MOUNTAIN BUILDING ON IO – PART 2: EFFECTS OF PREEXISTING FAULTS AND PORE SULFUR ON 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 (kirchoff@levee.wustl.edu and mckinnon@wustl.edu).

Introduction: A majority of the mountains on Io are tectonic, upthrusted blocks [1-8]. The mechanism behind their formation, however, is unknown. Mountain formation may be indirectly related to the prolific volcanism on Io [3]. Three major mountain formation hypotheses following from this idea include:

- convection-modified subsidence: global compressional stresses (subsidence) are created by the continual burial of older volcanic layers by new volcanism [3] and are further modified by degree-2 mantle convection [4]
- plume-focused subsidence: subsidence stresses are focused by upwelling mantle plumes impinging on the base of the crust [5,6]
- thermally-modified subsidence: subsidence stresses are combined with thermal stresses due to local or regional reductions in eruption rates, which increases the amount of heat conducted through the crust [7,8].

Our previous work demonstrated the plausibility of the thermally-modified subsidence hypothesis. First, we showed that thermal stress with some subsidence stress is large enough to fault Io's crust [7-9]. Furthermore, our spherical harmonic statistical analysis found that regions of mountain concentrations are anticorrelated to regions of volcano concentrations at any low harmonic degree [9,10]. This distribution is consistent with that predicted by the thermally-modified subsidence hypothesis. Finally, we have shown the observed pattern of mountain strike orientations within the regions of mountain concentrations is more-or-less circumferential to the centers of the regions. This indicates a stress pattern for Io's crust consistent with subsidence stresses possibly acting along with thermal stresses [9,11].

Here we extend our previous thermal and subsidence stress modeling [7-9] to include the pore pressure effects of liquid sulfur in the crust and change the boundary condition from horizontally confined to unconfined. These changes relax some simplifications in our previous modeling. The first is that Io's crust is purely composed of basalt. Only including sulfur is still a simplification, as other substances are likely found in Io's crust (e.g., SO_2), but it is a step forward. The second is that the horizontally confined boundary condition physically equates to preexisting faults not relieving stress or not being there at all. This is *sensu stricto* unlikely (except for maybe just after Io's crust forms!), therefore we now model the crust with a "free" horizontal boundary condition to simulate stress being relieved, on average, on preexisting faults.

Methods: *Unconfined Horizontal Boundary*. If the stress (σ) in Io's crust is relieved on preexisting faults, then the depth-integrated (average) stress should be equal to zero. Therefore, at each time step the depth-integrated stress is calculated with [12]

$$\overline{\sigma}(t) = \frac{\int_0^{D(t)} \sigma_{xx}(z,t)dz}{D(t)}, \tag{1}$$

where D is the crustal thickness. This average is subtracted from the stress profile, and then the resultant stress profile is viscously relaxed. This iteration is repeated until the depth-integrated stress is zero indicating that the unconfined stress profile has been found for this time step.

Sulfur. Io's crust is built by layer upon layer of interbedded silicate and sulfur rich volcanics. As the layers subside they heat conductively; eventually the sulfur melts and forms a pore fluid. Solid sulfur should also affect the frictional and strength properties of the crust, but here we concentrate on the effects of sulfur pore pressure after its melting point is reached (392 K [13]). Pore pressure will affect the failure limit (Byerlee's rule), which is calculated assuming "hydrostatic" conditions [14]

$$\sigma_f = C(\rho - \rho_s)gz, \tag{2}$$

where z is the depth in the crust, g is Io's gravitational acceleration, ρ is the density of basalt , ρ_s is the average density of liquid sulfur (1700 kg m^{-3} [15]) and C is a constant that changes value if calculating for compression (-3.7) or tension (0.8).

Results: *Unconfined Horizontal Boundary*. Figure 1 shows the thermal, subsidence, and overburden (Poisson) stresses in a horizontally unconfined crust. When the eruption rate (υ) decreases, the upper portion of the crust is in extensional failure and the lower is in compressional failure. This result is different from that for the confined crust, as shown by the solid thin blue line. These large extensional stresses near the surface

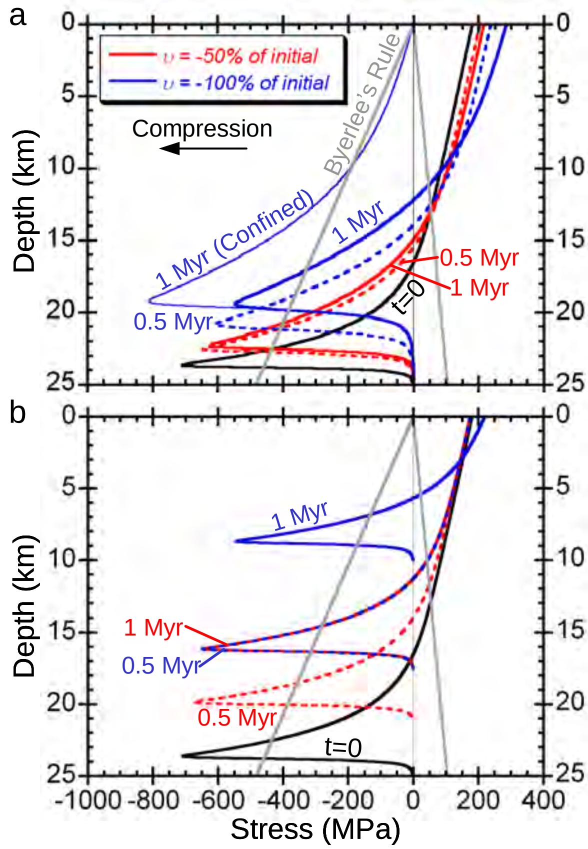

Fig. 1 Stress profiles for eruption rate (υ) decreases in a horizontally unconfined crust. (a) Fixed crustal depth. Near the surface Io's crust is in extensional failure and is in compressional failure near the base. (b) Crustal thinning. The region of compressional failure moves closer to the surface with time and eruption rate decrease.

are likely to produce normal or listric faults. Normal fault bounded and rotated crustal blocks are generally consistent with the morphology of Io's mountains, but are not obviously compatible with their great elevations. Large compressive stresses at depth would result in deep thrust faults; their propagation to the surface may be aided by the near-surface extensional environment. Thrust-fault bounded mountains may be even more easily produced at the surface if the crust is allowed to thin (i.e., if the heat flux into the base of the crust is independent of or uncoupled from the surface volcanic heat flow), as exhibited in Fig. 1b.

Sulfur. The effect pore pressure produced by liquid sulfur has on Byerlee's rule is shown in Fig. 2. In the lower crust, temperatures are high enough for sulfur to be liquid. In this region, pore pressure reduces the failure limit such that more of the lower crust is in failure. The overall effect on mountain formation at the surface is even greater when the uncoupled heat flow case is considered, where again everything is moved closer to the surface due to thinning as the eruption rate decreases.

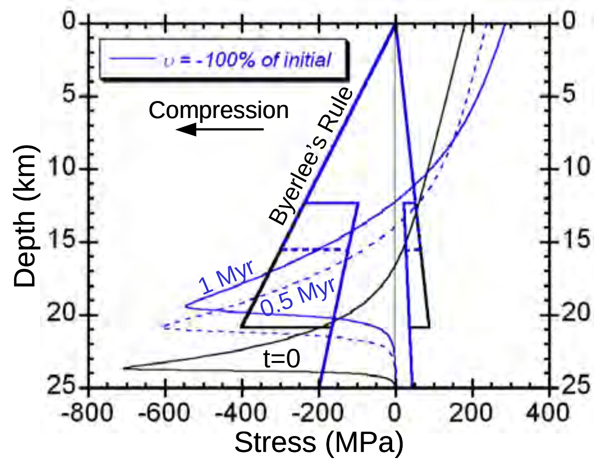

Fig. 2. Stress profiles and their failure limits (Byerlee's Rule) adjusted for the pore pressure due to liquid sulfur. Each stress profile is matched to its Byerlee's Rule by corresponding color and/or dashing. The section near the base of the crust effected by pore pressure grows as time passes for cessation of volcanism because the crust warms by conduction and sulfur's melting temperature migrates closer to the surface.

Conclusions: The unconfined crustal case is arguably more realistic than the confined crustal case, and the implied near-surface extensional environment may facilitate mountain formation by allowing deep crustal thrusting to reach the surface. Incorporating the crustal weakening due to potential sulfur pore fluids at depth only makes deep crustal thrust faulting more likely. If the crust is thinning at the same time due to a mismatch between surface volcanism and asthenospheric heat supply, the potential for profound crustal disruption ("chaos" on Io) is only increased.

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