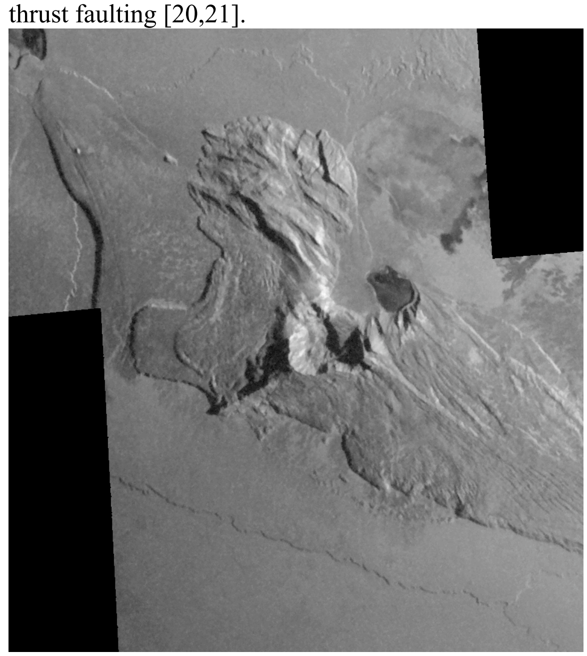
BUILDING MOUNTAINS ON IO: IMPLICATIONS FOR IO'S LITHOSPHERE. E. P. Turtle[1,2], W. L. Jaeger[1], M. Milazzo[1], L. P. Keszthelyi[3] and A.S. McEwen[1], [1]Lunar and Planetary Lab., Univ. of Arizona, Tucson, AZ 85721-0092; turtle@lpl.arizona.edu, [2]Planetary Science Institute, 1700 E. Fort Lowell, Suite 106, Tucson, AZ 85719, [3]Astrogeology Team, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001.

Io's mountains are intimately linked to its lithospheric processes and properties, and therefore provide insight into its interior. The mountains' heights, up to 17.5 ± 3 km [1], imply that they have a significant silicate component [*e.g.*, 2-4]. However, Io's numerous plumes must deposit extensive layers of volatile-rich material resulting in weak zones that facilitate massive landslides as may have happened at Euboea Mons [5] and Gish Bar Mons [*e.g.*, 6]. Many mountains appear to be collapsing outwards by means of slumping and landsliding [6,7]. Indeed, in some places (*e.g.*, Telegonus Mensae) both styles of mass wasting occur within a few kilometers of each other, perhaps indicating a spatial variation in material properties or composition [7].

The impressive heights of Io's mountains also require a lithospheric thickness of at least a few tens of kilometers [*e.g.*, 1,8-10], not only to provide support but also to provide sufficient building material. O'Reilly and Davies [11] demonstrated that a high subsidence rate makes localized advective heat transfer so effective that the lithosphere can be arbitrarily thick despite Io's high heat flow [*e.g.*, 12].

Only ~3% [10] of the 100-150 mountains [1,9,10] appear to be volcanic edifices. Although mountains are frequently bounded by paterae or volcanically active fractures [2,6,10,13], they seldom have paterae at, or flows emanating from, their summits. Instead, the mountains appear to have tectonic origins, resembling uplifted or tilted blocks, bounded by steep scarps and often fractured [*e.g.*, 6,14]. Despite their implied tectonic origins, there is no obvious global pattern in the mountains' distribution beyond a subtle variation with longitude which appears to be anti-correlated with the global distribution of volcanic centers [1,15]. However, in contrast, at the local scale many mountains are associated with paterae [2,10,15]: a statistically significant 41% [10] of mountains directly abut one or more paterae.

Although, in general, the mountains do not appear to be volcanic in origin, nonetheless, volcanism is likely to play a major role in their formation. Io's very high, global average, resurfacing (including some degree of shallow intrusion) rate of 0.1-10 cm/yr [16-19] implies a comparable rate of lithospheric subsidence. At 1 cm/yr, after 1 Myr of uniform resurfacing, the initial surface would be buried to a depth of 10 km, experiencing a 1% reduction in surface area [6]. It is this intense shortening that Schenk and Bulmer [5] proposed drives mountain building: the induced compressive stress is sufficient to cause brittle failure at depths of only a few kilometers [10]. Observed mountain morphologies are consistent with uplift by thrust faulting [5,10] and modeling has demonstrated the feasibility of this mechanism [6]. Kinematic analyses of thrust faulting are also consistent with observed mountain structures and provide insight into fault geometry; for example, the morphology of Tohil Mons (Figure) is consistent with uplift by imbricate thrust faulting [20,21].



The isolation of the mountains observed on Io requires a mechanism to focus compressive stresses in a lithosphere that is likely to be pervasively faulted. One possibility was suggested by the observation that many ionian mountains abut paterae, which may indicate a genetic link [10]. Given the strong tidal heating [*e.g.*, 12] and the level of volcanic activity observed, it is likely that Io's interior is strongly convecting [*e.g.*, 22,23]. We have used finite-element models to investigate whether regions of mantle upwelling and downwelling could perturb the stress field in the overlying lithosphere (as has been hypothesized for Earth [*e.g.*, 24-28]). Our simulations demonstrated that this mechanism does indeed lead to localized mountain building. Furthermore, we have documented other aspects of mountains that are consistent with this scenario [10]:

(1) the axial symmetry of this model predicts arcuate faults; (2) tension due to uplift could overcome the global compressional stress and allow rifting along normal or detachment faults as predicted by McEwen [29]; and (3) thermally buoyant mantle material impinging on the base of the lithosphere will generate melt that may erupt onto the surface through faults along which the compressive stress has been relieved. We are investigating other localization mechanisms, such as spatial variations in resurfacing rate.

In contrast to the compressive scenario, McKinnon *et al.* [30] proposed an extensional origin due to thermal stresses that develop as volcanic activity waxes and wanes over different parts of the planet. This hypothesis is consistent with the anti-correlation between mountains and volcanic centers that is observed at the global scale [1,15], although it does not explain the apparent affinity of mountains for paterae at the local scale [10,15]. Furthermore, Jaeger *et al.* [10] evaluated mechanical and thermal sources of lithospheric stress available to drive mountain building, and concluded that stresses due to subsidence are likely to dominate thermal stresses for all but the thinnest lithospheres.

Both of these formation scenarios are complicated by variations in subsidence rate and by localized stress relief due to faulting. Indeed, whether it is appropriate to use a uniform subsidence rate, which is based on the globally averaged resurfacing rate from a combination of direct observation and inference from the detected heat flow, in models of mountain building is an important question. This assumption is reasonable if the rate of change in the locations of sites of volcanic activity exceeds the subsidence rate. The lack of large volcanic edifices on Io supports the idea that migration is rapid: individual sites do not stay active long enough for edifices to be constructed. We are assessing the timescale over which regional variations in resurfacing rate must persist in order to affect local tectonic processes.

Another outstanding issue is how the mountains are supported and for how long. There is substantial evidence, predominantly from observed eruption temperatures consistent with mafic or ultramafic compositions [*e.g.*, 31-35], that Io's crust has undergone little differentiation; indeed, the interior may consist of a crystal-rich magma ocean [36-37]. This scenario implies relatively little density contrast between the crust and mantle, which means that if mountains were supported isostatically, roots would have to be inordinately deep. Furthermore, one mechanism for crustal recycling is basal melting [38], in which case roots would be ephemeral. The subsidence rate is sufficiently rapid that low temperatures are likely to persist deep into the crust [10,11,38], thus it is also possible that the crustal density could locally exceed that of the upper mantle thereby facilitating delamination [38]. We are performing thermal analyses of the heating and potential melting of Io's crust as a function of subsidence rate, based on the derived thermal structure, and adjusting the temperature-dependent lithospheric rheology (diabase from [39]) in our finite-element models of mountain formation to assess the mechanical integrity of the base of the lithosphere and how long it can persist. We are also incorporating the results of our analysis of the faulting style (or styles) which best accommodates lithospheric shortening under different conditions, to study the implications for mountain uplift. We will present the results of our analyses and their implications for Io's lithospheric conditions.

References: [1] Schenk, P.M., *et al.* (2001) *JGR 106,* 33,201-33,222. [2] Masursky, H., *et al.* (1979) *Nature 280,* 725-729. [3] Carr, M.H., *et al.* (1979) *Nature 280,* 729-733. [4] Clow, G.D., and Carr, M.H. (1980) *Icarus 44,* 268-279. [5] Schenk, P.M. and Bulmer, M.H. (1998) *Science 279,* 1514-1517. [6] Turtle, E.P., *et al.* (2001) *JGR 106*, 33,175-33,200. [7] Turtle, E.P., *et al.*, *Icarus*, in press. [8] Nash, D.B., *et al.* (1986) in *Satellites*, (Burns and Matthews, Eds.), 629-688. [9] Carr, M.H., *et al.* (1998) *Icarus 135*, 146-165. [10] Jaeger, W.L., *et al.* (2003) *JGR 108*, 10.1029/2002JE001946. [11] O'Reilly, T.C. and Davies, G.F. (1981) *GRL 8*, 313-316. [12] Peale, S.J., *et al.* (1979) *Science 203*, 892-894. [13] Whitford-Stark, J.L (1982) *LPSC XIII*, 859-860. [14] McEwen, A.S., *et al.* (2000) *Science 288*, 1193-1198. [15] Kirchoff, M.R., *et al.* (2003) *Eos. Trans. AGU 84(46)*, P41A-0399. [16] Johnson, T.V., *et al.* (1979) *Nature 280*, 746-750. [17] Blaney, D.L., *et al.* (1995) *Icarus 113*, 220-225. [18] Phillips, C.B., (2000) Ph.D. thesis, University of Arizona, Tucson, AZ. [19] Geissler, P.E., *et al.*, *Icarus*, in press. [20] Jaeger W.L., *et al.* (2002) *LPSC XXXIII*, #1741. [21] Jaeger W.L., and Turtle E.P. (2002) *Eos. Trans. AGU 83(47)*, P72B-0502. [22] Tackley, Paul J. (2001) *JGR 106*, 32971-32982. [23] Tackley, Paul J., *et al.* (2001) *Icarus 149*, 79-93. [24] Burke, K., and J.F. Dewey (1973) *J. Geol. 81*, 406-433. [25] Burke, K., (1976) *Tectonophysics 36*, 93-112. [26] Stofan E. R., *et al.* (1992) *JGR 97*, 13347-13378. [27] Squyres S. W., *et al.* (1992) *JGR 97*, 13611-13634. [28] Janes D. M, *et al.* (1992) *JGR 97*, 16055-16067. [29] McEwen, A.S. (1985) in *Heat and Detachment in Crustal Extension on Continents and Planets*, LPI, 76-80. [30] McKinnon, W.B., *et al.* (2001) *Geology 29*, 103-106. [31] Williams, D.A., *et al.* (2001) *JGR 106*, 33105-33120. [32] Davies, A.G., *et al.* (2001) *JGR 106*, 33,079-33,104. [33] Milazzo, M. P., *et al.* (2002) *LPSC XXXIII*, #1699. [34] Radebaugh, J., *et al.*, *Icarus*, in press. [35] Lopes, R.M.C., *et al.*, *Icarus*, in press. [36] Keszthelyi, L., *et al.* (1999) *Icarus 141*, 415-419. [37] Keszthelyi, L.P., *et al.*, *Icarus*, in press. [38] Jaeger *et al.*, *LPSC XXXV*, submitted. [39] Mackwell, S.J., *et al.* (1998) *JGR 103*, 975-984.