PATERAE ON IO: INSIGHTS FROM SLOPE STABILITY ANALYSIS. L. P. Keszthelyi[1], W. L. Jaeger[1], and C. Okubo[1], [1]Astrogeology Science Center, U. S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001.

Introduction: One of the enduring mysteries of Jupiter's moon Io is the relative role of silicates and sulfur compounds in the crust. While previous studies have provided essential constraints on the areal distribution of different materials [e.g., 1-2], different techniques need to be utilized to add the 3rd dimension – depth. The walls of volcanic pits called "paterae" provide a look into the upper few kilometers of Io's crust. In particular, the strength of these patera walls provide important constraints on the material properties, and hence composition of, the outer part of Io [3].

Previous Work: In a groundbreaking study, Clow and Carr [3] used the images from the 1979 Voyager flybys and numerical modeling to argue that the multi-kilometer, near-vertical walls of paterae required that the upper crust be dominantly silicate. However, their study assumed a very steep iotherm, leading to temperatures high enough to melt sulfur within a few kilometers of the surface. While a steep iotherm would appear to be an intuitive consequence of Io's high heat flow, O'Reilly and Davies [4] showed that the rapid volcanic resurfacing would actually result in a very shallow iotherm with the lithosphere essentially isothermal to depths within a few kilometers of the asthenosphere. More recent studies of Io's lithosphere support the idea of a very shallow iotherm [e.g., 5-7].

Hypothesis to be Tested: Jaeger and Davies [7] investigated the likely vertical distribution of sulfur, sulfur dioxide, and silicate materials in Io's crust and concluded that it was likely that the upper few kilometers were dominated by volatiles (Fig. 1). This led to the idea that paterae are formed when the heat from silicate intrusions locally remove this volatile-rich layer [8]. Basically, paterae would be exhumed sills. They would be more similar to the depression in the Vatnajökull glacier caused by the 1996 Grímsvötn eruption in Iceland than to classic calderas.

Slope Stability Model: We utilize the "limit equilibrium method" to investigate the stability of patera walls on Io. This technique has been widely used to investigate the stability of slopes on Earth and Mars. The stability analyses are conducted using the software *Slide* (http://www.rocscience.com).

The primary inputs to these slope stability analyses are the topographic profile of the slope and physical properties of the rock mass that constitutes this slope. For this study, we used the approximate profile for Chaac Patera described by Radebaugh et al. [9]. Material properties appropriate for basaltic rock, volcanic ash, and sulfur were investigated (Table 1).

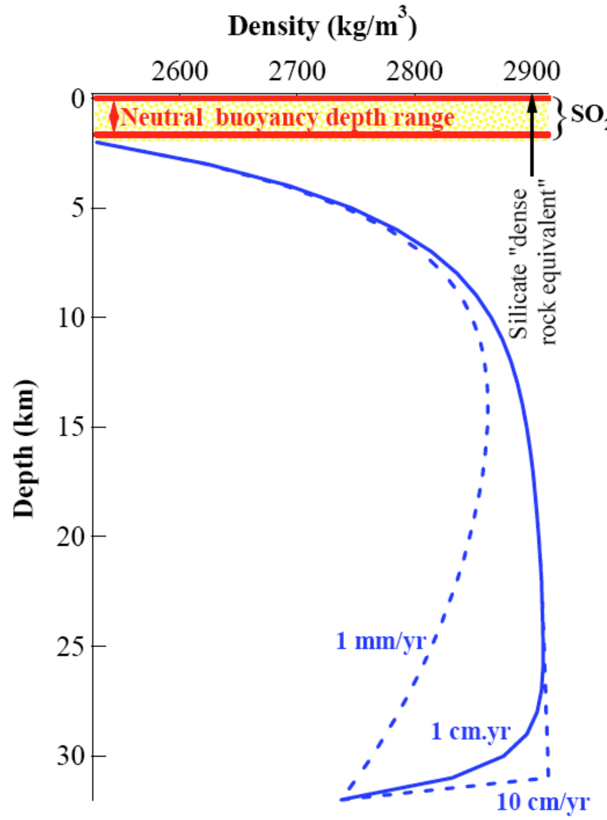


Figure 1. Plot of predicted globally averaged density versus depth of Io's lithosphere [7]. The uppermost few kilometers are predicted to be composed primarily of volatiles. Ascending magma may stall in this layer, producing a sill. The volatiles would then be driven off, leaving a patera.

Table 1. Material properties for patera wall.

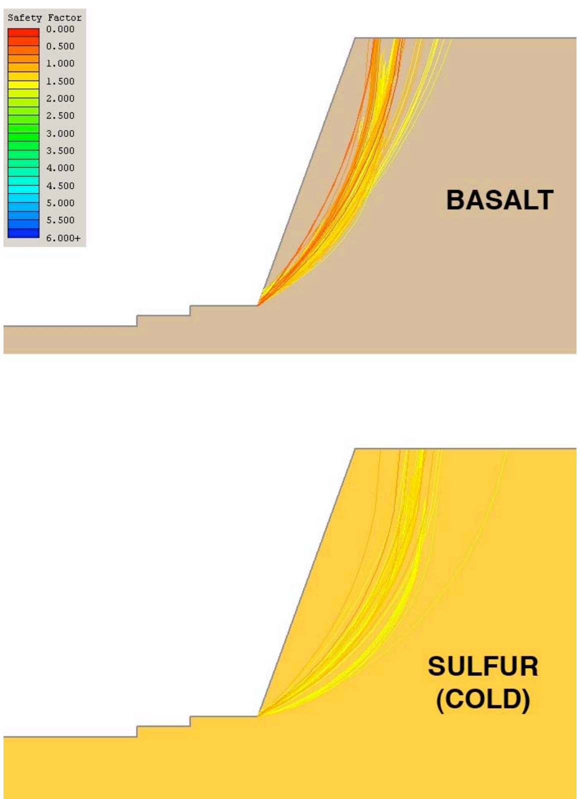
Material	Density	Cohesion	Friction
	kg/m^3	MPa	Phi (°)
Basalt	2900	100	N/A
Sulfur (cold)	2070	3	60°
Ash	1450	N/A	34°

The strength behavior of volcanic ash and sulfur is assumed to follow the response of soils. Accordingly, the strengths of these materials are prescribed using friction and cohesion. The Coulomb strength envelope defined by these strengths controls the failure potential of these materials.

The strength of basalt is handled somewhat differently, using the Hoek-Brown failure criterion for fractured rock masses [10]. Parameters are the unconfined strength of the intact rock and dimensionless representations of the degree of fracturing and block interlocking within the rock mass. Values are constrained by results of laboratory testing of terrestrial ‘a‘ā and pāhoehoe flows [11] and flood basalts [12]. These studies report values for unconfined compressive strength of 198 ± 98 MPa. To be as inclusive as possible, the strengths of minimally weathered, in situ basalt and highly weathered disturbed basalt end members were considered.

Preliminary Results: Our initial model results are mostly consistent with geologic intuition but include one surprise. First, the patera walls cannot consist of loose material without cohesion (e.g., unwelded ash deposits). Such materials cannot support slopes above the angle of repose and are inconsistent with the near-vertical cliff faces observed at Chaac and elsewhere.

Figure 2. Plots of predicted failure surfaces in the wall of Chaac Patera. Red and orange curves are unstable, yellow ones are very close to collapsing. The Patera wall is known to be ~4 km tall and ≥70° in average slope. Both basalt and cold sulfur can meet these observational constraints.



The second result is that the cliffs could be composed of either silicate lavas or cold sulfur (Fig. 2). This is actually consistent with the earlier work of Clow and Carr [3]. Without more detailed topography of the patera walls it is impossible to differentiate cold sulfur from silicate rock based on slope stability analysis. Even with better topographic information, the natural variations in the material properties of silicate and sulfur layers kilometers thick may preclude confident differentiation.

The third, and unexpected, result is that, even if made of basalt, the patera walls should collapse if subjected to any significant seismic shaking (>1 m/s^2). On Earth, such acceleration is readily achieved within 10 km of a M4 earthquake [13]. Given tall and youthful tectonic mountains, one might predict frequent large ioquakes. One possibility is that Io's tectonism takes place without large energy releases. It is plausible that the regular tidal flexing of the surface releases the faults every orbit (~40 hours), preventing large ioquakes. This would be consistent with the Jaeger et al. [5,7] model for Io's lithosphere where the globally averaged stress state is assumed to be close to the sliding friction of faults. However, additional work is needed to investigate an alternative explanation.

Future Work: It is possible that the steep patera walls are composed of S or SO_2 snow. The low density (~200 kg/m^3) of such deposits, with strong cohesion from interlocked crystals, may allow them to withstand seismic shaking. We plan to use data from various types of terrestrial H_2O snow as analogs. The residual CO_2 polar caps on Mars may also be useful analogs. Additionally, we will examine the effect of heating the lower part of a sulfur or SO_2 cliff in proximity to a hot silicate lava lake. It is possible that the timescale for heat conduction into the patera walls may provide useful constraints on their rate of formation.

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