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 yield a 1.44km 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.

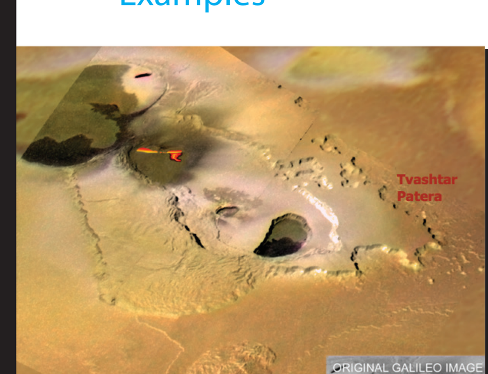
Paterae on Io

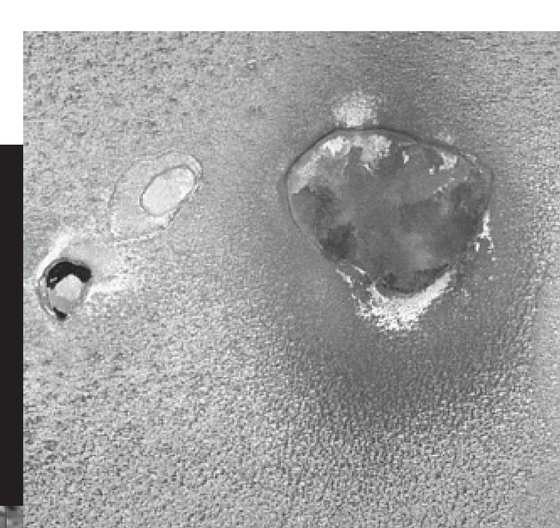
Qualitative examples

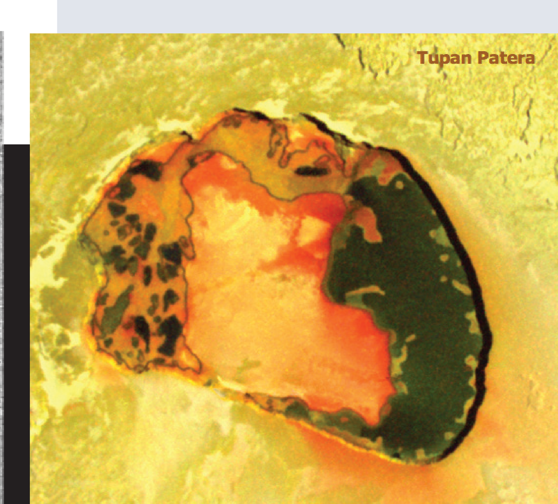
Paterae (Plural of Patera)

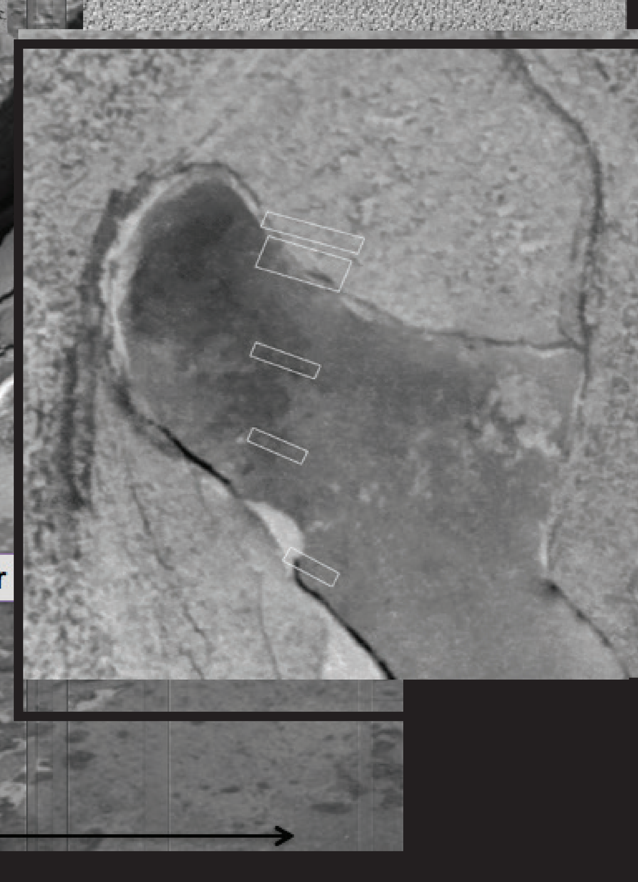
"Irregular crater[s] or complex one[s] with scalloped edges" (IAU)
(see Radebaugh, 2001)

Examples









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Slope Stability and Back Analysis

A Factor of Safety (FS) greater than 1 indicates a slope will not fail.

A Factor of Safety (FS) less than 1 indicates slope failure.

Compositional bounds for materials are modeled for the observed structural features of Ionian scarp formations (i.e. slope angles and vertical relief). A numer of variables govern the model.

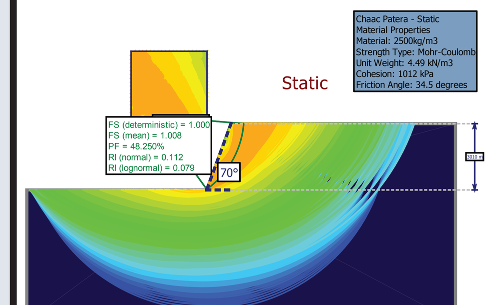
values are computed over a wide range of values until the upper and lower limits of each variable is determine

To accomplish this, the minimum (c = 0) and maximum (ϕ = 0°) values for cohesion of represented densities of slope θ are tested. Intermediate values with an FS of 1 are found by numerical methods.

Values for c and ϕ in terms of FS are given by the General Definiton of the Safety Factor.

General Definition of Factor of Safety

$$F = \frac{\text{shear strength of soil}}{\text{shear stress required for equilibrium}} \quad \text{(EQ1)}$$



Mohr-Coulomb Failure (Duncan 2014)

$$\tau = c' + \sigma' \tan\phi' \quad \text{(EQ2a)}$$

τ = effective shear stress
c' = effective cohesion
σ' = effective total normal stress
ϕ' = effective friction angle

$$\phi'_d = \arctan\frac{\tan\phi'}{F} \quad \text{(EQ3a)}$$

ϕ_d' = *effective developed friction angle*

Mohr-Coulomb Failure (Davis 2011)

$$\sigma_c = \sigma_0 + \tan\phi\,(\sigma_n) \quad \text{(EQ2b)}$$

σ_c = critical shear stress required for faulting
σ_0 = cohesive strength
$\tan\phi$ = coefficient of internal friction (μ)
σ_n = normal stress

Back-Analysis of Shear Strength Parameters

Back-Calculating Average Shear Strength

Assume $\phi = 0$

$$c'_d = \frac{c'}{F} \quad \text{(EQ3b)}$$

c'_d = effective developed cohesion

$$F = \frac{s}{\tau} \quad or \quad \tau = \frac{s}{F} \quad \text{(EQ4)}$$

F = 'FS' = Factor of Safety
s = available shear strength
τ = equilibrium shear stress

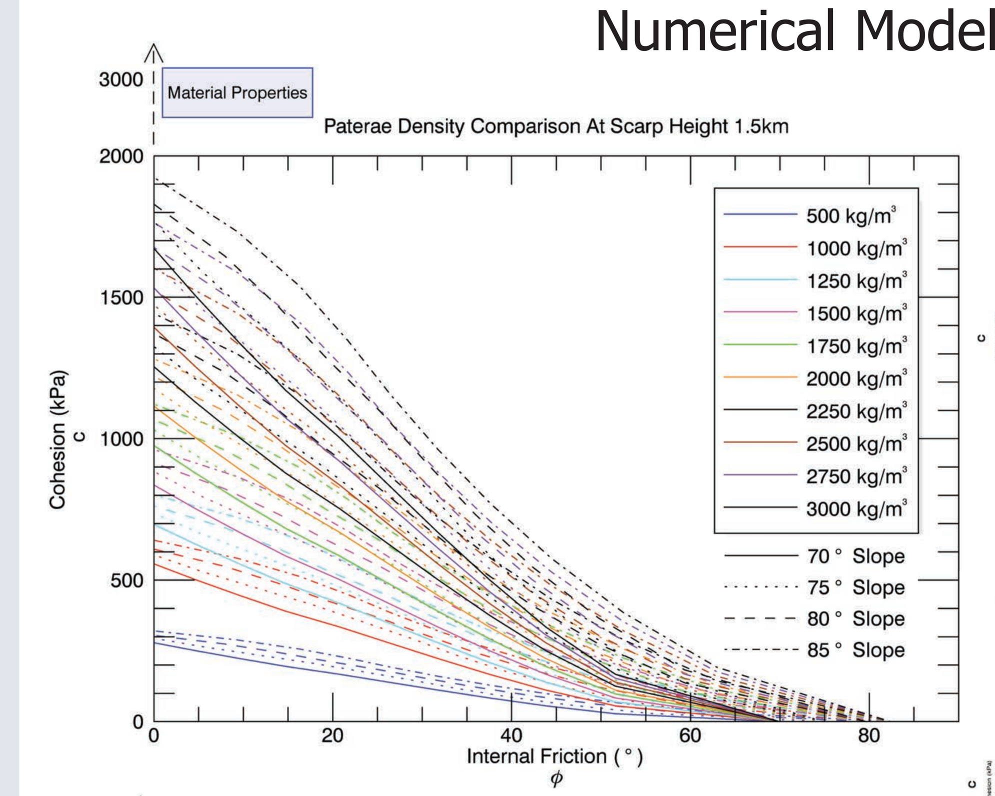
Soil Mechanics of Granular Materials

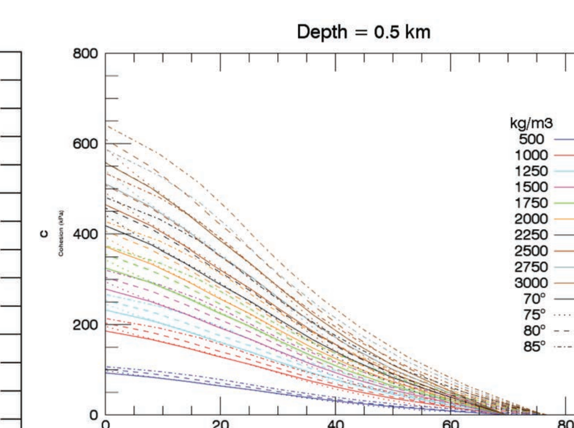
$$s = \sigma' \tan\phi' \quad \text{(EQ5)}$$

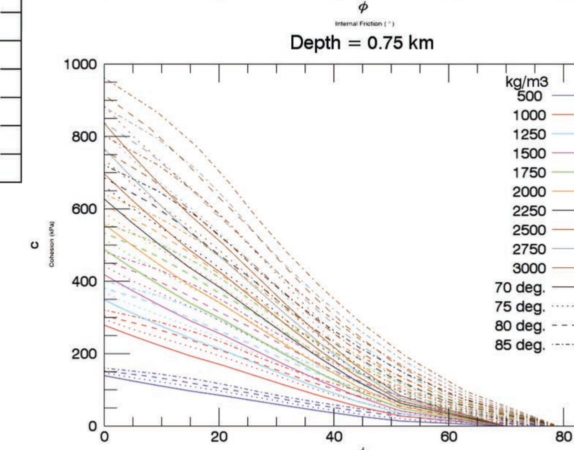
s = shear strength
σ' = effective normal stress on the failure plane
ϕ' = effective stress angle of internal friction

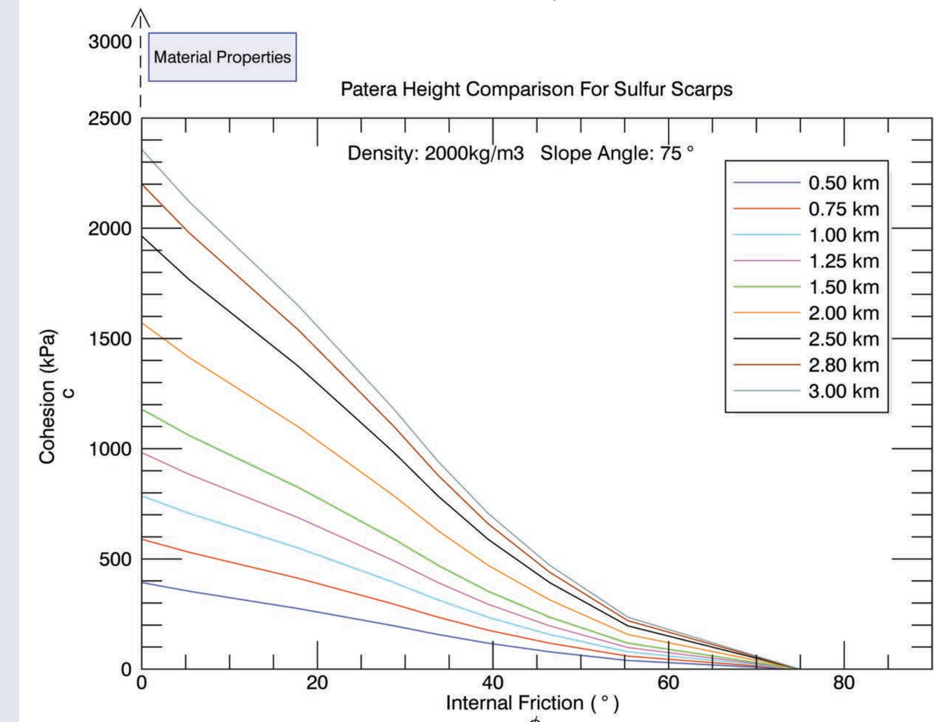
Mechanical properties of internal friction and cohesion (ϕ and c respectively) can only be determined via in-situ experimental studies. Rock and granular mechanics are independent of their constituent's physical and chemical properties.

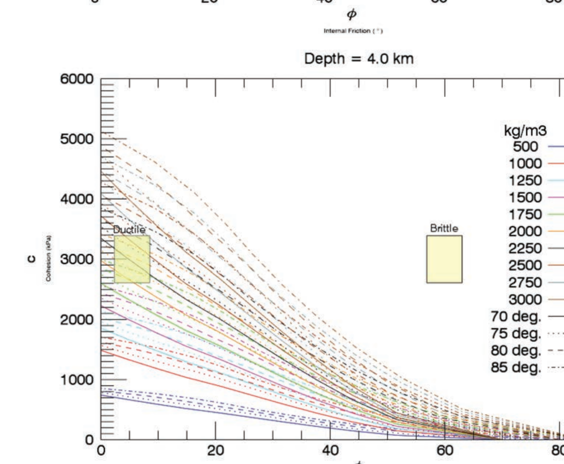
Numerical Modeling Plots











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 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 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.

Height h(km)	Density ρ (kg m^{-3})	Slope θ (°)	Cohesion C (kPa)	Phi ϕ (°)
2.8	2000	70	0.00	70.00
2.8	2000	70	208.17	51.61
2.8	2000	70	416.34	43.82
2.8	2000	70	624.51	37.51
2.8	2000	70	832.68	31.75
2.8	2000	70	1040.84	26.24
2.8	2000	70	1249.01	20.77
2.8	2000	70	1457.18	14.73
2.8	2000	70	1665.35	9.57
2.8	2000	70	1873.52	4.64
2.8	2000	70	2081.69	0.00
2.8	2000	75	0.00	75.00
2.8	2000	75	219.99	55.36
2.8	2000	75	439.97	46.45
2.8	2000	75	659.96	39.43
2.8	2000	75	879.95	33.73
2.8	2000	75	1099.93	28.74
2.8	2000	75	1319.92	23.28
2.8	2000	75	1539.90	17.80
2.8	2000	75	1759.89	11.59
2.8	2000	75	1979.88	5.38
2.8	2000	75	2199.86	0.00

Plot data example (22 of 4400 results)

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 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 but modeling is unable to provide valid predictions for mixtures. The suggested estimate proportion for materials is 30% Sulfur, 65% SO_2, and 5% silicate. The absence of measurements for SO_2 is critical.

Conclusion

Our results support the neutral buoyancy zone suggested by the Jaeger and Davies [15] model of Io's upper lithosphere. Depth estimate studies and DEMs [4]-[11],[14] provide critical data for numerical modeling however account for few of the total observed patera. The absence of SO_2 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 SO_2 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.

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