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Geology ana topography of Ra Patera, Io, in the Voyager era: Prelude to eruption

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Abstract. Voyager era stereo images are used to map the geology and topography of Ra Patera (a major active volcanic center and possible site of sulfur eruptions on Io). The summit of Ra Patera reaches only ~1 km above the surrounding plains. Pre-Voyager-era lava flows occur on slopes of 0.1-0.3°, comparable to the lunar mare. These flows were emplaced at either low viscosities, high eruption rates, or both. A 600-km-long ridged mountain unit (rising to ~8 km near Carancho Patera) forms a 60 by 90 km wide plateau ~0.5 km high 50 km east of Ra Patera. The new lava flows observed by Galileo flowed around the southern edge of this plateau.

Introduction

Most volcanic flows are influenced by local and regional topography and the numerous eruptions on Io should be no exception. Ra Patera (-8°, 325°) is the largest known of Io's radiating shield-like lava flow fields (width ~450 km, total area ~250,000 km^2; Fig. 1). It is a site of possible 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 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 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 image coverage of the Ra Patera region at four distinct viewing angles. The Voyager stereo image sequence FDS 16390.06 and 16392.57/59 (Fig. 1) provide the most useful stereo coverage for both geologic (Fig. 2) and topographic (Fig. 3) mapping. 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 ~1/5th 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 functions or visible colors. The large stereo separation angle (50°) and use of different filter images (clear and green in this case) result in contrast reversals within some small dark spots, and alter the relative brightnesses of some volcanic deposits. These photometric effects, and the lack of discrete features within the extensive smooth plains on Io can locally confuse the scene matching algorithm and result in noisy or erroneous data in the DEM. These data were removed from the DEM by masking data 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 roughly 1 km high. (Their topographic model in this region is based on only ~6 data points and is too coarse for detailed mapping.) We therefore assume the regional gradient across Ra Patera is negligible. 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 broad scale relief and overall structure and to maximize signal-to-noise. A second DEM (not shown) with resolution of 8 km (5x5 pixels) was made of the plateau and mountain unit associated with Carancho Patera east of Ra Patera (see below) to map high resolution detail.

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. These plains may be massive sheet flows or innumerable smaller overlapping flows that were not thick enough to bury the Ra Patera edifice. Numerous dark *patera floor* (or caldera) deposits occur across these plains.

Dark *longitudinal flows* radiate from the dark 35-km-long

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Figure 1. Stereo image pair of Ra Patera obtained by Voyager 1 in 1979. Ra Patera is the dark spot at center left in each view. See Figure 2 for sketch map of Ra Patera region. Stereo convergence angle is 50°, base-to-height ratio ~1.5, vertical exaggeration ~7.5, and image resolution 1.59 km/pixel. North is to the right in all figures.

central "caldera" 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). These flows are ~50 to 250 km long and ~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

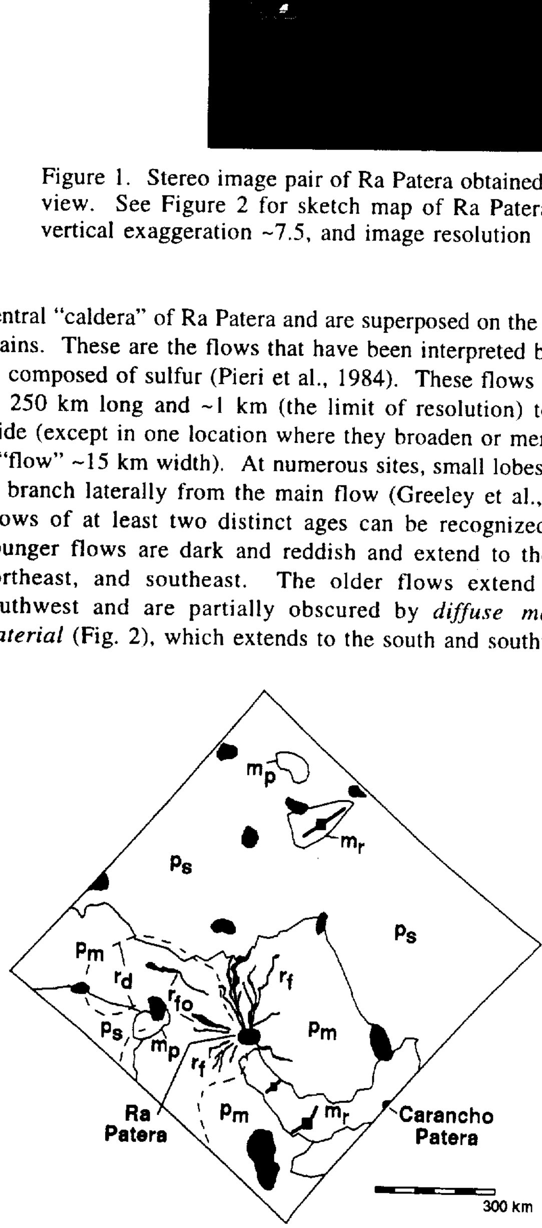

Figure 2. Sketch map of geologic units in the Ra Patera region as of 1979, based stereo pair in Fig. 1. Geologic units are: m_p, plateau and mesa material; m_r, ridged mountain material; p_m, mottled plains; p_s, smooth plains; (black ovoids), patera floor material; r_{fo}, older longitudinal lava flows; r_f, younger flows; r_d (and dashed line), diffuse mantling unit. The thick black bars with squares are topographic ridges.

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 pair reveals that (as of 1979) plateau and mountainous materials near Ra Patera are more extensive than previously mapped (Greeley et al., 1988). *Plateau and mesa materials* (Fig. 2) are 1-2 km high, flat-topped, and has outward facing scarps. These units may be thick lava extrusions or erosional remnants of older plains deposits. *Ridged mountain material* occurs in two locations (Figs. 1 and 2). A 100-km-long unnamed mountain due west of Ra Patera is striated or layered and is probably tectonic in origin. The second occurrance is a 600-km-long arcuate structure extending northeast or 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 small-scale ridges run parallel to the margins of the unit. These ridges may indicate the presence of thick volcanic flows (Greeley et al., 1988). These ridges are interrupted by two prominent transverse ridges. This mountainous unit has an average width of roughly 100 km and terminates in a scarp-bounded plateau 60 by 90 km across that reaches to 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, many of the geologic units in the Ra Patera region described above have been partially obscurred by 1994-1996 eruption deposits (Spencer et al., 1997a; Belton, et al., 1996).

Topography of Ra Patera (1979)

The Voyager DEM reveals that, as of 1979, the summit of Ra Patera rises only ~1.0±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 steeper slopes of 0.2 to 0.3° are observed to the southeast of

Figure 3. Color-coded topographic map (DEM) of Ra Patera (red=high, blue=low). Topographic data gaps are due to poor data quality (see text), or topography that exceeds range displayed here. Black spots are reseaux marks.

the central caldera. Ra Patera lava 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, this unit is 0.5 to 3 km high (Figs. 1, 2). The two transverse ridges that cross this unit south of Carancho Patera (Figs. 1, 3) are ~5 to 6 km high. These may also be related to fissure vents. The westernmost portion (adjacent to Ra Patera) forms a scarp-bounded plateau roughly 0.5 km high. This plateau is a potential topographic impediment to any eastward 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 (~15 km) are currently known to be higher on Io. The smaller unnamed mountain west of Ra Patera is 4-5 km high.) Carancho Patera is located on the flank of this dome, but is only 1 to 1.5 km above the plains and 6 to 7 km below its summit. The small pit on the summit of this dome may be a volcanic source vent.

Discussion

The slopes observed at Ra Patera in 1979 (<0.3°) 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 local slopes as low as 0.2°. The slopes on Ra Patera are 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 sulfur flows on Io may simply require higher 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 yet 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 on Earth are 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°) 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 may have been 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 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 (1996) 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 lava (see Davies [1996] for flow model parameters) with a viscosity of 1000 Pa s on a slope of 0.3°, the expected channel width for a combined flow and levee width of 2 km is 1200 m. A mass eruption rate inferred from this channel width (Davies,

Figure 4. Ra Patera region as viewed in 1996 by Galileo. Superposed is a simplified version of the Voyager-based (1979) geologic map from Fig. 2. Shown are the locations of (dark features) major pre-1979 lava flows, (m_p) plateau and mesa material, (m_r) ridged mountain material, and (dashed line) dark mantling material. The new 1994-1996 dark lava flow is visible near image center just left of the ridged mountain unit.

1996) is about 60 $m^3 s^{-1}$. Such a flow would have a central depth of ~6.5 m and advance very slowly (~10 $m^2 s^{-1}$). For a 5-km-wide flow, the channel width is 4200 m, flow depth is 9.4 m, and mass eruption rate is 2000 $m^3 s^{-1}$. 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 $m^3 s^{-1}$ (Davies, 1996), 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 0.1 km^3 per day: close to the 2000 $m^3 s^{-1}$ (0.17 km^3 per day) calculated for Ra Patera.

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° (as of 1979). Perhaps Ra Patera was higher (i.e., >3 km) and steeper (i.e., >1°) 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 may tend to produce shorter and wider flows. The lithosphere may be ~30 km thick (Nash et al., 1986), however (consistent with the support of 8 km of relief near Carancho Patera), and 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 could have led to emplacement of wider flows (Wilson and Head, 1983) during the new eruption phase compared to the pre-1979 flows.

Preexisting topography may have 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 (or at least flowed up against) the southeast edge of the plateau adjacent to the Ra Patera caldera (Fig. 4). The deflection around this plateau indicates that the new flow(s) are 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 was only 1 km high in 1979 with slopes of <0.3°, 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. The most significant positive relief features near Ra Patera is a 0.5 km high plateau ~50 km due east of the summit (and extending 600 km due northeast of Ra Patera, where it reaches heights of 5 to 8 km). The new 1994-1996 flows were apparently deflected to the southeast of this obstruction.

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