FORMATION MODELS OF IONIAN MOUNTAINS.

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Introduction: There are ~100 mountains and plateaus on Io, many of which have been determined from shadow measurements or stereo photogrammetry to be several kilometers high [1]. The highest peak measured to date is in Boosaule Montes and is 16 ± 2 km tall [2]. Surprisingly, despite Io's incredible volcanic activity, its mountains do not appear to be volcanoes; most have the appearance of tilted blocks which are bounded by steep scarps. The mountains are often fractured and covered with ridges, but no lava flows or plumes issue from their summits. However, volcanic calderas are often found at the margins of the mountains [3]. There are also no obvious global tectonic patterns in the distribution of mountains. Indeed, to first order, mountains appear to be evenly distributed over Io, although there may be some subtle variations with longitude [4].

These observations raise many questions about Io's huge mountains. We are using finite-element modeling to investigate how Ionian mountains form and what relationship, if any, exists between mountain formation and volcanism.

Modeling: Io has a global average resurfacing rate of 1 to 2 cm/yr ([5] based on cratering rates; [6] based on melt production consistent with heat flow) which implies a comparable global subsidence rate. After one million years, the amount of crustal shortening resulting from this subsidence can be accommodated by ~110 mountains, assuming they are all formed by low-angle thrust faulting as Schenk and Bulmer [2] proposed for Euboea Montes. Of course this is greatly oversimplified, the differences in mountain morphology imply that there may be multiple formation mechanisms at work. Furthermore, the resurfacing rate is not uniform; regions far from vents may experience ≤ 0.1 cm/yr, while in active regions it may be ≥ 150 cm/yr.

We are performing finite-element simulations to explore possible formation mechanisms for Ionian mountains. Our investigation focuses on relative motions of individual crustal blocks that may be subsiding, tilting, or overriding other blocks due to local differences in crustal density or resurfacing rates.

We are using the two-dimensional version of the finite-element code Tekton which was developed for use in simulating tectonic processes [7]. We have designed a mesh that extends to a depth of 340 km and out to a distance of 1000 km. It has rectangular elements 10 km wide which range from 1 to 10 km high depending on their proximity to the surface where a finer scale is necessary. The nodes along the bottom boundary are fixed vertically, but can move horizontally. Those along the left boundary are fixed horizontally, but can move vertically. And those along the right boundary are either fixed or moved a fixed amount of displacement horizontally, but allowed to move freely in the vertical direction.

Our current models are based on the theory that Io may have a crystal-rich magma ocean [*e.g.*, 8]. We use a 50 km thick crust with a density of 2900 kg/m^3 and a power-law rheology (A = 2.0 x 10^{-4} MPa^{-n}s^{-1}; n = 3.4, H = 260 x 10^3 J/mol). This overlies a mantle which is represented by a Newtonian fluid with a viscosity of 10^{10} Pa s and a density of 3000 kg/m^3. This viscosity is above the minimum range of 10^7-10^9 Pa s predicted by Webb and Stevenson [9] from their analysis of topographic subsidence on Io. The low density contrast between the crust and the mantle is predicted from the lack of differentiation that would occur in the magma ocean model [8].

We began by investigating flexural support using a simulation of volcanic loading on an unfaulted lithosphere. Under a 50 km wide, 15 km thick deposit of lava with a density of 3000 kg/m^3, the downward lithospheric displacement at the center of the load was 4.8 km, resulting in a volcanic plateau 10.2 km high. There was a 200 m high flexural bulge at a distance of 490 km. This is a greatly oversimplified model; there is a vertical scarp at the edge of the emplaced lavas and there is no infilling of the moat. Nonetheless, it illustrates that flexural support may be an unrealistic explanation for Ionian topography. First, this model would require the mountains to be built of recent lava flows, which is not observed. Secondly, it would affect topography in a wide region around the mountain, which also does not appear to be the case. Although we do not have high enough topographic resolution to be able to detect flexural moats and bulges directly, in a brief survey of Ionian mountains we did not find any examples of lava flows that appeared to have been diverted by topographic expression associated with flexural support near mountains.

We then ran simulations in which the lithosphere is cut every 200 km by 45° faults. In these cases the block that is loaded with lava subsides under the load and the neighboring blocks tilt inward with scarps of ~2 km facing away from the location of deposition. However, in these simulations, too, the topographic expression of the volcanic load is significantly larger than the scarps of the tilting crustal blocks.

We have also run simulations with a faulted lithosphere, without volcanic loading, and taking the compression due to global resurfacing and subsidence into account. After compression equivalent to 2 Myr of subsidence the models exhibit tilted crustal blocks with a few kilometers of relief in simulations in which all faults dipping in the same direction. In simulations with faults dipping in opposite directions the models exhibit plateaus with a comparable amount of relief. (Although the heights of scarps in these models do not achieve those observed on Io this is due to a limitation in the modeling method and not the formation mechanism. If the distortion of individual elements in the finite-element mesh becomes too great, numerical instabilities can develop.)

In each of the models with pervasively faulted crusts all of the individual crustal blocks exhibit the same behavior. This results in series of mountain ranges rather than the isolated mountains that are observed. Furthermore, the faults need to be introduced into the models *a priori*. We are investigating the effects of local variations in density, resurfacing rates, and fault resistance and orientation on isolating mountain building. Calderas abut many Ionian mountains, suggesting that there may be a genetic link between them. One possibility we are investigating is that mantle plumes rising beneath the lithosphere locally enhance the compressive stress (Figure) causing thrust faults to develop, along which the crust is uplifted to form mountains. The mountain bounding faults may then provide a conduit by which magma from the rising plume can erupt onto the surface.

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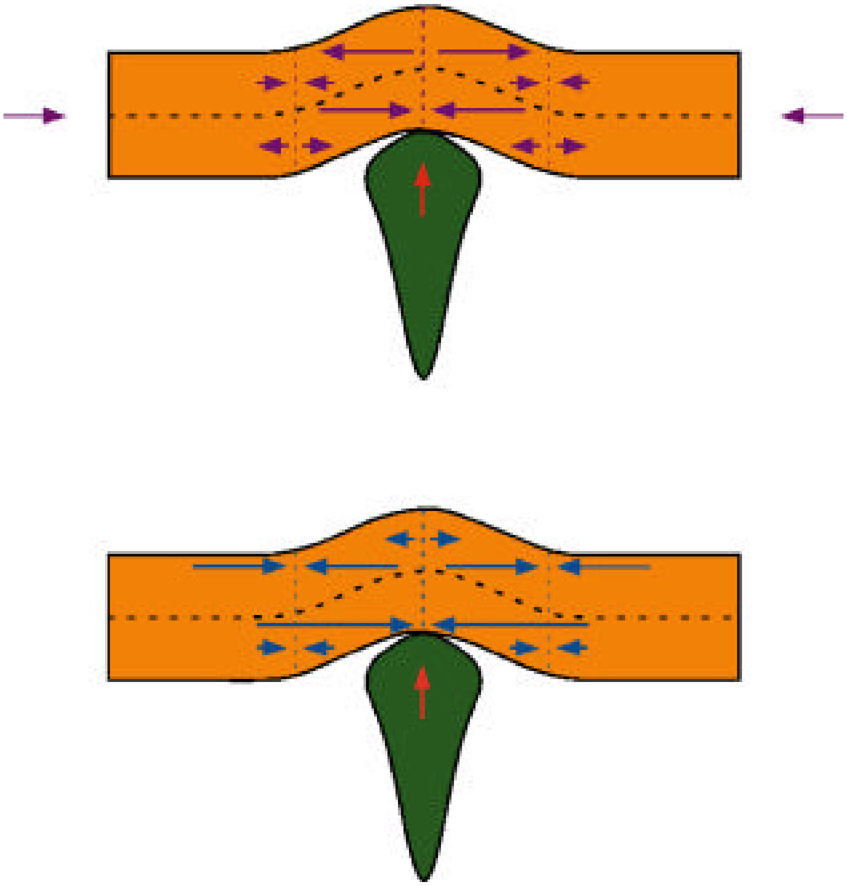

Figure: A schematic illustration of the stress field produced when a thermally buoyant plume (shown in dark green) impinges on the base of the Ionian lithosphere (orange). In the top figure the purple arrows drawn within the lithosphere represent the stresses due to the rising plume and those on either end of the lithospheric section represent the horizontal compression due to global subsidence. The blue arrows in the bottom figure show the combined stress field. In the absence of the compression due to subsidence, tensional fractures would first form in the upper lithosphere directly above the plume head. However, the horizontal compressional stress reduces the tension in the upper lithosphere making it more likely that thrusting will occur at the margins of the domical uplift.