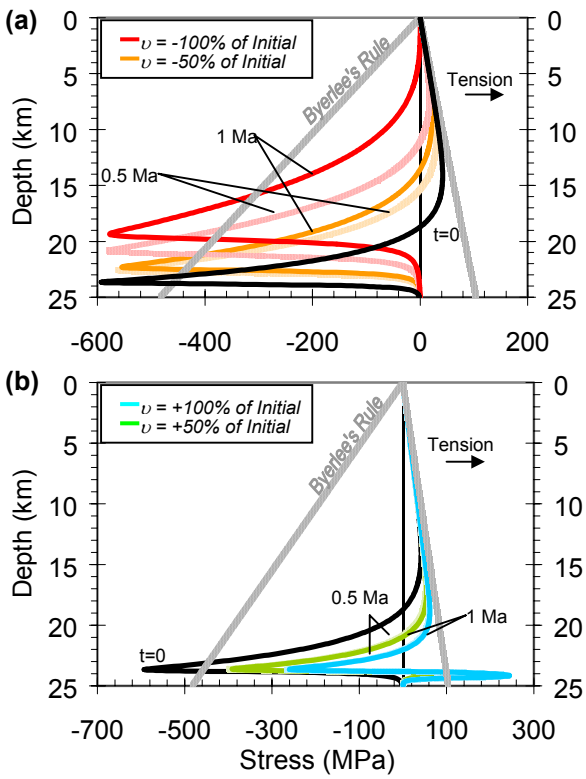

Figure 2. Stress profiles for fixed crustal thickness. Initial stresses include thermal and overburden. **(a)** Eruption rate decrease. For a complete shut down, the region of failure is pushed up into the lower mid-crust. **(b)** Eruption rate increase. The large compressional stresses are mitigated, and for doubling the rate, failure is reached in tension near the crust's base.

Uncoupled case (where the crust thins or thickens due to rate change). As the volcanism rate is decreased, compressional thermal stresses will develop in the thinning crust. However, due to the thinning they are now pushed into the upper crust. This will result in failure and faulting near the surface and, very likely, mountain building (Fig. 3a). On the other hand, when the rate is increased, the crust thickens. The deep crust cools off and reduces the initial compressive stresses, and the very base reaches failure in tension (Fig. 3b).

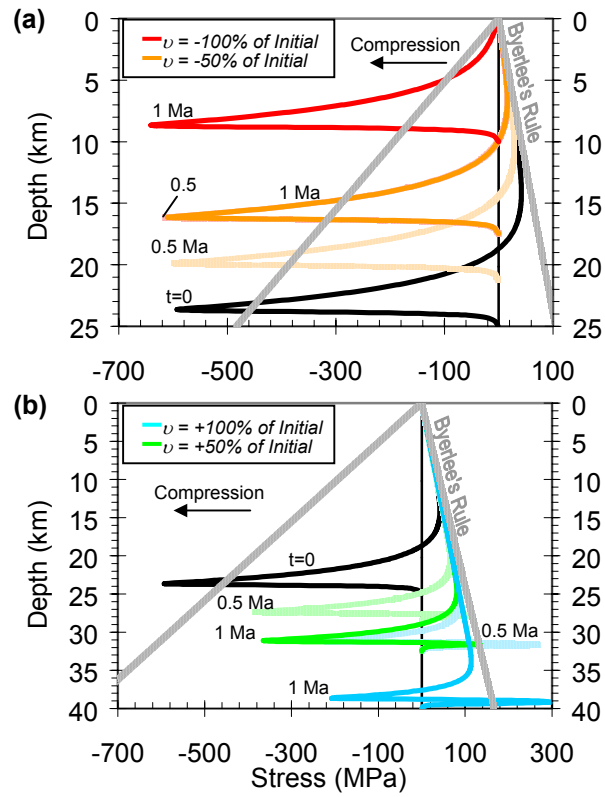

Figure 3. Stress profiles for the thermally uncoupled asthenosphere/crust case. Initial stress state includes thermal stresses only. **(a)** Eruption rate decrease. The failure zone is transported closer to the surface. **(b)** Eruption rate increase Compressive stresses are markedly reduced at depth.

Conclusion: Our model predicts regions of mountain production where volcanism is low or absent and that regions of extensive volcanism should have limited mountain building. This agrees with the work by Schenk *et al.* [1] that shows a global anti-correlation of mountains and volcanic centers on Io.

References: [1] Schenk P.M. et al. (2001) *JGR*, 106, 33201-33222. [2] McKinnon W.B. et al. (2001) *Geology*, 29, 103-106. [3] Solomon S.C. (1987) *EPSL*, 83, 153-158. [4] O'Reilly T.C. and Davies G.F. (1981) *GRL*, 8, 313-316. [5] Carr M.H. (1986) *JGR*, 91, 3521-3532. [6] Veeder G.J. et al. (1994) *JGR*, 99, 17095-17162. [7] Mackwell S.J. et al. (1998) *JGR,* 103, 975-984.