OROGENIC TECTONISM ON IO. W. L. Jaeger[1], E. P. Turtle[1], L. P. Keszthelyi[1] and A. S. McEwen[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721-0092 (jaeger@pirl.lpl.arizona.edu).

Introduction: Io, the innermost of Jupiter's four Galilean satellites, is strongly tidally heated by its orbital interactions with Jupiter, Europa and Ganymede. As a result, it is the most volcanically active body in the solar system. The surface of Io is spotted with ~400 low relief volcanic centers [1, 2] and more than 100 tall mountains [2], most of which appear to be tectonic rather than volcanic in origin [3]. Ionian mountains can reach heights in excess of 15 km [4] and they typically have rugged, asymmetric morphologies. Because of their soaring heights, the mountains are inferred to be dominantly silicate structures rather than sulfur-rich protuberances, as such volatiles could not support topography much in excess of 1 km [5]. The orogenic process or processes that erect these immense mountains are not yet well understood.

Schenk and Bulmer [4] present a mountain formation model in which the rapid volcanic resurfacing of Io buries concentric spherical shells of lithospheric material to smaller and smaller radii. At depth this process generates a large horizontal compressional stress that leads to mountain uplift by thrust faulting. Alternatively, McKinnon *et al*. [6] suggest that thermal stresses play an important and perhaps dominant role in mountain formation. In their model, spatial and/or temporal fluctuations in Io's resurfacing rate cause alternating episodes of compression and extension, and, as a consequence, the surface of Io resembles the chaos terrain of Europa, with tilted crustal blocks (*i.e*., mountains) in a matrix of highly disrupted material.

Discussion: In order to test these hypotheses, we quantify the effects of thermal expansion and subsidence on ionian mountain formation as a function of lithospheric thickness. However, the thermal expansion we compute does not come from the fluctuating thermal stress proposed by McKinnon *et al*. [6]. Although temporal and spatial variations in Io's resurfacing rate can produce large thermal stresses at the base of the lithosphere, the resulting thermal dilation is, in most cases, small compared to the volume change produced by the factors discussed below. In this study we consider a more general phenomenon: the thermal expansion that results from subsidence of a shell of material from Io's surface where the temperature is ~100 K [7] to the base of its lithosphere where the temperature is estimated to be ~1500 K. On Earth, the base of the thermal lithosphere is commonly taken to be the 1600 K isotherm [8]. However, the lower lithostatic pressure on Io and the presumably more primitive composition of the ionian lithosphere lead to substantial melting by 1600 K [9]. Incipient melting (and rapid weakening of the rock) probably occurs around 1500 K.

O'Reilly and Davies [10] calculate the temperature profile within a rapidly subsiding ionian lithosphere. The thermal stress induced as the lithosphere is heated along this temperature profile can be quite large and should be global. In order to determine the net effect of this stress, we integrate the volumetric strain it generates through the entire lithosphere. An important parameter in this calculation is the resurfacing rate of Io. Assuming the generally accepted, globally averaged resurfacing rate of 1 cm/yr [11, 12], we find that the volume of material uplifted by thermal expansion increases rapidly with increasing lithospheric thickness but then plateaus for thicknesses >5 km (Figure 1).

The subsidence-induced volumetric strain is calculated by integrating the change in the surface area of concentric shells of lithospheric material with depth. The volume of material that is vertically displaced by subsidence geometrically increases with increasing lithospheric thickness. In comparing the effects of subsidence and thermal expansion on ionian mountain formation, we find that thermal expansion largely drives orogenic tectonism for a lithosphere less than 12 km thick, whereas, subsidence dominates for a thicker lithosphere (Figure 1).

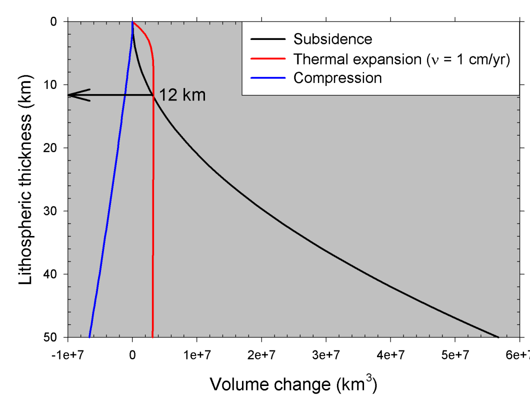

Figure 1. The volume of lithospheric material uplifted by subsidence (black) and thermal expansion (red) is plotted as a function of lithospheric thickness. The volume that is accommodated by rock compressibility (blue) is also shown.

In order to better understand the roles that thermal expansion and subsidence play in mountain formation, we must constrain the thickness of Io's lithosphere. We do this by determining the lithospheric thickness for which the observed volume of uplifted material equals the volume predicted by our calculations. For a given lithospheric thickness, the predicted volume of uplifted material is the sum of the volume changes caused by subsidence and thermal expansion minus the volume of material that is accommodated by rock compressibility. We estimate the volume taken up by compression within the lithosphere by integrating the three dimensional strain using the material properties of a mafic igneous rock. The negative volume change that results from rock compressibility monotonically increases in magnitude with increasing lithospheric thickness (Figure 1). The net volume of uplifted material (i.e. the sum of the three trends shown in figure 1) is plotted on figure 2 as a function of lithospheric thickness. This calculation neglects the decrease in porosity with depth.

Approximately 150 mountains have been identified on Io to date [2, 3, this study] and about 80% of the surface has been imaged at resolutions where mountains are readily identifiable (>2 km/pixel) [1]. Therefore, we project that there are ~180 mountains on Io. Using the average mountain dimensions given by Schenk et al. [2] and assuming that the mountains are triangular in cross section, we estimate that ~6 x 10^6 km^3 of material resides in Io's mountains. This corresponds to a lithospheric thickness of ~14 km (Figure 2). This number is a lower limit because uplifted material may reside in low relief features that have not yet been detected. Our results indicate that subsidence largely drives mountain formation on Io, but that subsidence-induced thermal expansion is non-negligible.

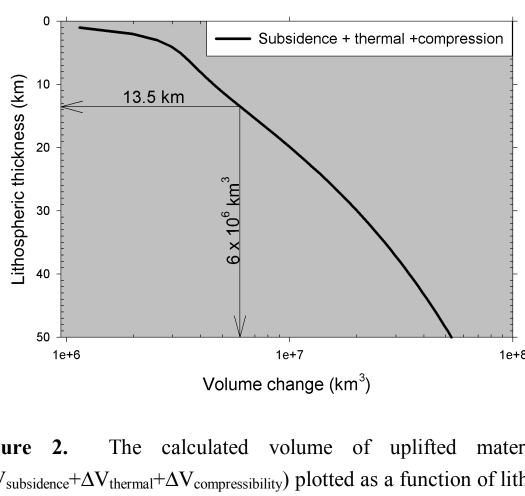

Figure 2. The calculated volume of uplifted material ($\Delta V_{subsidence}+\Delta V_{thermal}+\Delta V_{compressibility}$) plotted as a function of lithospheric thickness. The volume of material that resides in Io's mountains is estimated to be ~6 x 10^6 km^3, and the corresponding lithospheric thickness is ~15 km. This value is a lower limit.

This work still leaves open the question of how stresses are focused to uplift isolated mountains. A relatively homogenous compressional stress applied to a pervasively fractured lithosphere will produce imbricated thrusts rather than isolated peaks [13]. To determine the likely focusing mechanism, we cataloged the well-imaged ionian mountains and noted their relationship to nearby geologic features. We discovered a non-random association between the mountains and caldera-like depressions known as paterae.

These findings suggest that orogenic tectonics can facilitate patera formation. However, it seems that paterae commonly form without associated mountains [1]. One possible explanation is that upwelling asthenospheric diapirs impinging on the base of the lithosphere focus the stresses such that isolated mountains can form. The faults associated with the uplift of the mountain can also serve as conduits for magma ascent, allowing the formation of paterae as volcano-tectonic depressions.

Conclusions: We calculate the relative importance of subsidence and thermal expansion in ionian mountain formation as a function of lithospheric thickness. For the observed volume of uplifted material, we estimate that the lithosphere must be >14 km thick and that subsidence related stresses are marginally more important. We also find a non-random association between mountains and paterae, which supports the idea that asthenospheric diapers may focus the stresses to form isolated mountains

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