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Composition and location of volatiles at Loki Patera, Io

Robert R. Howell [a,*,1], Claire E. Landis [a], Rosaly M.C. Lopes [b]

[a] Dept. of Geology & Geophysics, University of Wyoming, Laramie, WY 82071, United States
[b] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, United States

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ABSTRACT

Volatiles play a critical role in determining the nature of volcanic activity on Earth, but their role in the volcanism on Io is less clear. To help determine that role we analyze Voyager and Galileo images of Loki Patera. Loki is the largest caldera in the Solar System and Io's most powerful volcano, however its eruptive behavior is still not understood. It appears to be relatively volatile poor, in comparison to other sites like Pele where volatiles drive a 350 km high plume. A resurfacing wave, either from spreading flows or from foundering of a lava lake crust, periodically sweeps around Loki Patera. Photometry from Voyager I and II violet and blue images shows that most of the features in and around Loki have colors well matched by macroscopic mixing of sulfur and basalt. The dark western portion of the patera has the color of bare basalt. Assuming such a macroscopic sulfur–basalt mix, in the Voyager I images most of the rest of the patera appears to be covered with a background of 13–38% sulfur. We infer this background sulfur was deposited from the nearby plume observed by Voyager I and II. The surface of the patera is also dotted by numerous small bright areas which have colloquially been called "bergs". We find that they are also composed of sulfur, with coverage ranging up to 100%. Darker regions adjacent to the patera, such as the "southwest overflow", are a mixture of intermediate amounts of sulfur and basalt. The "bathtub ring" at the edge of the overflow is again roughly 100% sulfur, perhaps with significant amounts of SO_2 included. Colors seen during the Voyager II flyby are also consistent with this general pattern, but most of the patera has a sulfur abundance higher than that seen in Voyager I, while the then-dark southern portion is again close to the reflectance of bare basalt. We have also analyzed the spatial distribution of the bergs. They clearly avoid the inner and outer margins of the patera, and they also avoid each other. While a simple explanation of the above patterns could be that the bergs are fumarolic sulfur deposited on a periodically resurfaced lava lake crust, other observations seem inconsistent with that simple model. Careful comparison of Voyager I and Galileo data shows that the largest bergs in the southern patera have survived the intervening 22 years. This requires that at least those larger bergs represent some more permanent feature, perhaps higher standing kipuka, which avoid inundation by the lava resurfacing wave.

1. Introduction

Volatiles play a critical role in determining the nature of volcanic activity on Earth, but their role in the volcanism on Io is less clear. While water and carbon dioxide are absent on Io, sulfur and sulfur compounds are clearly present and appear to vary considerably among volcanic centers. However abundance estimates are rare and highly uncertain. Also uncertain is how the volatiles participate in the general recycling of the crust. Most of Io's heat is thought to be brought to the surface by advection of silicate magma which then spreads horizontally, cools, solidifies, then subsides more-or-less uniformly on a global scale until it reaches some melting depth (O'Reilly and Davies, 1981). However the fraction of sulfur and sulfur dioxide in the crust, the depth to which these subside before melting and presumably separating from the still-solid silicates, and the manner in which they are incorporated back into rising magma, is largely unknown (Leone et al., 2011). Variations in how this occurs presumably explain why some sources such as Pele are volatile rich (McEwen and Soderblom, 1983; Howell and Lopes, 2011), while other sources such as Loki Patera appear volatile poor (Howell and Lopes, 2007; Matson et al., 2006; Rathbun et al., 2002; Rathbun and Spencer, 2006).

We previously reported on the volatile content of Pele (Howell and Lopes, 2011) and here address the volatile content of Loki Patera. We are concerned primarily with those sources where the volatiles appear to erupt with the magma. Therefore we do not address in this paper the very different Prometheus class plumes created when silicate magma flows onto surface sulfur-dioxide frost fields, vaporizing that frost (Kieffer et al., 2000; Milazzo et al.,

* Corresponding author.
E-mail addresses: rhowell@uwyo.edu (R.R. Howell), claire.landis@gmail.com (C.E. Landis), Rosaly.M.Lopes@jpl.nasa.gov (R.M.C. Lopes).
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2001; McEwen and Soderblom, 1983). We note that the Loki Plume, seen by Voyager to be erupting from what appeared to be a fissure approximately 100 km NE of the closest edge of Loki Patera (Fig. 1), is in retrospect likely to be a Prometheus class plume and the "fissure" is most likely a lava flow field (John Spencer, personal communication). While our primary focus is on volatiles originating from the magma in Loki Patera, we also discuss the effects of the nearby plume.

Loki Patera provides a useful target for this work not only because of its apparent low volatile abundance, but because it is one of the most important and best studied hot spots on Io. It is the largest patera on Io, approximately 200 km in diameter, and contributes approximately 10% of the total heat flow from Io z(Veeder et al., 2012; Spencer et al., 2000). It was recognized as an infrared hot spot by Voyager I (Hanel et al., 1979) which also imaged the plume coming from the west end of the nearby Loki "fissure" flow field (Smith et al., 1979b). Four months later Voyager II showed a plume coming from the east end of the "fissure" flow field as well, and obtained lower resolution images which showed that the eastern and northern patera had lightened, apparently being covered by plume fallout, while the southern patera remained dark. Therefore it was a surprise when Galileo images showed its appearance had reverted to something much closer to the Voyager I state, with most of the patera relatively dark. Galileo also discovered that the "fissure" plume had ceased. Unfortunately Galileo's orbit resulted in most Io flybys viewing the opposite hemisphere and it obtained only limited resolution images of Loki. But infrared observations with NIMS did reveal morphology, such as higher temperatures near the margins, which seemed consistent with a crusted-over lava lake (Lopes et al., 2004).

Because of its large thermal output, Loki has been readily observable from Earth in the infrared. Those observations revealed, during the 1990s, a pattern of semi-periodic activity (Rathbun et al., 2002; Rathbun and Spencer, 2006). A wave of infrared brightening, lasting a little over 200 days, appears to sweep counterclockwise around the patera roughly every 540 days. Spencer et al. (2000) reported Galileo Photopolarimeter-Radiometer (PPR) observations from the I24 flyby showing hot material in the southwest section, which they attributed to either spreading flows or an overturning lava lake. Rathbun et al. (2002) further developed the model of periodic foundering of a lava lake crust. The crust is initially buoyant because of vesicles, but as the crust thickens vesicles become smaller, the crust becomes too dense, and a wave of foundering ensues. Rathbun and Spencer (2006) reported that as of 2001 the period of the activity lengthened (and became more irregular) and they speculate the change may be due to a small change in volatile content. Matson et al. (2006) further developed the crust-vesicle model and examined other thermal aspects of the activity. Howell and Lopes (2007) refined the analysis of the Galileo-NIMS observations from the 2001 I32 encounter. Those observations reveal the detailed progress of the thermal wave in the southern patera (see the time contours in Fig. 1), and also revealed other puzzling aspects of the thermal pattern discussed later.

While the foundering wave model addresses many aspects of the observations, this type of organized foundering is different than that seen on terrestrial lava lakes. Perhaps that is due to the much larger spatial scale of Loki. However other models which might produce the wave, such as spreading flows (Davies, 2003; Gregg and Lopes, 2008) have also been proposed. In this paper we examine the details of the reflectivity of Loki Patera to estimate surface volatile abundances and composition, and examine temporal variations between Voyager I, Voyager II, and Galileo, to further define the role of volatiles and to test the viability of the various brightening wave models.

One of the major characteristics of Loki Patera is the set of small bright spots scattered across the dark patera surface. They were colloquially called "bergs" immediately after the Voyager I encounter, when the patera was thought to be a large molten sulfur lake (hot-enough liquid sulfur is dark), and these were thought to perhaps be solid sulfur bergs floating in that sulfur lake. Since then detailed thermal models (Carr, 1986; Davies, 1996; Howell, 1997) have clearly shown that molten silicates, covered by a solidified

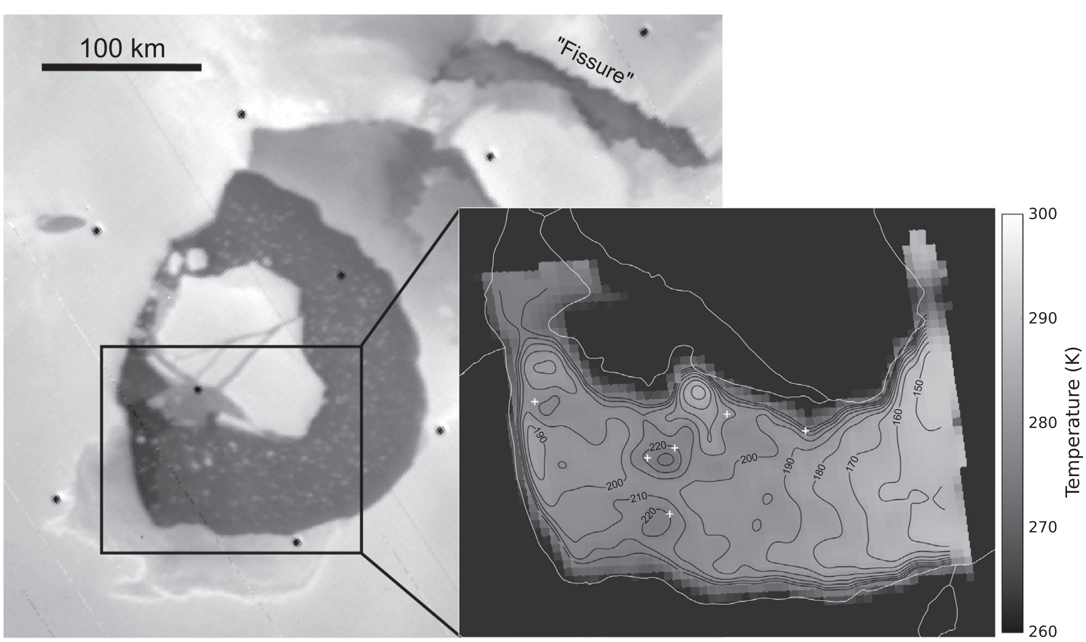

Fig. 1. The best image of the Loki region (Voyager I 1979, blue filter) and Galileo-NIMS (2001) thermal observations. The NIMS observations were taken after one of the periodic resurfacing waves had swept counterclockwise around the patera. The gray-scale tone gives the temperature of the patera surface, and the contours give the temperature-derived model age in days (Howell and Lopes, 2007). The wave advances approximately one km/day counterclockwise around the patera. To aid in comparison an outline of the patera is shown in white, and 6 prominent bergs are marked with crosses. As discussed in Section 4 the pair near the upper 220 day contour appear to be long-lived features. The blue image covers 7.80–20.00°N, 299.92–314.00°W. In this and all our images, north is up.