# Paterae On Io: Compositional Constraints From Slope Stability Analysis

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## Synopsis

Io is the most volcanically active planetary body in the solar system. Persisting from initial debates prompted by observations from the Voyager mission, the relative roles of sulfurous and silicate materials in Io's surface and upper-crust have yet to be resolved. This project utilizes numerical slope stability analysis to perform a compositional back-analysis of candidates amenable to fit the structural constraints observational data provides. Compositional constraints are examined in both static and dynamic environments for a range of representative materials ranging from ash to mafic rock. We find that a scarp composition of α-sulfur lies on the threshold of stability for highly dense materials, mafic rock far exceeds thresholds, and snow falls below all threshold lines.The results of this study seek to provide provide data to qualitatively test the Jaeger and Davies [2006] model for Io's crust.

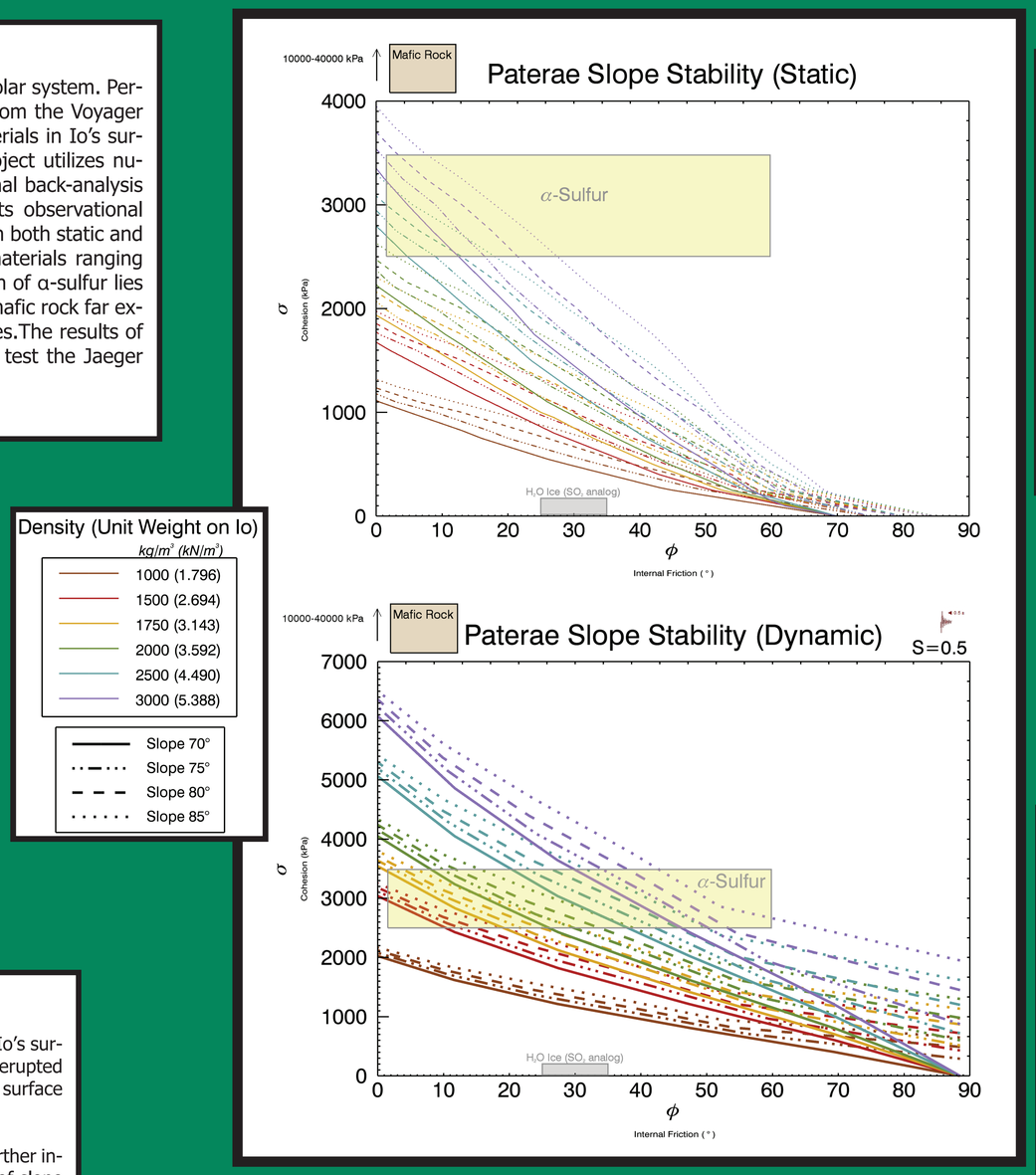

## Background

Subsequent to the obervations from the Voyager fly-bys when Io's surface geology was first resolved, extensive debate subsequently erupted over the comparative roles of sulfur and silicate materials in the surface and crust.

Clow and Carr (1980) provide powerful baseline concepts for further investigation of Io and the pro-continuity that applied methods of slope stability analyses allow. This study continues upon previous work however seeks advantage in technological development and substantiall gains in the Io dataset.

The withstanding masses of observed scarp formations on Io, such as the 3km tall scarp at Chaac Patera (image provided above) with observed slopes of 70° to 90° (Radebaugh et al., 2001) hold clues to Io's interior.

Provided known values for physical and mechanical properties of rock and soil material compositions supported by evidenced from observation, structural characteristics observations allow viable compositions to be constrained. This study varies values for physical properties density (ρ), slope angle (θ), as well as mechanical properties, cohesion (σ) and angle of internal friction (ϕ). While these factors each have their own interdependency, comprehensive end-members may be placed where no constraints currently stand.

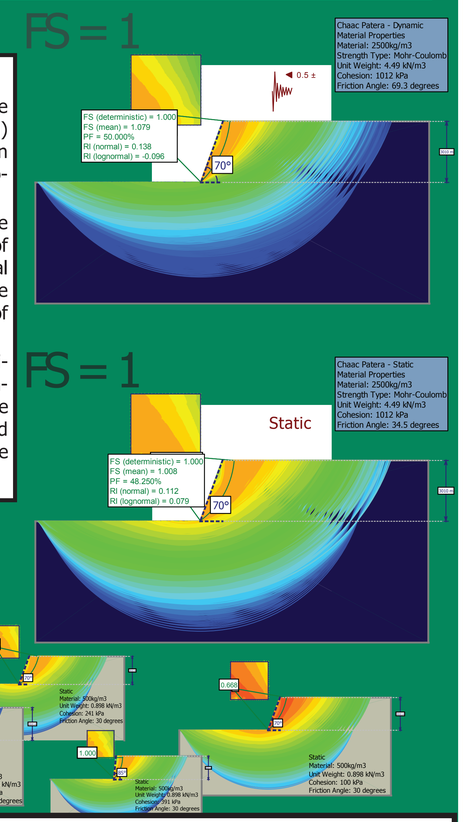



## Slope Stability Analysis

A Factor of Safety greater than 1 indicates that the slope will maintain equilibrium (and will not fail) under static conditions. A Factor of Safety less than 1 that the slope will fail and will not reach it's equilibrium of stability (Okubo et al., 2011).

In order to provide compositional constraints be placed upon the observed structural features of Ionian scarp formations (i.e. slope angles and vertical relief), numerical integrations computed over a wide range of values until the upper and lower limits of each variable is determined.

To accomplish this, the minimum (σ = 0) and maximum (ϕ = 0°) values for cohesion of the tested densities per each slope θ are located. Intermediate values are estabilished from cohesive variability and internal friction values are manipulated to determine values corresponding to a factor of safety of 1.




## Results

Slope stability plots are displayed displays the threshold between allowed and disallowed mechanical properties in the modeled 3-km-tall scarp, under static and dynamic conditions. Materials with mechanical properties above the thresholds the plot lines represent viable compositional constituents 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 a seismic element is introduced 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/m3) borders the mechanical property capacity of α-sulfur in both static and dynamic conditions at approximately the same magnitude.

## Methodology

The Slide (5.0) software (Rocscience Inc.) allows a multivariable platform for running the in the architecture of each numerical simulation runs is required to allocate viable data sets. Corrections for Io's gravitational acceleration are implemented into model parameters by a conversion factor of .0001796 (Io gravity ~1.796 km/m3) when translating a given material's terrestrial density (kg/m3) into its respective Ionian Unit Weight (kN/m3).

The Bishop Simplified analysis method to determine the factor of safety is chosen for this study as it is the most universal (and planetary) methodology for highly reliable, general slope stability analysis (Spencer, 1967). The two values of prime importance in the study's examination of material that permits near-vertical slope retention include internal friction ($\phi$) and cohesion ($\sigma$), given by the Coulomb Failure Criterion:

$$\tau = \sigma \tan(\phi) + c$$

Utilizing the Slide Software (rocscience.com) and datasets acquired since Clow and Carr (1980), additional constraints can be applied, Mohr-Coulomb Failure Criterion: $\tan(\phi)' = c' + \mu' \sigma_n'$ (Maximum values for ϕ and σ are determined (per θ), (per ρ).)

Represented materials tested range from ash to mafic rock to estabilish end-member constraints. Dynamic modeling implies a seismic element that is appropriate a priori in consideration of the gravatational interaction and tidal flexing Jupiter incurs on Io. Dynamic modeling incorporates a seismic coefficient of 0.5, a midpoint of the coefficient range, as no empircal evidence suggests Io's tectonism is silent or violent, just that it very likely exists. In classifications of earthquakes rather than ioquakes, S=0.5 is representative of "catastrophic" earthquakes.

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