PATERAE ON IO: COMPOSITIONAL CONSTRAINTS FROM SLOPE STABILITY ANALYSIS.
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Introduction: Observations from the *Voyager*, *Galileo*, *Cassini*, and *New Horizons* missions have greatly advanced our understanding of Io's geology, however many questions remain unresolved. Persisting from Voyager's initial observations is the dispute regarding the relative roles of sulfurous and silicate materials in Io's crust. This study provides new compositional constraints at scarps on Io, using numerical slope stability modeling to gain new insight into the roles of such materials in subsurface processes by testing the Jaeger and Davies (2006) [1] model for Io's crust.

Previous Work: Clow and Carr [2] conducted slope stability analysis of scarp formations on Io using the Mohr-Coulomb failure criterion, and our study seeks to replicate the methodology used, but differs in it's capabilities with 30+ years of technological advancement, and a significantly improved Io dataset. Preliminary results of this study were provided by Keszthelyi et al. (2010) [3] and yield the basis from which this study was done.

Methodology: In order to characterize a compositional profile for the observed, 1-4-km-tall, near-vertical, scarps on Io, observed structural characteristics allow compositional limitations to be applied. An analysis of the supporting force required to maintain such scarps constrain the mechanical properties of the material(s) of which a formation is comprised. Maintaining consistency with previous work [e.g., 3], we employ the Slide software [4] for numerical slope stability modeling and the Mohr-Coulomb and Bishop simplified failure criteria used therein.

Model parameters vary slope angle θ and material density ρ, against an assumed cohesion σ, and values for internal friction ϕ are assigned up to a Factor of Safety (FS) = 1. A Factor of Safety less than 1 indicates a tendency for slope failure, whereas a Factor of Safety greater than 1 indicates that slope failure is unlikely. The models equipped in this study have assumed isotropy, representing uniformity in material particle characteristics at static temperature. It is imperative to simplify the parameters of our results prior to the introduction of anisotropic elements to later quantify iothermal boundaries.

Due to the large amount of tidal stress Io incurs from Jupiter, incorporation of dynamic stress (e.g., seismicity) into some models provides a representation of the ioquakes that must occur as a result of Io's flexing lithosphere and voracious volcanic flux. The dynamic loads presented in the models are prescribed by a pseudostatic horizontal ground acceleration acting in the out-of-slope direction [5] related to a dimensionless seismic coefficient. In terms of Io, this seismic coefficient effectively describes the maximum horizontal acceleration due to ioquakes as a fraction of the acceleration due to gravity on Io's surface (g_{Io} = 1.796m/s^2).

Results: Work conducted thus far now provides constraints at both static and dynamic conditions for material (mechanical) properties ranging from snow to SO_2 solid to mafic rocks.

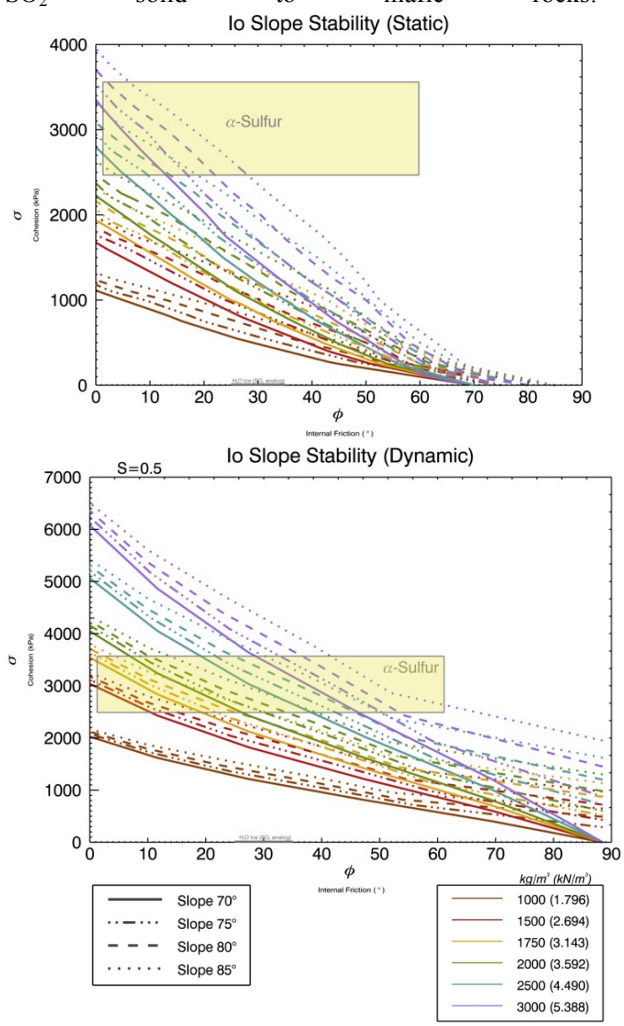

Figure 1. Plots of modeled results corresponding to a Factor of Safety = 1 under static and dynamic conditions at various steep-angle slopes for densities spanning tested compositional end-members.

Cohesion values are expected to be 10-40 MPa for mafic rocks [6], 3 MPa for (orthorhombic) sulfur [2] and snow (analogous to SO_2 frost) 1-10 kPa [7]. Values of internal friction for most terrestrial rocks range from ~25°-35° [8] and ~32°-52.7° for Martian soil [9]. Clow and Carr [2] provide internal friction coefficients for ductile and brittle SO_2.

Figure 1 displays the threshold between allowed and disallowed mechanical properties in the modeled 3-km-tall scarp, under static and dynamic conditions respectively. Materials with mechanical properties above the threshold lines given in the plot denote materials that are viable constituents representative of the materials that could allow such scarps to persist. Materials with mechanical properties placed on the plot below a threshold line indicates that the material will result in slope failure and collapse under prescribed conditions. Pale yellow boxes describe the mechanical property parameters of α-sulfur, mafic rock far exceeds maximum cohesion values represented by the plot, and snow falls below all threshold lines.

We find that α-sulfur is at the threshold of failure only for unrealistically high densities. When seismic shaking is added in the model, sulfur remains plausible, but is consistently at the threshold for failure. Even moderately weathered mafic rock is capable of accommodating the supportive force for the scarp and is able to withstand mild-ioquake loads. The plausibility of solid sulfur dioxide remains largely unknown as its mechanical properties are largely unconstrained, however the modeled density of solid sulfur dioxide (2000kg/m^3 [10]) borders the mechanical property capacity of α-sulfur in both static and dynamic conditions at approximately the same magnitude, possibly an indication of diagenesis.

In summary, slope stability does not provide a definitive conclusion about the composition of Io's upper crust. However, if the scarps on Io are actively collapsing (i.e., are right at the threshold of failure), a sulfur-rich composition may be the most likely.

Future Work: While photoclinometry derived scarp height estimates [11] are sufficient in establishing end-member limitations, more realistic constraints provided via DEM would greatly improve the accuracy of these results as the accuracy in elevation dictates the translational dependency of our model. Further modifications to be made to the variables already in play include modification of scarp height and affixing various other seismic factors to the model. While general orientations of trending lines in manipulation of these variables may be established a priori, successive definition will allow the subtleties of model variables to be exploited and further explored. Additionally, the incorporation of anisotropic elements into the model is a necessary evolution in the course of determining if our empirical results and the Jaeger and Davies (2006) [1] model are correlative.

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Acknowledgements: This research was funded by National Science Foundation Grant AST-1004107. Additionally, the authors wish to acknowledge and thank the NAU Physics and Astronomy REU program, the United States Geological Survey Astrogeology Science Center, and the Ronald Greeley Center for Planetary Studies (the NASA Regional Planetary Information Facility (RPIF) at ASU) .