MOUNTAIN BUILDING ON IO: AN UNSTEADY RELATIONSHIP BETWEEN VOLCANISM AND TECTONISM. 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.

Introduction: Most mountains on Io are formed through tectonic mechanisms, since few observed seem to be volcanic [1-3]. Volcanism may still play an important role in mountain formation, however, e.g., as indicated by the now famous degree-2 anticorrelation between mountain and volcano distributions [1,4-6]. Three major hypotheses for mountain formation that have been proposed are *a) convection-modified subsidence*, which states that burial of older volcanic layers by new ones (subsidence) creates large, global compressional stresses [1,7], which are modified by degree-2 mantle convection resulting in two broad regions each of compression and relative tension [1]; *b) plume-focused subsidence*, where subsidence stresses are focused by upwelling mantle plumes impinging on the base of the crust to produce isolated mountains [8,9]; and *c) thermally-modified subsidence*, which proposes that mountains are formed by a combination of thermal and subsidence stresses, the former created in the crust due to localized or regional reductions in eruption rates, which cause strong increased conductive heating [4,10,11].

Here, we summarize our results from modeling thermoelastic stresses created by eruption rate increases/decreases in Io's lithosphere (crust), and the implications these stresses, along with subsidence stresses, have for thrust faulting and mountain formation [10,11]. In addition, findings from a spherical harmonic statistical analysis of the mountain and volcano distributions are presented [5,6]. Given that each hypothesis introduced above predicts different distributions, these results may indicate which hypothesis is most likely to apply to Io. Results of a statistical analysis of mountain strike orientations and implications for Io's global stress field are discussed as well [12]. Finally, the uncertainties in our understanding of Io's tectonic regime are reviewed.

Thermal Stresses: Io's heat is advected through the crust by magma [13]. Therefore, when the eruption rate changes, the crust's temperature profile adjusts and thermal stresses are produced. To determine if, and when, thermal stresses (with or without subsidence stress) reach failure, different rate decreases/increases were modeled. The initial, steady-state thermal stress produced by the temperature change due to continual burial was also included. Our modeled crust is horizontally confined and viscously relaxed at the base. Different scenarios of the asthenospheric heat budget as related to eruption rate changes were considered.

We found that the initial, compressional, steady-state thermal stress is already in failure near the base of the crust. When the eruption rate is decreased, the region of the crust in compressional failure moves into the lower mid-crust. The faults may then breech the surface, resulting in mountains. Moreover, when subsidence stresses are combined with thermal stresses, the region in failure widens – a potentially powerful condition for orogenesis. If decreasing volcanism implies crustal thinning, compressional thermal stresses in failure are forced closer to the surface, and observable faulting is even more likely.

Mountain and Volcano Distributions: *Convection-modified subsidence* predicts that concentrations of mountains and volcanoes should be degree-2 anticorrelated. *Plume-focused subsidence* predicts mountains should be adjacent to individual volcanic features, and thus positively correlated at all degrees. Finally, *thermally-modified subsidence* predicts concentrations of mountains and volcanoes should be anticorrelated at any low degree. To determine the relationship between these distributions [1], they were expanded into spherical harmonics [14]. The spectral power per degree for each distribution [15] and the correlation coefficient per degree between the distributions [14] were calculated.

As previously shown in counting circle analyses [1,4], mountains are distributed in two regions ~antipodal to each other (Fig. 1a). Spectral power peaks at l = 2 and is statistically significant, with a subsidiary peak at l = 1 and less power at higher degrees. The (normalized) volcano spectral power distribution has a very strong peak at l = 2, with less significant power at l=1 and little power for $l \geq 3$. This distribution also shows two concentrations ~antipodal to one another (Fig. 1b).

Statistical analysis shows that mountainous regions are anticorrelated with respect to the volcanic ones at low degrees, with greater or lesser levels of statistical significance at degrees 1 and 2, depending on the weighting assigned to the mountain distribution. This is consistent, in part, with the hypothesis of Schenk et al. [1] that mountain formation should occur in regions that are anticorrelated from the volcano distributions with a degree-2 pattern, because of the modification of global subsidence stresses by large-scale, l = 2 convection in the mantle, but does not obviously explain the behavior at other low l. The anticorrelations at low degree are contradictory to *plume-focused subsidence*,

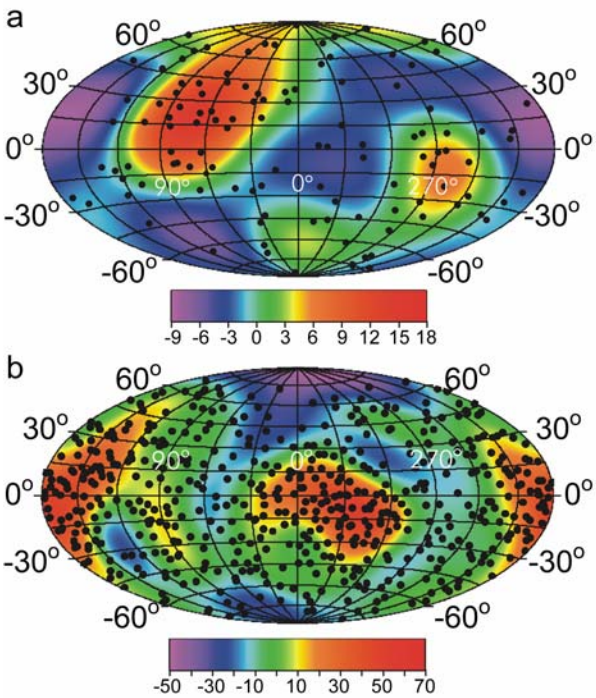

Figure 1. Hammer equal-area projections of the spherical harmonic expansions of the a) mountains ($1 \le l \le 4$) and b) volcanoes ($1 \le l \le 6$). The dots show actual positions.

because positive correlations at all degrees are predicted. *Thermally-modified subsidence* is consistent with our analysis, because the predicted anticorrelation should occur at all low degrees. There is, however, a rising level of positive correlation at large degree (l > 10). This *is* consistent with the hypothesis that, locally, volcanism can induce tectonism and vice versa, and thus with observations that show such structural interactions [8,9].

Mountain Strike Orientations: The fact that the mountains are concentrated into two regions ~antipodal to each other [1,4-6] indicates a natural symmetry for the global stress pattern. We statistically explored the mountains' dominant horizontal orientations for patterns in a coordinate system that aligns a "north-south" tectonic axis with the ~center of the mountain concentrations. These patterns are tested against that of the stress field produced in a plastically yielding, axially symmetric cap responding to globally uniform compression combined with in-plane compression applied at the cap edge.

We find that for all reasonably sized representations of the mountain concentrations ("caps"), the strike orientations in the region outside of these caps are random. The orientations within the caps, however, preferentially align with lines of "latitude" (Fig. 2). Stress calculations in the caps predict thrust faults that align with lines of "latitude" as well.

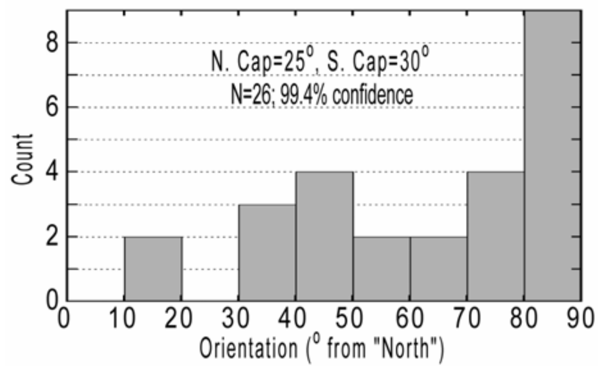

Figure 2. Histogram of mountain strike orientations. Percentage shown is the confidence with which this distribution is not random based upon a standard chi-squared calculation. Most orientations align with lines of "latitude."

Conclusions: Thermal stresses produced in Io's crust by eruption rate decreases are large enough to fracture the crust. When subsidence stress is included and/or the crust thins, powerful conditions develop for building mountains at Io's surface. This type of formation mechanism predicts that mountains are built where volcanism is decreasing, and therefore agrees with the spherical harmonic analysis. Analysis of mountain strike orientations demonstrates that mountains in the concentrations are preferentially aligned with lines of "latitude" in our rotated system (Fig. 2). This pattern matches that produced in an elastic-plastic "cap" responding to a global compressional stress regime that combines subsidence stresses with an oriented in-plane compression. The latter may be produced by enhanced volcanism outside of the caps (observed) or by the basal drag induced by tidal-heat-driven convection. The characteristics of the latter are still quite uncertain, and so the stress levels induced in Io's lithosphere are as well. The very existence of plumes in a strongly internally heated mantle is also questionable; indeed, conventional thermal convection, as opposed to porous flow, may not be taking place at all [16].

References: [1] Schenk P.M. et al. (2001) *JGR, 106,* 33201–33222. [2] McEwen A.S. et al. (2004) in *Jupiter-the Planet, Satellite, and Magnetosphere.* CUP, 307-328. [3] Schenk P.M. et al. (2004) *Icarus*, *169*, 98-110. [4] McKinnon W.B. et al. (2001) *Geology*, *29*, 103-106. [5] Kirchoff M.R. et al. (2003) *EOS*, *46*, F962. [6] Kirchoff M.R. et al. (2005) submitted. [7] Schenk P.M. and Bulmer M.H. (1998) *Science, 279*, 1514-1517. [8] Turtle E.P. et al. (2001) *JGR*, *106*, 33175-33199. [9] Jaeger W.L. et al. (2003) *JGR, 108*(E8), 5093. [10] Kirchoff M.R. and McKinnon W.B. (2003) *LPS XXXIV*, Abstract #2030. [11] Kirchoff M.R. and McKinnon W.B. (2005) submitted. [12] Kirchoff M.R. et al. (2004) *BAAS*, *36*, 1100. [13] O'Reilly T.C. and Davies G.F. (1981) *GRL*, *8*, 313-316. [14] Johnson C.L. and Richards M.A. (2003) *JGR*, *108*(E6), 5058. [15] Ribe N.M. and de Valpine D.P. (1994) *GRL*, *21*, 1507-1510. [16] Moore W.B. (2001) *Icarus*, *154*, 458-550.