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Spatial distribution of volcanoes on Io: Implications for tidal heating and magma ascent

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ABSTRACT

Extreme volcanism on Io results from tidal heating, but its tidal dissipation mechanisms and magma ascent processes are poorly constrained. Here we analyze the distribution of volcanic hotspots and paterae identified within the first 1:15,000,000-scale global geologic map of Io to characterize their patterns of spatial organization. Ionian hotspots correspond to the locations of positive thermal anomalies that have been detected since 1979, whereas paterae are caldera-like volcano-tectonic depressions that record locations of volcanic activity over a longer period of geologic time (up to ~1 million years). Some (~20%) of patera floor units are associated with active hotspots, but the majority appeared to be extinct or dormant at the time of observation. Volcano distributions are useful for testing interior models of Io because the relative strength of tidal heating in the asthenosphere and deep-mantle greatly affect expected patterns of surface heat flux. We examine the spatial distribution of volcanic centers using nearest neighbor (NN) statistics and distance-based clustering. Nearest neighbor analysis reveals that hotspots (i.e., sites of active volcanism) are globally random, but closer to the equator, they are uniform (i.e., more widely spaced than a random model would predict). This suggests that magma scavenging around active volcanic systems in the near-equatorial region may drive hotspots apart, whereas vigorous mantle convection and/or deep-mantle heating may reduce surface heat flux variations and promote spatial randomness on a global scale. In contrast to the hotspots, NN patera floor units tend to be clustered, which implies that multiple eruptive units tend to form in association with most volcanic systems. Generalized paterae, which represent volcanic systems, tend to be uniformly distributed, except in the northern regions, where their distribution is random. This implies that most volcanic systems interact with one another and repel, except at high northern latitudes, where they appear to form independently. Distance-based clustering results support a dominant role for asthenospheric heating within Io, but show a 30–60° eastward offset in volcano concentrations from predicted locations of maximum surface heat flux along the tidal axis. This offset may imply faster than synchronous rotation, a role for lateral advection of magma within Io's interior prior to its eruption, state of stress controls on the locations of magma ascent, and/or a missing component in existing tidal dissipation models, such as the effects of fluid tides generated within a globally extensive layer of interconnected partial melt.

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1. Introduction

Io, the innermost of Jupiter's Galilean satellites, is the most volcanically active body in the Solar System (McEwen et al., 1998, 2000a, 2000b; Lopes-Gautier et al., 1999; Spencer et al., 2000). Io's global mean heat flow is not precisely known, but estimates generally range from 1.5 to 4.0 W m^{-2} (Moore et al., 2007), with the most recent astrometric observations supporting a value of 2.24 ± 0.45 W m^{-2} (Lainey et al., 2009). This mean surface heat flux is ~20 times larger than the Earth's (Turcotte and Schubert, 2002), but unlike the Earth, Io's internal heat comes primarily from the dissipation of tidal energy and not from radiogenic sources (Peale et al., 1979; Moore et al., 2007). Io's Laplace resonance with Europa

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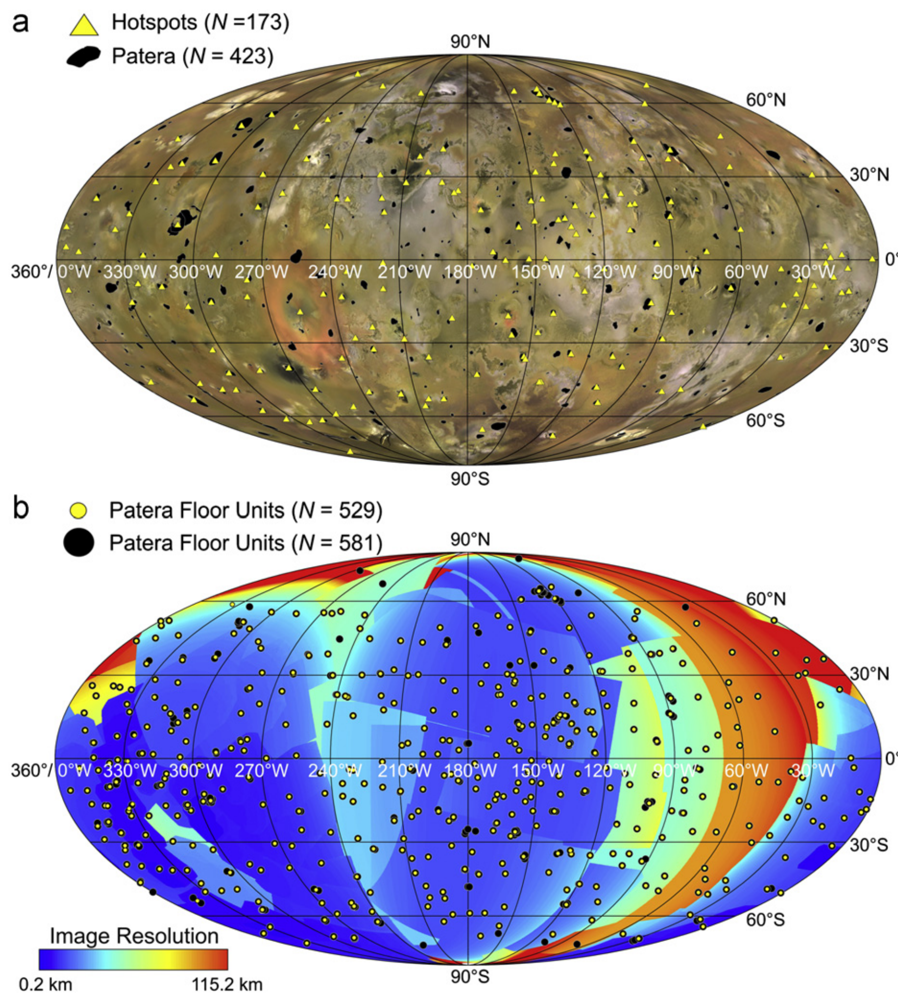

Fig. 1. Mollweide projections of the global distribution of volcanoes on Io. (a) Hotspots ($N=173$) and caldera-like paterae ($N=423$) overlaid on a *Galileo-Voyager* image mosaics reprocessed to a spatial resolution of 1 km/pixel (Becker and Geissler, 2005). (b) Centroids of patera floor units from Williams et al. (2011a) $N=529$, and Williams et al. (2011b) $N=581$, overlaid on a map showing the variability of the best imagery used to make the *Galileo-Voyager* basemap. The color bar has a linear stretch between 0 and 116 km, with a range of resolutions spanning from 0.2 km to 115.2 km. In this study, all coordinates are west positive, measured from a prime meridian crossing through the subjovian point of Io.

and Ganymede maintains all three satellites in noncircular orbits, which results in continuous deformation and frictional heating of the satellite's interior (e.g., Peale et al., 1979; Ross and Schubert, 1985; Ross et al., 1990; Schubert et al., 1986; Segatz et al., 1988; Tackley, 2001; Tackley et al., 2001; Moore et al., 2007). Heat produced within Io's interior is predominantly advected to the surface by ascending silicate magma and not conducted through its lithosphere (McEwen et al., 2004). The heat-pipe mechanism proposed for transporting Io's internal thermal energy to the surface (O'Reilly and Davies, 1981) involves bringing magma upward through "hotspots" that are embedded within a relatively cold lithosphere. Analysis of Io's global distribution of volcanoes (Fig. 1) can therefore provide information about the moon's internal structure, thermo-rheological properties, tidal dissipation mechanisms, processes of melt generation, and magma transport. Better understanding these processes for Io also provides insight into similar tidal heating mechanisms operating on other worlds, such as Europa and Enceladus, as well as tidally-heated exoplanets.

2. Io's internal structure and its relation to tidal dissipation models

The *Galileo* mission revealed that Io is a differentiated body consisting of a metallic iron core, with a radius of 650–950 km, surrounded by a silicate mantle (Moore et al., 2007). The thickness and composition of the crust are unknown, but must contribute to a strong lithosphere that is capable of supporting the elastic stresses that are associated with mountains up to $\sim$18 km in height (Schenk et al., 2001; Jaeger et al., 2003). The structure and temperature distribution within the mantle are debated, but Keszthelyi et al. (2007) suggest a potential temperature between 1523 and 1723 K, with a preferred value of $\sim$1573 K. They also claim that the top of the mantle is likely partially molten, with 20–30 vol% rock melt. The presence of a global layer with $\geq$20% interconnected partial melt and $>$50 km thickness (i.e., the proposed asthenosphere) is consistent with *Galileo* magnetometer data of Io's induced magnetic field (Khurana et al., 2011).

In end-member tidal dissipation models, the bulk of Io's heating occurs either within the deep-mantle or within the asthenosphere (Ross and Schubert, 1985; Schubert et al., 1986; Segatz et al., 1988; Tackley et al., 2001), while in mixed models heating is partitioned between these end-members (Ross et al., 1990; Tackley et al., 2001). Computations of heat production usually assume a spherically symmetric interior (for a 3D approach see Běhounková et al., 2010) having a linear viscoelastic rheology of the Maxwell type. In the simplest approximation, heat is transferred radially to the surface by an unspecified mechanism, but in more realistic models, heat is transported either by

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