

GEOLOGY AND TOPOGRAPHY OF RA PATERA, IO, IN THE VOYAGER ERA:
PRELUDE TO ERUPTION

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ABSTRACT

Ra Patera is a major active volcanic center on Io and a possible site of liquid sulfur eruptions. Voyager stereo images are used to map the geology and topography of Ra Patera as of 1979 in order to characterize factors that influenced eruptions observed in 1994-95 (Spencer et al., 1997a). In 1979, the summit of Ra Patera reached a height of only ~1 km. Pre-Voyager-era lava flows, up to 250 km in length, occur on slopes averaging 0.1 to 0.3°, comparable to those on the lunar mare. The only significant positive relief near Ra Patera is a 600-km-long mesa and mountain unit that reaches a maximum height of ~8 km near Carancho Patera. This unit also forms a 60 by 90 km wide plateau ~0.5 to 1 km high extending to within 50 km of Ra Patera. The broad dark flow observed by Galileo (Belton et al., 1996; McEwen et al., 1997) extending southeast of the Ra Patera caldera flowed around the southwestern edge of the plateau on slopes of ~0.2 to 0.3°. Modeling suggests that lava flows on Ra Patera were emplaced with either low viscosities, high eruption rates, or both.

Introduction

Most volcanic flows are influenced by local and regional topography and the numerous eruptions on Io should be no exception. Ra Patera ($-8^\circ, 325^\circ$) is the largest known of Io's radiating shield-like lava flow fields (width ~ 450 km, total area $\sim 250,000$ km²; Fig. 1). It is a controversial site of sulfur or sulfur-rich lava flows (Pieri et al., 1984; McEwen et al., 1989; Greeley et al., 1990; Moses and Nash, 1991) and has been the scene of some of the most dramatic surface changes observed over the 17 years since the 1979 Voyager encounters. HST observed a major brightening at Ra Patera between March 1994 and July 1995 (Spencer et al., 1997a). Galileo images in 1996 showed an active plume, extensive diffuse bright deposits, and a large dark deposit interpreted to be a massive lava flow or flow field extending southeast from the central vent area (Belton et al., 1996). Our goal is to characterize pre-eruption factors that influenced the shape and location of new lava flows and deposits. The style and sequence of past volcanic events at Ra Patera may also provide insights into more recent and future volcanic activity. We have used recently processed 1979 Voyager stereo images to remap the pre-1994 geology and to produce the first high-resolution topographic maps of Ra Patera.

Voyager 1 Stereo Coverage

Voyager obtained redundant image coverage in 1979 of the Ra Patera region at four distinct viewing (or phase) angles. Voyager FDS image sequences 16390.06/10 and 16392.57/59 (Fig. 1) provide the most useful stereo coverage for both geologic (Fig. 2) and topographic (Fig. 3) mapping, with an effective ground resolution of 1.6 km/pixel and a stereo phase angle of 50° . Once control nets for each image pair were updated, topography was mapped using automated stereogrammetry correlation software developed at LPI from related PICS/ISIS (USGS, Flagstaff) software. The software uses a scene recognition algorithm to locate features in each of the stereo images to $\sim 1/5$ th pixel accuracy. The observed relative displacement of each feature is a measure of parallax, from which height is calculated. These relative heights are used to produce a topographic map or digital elevation model (DEM) of the scene (Fig. 3), with a nominal vertical resolution of 210 m for the image pair used here.

Several problems affect stereo topography mapping on Io. Some volcanic materials on Io have very different photometric curves or visible colors. The large stereo phase angle difference (50°) and use of images taken through different filters (clear and green in this case) result in contrast reversals within some small dark spots, and alter the relative brightness of some volcanic

deposits. These photometric effects, as well as the lack of discrete features within the extensive smooth plains on Io confuses the scene matching algorithm and results in large areas of noisy or erroneous data in the DEM. These areas were removed from the DEM by masking data points with large errors or by visual inspection (Fig. 3).

The global topographic model of Gaskell et al. (1988) indicates that Ra Patera is centered on a broad regional dome only 1 km high. (Their topographic model in this region is based on only ~6 data points and is too coarse for detailed mapping. Galileo will ultimately provide an improved global topographic datum that can be used to more precisely control our higher resolution topographic models.) We therefore assume that the regional gradient across Ra Patera is approximately zero.

The horizontal resolution of our DEM is controlled by the sampling window used during scene matching. For Ra Patera, a DEM resolution of 33 km (21x21 pixels) was chosen to emphasize large scale relief and overall structure and to maximize signal-to-noise (due to the presence of diffuse deposits and smooth plains within Ra Patera). A second DEM with resolution of 8 km (5x5 pixels) was made of the plateau and mountain unit associated with Carancho Patera east of Ra Patera (discussed below) to map smaller-scale detail in that area.

Geology of Ra Patera (1979)

The radiating dark flows observed by Voyager at Ra Patera in 1979 formed on a *mottled plains unit* that is smooth and relatively bright with numerous dark spots (Figs. 1, 2). This unit may be comprised of multiple overlapping but unresolved volcanic deposits (Greeley et al., 1988) and is the oldest unit recognized in the region. Beyond the mottled plains unit is an extensive *smooth plains unit* (Figs. 1, 2) that is darker than the mottled plains and generally featureless at Voyager resolution (Greeley et al., 1988). These plains may be massive sheet flows or innumerable smaller overlapping flows that were not deep enough to bury the Ra Patera edifice. Numerous dark *patera floor* (or caldera) deposits occur throughout these plains.

Dark *longitudinal flows* radiate from the dark 30-km-long central vent of Ra Patera and are superposed on the mottled plains. These are the flows that have been interpreted by some as composed of sulfur (Pieri et al., 1984). They are ~50 to 250 km long, and from ~1 km (the limit of resolution) to 4 km wide (except in one location where they broaden or merge into a “flow” ~15 km width). At numerous sites, small lobes appear to branch laterally from the main flow (Greeley et al., 1988). Flows of at least two distinct ages can be recognized. The younger flows are dark

and reddish and extend to the west, northeast, and southeast. The older flows extend to the southwest and are partially obscured by *diffuse mantling material* (Fig. 2), which extends to the south and southwest of Ra Patera and is among the youngest pre-1979 deposit recognized to date. The contact of this dark reddish unit is gradational over 20 km. This diffuse unit crosses but does not obscure preexisting geologic contacts, indicating it is a topographically thin covering, and is probably a plume-like deposit that may have preceded the younger lava flows.

The stereo images reveal that (as of 1979) plateau and mountainous material near Ra Patera is more prominent than earlier thought. *Plateau and mesa material* is topographically thick and has sharp outward facing scarps. These occur at several sites surrounding of Ra Patera (Fig. 2). These units may be thick lava extrusions or erosional remnants of older plains deposits. *Ridged mountain material* consists of elevated plateau and ridged material and occurs in two locations (Fig. 2). A 100-km-long unnamed mountain due northwest of Ra Patera is striated or layered and is probably tectonic in origin. The second occurrence is a 600-km-long arcuate structure extending northeast of Ra Patera and crossing Carancho Patera. North of Carancho Patera, this unit forms an ~50x100 km wide elongate dome capped by a small summit pit a few kilometers across (see VGR FDS 16390.56). South of Carancho Patera, numerous ridges run parallel to the margins of the unit. These ridges are interrupted by two prominent transverse ridges. This mountainous unit has an average width of almost 100 km and merges with a scarp-bounded plateau 60 by 90 km across that reaches within 50 km of the center of Ra Patera. The relative ages of the plateau and mesa units and the ridged mountain units are uncertain. Finally, most of the geologic units in the Ra Patera region described above have been partially or completely obscured by the 1994-1996 eruption deposits (Spencer et al., 1997a; Belton, et al., 1996).

Topography of Ra Patera (1979)

The Voyager DEM reveals very little relief across Ra Patera as of 1979. The summit of Ra Patera rises only $\sim 1.0 \pm 0.2$ km above the surrounding dark smooth plains. Slopes across the mottled plains on which the 250-km-long dark flows formed average 0.1 to 0.2° . Slightly higher slopes of 0.2 to 0.3° are observed to the southeast of the central caldera. Individual Ra Patera flows are not resolved in the DEM, giving an upper limit on their thickness of ~ 200 m.

The only substantial relief within the Ra Patera region is associated with the ridged mountain unit extending east of Ra Patera to north of Carancho Patera (Figs. 1, 2, 3). Between Ra Patera and Carancho Patera, these units are 0.5 to 2.0 km high (Figs. 1, 2). The westernmost portion (which reaches within 50 km of the summit of Ra Patera) forms a plateau roughly 1 ± 0.5 km high.

This plateau is a potential topographic impediment to any eastward lateral flow of lava from Ra Patera after 1979.

The oval dome just northwest of Carancho Patera (Fig. 1, 2) is ~8 km high and has some features that suggest a volcanic origin. (Only Haemus Mons (9 km), Euboea Montes (10.5 km), and Boosaule Montes (~13 km) are currently known to be higher on Io [Schenk and Bulmer, 1997]. The smaller unnamed mountain northwest of Ra Patera is 4-5 km high.) Carancho Patera is located on the flank of this mountain, but is only 1 to 1.5 km above the surrounding plains and nearly 7 km below the summit. The small pit on the summit of this dome may be a volcanic source vent. South of Carancho Patera, the ridged mountain unit is 2 to 3 km high. The parallel ridges may indicate the presence of thick volcanic flows (Greeley et al., 1988). Several transverse ridges ~5 to 6 km high (Fig. 2) cross this ridged mountain unit south of Carancho Patera (Figs. 1, 3). These may also be vent sources.

Discussion

The slopes observed at Ra Patera in 1979 ($<0.3^\circ$) are very low compared to most planetary shield volcanos, such as Mauna Loa and Olympus Mons (Moore et al., 1978), and many Venus volcanos (Schaber, 1991). The compositions of these volcanos are usually assumed to be basaltic. Alba Patera on Mars (Mouginis-Mark et al., 1988), and a few venusian shields (Schaber, 1991) have slopes as low as 0.2° . The slopes on Ra Patera are also similar to those on basaltic plains such as Mare Imbrium (Moore and Schaber, 1975), portions of the Snake River plains (Greeley and King, 1977), and a few large flow fields on Venus (Roberts et al., 1992).

The low slopes on Ra Patera do not directly answer the question of whether Ra Patera flows are composed of sulfur, the rheological properties and flow behavior of which may be complex (Fink et al., 1983; Greeley et al., 1990). Natural leveed sulfur flows up to 1 km long are observed on Earth (e.g., Watanabe, 1940). Formation of long Ra flows as sulfur may simply require high eruption rates or durations than the terrestrial example. Rapid formation of crusts may reduce heat loss to the point where flow lengths can be increased dramatically (Greeley et al., 1990) but we have no analogs for 250 km long sulfur flows over slopes as low as 0.1° . We note that despite the recent 1994-1996 eruption, no high-temperature hotspots (usually associated with silicate volcanism) have been observed at Ra Patera (Spencer et al., 1997b), which allows for the eruption of molten sulfur. The very low slope basaltic flows on Mare Imbrium flows (up to 400 km long) are inferred to have formed at very low viscosities (due to low silica and/or high metal

content; Carr, 1973) or very high eruption rates (Schaber, 1973). By inference, the Voyager-era flows on Ra Patera, whether silicate or sulfur, might also be characterized as having low viscosity, high eruption rates, or both.

Extensive flow fields are, on Earth, generally emplaced as a series of lobes that over time extend the flow field. One mechanism of emplacement is lobe inflation, used to explain emplacement on very low slopes ($<0.1^\circ$) of the Columbia River flood basalts (Self et al., 1996). Emplacement takes place over days to years. Stagnant freezing occurs over months to decades. The pre-1979 Ra Patera flows were most likely emplaced in a similar fashion. Alternatively, high mass eruption rates have taken place on Earth, for example, at Laki, Iceland (Thordarson and Self, 1993) and inferred at Loki on Io by Davies (1997), who applied the Bingham-type model of Hulme (1974) to ionian eruption and environmental conditions.

If high eruption rate flows took place at Ra Patera (pre-1979), then estimates of mass eruption rates can be inferred using the analysis of Davies (1997) together with our new slope measurements. Flow channel width is proportional to the mass eruption rate and inversely proportional to the underlying slope (see Wilson and Head, 1983). For a basaltic magma (see Davies [1997] for flow model parameters), with a viscosity of 1000 Pa s, and a slope of 0.3° , the expected channel width for a 2-km-wide flow with levees on either side is 1200 m. A mass eruption rate inferred from channel width (Davies, 1997) is about $60 \text{ m}^3 \text{ s}^{-1}$. Such a flow would have a central depth of $\sim 6.5 \text{ m}$ and advance very slowly ($\sim 10 \text{ m}^2 \text{ s}^{-1}$). For a 5-km-wide flow, the channel width is 4200 m, flow depth is 9.4 m, and mass eruption rate is $2000 \text{ m}^3 \text{ s}^{-1}$. This flow would take ~ 40 days to reach 250 km (280 days for the smaller width flow). A change of width from 2 to 5 km could be achieved by a simple change in slope of as little as 0.1° . If the pre-1979 Ra Patera flows were tube-fed, then the eruption rates calculated here are probably overestimated.

The mass eruption rates implied for the pre-1979 flows are considerably less than those associated with the large 4.8 micron thermal outbursts associated with Io: the Loki outburst of January 1990 has been modeled with mass eruption rates of $10^5 \text{ m}^3 \text{ s}^{-1}$ (Davies, 1997), in the range of the lunar mare basalt emplacement rates (e.g., Schaber, 1973). On Earth, the largest mass eruption rate observed is for the Laki, Iceland eruption of 1783. Basalt from a 25 km long fissure erupted for 7 months, for the first two months at a rate of 0.1 km^3 per day: close to the $2000 \text{ m}^3 \text{ s}^{-1}$ (0.17 km^3 per day) calculated for the Ra Patera flows. Indeed, there are striking geomorphological similarities in the shapes and scales of the Laki and Ra Patera flows.

The Post-Voyager Lava Flows (1994-1996)

The new dark volcanic deposit observed at Ra Patera by Galileo (Belton et al., 1996) and emplaced between 1994 and 1996 appears to be much broader and shorter in length than the major pre-1979 flows seen by Voyager (Figs. 1, 4). This new deposit may be one massive flow or a consolidated flow field comprised of numerous small flows. Several factors may explain this apparent change from narrow to wide flows. Measured slopes in the region of the new flows are $<0.3^\circ$ (as of 1979). Perhaps Ra Patera was higher (i.e., >3 km) and steeper (i.e., $>1^\circ$) during formation of the pre-1979 flows but subsided after flow formation due to volcanic deflation or lithospheric mass loading. A significant reduction in regional slope would tend to produce shorter and wider flows. No evidence of concentric fracture patterns or topographic flexure or swells is observed near Ra Patera, however, and the lithosphere may be ~ 30 km thick (Nash et al., 1986), consistent with the support of 8 km of relief near Carancho Patera. We conclude that significant deflation of Ra Patera was unlikely. Alternatively, the DEM suggests that there may be a very shallow depression 200 ± 200 m deep in the area where the new flows formed. This may have caused the new flow(s) to spread laterally and pond. Also, a higher mass eruption rate, higher viscosity, or lower yield strength lavas would lead to emplacement of wider flows (Wilson and Head, 1983) during the new eruption phase compared to the pre-1979 flows.

Preexisting topography has had a direct influence on the new 1994-1996 lava flows at Ra Patera. Comparison of the location of the new dark flow (Belton et al., 1996) indicates that this deposit flowed around the southeast edge of the plateau located 50 km due east of Ra Patera central vent (Fig. 4). The apparent deflection around this plateau indicates that the new flow(s) are less than 1 km thick, and perhaps less than 0.5 km thick.

Conclusions

Voyager observations indicate that the eruption history of the ionian shield volcano Ra Patera includes at least one cycle of eruption of longitudinal lava flows preceded (or followed) by the eruption of plume-like deposits, consistent with observations of both effusive and explosive volcanism at Ra Patera in 1994-1996 (Belton et al., 1996). Ra Patera is only 1 km high with slopes of $<0.3^\circ$, much shallower than most shield volcanos but comparable to those on the lunar mare. Whether the pre-1979 flows at Ra Patera were composed of sulfur or silicates, modeling suggests that these flows formed at relatively high eruption rates and low viscosities. A prominent 1-3 km high plateau ~ 50 km due east of the summit and extending 600 km due northeast and then northwest are the only significant positive relief features near Ra Patera. The new 1994-1996

flows were apparently deflected to the south of this obstruction.

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FIGURES

Figure 1. Stereo image pair of Ra Patera. Several dark longitudinal lava flows extend up to ~250 km from the summit of Ra Patera (oval dark area at lower left center). Ra Patera itself has very little relief. The only exceptional relief occurs along a complex mesa and mountain unit east and northeast of Ra Patera. The convergence angle for this stereo pair is 50° , base-to-height ratio ~1.5, and vertical exaggeration ~7.5. North is to the right, and image resolution is 1.35 km/pixel.

Figure 2. Geologic sketch map of Ra Patera region.

Figure 3. Color-coded topographic map of Ra Patera (red=high, blue=low). The prominent plateau unit just below Ra Patera is inadequately represented due to the large sampling area (33x33 km) used here to map topography.

Figure 4. Comparison of the new Ra Patera flow location from Galileo (Belton et al., 1996) with geologic map (Fig. 2) based on Voyager images. Compare the location of the dark flow in image center and the location of mesa and mountain units (yellow in map) near Ra Patera. Scene width is ~1000 km.