Slope Stability Analysis of Scarps on Io’s Surface: Implications for Upper Lithospheric Composition

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Synopsis

Io is the most volcanically active planetary body in the solar system. Features termed “Paterae” are irregular surface depressions with scalloped edges. These volcanic structures have been observed on Io’s surface by multiple spacecraft and are suggested to be possibly analogous to terrestrial collapse calderas. Over 144 paterae have been identified on Io’s surface and depth measurements estimate a 0.5 – 4.0 km range for exposed scarps at near vertical angles. Revealing kilometers of material from the paterae floor to the upper shelf (Io’s surface), these scarps provide cross-sections through Io’s upper crust.

The objective of this study is to derive the minimum material strength of Io’s upper crust based on these structural observations and to use this data to place quantitative constraints on its composition. We find scarp modeling results from slope stability analysis support silicate and sulfur-dominated compositions for the upper kilometers of Io’s crust. Our results support the neutral buoyancy zone suggested by the Jaeger and Davies [15] model of Io’s upper lithosphere.

Background

The comparative roles of sulfur and silicate materials in Io’s surface and upper crust are continually debated. Depth measurements are not well constrained. The comprehensive mean value from estimates provided in the literature yields a 1.4-km depth for observed paterae. Clow and Carr (1980) provide methods of slope stability analysis with applications to observer scarps on Io. This work uses similar methodology. We continue upon previous work and results but return with an order of magnitude more data. Our models take into consideration additional structural details of the scarps, the upper few kilometers of crust, revealed by the exposed walls of paterae on Io.

Paterae on Io

Qualitative examples

Paterae (Plural of Patera)

“Irregular craters(s) or complex one(s) with scalloped edges” (IAU) (see Radebaugh, 2001)

Material Properties

Chaac Patera - Static

Friction Angle: 34.5 degrees

Material: 2500 kg/m³

Discussion

The minimum height for a sulfur composition scarp to fail occurs at 4 km height for ductile (285k) sulfur. This is however unlikely because most slopes are much less than tall and unlikely that the temperatures are raised high enough for sulfur to be this weak. Upper deposits could support a porous substrate from volcanic resurfacing and the widespread presence of solid sulfur dioxide ice on Io’s surface implies a significant role in the composition of Io’s upper crust. The material that comprises the upper crust and the observed scarps might be a material mixture of heterogeneous properties but modeling is unable to provide valid predictions for mixtures. The suggested proportion for materials is 30% Sulfur, 65% SO₂, and 5% silicate. The absence of measurements for SO₂ is critical.

Results

We have examined the variability in both structural and material property parameters to resolve upper and lower bounds for constraints on sulfur in Io’s upper crust. Isotropic modeling results are used to examine the range of all compositions inferred by observations. Threshold values of cohesion and internal friction for given structural characteristics are represented by the plotted curves. Using equations (EQ3a/b) and (EQ4) upper and lower limits of mechanical properties for a given structure can be calculated.

Material mechanical property measurements that exceed the curves are capable of supporting the required shear strength of a modeled structure and materials with values that plot under a curve will not satisfy the minimum shear strength of the structure needed.

Sulfur scarps modeled to heights of 3 km are able to provide the supporting force to withstand failure. Investigated materials modeled at an average scarp height of 1.5 km exceed minimum strength thresholds and could therefore maintain stability of such scarps. The numerical modeling results of this study allow quantitative testing of the Jaeger and Davies [7] model that predicts the distribution of volatiles in Io’s lithosphere.

Conclusion

Our results support the neutral buoyancy zone suggested by the Jaeger and Davies [15] model of Io’s upper lithosphere. Depth estimates and DEMs (14) provide critical data for numerical modeling however account for few of the total observed patera. The absence of SO₂ mechanical property values limits the ability of our modeling to account for its implications in slope stability and Io’s upper crust. Our results provide valid constraints for many structures and material densities, modeling however is exhausted without SO₂ experimental values and further, more precise estimates of depth. The Io Volcano Observer (IVO) mission would surely solve many of these outstanding issues in planetary science.

References

[3] Seq: c0539932078r
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