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

Christopher Hamilton1, Ciarán Beggan2, Susanne Still3, Mikael Beuthe4, Rosaly Lopes5, David Williams6, Jani Radebaugh7, and William Wright3

1Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA, 2British Geological Survey, Edinburgh, UK, 3 Information and Computer Sciences, University of Hawai‘i at Mānoa, Honolulu, USA, 4Royal Observatory of Belgium, Brussels, Belgium, 5 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA, 6 School of Earth and Space Exploration, Arizona State University, Tempe, USA, 7 Geological Sciences, Brigham Young University, Provo, USA.
Global Distribution of Volcanoes on Io

Hypothesis:
The spatial distribution of volcanic centers on the surface of Io can be used to test tidal dissipation models and infer internal structures and processes.
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Approach:
We use nearest neighbor analysis and distance-based clustering to characterize the distribution of volcanic centers (i.e., hotspots and paterae) and compare the
Io is the most volcanically active body in the Solar System.
Paterae are volcano-tectonic depressions that may be analogous to terrestrial calderas.
Global Distribution of Volcanoes on Io

Paterae:
Paterae record of the locations of volcanism over the timescale of Io’s resurfacing (~ 1 million years)

Williams et al. (2011) subdivided paterae into bright, dark, and undivided paterae floor units

Here we focus on the distribution of paterae floor units under the assumption
Global distribution of volcanoes on Io

Hotspots:
Hotspots are positive thermal anomalies. They provide a sample of the locations of active volcanism integrated over the past ~30 years.

A subset of the paterae floor units include hotspots and are thus active, but most paterae are inactive.
Global distribution of volcanoes on Io

Paterae floor units \((N = 529)\) 90°S
Global distribution of volcanoes on Io

- **Paterae floor units** ($N = 529$)
- **Hotspots** ($N = 173$)
Global distribution of volcanoes on Io

- Paterae floor units ($N = 529$)
- Hotspots ($N = 173$)
Tidal Dissipation

- Jupiter
- Tidal Bulge
- Io
- 0°, 90°, 180°, 270°
Tidal Dissipation

- Jupiter
- Io
- Europa

Tidal Bulge
Tidal Dissipation

- Asthenosphere
- Crust
- Deep-mantle
- Core

- 1821 km
- 675–950 km
- 50–100 km
- ~680 km
- / ~100 km
- / 50–100 km
- ~680 km
- 675–950 km
Tidal Dissipation

Deep-mantle heating end-member

Asbestospheric heating end-member

Tackley et al. (2001)
Tidal Dissipation

Deep-mantle heating end-member

Asthenospheric heating end-member
Surface heat flux patterns computed based on Segatz et al. (1988) and Tobie et al. (2005).

Assumes (1) a spherically symmetric incompressible body, (2) Maxwell rheology, and (3) radial heat flow to the surface.
Surface heat flux patterns computed based on Segatz et al. (1988) and Tobie et al. (2005).

Assumes (1) a spherically symmetric incompressible body, (2) Maxwell rheology, and (3) radial heat flow to the surface.

Shear modulus $\mu$ and viscosity $\eta$ adjusted to generate correct total power (Spohn, 1997).

In the deep-mantle end-member heating model $\mu = 3.5 \times 10^9$ Pa and $\eta = 10^{15}$ Pa · s.

In the asthenospheric end-member model $\mu = 4 \times 10^4$ Pa and $\eta = 10^{10}$ Pa · s, assuming a 50 km thick asthenosphere.
Tidal Dissipation

Deep-mantle heating end-member

1/3 Deep-mantle 2/3 asthenospheric heating

Asthenospheric heating end-member
Tidal Dissipation

Deep-mantle heating end-member

1/3 Deep-mantle 2/3 asthenospheric heating

Minimum surface heat flux variation (61% deep-mantle 39% asthenospheric heating)
Deep-mantle heating end-member

As the nospheric heating end-member

Geospatial Analysis: Longitudinal Variation
Geospatial Analysis: Latitudinal Variation

Deep-mantle heating end-member

Asthenospheric heating end-member
Geospatial Analysis: Latitudinal Variation

Minimum surface heat flux variation
(61% deep-mantle 39% asthenospheric heating)

1/3 Deep-mantle 2/3 asthenospheric heating
Globally Variable Image Resolution

(a) Hotspots (N = 173)
   Paterae (N = 423)

(b) Patera Floor Units (N = 529)
    Patera Floor Units (N = 581)

Image Resolution

0 km to 116 km
Resolution bias may affect the observed frequency distributions of hotspots and paterae at high latitudes and near $30^\circ-60^\circ$ but otherwise are not expected to affect the statistical significance of our results.
Geospatial Analysis: Nearest Neighbor Analysis

Clustered

Poisson (Random)

Uniform
Geospatial Analysis: Nearest Neighbor Analysis

\[ R = \frac{R_a}{R_e} \]

- **Ra** (MEASURED): average actual distance between nearest neighbors
- **Re** (PREDICTED): average expected distance between nearest neighbors drawn from a Poisson (random) distribution

3 Scenarios:
- If \( R < 1 \) then null hypothesis rejected (clustered)
- If \( R = 1 \) then null hypothesis cannot be rejected
- If \( R > 1 \) then null hypothesis rejected (repelled)
Geospatial Analysis: Nearest Neighbor Analysis

\[ c = \frac{R_a - R_e}{\sigma_{Re}} \]

- **c**: test statistic for measuring the departure from randomness
- **\( \sigma \) (PREDICTED)**: standard deviation of the mean nearest neighbor distance in a Poisson distribution

If \(|c| > 1.96\) then the spatial distribution is not random at the 0.05 significance level.
Geospatial Analysis: Nearest Neighbor Analysis

Bias in $R$

Bias in $c$

Standard Deviation in $R$

Standard Deviation in $c$
Geospatial Analysis: Nearest Neighbor Analysis

Full Sphere

- Increasingly Uniform Relative to Poisson
- Increasingly Clustered Relative to Poisson

Parameters:
- Hotspots
- Paterae
- Global

Thresholds:
- $+2\sigma$ Threshold
- $+1\sigma$ Threshold
- Ideal Value for Poisson
- $-1\sigma$ Threshold
- $-2\sigma$ Threshold

Variables:
- $R$
- $N$
- $C$

Graphs show the relationship between $N$ and $R$, $N$ and $C$, illustrating the distribution of events relative to the Poisson distribution.
Geospatial Analysis: Nearest Neighbor Analysis

Full Sphere

Half Sphere

- Hotspots
- Paterae
  - Global
  - +2σ Threshold
  - +1σ Threshold
  - Ideal Value for Poisson
  - -1σ Threshold
  - -2σ Threshold

- Increasingly Uniform Relative to Poisson
- Increasingly Clumped Relative to Poisson
- Increasingly Significant Departure from Poisson

$R$ vs $N$

$C$ vs $N$
Geospatial Analysis: Nearest Neighbor Analysis

Full Sphere

Hotspots Paterae
- Global
- +2σ Threshold
- +1σ Threshold
- Ideal Value for Poisson
- -1σ Threshold
- -2σ Threshold

Increasingly Uniform Relative to Poisson

Increasingly Clustered Relative to Poisson

Half Sphere

Hotspots Paterae
- Northern
- Southern
- Subjovian
- Antijovian
- Leading
- Trailing

Third Sphere

Hotspots Paterae
- North Polar
- Equatorial
- South Polar

Increasingly Significant Departure from Poisson

Increasingly Significant Departure from Poisson
Geospatial Analysis: Nearest Neighbor Analysis

<table>
<thead>
<tr>
<th>Latitude Band (degrees)</th>
<th>Hotspots</th>
<th>Paterae</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 to 60</td>
<td>Random</td>
<td>Clusters</td>
<td>Tidal dissipation in the deep mantle generates partial melt that accumulates into magma diapirs. The rise independently of one another to produce random distributions of hotspots at the surface. These large mantle plumes also tend form larger paterae than within the near-equatorial region because the polar volcanic systems are not forced to compete for magma.</td>
</tr>
<tr>
<td>60 to 30</td>
<td>Random</td>
<td>Clusters</td>
<td>Tidal heating occurs mainly in the asthenosphere, producing the highest heat flux and largest number of volcanoes near the equator. Nascent magma diapirs in the asthenosphere have a smaller volume from which to scavenge melt, which causes self-organization into a uniform arrangement. Over the time, numerous upwellings generate a random paterae distribution.</td>
</tr>
<tr>
<td>30 to 0</td>
<td>Uniform</td>
<td>Random</td>
<td>Over the lifespan of the randomly distributed active mantle plumes, magma pathways branch out in the lithosphere, thereby starving some volcanic systems and forming paterae by collapse into the partially evacuated shallow magma chambers. New hotspots fed by the same mantle plumes at greater depth generate clustered paterae as new hotspots form near old ones.</td>
</tr>
<tr>
<td>0 to -30</td>
<td></td>
<td></td>
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<tr>
<td>-30 to -60</td>
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<tr>
<td>-60 to -90</td>
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</tbody>
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<tr>
<th>Mean Paterae Area (km²)</th>
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<tbody>
<tr>
<td>1000</td>
</tr>
<tr>
<td>1500</td>
</tr>
<tr>
<td>2000</td>
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<tr>
<td>2500</td>
</tr>
<tr>
<td>3000</td>
</tr>
<tr>
<td>3500</td>
</tr>
</tbody>
</table>
Summary of Implications

Hotspots are globally random, but uniform near the equator—implying resource competition at low latitudes.

Paterae floor units are globally clustered, but random near the equator—implying overprinting at low latitudes.

Competition for magma between near-equatorial volcanic systems may limit the size of associated units.

Volcano distributions generally support asthenosphere-dominated tidal heating models.
Kirchof et al. (2011) show statistically significant clustering of volcanoes (>2σ levels) at degrees 2 and 6.

We use a distance-based clustering technique optimized using a deterministic annealing algorithm to find the locations of 2 and 6 cluster centers.
Distance-based Clustering ($k = 2$)

Deep-mantle heating end-member

Asthenospheric heating end-member
Distance-based Clustering ($k = 6$)

Deep-mantle heating end-member

Asthenospheric heating end-member
Summary of Implications

Cluster center locations are generally consistent with heat flux patterns predicted by asthenospheric-dominated models. However, there is a 30–60° eastward offset between volcano cluster centers and sites of expected maximum surface heat flux. This offset may be explained by: (1) faster than synchronous rotation, (2) structural controls on locations of magma ascent, and (3) differences in maximum heating.
Summary of Implications
Summary of Implications: Scenario 1

Sites of magmatic upwelling occur preferentially along the tidal axis and correspond to sites of maximum heat production predicted by a the nospheric-dominated solid body tidal heating models.
Summary of Implications: Scenario 1

Faster than synchronous rotation displaces older concentrations of volcanos to the east.

This does not explain the concentration of currently active...
Summary of Implications: Scenario 2

Magma is preferentially generated along the tidal axis and migrates eastward in a subsurface layer.
Summary of Implications: Scenario 2

Magma reaches the surface at locations with a state of stress favoring ascent.

Cluster centers agree with locations of maximum tensile stress caused by orbital flexure, but the magnitudes are too small to be significant.
Galileo magnetometer data provides evidence of a global subsurface magma layer >50 km-thick and with a rock melt fraction ≥20% (Khurana et al., 2011).
Summary of Implications: Scenario 3

If there is a global “magma ocean” on Io then the fluid tidal response may affect the locations of maximum heat production and the moon’s state of stress, thereby explaining the Eastward offset of volcanic clusters.
Preliminary results by Taylor et al. (in prep.) suggest that including a fluid tidal response in Io’s thermal budget provides a better correlation between predicted surface heat flux and...
Conclusions

Geospatial analyses support asthenospheric-dominated tidal heating models.

However, there is an eastward offset between volcano cluster centers and predicted heat flux maxima.

The offset may be explained by lateral advection of magma at depth prior to magma ascent.