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

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Introduction: Io is the most volcanically active planetary body in the solar system. Despite observations from the *Voyager*, *Galileo*, and *New Horizons* missions, a fundamental understanding of how Io's crust permits, or fuels this dynamic activity remains unknown. Volcanic features observed on Io's surface termed "paterae" are irregular surface depressions with scalloped edges possibly analogous to terrestrial collapse calderas. The near-vertical 0.5 – 4.0 km scarps in paterae reveal cross-sections through Io's upper crust. The objective of this study is to derive the minimum material strength of Io's upper crust and to use this to place quantitative constraints on its composition.

Background: Former works ([1], [2]) provide our preliminary insights and direction for the approach we use in this study and we follow the methodology of Clow and Carr [3] using the Mohr-Coulomb failure criterion. Our study makes use of significant advancements in modeling and an improved Io dataset. Reliable estimates of the distance between the patera floor to its upper shelf are critical to modeling parameters and results, measurements of scarp height are collated from prior studies [4]-[11]. Measurements provided by these studies comprehensively yield an average paterae depth (scarp height) on Io of 1.44 km.

Method: Slope stability analysis and numerical modeling are employed using geotechnical software Slide [12] and procedures [13] to examine scarps representative in the range of parameters observed. Models are constructed for scarps differing in height and slope angle across a range of reasonable material densities. The mechanical properties of materials (Table 1) are inherent characteristics and determine whether or not a scarp will fail under static conditions. Values for cohesion and internal friction are incorporated into modeling parameters to compute a Safety Factor using the Mohr-Coulomb failure criterion and Bishop Simplified analysis method. A Safety Factor less than 1 indicates slope failure, a Safety Factor greater than 1 indicates that the slope will not fail.

Table 1	Density	Unit Weight	Cohesion	Internal Friction
	kg/m^3	kN/m^3	kPa	(°)
Sulfur (Ductile)	2070	3.718	3000	60
Sulfur (Brittle)	2070	3.718	3000	1.5
Silicate (Rock)	2900	5.204	66000	30
SO_2[†]	1920	3.448	?	?

Modeling: The models assume static conditions and both isotropic and anisotropic instances of slope wall and patera floor compositions are tested. To constrain the compositions that could form the scarp structures, we generate data for all compositional instances of the physical and structural characteristics of the observed slopes. These parameters allow a back-analysis of mechanical properties for differing materials of known density. Corrections for Io's acceleration due to gravity (1.796 m/s^2) are implemented into the model. We use the mechanical property measurements of brittle and ductile sulfur [3] and silicates [14].

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. Our results provide parameters at an order of magnitude higher resolution than the constraints of previous work. Threshold values of cohesion and internal friction for given structural characteristics are represented by the plotted curves. Materials with 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

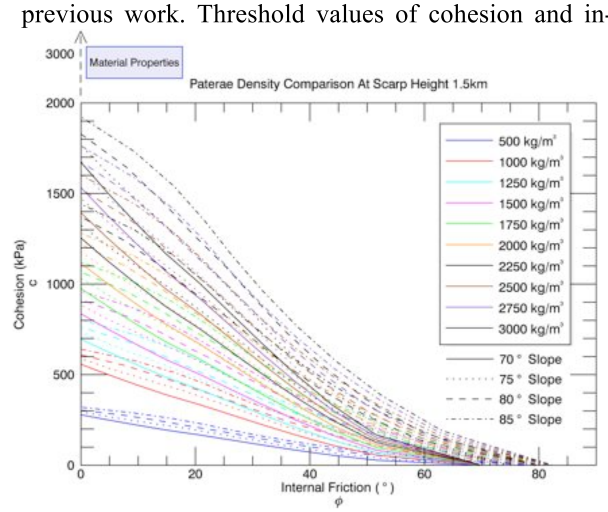

Figure 1. ***Plot of numerical thresholds of density and slope angle for a 1.5 km tall scarp***.

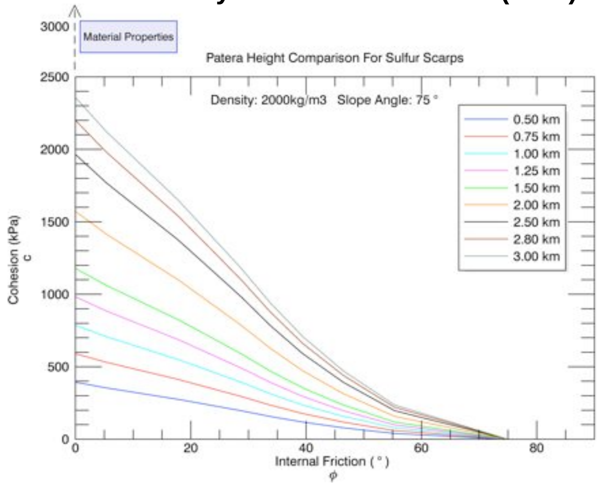

Figure 2. ***Plot of numerical modeling thresholds for a sulfur density scarp at various heights.***

under a curve will not satisfy the minimum shear strength of the structure and will fail.

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 (Figure 2) 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.

Discussion: Scarp modeling results from slope stability analysis support both silicate and sulfur-dominated compositions for the upper few kilometers of Io's crust. The minimum height for a sulfur composition scarp to fail occurs at 4 km height for ductile sulfur (Figure 3). This is however unlikely because most slopes are much less than 4 km tall and it is unlikely that the temperatures are raised high enough for sulfur to be this weak. It is possible that upper deposits could support a porous substrate from volcanic resurfacing and the widespread presence of solid sulfur dioxide ice on Io's surface implicates 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 and modeling is unable to infer representative material distributions or provide valid predictions for mixtures. Incorporation of sulfur dioxide ice into upper layer materials cannot be examined because the mechanical properties of solid sulfur dioxide do not exist in the literature and have not been measured.

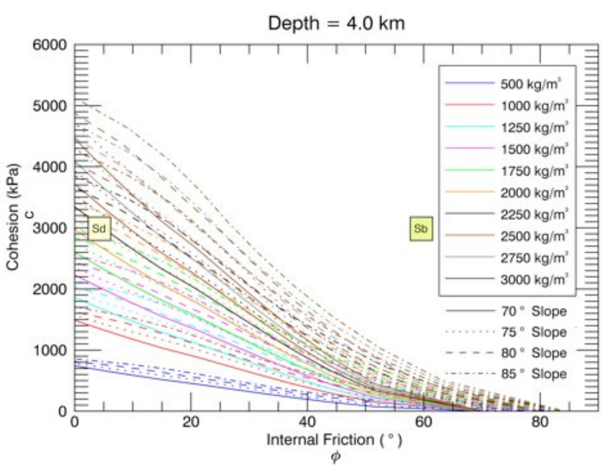

Figure 3. ***Plot of a 4 km scarp and the mechanical properties of ductile (Sd) and brittle (Sb) sulfur.***

Conclusions: Isotropic modeling results for scarps up to 4 km tall suggest silicate-dominant scarps will not fail, end-members for sulfurous compositions indicate scarp failure will occur for ductile sulfur (285 K) but will not exhibit failure for brittle sulfur (127 K). 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. The primary limitation encountered in this study is the absence of mechanical properties data for solid SO_2 ice.

Future Work: Measurements of the mechanical properties of SO_2 ice must be resolved for slope stability analysis to continue. Experimental opportunities are currently being pursued. Future modeling will include seismic accelerations to simulate tectonic activity.

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