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HOT-SPOT TECTONICS ON IO. Alfred S. McEwen, Department of Geology, Arizona State University, Tempe AZ 85287; U.S. Geological Survey, Flagstaff AZ 86001.

Introduction. The thesis of this paper is that extensional tectonics and low-angle detachment faults probably occur on Io in association with the hot spots. These processes may occur on a much shorter timescale on Io than on Earth, so that Io could be a natural laboratory for the study of thermotectonics. Furthermore, studies of heat and detachment in crustal extension on Earth and the other terrestrial planets (especially Venus and Mars) may provide analogs to processes on Io.

The geology of Io is dominated by volcanism and hot spots, most likely the result of tidal heating [1,2]. Hot spots cover 1-2% of Io's surface, radiating at temperatures typically from 200 to 400 K, and occasionally up to 700 K [3-7]. Heat loss from the largest hot spots on Io, such as Loki Patera [6], is about 300 times greater than the heat loss from the Hawaiian Swell [8] and 2000 times the heat loss from Yellowstone [9], so a tremendous quantity of energy is available for volcanic and tectonic work.

Active volcanism on Io results in a resurfacing rate as high as 10 cm per year [10], yet many structural features are apparent on the surface. Therefore, the tectonics must be highly active. Structural features on Io include calderas over 100 km wide and up to 2 km deep, grabens and scarps hundreds of kilometers long and up to 2 km high, and tectonically disrupted mountains up to 10 km high [11]. All of these structures appear to be local rather than global features, although tidal stresses may influence lineament directions [11]. Many of the structures may be related to broad isostatic uplift and rifting over thermal anomalies, due primarily to density changes in the lithosphere, as modeled by [12].

The surface of Io is covered by SO_2 and other sulfur-rich materials [2], but the tectonic features and topographic relief indicate that the lithosphere of Io, on the scale of kilometers, consists of some material with considerable strength, such as silicates [13]. Also, the bulk density of Io (3.55 g cm^{-3}) is consistent with a dominantly silicate composition. However, sulfur and SO_2 may be significant volatiles within the crust, and may influence fault movements. Sulfur and SO_2 should be liquids within the shallow subsurface (within a few kilometers depth, depending on the local thermal gradient). Several lines of evidence suggest that liquid sulfur is present at the surface or in the shallow subsurface near the hot spots [14]. Although SO_2 will vaporize near the hot spots, it may be present as a liquid in the shallow subsurface at some distance from the thermal anomalies, and many bright white, high UV-reflectivity deposits (consistent with SO_2 frost) are present along faults and lineaments on Io, so subsurface SO_2 may be common [15]. Liquid sulfur or SO_2 may provide high pore pressures to facilitate low-angle fault movements as does water on Earth [16].

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The total heat loss from Io is 6-10 x 10^{13} W [7,14], about twice that of Earth (4.2 x 10^{13} W [17]). However, Io is much smaller than Earth, so the mean global heat flow is 1.8 ± 0.5 W m^{-2} on Io compared to 0.08 W m^{-2} on Earth. If all of Io's heat flow was uniformly conducted to the surface, then the solid silicate lithosphere would be only about 5 km thick, overlying a molten interior [1,18]. However, most of the heat loss occurs through the hot spots [4], and the presence of mountains 5-10 km high suggests that the crust is (locally) at least 30 km thick [18,19]. These mountains, as well as ~90% of the hot-spot heat flow [14], and all of the very large volcanic plumes [20] are concentrated in one region of Io centered on 30° S, 310° W, covering about half of the surface; the opposite region of Io may have a much thinner crust [21].

Hot-Spot Tectonics. A number of thermotectonic models have been proposed to explain the late Cenozoic crustal extension of the Basin and Range [e.g. 22-26]. These models have a number of common elements, including high heat flow, associated magmatism, topographic uplift, and thin-skinned tectonics involving listric normal faults and low-angle detachment faults. The driving mechanisms are thermal, so similar tectonic styles might be found in association with the hot spots on Io.

According to the thermotectonic model of Lucchitta and Suneson [26], a detachment fault forms along a critical isotherm marking the brittle/ductile transition in hot spots with steep thermal gradients. This is an attractive model for Io because of the predominance of the hot spots and because the low equilibrium surface temperature of Io (~100 K) will contribute to steep thermal gradients. For movement to occur along a surface, the shear stress, τ, divided by the normal stress, σ, must exceed the internal friction of the material [27]. The ratio τ/σ along a surface (from x_1 to x_2) is given by:

$$\tau/\sigma = \int_{x_1}^{x_2} \frac{(\sigma_1-\sigma_3)2\sin\alpha\cos\alpha}{(\sigma_1+\sigma_3)+(\sigma_1-\sigma_3)(\cos^2\alpha-\sin^2\alpha)}\,dx$$

where σ_1 is the maximum principal stress, σ_3 is the minimum principal stress, and α is the slope of the fault. If a heat source at depth is modeled as a point and the surface is considered planar or parabolic, then the isotherms due to conduction will be parabolas (or paraboloids in 3-dimensions) [28]. Thus, if detachment occurs along a parabolic isotherm, $\sin\alpha$ and $\cos\alpha$ are:

$$\sin\alpha = 2x/a\ (1+4x^2/a^2)^{-1/2}$$

$$\cos\alpha = (1+4x^2/a^2)^{-1/2}$$

where a/4 is the distance from the isotherm to the heat source (Figure 1).

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A first-order model for the principal stresses considers the force of gravity:

$$\sigma_1=\rho g d$$

$$\sigma_3=\rho g(d-U)$$

where ρ = density, g = acceleration of gravity, d = depth to the isotherm, and U = topographic relief over the thermal anomaly. For reasonable values of internal friction for most silicate rocks (~0.5) and assuming a shallow depth to the heat source (a few kilometers), movement due to gravity may occur for a topographic relief greater than ~1 km (on both Earth and Io), provided that cohesive strength is overcome. Movement may occur from much smaller stresses if enhanced pore pressures are present. The first fracture in the upper plate will most likely occur over the apex of the parabola, due to the tensile stress created by the shearing stresses along the isotherm on each side of the apex (Figure 1). This may contribute to the occurance of rifting at the apex of domal uplifts.

Thermotectonic features on Io. The surface expression of hot-spot tectonics expected on Io, in the absence of significant erosion, includes elevated topography, normal faults, rotated blocks, detachment faults, and either an elevated heat flow or evidence for a formerly elevated heat flow (e.g. volcanic vents). Several features on Io show some or all of these characteristics. The best example is a rifted plateau just south of the vent to Pele (18° S, 256° W, where a plume eruption was active during the Voyager 1 encounter). The plateau is broken into four main segments which apparently have rotated and slid radially outwards. These segments fit together in a jigsaw-puzzle fashion, but have separated by ~30 km. The plains surrounding the plateau appear to be intact, suggesting that the segments moved along low-angle detachment faults. The vent region of Pele was detected as a hot spot by the Voyager 1 infrared spectrometer [6]. There are several other examples on Io of uplift and normal faulting associated with hot spots or volcanic vents (e.g. Ulgen Patera, 38° S, 286° W; Aten Patera, 48° S, 311° W; and a feature at 50° S, 35° W).

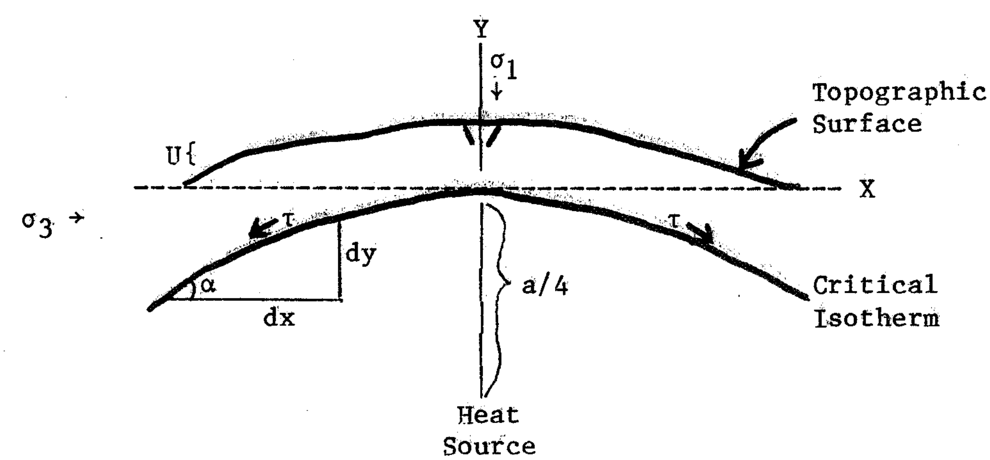

Figure 1. Stresses along a parabolic isotherm

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