Lineations and structural mapping of Io's paterae and mountains: Implications for internal stresses

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Abstract

Io is the most volcanically active and tidally influenced body in the solar system. Its paterae and mountains are among its most distinguishing features. Paterae, similar to calderas, are volcano-tectonic collapse features, often with active lava flows on their floors. Io's mountains are some of the highest in the solar system and contain many linear features that reveal global and regional stresses. This study investigates the relationship of linear features associated with paterae and mountains to stress fields associated with proposed mechanisms of formation: tidal forces, crustal loading, and local tectonics.

1. Introduction

Io, the innermost of the Galilean satellites, experiences great amounts of tidal stress as it orbits between Jupiter and the other Galilean moons Europa, Ganymede, and Callisto. This has enabled accumulation of vast stores of internal heat (Peale et al., 1979) and has made Io the most volcanically active object in the solar system (Davies, 2001), evidenced by abundant lava flows and lava fountains (Radebaugh et al., 2001). Io also contains some of the largest mountains in the solar system, supported by a silicate-rich crust interlayered with sulfurous frosts (Schenk et al., 2001). Chalcophile elements and mafic lavas give Io its distinctive red, black, and yellow colors (Kargel et al., 1999).

Despite the variety of surface features on Io, it is still unclear whether tectonics on Io are dominated by regional or global scale processes. Paterae and mountains are widely distributed and among Io's most important volcanic and tectonic features. As such, they can provide valuable insight into the volcanic and tectonic processes operating on Io.

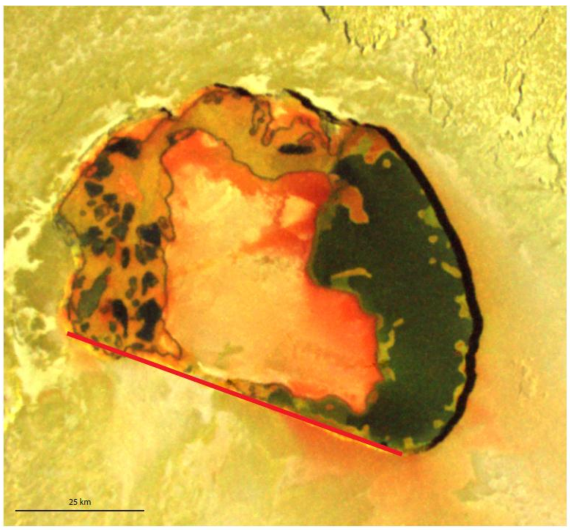

Figure 1: Tupan Patera, an example of a patera with a straight margin that was marked in this study. Image centered at 18° S, 141° W. Patera edge lineation is marked by the red line. Image from NASA *Galileo*.

2. Paterae and Mountains

Paterae have been defined as volcano-tectonic depressions with steep walls and flat floors. They may form from a variety of possible processes linked to volcanism and tectonism, similar to calderas on Earth (Radebaugh et al., 2001). One model for patera formation involves collapse due to the sublimation of abundant, sulfur-rich frosts in the crust heated from the interior (Keszthelyi et al., 2004). Paterae are not always round or sub-round. Instead, many have straight portions to their margins that are adjacent to mountains or may be associated with faults (Figures 1 & 2). This suggests some kind of tectonic component involved in their formation and evolution. In total, about 450 paterae have been identified (Barth and Radebaugh, 2010). Average patera diameter (diameter of a circle having the same area as patera) is 41 km (Radebaugh et al., 2001). The majority of paterae have floors partially or completely covered by lava flows that are thought to be active (McEwen et al., 1985).

Mountains are isolated, uplifted, tilted blocks that seem to be associated with fractures and faults and also contain lineations (Figure 2). Many appear to be heavily influenced by mass wasting. The average length of the 115 mountains on Io is 157 km and the mean height is 6.3 km, with the highest peak, Boösaule Montes, rising 17.5± 3 km above the surface (Schenk et al., 2001). A possible formation mechanism for these high mountains includes deep thrust faulting and rotation of blocks due to compression from loading of the crust by erupted material (Schenk and Bulmer, 1998). However, tidal forces have not been ruled out as an explanation for shortening in the crust. Local convective upwelling, driven by global tidal heating, seems to factor into the formation of chaos terrains on Europa, just as it may create topographic and volcanic features on Io. (McKinnon et al., 2000).

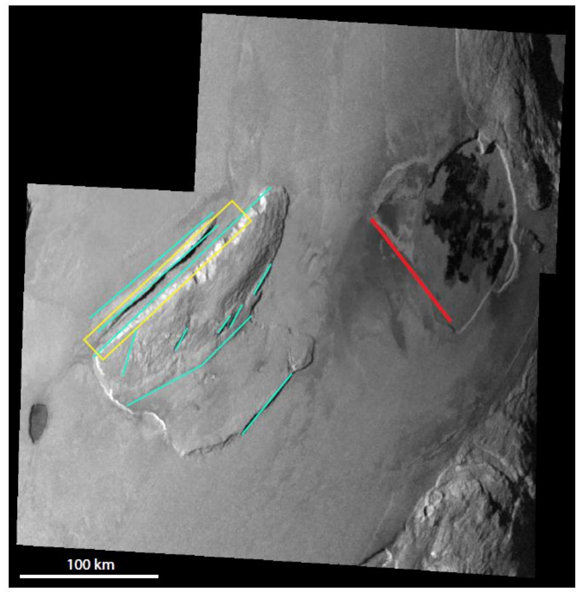

Figure 2: Shamshu Mons, an example of a mountain with structural lineations marked in this study. Image centered at 9.5˚ S, 68.2˚ W. Structural lineations are marked by turquoise lines and the patera edge lineation is marked by the red line. The yellow box marks what has been identified in this study as a graben from localized extension resulting from thrusting and uplift of Shamshu Mons. Image from NASA *Galileo*.

3. Methods

All lineations considered in this study were traced in ArcGIS using the Io Global Color Mosaic, North Pole Mosaic, and South Pole Mosaics as basemaps under the Io 2000 Geographic Coordinate System and North and South Pole projections. This adds upon work done on the Io ArcGIS Project set up by Williams et al. (2012) and a lineation study by Radebaugh et al. (2011). The mosaic basemap images come from the stitching of Voyager I and Galileo images. Resolution ranges from 1.3-21

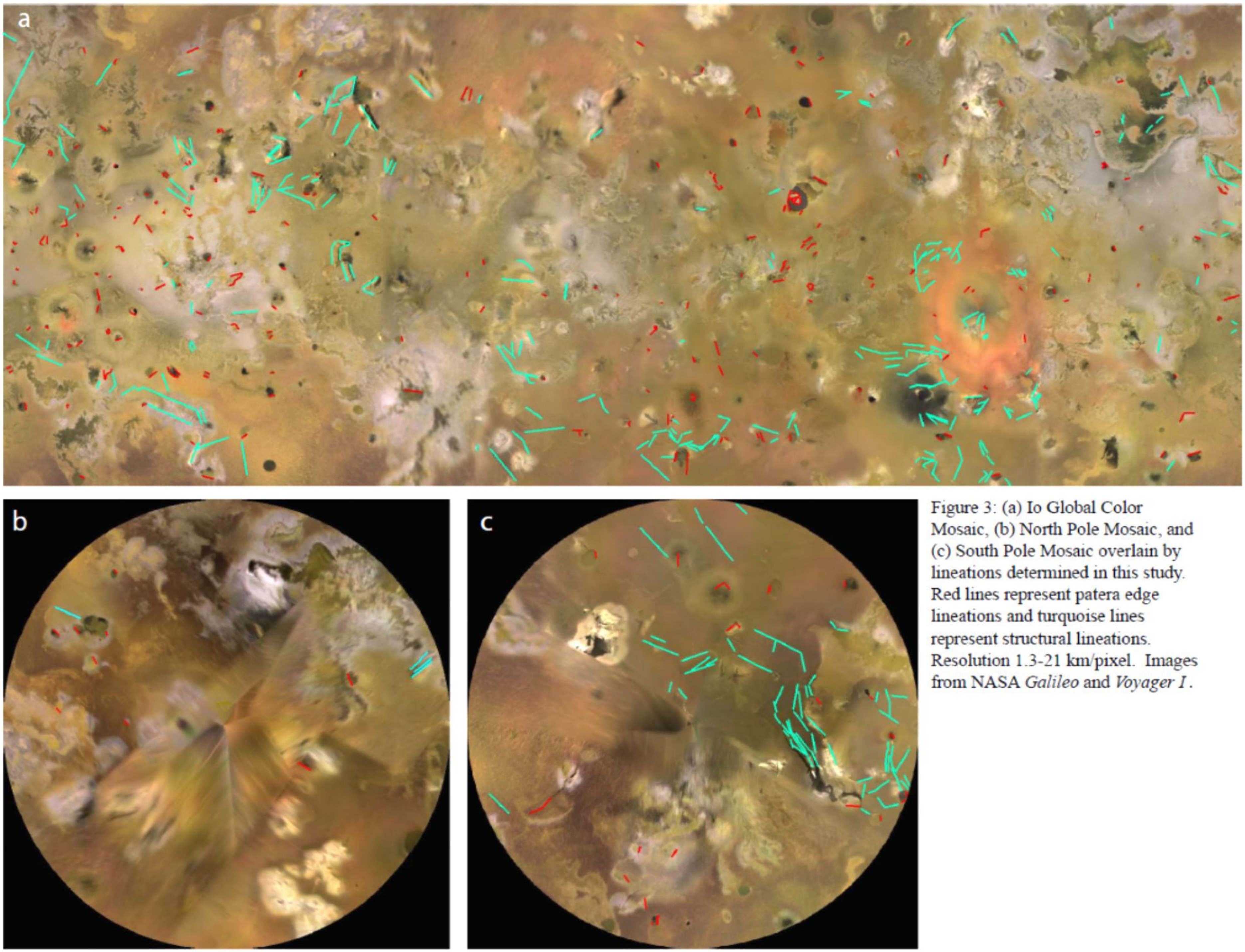

Figure 3: (a) Io Global Color Mosaic, (b) North Pole Mosaic, and (c) South Pole Mosaic overlain by lineations determined in this study. Red lines represent patera edge lineations and turquoise lines represent structural lineations. Resolution 1.3-21 km/pixel. Images from NASA *Galileo* and *Voyager I*.

km/pixel. There is no coverage within 5 degrees of the north and south poles.

Lineations were first divided into 2 categories: patera edge lineations and structural lineations, only (Figure 3). Structural lineations include possible faults or fractures, but exclude those related to mass wasting.

In total, there were 306 patera edge lineations and 345 structural lineations. 47% of paterae have at least one lineation associated with them and 10% have at least two lineations associated with them. Most mountains contain at least one lineation, but most contain several.

In order to distinguish between global and regional stress fields, structural lineations were then later divided into 6 categories: large-scale thrust faults possibly associated with a global stress field, thrust faults or folds associated with local stresses, large-scale normal faults possibly associated with a global stress field, normal faults associated with local extension, en echelon normal faults/strike-slip faults, and mass wasting scars. Some higher resolution images from Voyager I and Galileo were imported into the Io ArcGIS Project to facilitate separation of structural lineations into these categories. Additionally, detailed structural maps are currently being produced from these higher resolution images. The addition of mass-wasting lineations became appropriate given that mass wasting seems to be a frequent player in shaping Io's topographic features.

The azimuths of all lineations are being calculated in ArcGIS using the COGO Toolbox. Preliminary results are shown in Figure 4. These will be analyzed separately by azimuth and spatial distribution to determine the relative influences of global versus local stress fields throughout the surface, but especially so in areas of higher-resolution. We will compare them to current models for tidal stresses (Bart et al., 2004) and expected stress directions for crustal loading.

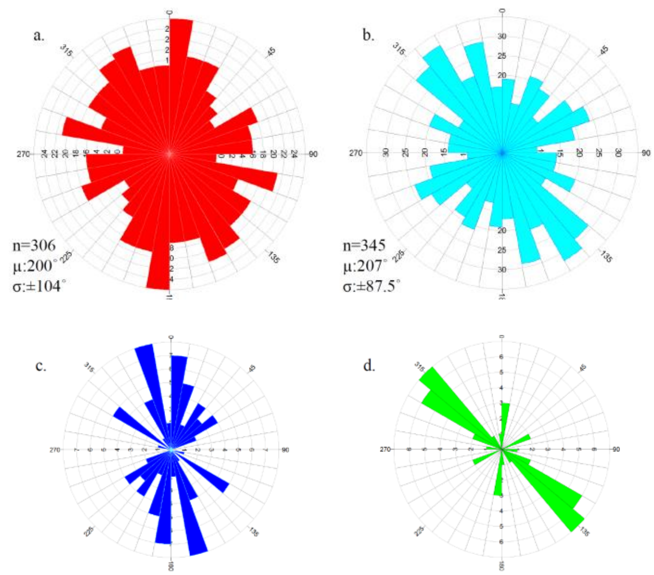

Figure 4: Preliminary rose diagrams of some of the lineations identified in this study: (a) patera edge lineations, (b) structural lineations, structural lineations further divided into (c) large-scale thrust faults and (d) large-scale normal faults. Colors correspond to colors used in other figures throughout this paper. The randomness of the distribution of patera edge lineations and structural lineations has led to further differentiation of lineations in an attempt to define stress directions. (c) and (d) represent the start of that process.

4. Discussion

Preliminary findings indicate that a global stress field plays a major role in mountain formation and evolution, and helps shape the morphology of some paterae. Mountain clusters show very similar directions of compression and extension within in the individual mountains, indicating that they were formed under the same stresses. Their evolution may have been governed by local tectonics, but their formation may be attributed to larger-scale processes. In some locations, paterae seem to have collapsed along extensive faults associated with these stresses (Figure 5). This global stress field may be consistent with stresses expected from both tidal flexing as predicted by Bart et al. (2004) and by loading of the crust through resurfacing (Turtle et al., 1999). Bart et al. suggest that principal stresses will be north-south tension and east-west compression at the equator, with these stresses becoming more oblique toward the poles (2004). Resurfacing by volcanism, such as happens frequently on Io, could generate horizontal shortening by effective contraction of the moon's radius sufficient to produce basement-cored mountain uplifts. These may be comparable to uplifts seen as a result of deep-rooted basement thrusts of Wyoming, USA (Wise, 1963). It is likely that this process, along with tidal massaging, is producing the types of topographic features observed on Io.

In addition to global stresses, there seems to be overprinting due to localized stresses on many features. Several mountains, such as Skythia Mons, Monan Mons and Shamshu Mons, have central grabens. Although the mountains are compressional features related to horizontal shortening on a larger scale, local tectonism is imposed as grabens produced by extension related to neutral surface folding (Figure 2). Additionally, ridges hypothesized by Bart et al. (2004) to be tidally influenced may actually be the result of local shortening or extension accommodating larger structures (Figure 5). Others may be erosional features.

Additional structural maps being produced will aid in further understanding of global and local stresses.

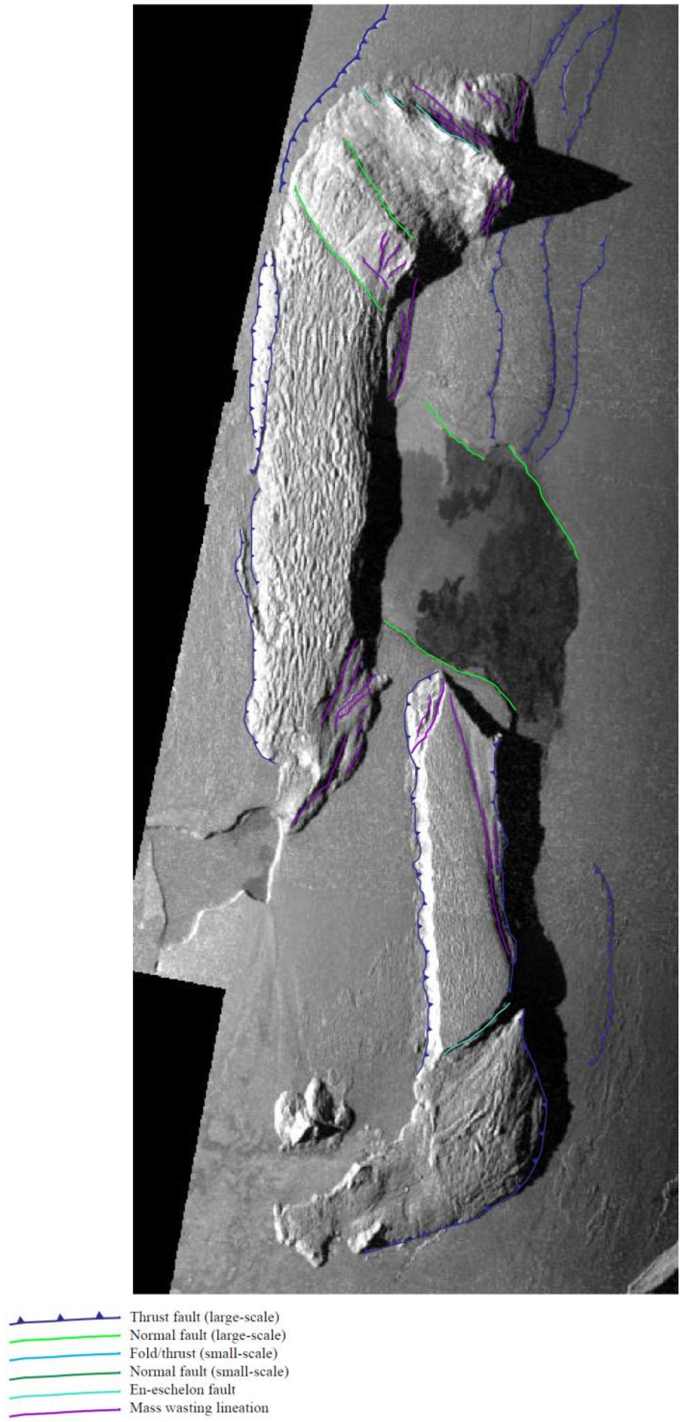

Figure 5: Preliminary detailed structural map of Hi'iaka Mons (5°S, 80°W) indicating locations and interpretations of linear features identified in this study. The image is from NASA *Galileo*. Resolution is 260 m/pixel. Sun illumination is from the left. The sharp peak at the top of the image is about 11 km high and the two plateaus are roughly 3.5 km high (Milazzo, 2000). The relatively parallel ridges on top of the plateaus are still under debate as being short-wavelength folds or horst-and-graben structures derived from extension above the neutral surface during the shortening that produced these plateaus.

5. Conclusions

Large-scale features and patterns on Io can possibly be explained by tidal massaging combined with longer-lived processes, such as crustal loading. Smaller-scale accommodation features indicate local stresses still play a role in the evolution of topographic features.

This study will continue to investigate the effects of global and local stress fields through continuation of structural mapping, analysis of high-resolution photos, statistical tests of significance, and spatial statistics of features and lineations. It will attempt to quantify the roles of different stress fields and processes forming the unique surface features observed on Io.

There is no body in the solar system affected by tidal forces to the degree that Io is. Tidal massaging is responsible for anomalously high rates of volcanism and crustal recycling. Investigating the effects of extreme processes is crucial to understanding what is possible within the reaches of the solar system.

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