

Temperature, age and crust thickness distributions of Loki Patera on Io from *Galileo* NIMS data: Implications for resurfacing mechanism

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Received 8 August 2003; accepted 4 September 2003; published 15 November 2003.

[1] A high-spatial-resolution, multi-wavelength observation by the *Galileo* NIMS instrument has been analysed to determine the temperature and area distribution of a large portion of the ionian volcano Loki Patera. The temperatures of the cooler components from a two-temperature fit to the data can be used to determine ages of the surface. The age of the floor along a profile across the floor of the caldera ranges from ~ 10 to ~ 80 days. This puts the start of the resurfacing in July/early August 2001, yielding a resurfacing rate of approximately 1 km/day, with the new lava spreading from the SW corner of the caldera in a NE direction. This rate is consistent with resurfacing by foundering of the crust on a lava lake. However, the temperature distribution may also result from the emplacement of flows. Implied crust thicknesses (derived using a lava cooling model) range from 2.6 to 0.9 m. **INDEX TERMS:** 5465 Planetology: Solid Surface Planets: Rings and dust; 5480 Planetology: Solid Surface Planets: Volcanism (8450); 6218 Planetology: Solar System Objects: Jovian satellites; 8040 Structural Geology: Remote sensing; 8414 Volcanology: Eruption mechanisms. **Citation:** Davies, A. G., Temperature, age and crust thickness distributions of Loki Patera on Io from *Galileo* NIMS data: Implications for resurfacing mechanism, *Geophys. Res. Lett.*, 30(21), 2133, doi:10.1029/2003GL018371, 2003.

1. Introduction

[2] The ionian volcano Loki Patera is the most powerful volcano in the Solar System, with a thermal output that at times is as much as 25% of Io's global output. Debate about the origin and volcanic style at Loki centers on whether Loki is a lava lake or is resurfaced with flows [Davies, 1996; Rathbun *et al.*, 2002]. An active lava lake is truly a window into the interior of a planet, being an open system through which volumes of lava circulate between deep reservoirs and the surface. Study of the visible surface expression of this activity allows modelling of supply mechanism and volumetric rates. So far, only Pele exhibits all of the characteristics of an active lava lake on Io [Davies *et al.*, 2001a], although lava lakes have been proposed at other locations [Radebaugh *et al.*, 2002]. A high-spatial-resolution, multi-wavelength observation was obtained by the *Galileo* Near Infrared Mapping Spectrometer (NIMS) of part of the Loki caldera on 16 October 2001 during orbit I32. This observation allowed a close look at the temperature and area distribution on the floor of the caldera, from which has been determined surface age and crust thickness distributions.

2. Observations of Loki

[3] Prior to 1999, only low-spatial-resolution infrared images of Loki existed, obtained by ground-based telescopes, instruments on the *Voyager* spacecraft, and by *Galileo* from great distances. Loki, even with a diameter of more than 150 km. was always sub-pixel in these infrared data. Nevertheless, this allowed charting of Loki's volcanic output as a function of wavelength, and also fits of *Galileo* NIMS data that showed that a small part of Loki was at silicate temperatures [>1000 K; Davies *et al.*, 2000a]. Additionally, Loki was seen faintly in eclips by the visible wavelength imagers on both *Galileo* and *Cassini*, indicating the probable presence of silicate volcanism [Davies *et al.*, 2001b]. From an analysis resulting from charting the 3.5 and 3.8 micron thermal output from Loki, Rathbun *et al.* [2002] concluded that Loki demonstrated a periodicity of activity. This period of activity (540 days) reinforced the idea that Loki was a lava lake, with the periodicity caused by the thickening of a crust on the lake with time, and the eventual foundering of the crust in a relatively quiescent fashion. This is a different mechanism to the 'plate tectonic' lake resurfacing style proposed by Davies [1996]. The Rathbun *et al.* analysis fitted *Galileo* Photo-Polarimeter Radiometer (PPR) data of Loki, which showed an apparent resurfacing wave first seen moving in the southern part of the caldera, and then in the eastern part of the caldera some months later. The implication was that a resurfacing wave was moving in a counter-clockwise direction around the caldera, starting in the always-active south-west margin [Spencer *et al.*, 2000]. NIMS also obtained a high-resolution observation in October 1999 that indicated that parts of the margin of the caldera were active [Lopes-Gautier *et al.*, 2000].

[4] *Galileo* NIMS obtained 32INTHLOK101, a high-spatial-resolution observation (~ 3 – 5 km per pixel) of a large portion of the Loki Patera floor in October 2001 (Figure 1). Each pixel spectrum had up to 12 wavelengths in the range 1 to 5 microns. For the first time, detailed thermal modelling of the caldera floor was possible. Study of the 1 micron image showed an active western edge of the caldera, and areas along the southern edge that might be indicative of intense activity (evidence of exposure of high-temperature lava).

3. Resurfacing of Loki: Lake or Flows?

[5] The question of resurfacing mechanism at Loki is perplexing. Loki may be a massive lava lake, but if it is, it is many orders of magnitude larger than terrestrial lava lakes. For example, the permanent lava lake at Erta Ale in Ethiopia is less than 100 m across [Barberi *et al.*, 1973]. Loki spans over 180 km. Additionally, the distribution of surface temperatures from a slowly overturning lava lake, and from

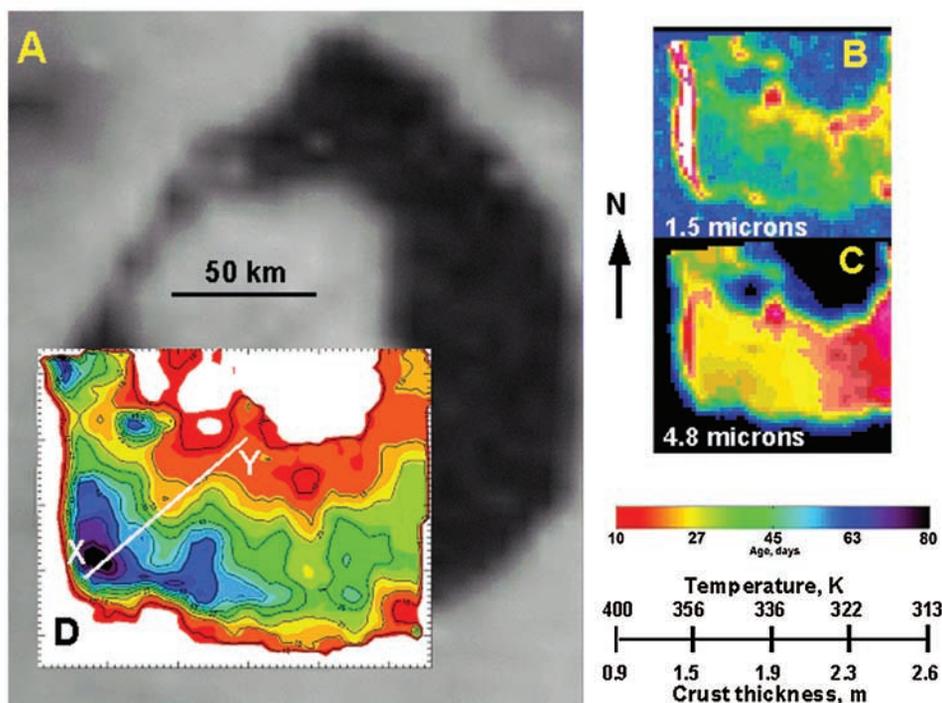


Figure 1. Image (A) is the highest resolution SSI image of Loki. The NIMS 32INTHLOKI01 Loki observation of 10 OCT 2001 is shown at 1.5 (B) and 4.8 microns (C) showing areas of greatest intensity in white. The derived age distribution (ranging from 10 to 80 days) of the surface (D) is superimposed on the SSI image. The youngest crustal areas are at the greatest distances from the active western edge of the patera. The oldest surface is adjacent to the active area in the southwest of the Patera. A resurfacing wave has propagated diagonally across the floor of the caldera towards the NE. Crust thickness and cool-component temperature scales are also shown. Implied crust thickness is derived from surface temperature using the method of *Head and Wilson* [1986], applied to Io by *Davies* [1996].

resurfacing by laminar, inflating flows may produce similar temperature and area distributions, as shown for Loki by *Davies* [1996]. This complicates diagnosis of resurfacing mechanism from temperature and area distribution alone.

4. Temperature Fits to NIMS Loki Data

[6] It is possible to derive surface ages for each pixel in the 32INTHLOKI01 observation by determining how long exposed silicate lava takes to cool to the observed temperature. However, firstly, the temperature of the surface has to be determined. This was achieved by fitting each NIMS spectrum (for each pixel) with the two-temperature black body model used by *Davies et al.* [1997]. Two-temperature fits to NIMS data generally yield a small-area, high-temperature component that corresponds to newly exposed or recently emplaced lavas, and includes new lava breakouts and thermal emission through cracks in crusts on lava flows and lava lakes. The cooler component corresponds to the relatively much cooler crust. In this case, the number of variables can be reduced from four (two temperatures and two areas) to three by fixing the temperature of the hot component. This is a reasonable assumption to make, considering the scenario being tested. If the surface observed at Loki is the recently-emplaced crust on a lava lake, as proposed by *Rathbun et al.* [2002] then any crack through the crust to the molten material beneath will expose the same temperature. Two-temperature fits to the NIMS Loki data were made, and two checks on the accuracy of the model fits

carried out. Firstly, the ages determined from the NIMS observation ‘tube’ product (a raw data product which has not been re-projected to remove the 50% mirror-swathe overlap, a process that involves averaging a pixel emission value with those of its neighbors; see *Davies et al.* [2000b]) were compared with ages determined from the re-projected data ‘cube’ product, and it was found that the difference was less than 9 days between the products. This was an indication that the temperature variation across adjacent pixels was relatively very small. Secondly, the total area of the hot and cool components was compared with the total area of the pixel. The two-temperature model was run iteratively on a number of randomly chosen samples, fixing the high-temperature component at temperatures from 1400 K to 500 K to determine at which high-component temperature the NIMS pixel was filled by both component areas. Some pixels were clearly better fitted with a single, low temperature: in these cases, the area of the hot component was so small as to make little difference to the total hot + cool component area. Therefore, for the bulk of the floor of Loki, the ‘hot area’ temperature is approximately 630 K, and the low temperature component is typically in the range 400 K to 320 K, although there are some isolated pixels at temperatures as low as 260 K and as high as 580 K.

5. Deriving the Age of Loki’s Surface

[7] From the temperature distribution derived for the caldera floor, an age can be determined for each pixel from

the cool (crust) temperature. Age is derived by fitting the temperature to a cooling curve for emplaced lava in an Ionian environment [Davies, 1996] using basalt thermal characteristics [Davies *et al.*, 2001a]. The cooler a surface, the lower the subsequent cooling rate. For a semi-infinite body with a crust temperature of 400 K, this leads to an age of 10 days, with an error of +2 days and -1.5 days, based on the cooling of such a basalt lava body on Io. This body cools to 320 K in about 80 days.

[8] What is the significance of the 630 K high temperature, which is much less than the liquidus temperature of basalt (~1450 K)? This can be explained by considering two processes. From the eruption temperature, cooling of newly exposed lava is rapid and dominated by radiative cooling. An insulating crust thickens with time on the upper and lower surfaces of the lava body. Beneath the brittle crust is a visco-elastic zone [e.g., Harris *et al.*, 1998] at a temperature from the crust base temperature to approximately 1100 K, beneath which is a lower-viscosity molten core at high (liquidus, or near-liquidus) temperature (1470 K). Stresses in the crust lead to the formation of cracks, which may extend down into the molten core of the lava. As time passes, the crust thickens. Cracks may extend down only to the visco-elastic zone or remain in the crust, so the high temperatures of the molten interior are not exposed. With effusive activity appearing to dominate at Loki, the formation of both stable crusts and visco-elastic zones can take place, leading, over time, to the observed temperature distribution. The second possible explanation is that the hot bases of the cracks are not seen due to viewing geometry [Stansberry, 1999], but a viewing angle of ~25 degrees, as with this observation, should have little effect. Volcanism at Loki is apparently non-explosive. The Solid State Imaging experiment on *Galileo* observed Loki during the time when Loki was emitting the most energy as seen by NIMS in the 0.7 to 5.2 micron range (i.e., in June 1997, during orbit C9: see Davies *et al.* [2000a]) but saw only a faint high-temperature component at Loki at this time, or any other. This may have possibly been due to a wide distribution of cracks, diffusing the thermal energy; or because, at the time of the observation, the emplacement of material was taking place in a very low-energy, effusive manner, there was little disruption of the crust to create cracks and breakouts of high-temperature, molten lava; or a stable, thick crust had formed with relatively cool cracks. There was no evidence of explosive activity at Loki in any *Galileo* data, implying a low gas-content of the lava.

[9] Figure 1d shows the age distribution of the surface of the floor of Loki Patera. The most intense (thermally active) and hottest pixels are found at the western edge of the caldera, with some other intense pixels located around the remainder of the edge of the caldera. According to the cooling model used these pixels have a very young age. The bulk of the floor of the caldera has a surface age of between 80 in the west to only 10 days in the north-east of the observation. It appears that the active front of resurfacing was not covered in this observation. Figure 2 shows the profile across the steepest age gradient of the caldera floor. If this is an indicator of the direction of resurfacing, then the resurfacing process starts in the SW corner of the caldera and moves diagonally across the floor in a roughly NE direction. The rate of movement of the resurfacing is

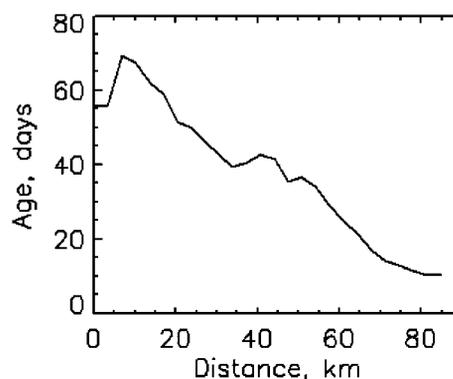


Figure 2. Example age profile across the floor of the caldera from X (sample 29, line 18) to Y (sample 54, line 36) in Figure 1. Dividing the distance covered from the peak at ~10 km from the start of the profile (78 km) by the age difference (60 days) yields an average rate of resurfacing of ~1 km/day.

approximately 1 km per day, again consistent with the observations of Spencer *et al.* [2000] and Rathbun *et al.* [2002] of previous resurfacing episodes.

[10] With a maximum surface age (from modeling) of ~80 days, this would put the start of this resurfacing episode sometime around July 27th 2001.

6. Crust Thickness

[11] The Davies [1996] model derives the age of the surface by considering the formation of a crust through which heat is conducted from the molten interior of the lava body. The surface temperature is a function of the age of the flow, the physical properties of the lava, and the thickness of the crust that has formed at this time [Head and Wilson, 1986; Davies, 1996; Howell, 1997]. From the determination of temperature, age is calculated for flows in an ionian environment, and additionally, flow crust thickness is also derived during this calculation [see Davies, 1996]. Ranges of thicknesses are from 2.6 m in the west, close to the active western margin of Loki Patera, to 0.9 m in the north-east of the observation. This is a minimum thickness for lava flows. If these flows are thinner than 2.6 m then cooling would have been more rapid than if the flows were buffered by release of latent heat. This would mean that resurfacing progressed at a faster rate across the floor of the caldera if the mechanism was thin flows, and the flow surfaces are younger than in the lava lake (thermally-buffered) case.

7. Direction and Rate of Resurfacing

[12] Taking the direction of resurfacing as being in the direction as the steepest age gradient, the analysis reveals a movement diagonally across the flow of the caldera, starting in the southwest corner of the caldera (the areas of lowest albedo and highest thermal activity, and suggested as the starting point of resurfacing by Spencer *et al.* [2000]). This also explains how resurfacing activity at Loki changes from West-to-East to South-to-North around the 'island' in a seemingly coherent way, without the outside edge of the resurfacing wave needing to move faster than the inside

edge to produce the observed PPR observations. Study of the PPR data, obtained at low spatial resolution, indicates that a diagonal resurfacing wave is not unreasonable.

8. Discussions and Conclusions

[13] Is Loki a huge lava lake? Although the ‘resurfacing wave’ theory is attractive for a lava lake, as is the idea that active margins may indicate the presence of a lava lake at this and other locations on Io [Lopes *et al.*, 2003], there are other mechanisms that must be considered. Firstly, the caldera may be being covered by lava flows. These flows would need to be thicker than the derived crustal thicknesses. Flows that may be inflating and spreading across the floor of the caldera would produce similar temperature distributions as the lava lake model [Davies, 1996]. The active spots along margins proposed as the breakup of a lava lake crust could be where these flows are breaking out at the margins of lateral extent, or even where lava is first reaching the surface. Loki may be a large, ponded lava flow. The important difference between a lava pond, essentially a confined flow, and an active lava lake is that the active lava lake feature is in balance with the subsurface supply mechanism and thus reveals through energy output the mass flux, which in turn can be used to determine the interior plumbing of the volcano [see Harris *et al.*, 1999; Davies, 2003]. A ponded flow cannot be treated in the same way, as the resulting mass and energy fluxes are determined by topography (which we do not know) more than mechanism of supply. It may be that the true nature of Loki will not be known until further observations are made, perhaps from within the jovian system at high spatial and temporal resolutions during a resurfacing episode. Such data may be obtainable remotely with adaptive optics. High-temporal resolution observations of the evolution of the temperature and area distribution should reveal the mechanism that makes Loki tick. Until then, this current analysis of crustal thickness (and by implication, crust mass distribution) will allow further modelling of lava emplacement at Loki and elsewhere on Io. Crust thicknesses alone can be used in modelling minimum possible flow thicknesses for the resurfacing by flows mechanism [Davies *et al.*, 2003], and for constraining flow formation and foundering mechanisms for the ‘overturning lava lake’ model.

[14] **Acknowledgments.** This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. The author is supported by a NASA Planetary Geology and Geophysics grant. AGD thanks Julie Rathbun and Dave Williams for their

reviews, and Alison Canning Davies for catching a whopping typo in the proofs.

References

- Barberi, F., J. L. Cheminee, and J. Varet, Long-lived lava lakes of Erta Ale volcano, *Rev. Geograph. Phys. Geol. Dynam.*, 15, 347–352, 1973.
- Blaney, D. L., T. V. Johnson, D. L. Matson, and G. J. Veeder, Volcanic eruptions on Io: Heat flow, resurfacing and lava composition, *Icarus*, 113, 220–225, 1995.
- Davies, A. G., Io’s volcanism: Thermo-physical models of silicate lavas compared with observations of thermal emission, *Icarus*, 124, 45–61, 1996.
- Davies, A. G., A. S. McEwen, R. Lopes-Gautier, L. Keszthelyi, R. W. Carlson, and W. D. Smythe, Temperature and Area Constraints of the South Volund volcano on Io from the NIMS and SSI Instruments during the Galileo G1 orbit, *Geophys. Res. Lett.*, 24, 2447–2450, 1997.
- Davies, A. G., et al., Eruption evolution of major volcanoes on Io: Galileo takes a close look, *Lunar. Plan. Sci. Conf. XXXI, abstract on CD-ROM*, 2000a.
- Davies, A. G., et al., Silicate cooling model fits to Galileo NIMS data of volcanism on Io, *Icarus*, 148, 211–225, 2000b.
- Davies, A. G., et al., Thermal signature, eruption style and eruption evolution at Pele and Pillan on Io, *J. Geophys. Res.*, 106, 33,079–33,104, 2001a.
- Davies, A. G., et al., Temperature-area determination from observations of Loki by Galileo and Cassini, *BAAS*, 33, no. 3, p. 1029, 2001b.
- Davies, A. G., The pulse of the volcano: Discovery of episodic volcanism at Prometheus on Io, *Lunar. Plan. Sci. Conf. XXXIV, abstract 1455*, 2003.
- Davies, A. G., D. L. Matson, G. J. Veeder, T. V. Johnson, and D. L. Blaney, Lava flows on Io: Modelling cooling after solidification, *Lunar. Plan. Sci. Conf. XXXIV, abstract 1460*, 2003.
- Harris, A. J. L., et al., Calculation of lava effusion rates from Landsat TM data, *Bull. Volc.*, 60, 52–71, 1998.
- Harris, A. J. L., et al., Mass flux measurements at active lava lakes: Implications for magma recycling, *J. Geophys. Res.*, 104(B4), 7117–7136, 1999.
- Head, J. W., and L. Wilson, Volcanic processes and landforms on Venus: Theory, predictions and observations, *J. Geophys. Res.*, 91, 9407–9466, 1986.
- Howell, R. R., Thermal emission from lava flows on Io, *Icarus*, 127, 394–407, 1997.
- Lopes-Gautier, R., et al., A close-up look at Io in the Infrared: Results from Galileo’s Near Infrared Mapping Spectrometer, *Science*, 288, 1201–1204, 2000.
- Lopes, R., et al., Paterae on Io: Volcanic activity observed by Galileo’s NIMS and SSI, *Lunar. Plan. Sci. Conf. XXXIV, abstract 1837*, 2003.
- Radebaugh, J., A. S. McEwen, L. P. Keszthelyi, M. Milazzo, and A. G. Davies, Lava Lakes in Io’s Paterae: Surface expressions of subsurface processes, *Eos Trans. AGU*, 83(47), *Fall Meet. Suppl., Abstract P12C-12*, 2002.
- Rathbun, J., J. R. Spencer, A. G. Davies, R. R. Howell, and L. Wilson, Loki: A predictable volcano?, *Geophys. Res. Lett.*, 29, no. 10, 84–88, 2002.
- Spencer, J. R., et al., Io’s thermal emission from the Galileo Photopolarimeter-Radiometer, *Science*, 288, 1198–1201, 2000.
- Stansberry, J. A., Thermal emission from Io’s lava flows: Spectral dependence on Emission angle, *Lunar. Plan. Sci. Conf. XXX, abstract 2009*, 1999.
- Veeder, G. J., D. L. Matson, T. V. Johnson, D. L. Blaney, and J. D. Goguen, Io’s heat flow from infrared radiometry: 1983–1993, *J. Geophys. Res.*, 99, 17,095–17,162, 1994.

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