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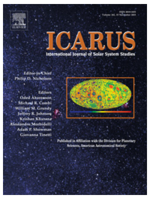

Magma ascent pathways associated with large mountains on Io

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ABSTRACT

While Jupiter's moon Io is the most volcanically active body in the Solar System, the largest mountains seen on Io are created by tectonic forces rather than volcanic construction. Pervasive compression, primarily brought about by subsidence induced by sustained volcanic resurfacing, creates the mountains, but at the same time inhibits magma ascent in vertical conduits (dikes). We superpose stress solutions for subsidence, along with thermal stress, (both from the "crustal conveyor belt" process of resurfacing) in Io's lithosphere with stresses from Io mountain-sized loads (in a shallow spherical shell solution) in order to evaluate magma ascent pathways. We use stress orientation (least compressive stress horizontal) and stress gradient (compression decreasing upwards) criteria to identify ascent pathways through the lithosphere. There are several configurations for which viable ascent paths transit nearly the entire lithosphere, arriving at the base of the mountain, where magma can be transported through thrust faults or perhaps thermally eroded flank sections. The latter is consistent with observations of some Io paterae in close contact with mountains.

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1. Introduction

Jupiter's moon Io is the most volcanically active planetary body in the Solar System, and the only one other than Earth known to be currently erupting silicate magmas (e.g., Lopes and Spencer, 2007; McEwen et al., 2004). Tidal heating of Io's interior, driven by Jupiter's gravitational field and the eccentricity of Io's orbit generates a magmatic flux sufficient to produce the observed hotspots and volcanic plumes and remove all observable trace of resolvable impact-related structures (e.g., Lopes and Spencer, 2007; McEwen et al., 2004), and perhaps even generate a global magma ocean (Khurana et al., 2011). Thermal observations of Io's hotspots yield very high temperatures consistent with mafic to ultramafic volcanism (e.g., Carr, 1986; Johnson et al., 1988; McEwen et al., 1998; McEwen et al., 2000; Williams et al., 2000). While these indications of volcanic vigor might conjure visions of a planet studded with grand basaltic edifices like the Tharsis Montes of Mars, in fact most of Io's volcanic sources are associated with very low-relief paterae or shield structures; only a handful of conical volcanic edifices (of relatively modest width) have been detected (e.g., Schenk et al., 2001; Jaeger et al., 2003; Turtle et al., 2007).

Io does indeed have mountains (topographic features with relief greater than a kilometer or two), as unveiled by the close encounters of the *Voyager* and *Galileo* missions. However, most of them have a characteristic tilted-block morphology that is suggestive of a tectonic (compressional) origin (e.g., Schenk and Bulmer, 1998; Carr et al., 1998; Schenk et al., 2001; Turtle et al., 2001; McEwen et al., 2004). To explain the observed structure of Io's mountains in the context of a body with high resurfacing rate, Schenk and Bulmer (1998) proposed that burial-induced subsidence would over time produce a compressive stress state due to the reduction in volume with depth inside a spherical shell. Thus, Io's lithosphere may be essentially a resurfacing "conveyor belt", generating compression at depth.

We perceive a strong sense of contradiction in these characterizations of Io's behavior. The idea of a compression-dominated lithosphere allowing vigorous ascent of magma through it confounds traditional notions of intrusive ascent pathways (e.g., Anderson, 1951): compression favors trapping of magmas in sub-horizontal sills rather than ascent in vertical dikes. Looked at from the perspective of mountain building, this contradiction can be turned on its head: on the most volcanic planetary body of all, the most prominent mountains are produced tectonically and not as volcanically constructed edifices. And yet Io churns along, indifferent to our struggles to understand its enigmatic history.

Here we explore the paradox of copious volcanism on a compression-dominated planet via quantitative modeling of the evolution of stresses in and deformation of Io's lithosphere from two sources: mountain loading and crustal recycling. Model

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inputs for mountain stress calculations are informed by Digital Terrain Models (DTMs) produced via stereogrammetry techniques. The model results constrain scenarios for mountain building and associated volcanic features on Io, while also yielding estimates of the thickness of the crust/lithosphere that are most consistent with the proposed crustal resurfacing/recycling scheme.

2. Measuring heights of mountains on Io

Our knowledge of Io's mountains comes from spacecraft imagery (*Voyager* and *Galileo*). Mountains on Io tend to be spatially isolated and are not part of broad-scale mountain belts as seen on Earth and Venus. Morphology of mountains can range from relatively flat, low plateaus and mesas to asymmetric ridges similar to flatirons on Earth to tall peaks. Their heights can be as low as 1–2 km (the lower limit for the classification) to ~18 km for Boösaule Montes, with an average height of ~6 km for all identified mountains. Their widths and lengths can range from ~13 km to ~570 km, with averages of ~80 and 160 km, respectively. When combined, these dimensions indicate that about 3% of Io's surface is covered by mountains (Schenk et al., 2001; McEwen et al., 2004). The mountains have been shown to be anticorrelated at low harmonic degree on a planetary scale with the volcanic sources (Kirchoff et al., 2011; Schenk et al., 2001; McKinnon et al., 2001; Hamilton et al., 2013), although at smaller scales, a fraction (~40%) of Io mountains have paterae on their margins (Turtle et al., 2001; Jaeger et al., 2003).

Our primary tools to characterize mountain shapes and morphology in detail are regional and high-resolution stereo image pairs. We use digital stereogrammetry to produce 3-dimensional topographic maps, or Digital Terrain Models (DTMs) of the surface (e.g., Schenk et al., 2004; Schenk and Bulmer, 1998; White et al., 2014). DTM generation involves refinement of stereo mapping parameters, including scene matching spot size, best-fit equation order, and other parameters designed to optimize the stereo matching procedure. This process is complex on Io due to ongoing volcanism, non-uniform photometric function and the necessity of sometimes using different filter images in a given stereo pair, all of which can potentially change surface feature appearance between exposures. In addition, Io stereo DTMs typically include a significant amount of noisy patches due to the lack of surface contrast, which most commonly exist in the featureless plains interstitial to volcanic centers and mountain ranges. Sunlit portions of mountain ranges themselves are typically less affected by noise as they possess high albedo contrast and strong parallax due to their high relief; shadowed portions of mountain ranges in either image of the stereo pair, however, will create noise in the resulting DTM. Areas of noise will be removed using our noise removal criteria, including height error, pixel shift, correlation coefficient and standard threshold noise filters; if necessary, noise can also be removed manually. The maximum lateral resolution attained by a stereo DTM is governed by the lowest resolution image in the original stereo pair – lateral resolutions of our DTMs typically achieve several hundred meters to more than a kilometer per pixel. The vertical precision of stereo DTMs is a function of the lateral resolution and viewing angles of the separate images in each stereo pair – vertical precisions of our DTMs typically achieve a few hundred to several hundred meters. Finally, our stereo DTMs are controlled using Galileo limb profiles in order that they fit the triaxial ellipsoid of Io as defined by the limb profiles (Thomas et al., 1998). The reader is directed to White et al. (2014) for further details of the stereo and controlling processes.

Boösaule Mons (Fig. 1) is the tallest known mountain on Io, reaching about 18 km above the Io datum. The maximum relief on the topographic profiles in Fig. 1b is more than 20 km. The lateral extent of this mountain is 160–180 km. The summit is not located at the center of the elevated region but rather is displaced toward the south. Thus, the southern flank is the steepest flank, and it is cut by a topographic discontinuity that may be a flank failure. Tohil Mons (Fig. 2) has a peak elevation of about 10 km above the datum and 11 km maximum relief, with a lateral extent of more than 300 km. The highest elevations form an arcuate ridge surrounding a central depression. A sector of low plains (−1 to −2 km elevation) is embedded in the northeast sector of the edifice, and this sector includes a dark patera (Radegast Patera). Euboea Mons (Fig. 3) has a peak elevation of more than 9 km above the datum and more than 11 km maximum relief. The main edifice is about 275 km in lateral extent, although there are several adjacent mountains to the northwest and northeast. There are also two volcanic shields with central calderas and radiating flows to the northeast of Euboea Mons: at least one of them has positive relief (see profile A–B between 300 and 400 km distance in Fig. 3b). A dark patera (Creidne Patera) lies adjacent to the northwest flank of Euboea Mons. Other mountains on Io also have low-lying paterae in close proximity: examples are listed in Table 1.

Table 1
Locations of mountains and associated paterae on Io, with distances between them.

Mountain	Patera	Distance (km)*
Danube Planum 22.6°S, 258.1°W	Pele 18.7°S, 255.3°W	147
Euboea Montes 48.0°S, 335.8°W	Creidne Patera 53.3°S, 342.6°W	219
Euxine Mons 26.3°N, 126.4°W	*Unnamed patera* 23.8°N, 125.7°W	86
Gish Bar Mons 18.5°N, 89.0°W	Gish Bar Patera 16.2°N, 90.3°W	84
	Estan Patera 21.5°N, 87.6°W	104
Hi'iaka Montes 4.7°S, 82.0°W	Hi'iaka Patera 3.6°S, 79.5°W	87
Monan Mons 15.5°N, 104.2°W	Monan Patera 19.8°N, 104.8°W	138
	Ah Peku Patera 10.4°N, 107.0°W	186
Nemea Planum 72.3°S, 265.8°W	*Unnamed patera* 63.7°N, 244.3°W	396
Ot Mons 4.3°N, 215.7°W	Ot Patera 1.1°S, 217.4°W	180
Rata Mons 36.4°S, 201.3°W	Rata Patera 35.6°S, 199.7°W	49
Tohil Mons 28.4°S, 161.6°W	Tohil Patera 26.3°S, 158.1°W	121
	Radegast Patera 27.8°S, 160.0°W	49
Tvashtar Mensae 61.6°N, 120.0°W	Tvashtar Paterae 62.8°N, 123.5°W	64
Zal Montes 38.4°N, 77.2°W	Zal Patera 40.1°N, 47.5°W	85
Unnamed mons 1.6°N, 341.3°W	Nyambe Patera 0.3°N, 343.2°W	72
Unnamed mons 38.8°S, 285.0°W	Ülgen Patera 40.7°S, 287.2°W	82
Unnamed mons 46.0°N, 126.1°W	Savitr Patera 48.5°N, 123.2°W	103
Unnamed mons 1.0°S, 317.3°W	Carancho Patera 1.5°N, 317.3°W	81
	Tol-Ava Patera 1.8°N, 322.0°W	175

* Between center coordinates given for each feature.

3. Magma ascent criteria

Our best attempts to understand the crustal/lithospheric dynamics of a planetary body like Io lead to an apparent paradox: pervasive extrusive volcanism at the surface produces a vertical subsidence "conveyor belt" that via mechanical and pos-

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