An Extensionally Fractured Upper Lithosphere on Io

Paul K. Byrne[1*], Rosaly M. C. Lopes[2], Jani Radebaugh[3], and David A. Williams[4]

[1]Washington University in St. Louis, St. Louis, MO 63130, USA.

[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.

[3]Brigham Young University, Provo, UT 84602, USA.

[4]Arizona State University, Tempe, AZ 85287, USA.

*Corresponding author: Paul Byrne (paul.byrne@wustl.edu)

Key Points:

- A distinctive polygonal "island" in Io's largest patera may be a fractured crustal block
- There are numerous other indicators for a pervasively fractured Ionian lithosphere
- We propose a lithospheric model for Io with major shortening and extensional tectonics in the lower and upper portions, respectively

Abstract

The Jovian moon Io features hundreds of paterae, broad depressions often filled with lava. The largest such example, Loki Patera, features a large, polygonal, and fractured island in its center. This island may reflect the fragmentation of the upper Ionian lithosphere by a shallow magma body, facilitated by a great number of shallow extensional structures. We propose a model for the Ionian lithosphere in which the upper portion is heavily deformed by joints, normal faults, and graben resulting from combined tidal, subsidence, and thermal stresses, and a lower portion rife with major thrust faults formed by horizontal compression of deeper crustal levels from the continued burial of surface units. Some of those thrusts may be reactivated normal faults. An extensionally fractured upper lithosphere accounts for the Loki Patera island, for observations of more than 175 paterae with straight edges, for the fact that almost 95% of Io's surface is covered with volcanic flow and plains units, and for widespread instances of mass wasting within Io's gigantic mountain blocks. Additional, high-resolution image and topographic data are required to test this hypothesized model for the moon's lithosphere.

Plain Language Summary

Io is a large moon of Jupiter, and one of the most volcanically active bodies in the Solar System. Io has a distinctive landform type called "paterae" ("patera" in singular form), which are essentially large depressions filled with lava. The biggest patera is called Loki Patera, and in its middle is a polygonal island. We interpret this island as a fractured block of Io's crust. If this interpretation is correct, then it is possible that much of the upper portion of Io's crust is riddled with extensional fractures caused by several overlapping processes. A huge number of extensional fractures explains other aspects of Io's geology, such as the fact that almost half of all the moon's paterae have straight edges—which is something we'd expect to happen if paterae form in a heavily extensionally fractured crust. Io also has gigantic mountains, which are formed by compression of the lower crust as tremendous amounts of

lava erupt and bury everything around them. But even those mountains show lots of extensional tectonic structures, which provide further support for our idea about Io's crust.

1 Introduction

Jupiter's rocky moon Io is replete with towering mountain blocks (Schenk et al., 2001) and lava flows that cover virtually the entire surface (McEwen et al., 1998; Williams et al., 2011). Internal heat energy is principally supplied by tidal interactions with Jupiter and its neighboring moons (Peale et al., 1979). Chief among the satellite's most notable landforms are the paterae, broad depressions that are widespread and commonly filled with lavas (Radebaugh et al., 2001).

First described by Carr et al. (1979), paterae (*sing*. patera) are quasi-circular, shallow depressions with curved, straight, or scalloped edges. These landforms may be the Ionian equivalent to the calderas seen on Earth, Venus, and Mars, but a formation via collapse into a subsurface void space—the principal means by which calderas form (Lipman, 1997)—has yet to be confirmed for Io's paterae. Radebaugh et al. (2001) identified at least 417 paterae (425 including nested features: Williams et al., 2011) distributed across the ~80% of Io imaged at 2 km/pixel or better, with diameters ranging from 2.5 to 202.6 km.

That largest patera is Loki, situated in Io's eastern hemisphere. Loki Patera features a prominent "island" in its center (Lopes-Gautier et al., 2000). Dark lines that cross this island are suggestive of tectonic lineaments—raising the possibility that the island is a fractured crustal block. If so, then the break-up of this block may offer valuable insights into the properties and tectonic state of Io's lithosphere.

2 The Loki Patera Island

Seen with combined data from the Voyager 1 Imaging Science Subsystem narrow-angle camera and the Galileo Solid-State Imaging System (SSI) camera (Figure 1a), the island is distinctly polygonal in

74 outline and measures approximately 115 × 110 km in spatial extent along its north–south and east–west
75 axes, respectively. A prominent lineament about 85 km long strikes east–northeast across the island,
76 with two additional linear features (55 and 30 km long, respectively) striking to the northeast and
77 abutting the first. Each of these features is ~2–3 km across. Smaller polygonal "islands" are present to
78 the northwest and southwest of the larger block, and the dark patera floor is dotted with bright spots
79 (termed "bergs") that may be locally high-standing topography and/or surface deposits (Howell et al.,
80 2013).

81 The morphology of these lineaments strongly suggests that they are extensional tectonic structures.
82 Although lava flows can be much longer than they are wide, they tend to show digitate ends and widen
83 with distance from their source vents (e.g., Carr et al., 1977) and so are not morphologically consistent
84 with the Loki Patera island lineaments. Neither are other geological landforms that can have relatively
85 linear planforms, such as mass-wasting deposits nor secondary crater chains (of which no examples are
86 yet known for Io). Dikes often have straight margins that extend for tens of kilometers or more, but on
87 that scale are bounded by steep, near-vertical fractures (e.g., Ernst et al., 2001). We therefore interpret
88 these lineaments as being extensional in nature, either tensile fractures (i.e., joints) or, more likely
89 given their scale, are paired, antithetic, inward-dipping normal faults (i.e., graben).

90 Near-Infrared Mapping Spectrometer data returned by the Galileo mission indicate that both the
91 patera floor and the material within these fractures are warmer than the island and the plains
92 surrounding the patera (Lopes-Gautier et al., 2000); these thermal characteristics are shared by many
93 other paterae on Io (Radebaugh et al., 2001). Per our reasoning, the Loki Patera island is in fact several
94 discrete (but formerly contiguous) blocks that have rafted apart in a manner akin to pack ice, and the
95 material between the blocks is the lava the covers the entire patera floor. Comparison of image data of
96 Loki Patera from the Galileo and Voyager missions indicate that the island and its constituent fractures
97 show no resolvable change in position or size over the intervening two decades (Lopes-Gautier et al.,
98 2000). Moreover, the kinetic and thermal effects of two concurrent resurfacing "waves" observed in

March 2015 did not appear to disrupt or destroy the island, strongly indicating that this feature has persisted for at least the 36 years since its discovery in 1979, and that it may now be sitting on, or is anchored to, the patera floor (de Kleer et al., 2017).

3 Implications for Ionian Volcanotectonics

3.1 Patera Formation

As large, irregular depressions overwhelmingly associated with lava flows, paterae have been interpreted as the Ionian counterparts to calderas on Earth, Venus, and Mars (e.g., Carr et al., 1979). Yet calderas on those worlds are generally characterized by quasi-circular or arcuate outlines (Crumpler et al., 1996) and peripheral zones of crustal extension (Walter and Troll, 2011), and are frequently associated with voluminous deposits of lava, ash, or both (Lipman, 1997). Indeed, 42% of the 417 paterae surveyed by Radebaugh et al. (2001) have straight or irregular margins that terminate at sharp corners (e.g., Figure 2). Adjacent extensional structures are not commonly observed, although this dearth of extensional tectonics may be a function of available image resolution and Io's prodigious global resurfacing rate of ~1.5 cm/yr (Kirchoff and McKinnon, 2009). And no volcanic deposits of sufficient volume to match the observed depression have been unequivocally recognized proximal to, and having come from, any patera (Keszthelyi et al., 2004).

Paterae may instead be the result of the stalling of silicate magma at shallow depths that undermines the overlying crust, particularly if that crust is SO_2 rich and porous (Keszthelyi et al., 2004). Under this scenario, the heat from an intrusion melts sulfur and/or SO_2, which mobilizes into the surrounding country rock and leaves behind pore space. With continued melting, a substantial depression forms or the magma chamber can even be fully unroofed (Keszthelyi et al., 2004). By this view, Io's paterae differ from conventional calderas by forming not because of the eruption or lateral withdrawal of magma but by the migration of volatiles through a crust that becomes increasingly porous or otherwise mechanically weak (cf. Kargel et al., 1999).

Regardless of the means of collapse, the disruption of a magma chamber roof would be readily enhanced by pre-existing extensional fractures in the crust—such as those that cross the Loki Patera island. We infer that these structures predate the formation of Loki Patera for two reasons: a) they do not have a spatial distribution or arrangement consistent with extensional strains associated with magma chamber tumescence or collapse (e.g., Walter and Troll, 2001); and b) at tens of km long, their dimensions are comparable to the lengths of those portions of other paterae margins that are straight and have been interpreted to reflect tectonic control (e.g., Radebaugh et al., 2001).

It may be, then, that the island is a remnant of fractured crust that overlaid and foundered into a shallow, stalled magma body. The rest of the roof material might even have been subsumed by lava entirely, accounting for why there are few similar, fractured islands in other paterae. (Some other paterae have islands, such as the 28 km-diameter Steropes Patera (Radebaugh et al., 2001) or the 75 km-wide Tupan Patera (Black, 2006), but available image data are insufficient to survey all such examples on Io, or determine how many, if any, are also fractured.) Further, should the Loki block be sitting on the patera floor, sufficiently anchored so as to remain seemingly stationary at least since its first observation in 1979 (de Kleer et al., 2017), then it follows that as a result of the creation of void space in the subsurface, the block's upper surface should be lower than the surrounding plains. Lava from floor eruptions could then exploit and undermine fractures in the island to thermally erode and enlarge them, such that those structures become visible at Voyager image resolutions.

3.2 Fracturing of the Ionian Upper Lithosphere

The fractured block in Loki, the finding of almost half of all paterae having straight margins, and the fact that some patera walls are steep and stand kilometers tall—such as the margins of Chaac Patera, which are 2.7 km high and have slopes of 70° (Radebaugh et al., 2001)—together imply strong tectonic control on the formation of at least some paterae. Certainly *thrust* faults are widespread on Io, with the straight margins of many of the moon's enormous mountain blocks (Figure 3) taken as evidence of

149 shortening tectonics, attributed to subsidence of the crust under continually emplaced lavas (Schenk
150 and Bulmer, 1998; Turtle et al., 2001).

151 But there are reasons to expect substantial *extensional* deformation of the upper Ionian lithosphere,
152 too. For example, temporally and spatially localized decreases in eruptive activity, set against a
153 backdrop of sustained tidal heating, are predicted to generate considerably large, horizontally
154 compressive stresses deep in the Ionian crust, but horizontally extensional stresses near the surface
155 (McKinnon et al., 2001; Kirchoff et al., 2020). Similarly, the formation of Io's gigantic mountain
156 blocks along deep-seated thrust faults is thought to be accompanied by widespread extension and the
157 formation of normal faults and graben (Bland and McKinnon, 2016). Some of these extensional
158 structures may penetrate as much as 15 km into the footwall (Bland and McKinnon, 2016)—consistent
159 with the great heights and slope angles of, for instance, the Chaac Patera walls. Extensional fractures
160 would efficiently conduct ascending magma to the surface (Bland and McKinnon, 2016; McGovern et
161 al., 2016; Byrne et al., 2018), allowing magma to erupt that would otherwise be too dense to avoid
162 stalling in the shallow crust (Keszthelyi et al., 2004). At least some of these extensional structures have
163 a dip component of slip (Ahern et al., 2017).

164 Even within the uplifted and tilted mountain blocks, there is considerable extensional deformation,
165 such as the scarp-parallel lineaments on the back scarps of the Hi'iaka Montes (Ahern et al., 2017)
166 (Figure 3). Similarly, Schenk and Bulmer (1998) documented landslide scarps on Euboea Montes—
167 presumably great listric normal faults, on the basis of comparisons with landslide deposits on Earth and
168 other planets (e.g., Lopes et al., 1980; Riley et al., 1999).

169

170 **4 Discussion**

171 A highly extensionally deformed upper, brittle lithosphere accounts for several separate but related sets
172 of observations of Io.

Firstly, the prevalence of such structures explains why the central island in Loki Patera has a polygonal outline and appears dissected by fractures: the island is a formerly coherent block that broke apart along pre-existing fractures atop a shallow magma body as that body (and the patera) grew, by the withdrawal and/or eruption of magma, via the mobilization of sulfur-bearing volatiles (Keszthelyi et al., 2004), or by a combination of these processes. In any case, since *some* subsurface material was removed, that central island must now be at a lower elevation than the surrounding plains and is perhaps sitting on the patera floor. The smaller islands and bergs in Loki may be other, smaller fragments of the original chamber roof, consistent with the view of Howell et al. (2013) that such features are not concentrations of sulfur deposits but are instead isolated areas of terrain that avoided burial by subsequent lavas. It is not clear why the large island has remained intact, in contrast to some of the smaller fragments throughout the patera floor (Howell et al., 2013), although there may well be a resolution effect at play since those smaller fragments visible in Voyager images are not resolved with Galileo data. The island may simply be the largest remaining piece of an ongoing process that will ultimately destroy the original roof over the magma body entirely, in which case Loki will eventually come to resemble other paterae where no large islands are present—and, by implication, other paterae may once have had large island fragments.

Secondly, widespread joints and normal faults in the crust account for the straight margins of a substantial number of Io's paterae (Radebaugh et al., 2001), with these structures forming the boundary(ies) of patera(e) as shallow magma bodies undermined and drove the collapse of the overlying, fractured roof material (Keszthelyi et al, 2004). The numerous instances of sharp paterae corners noted by Radebaugh et al. (2001) might reflect the tectonic influence of intersecting sets of joints or normal faults. Moreover, the extension associated with the mountain formation models of Bland and McKinnon (2016) and Kirchoff et al. (2020) is consistent with the finding that paterae—assuming their form is controlled by pre-existing normal faults—are much more commonly collocated with mountains than predicted by chance alone (Radebaugh et al. 2001; Jaeger et al., 2003).

198 Thirdly, abundant extensional structures provide ready conduits for magma to reach the surface;
199 indeed, the normal and transtensional fractures that characterize an extensional tectonic regime are
200 more conducive to magma ascent than reverse or transpressional fractures, given that crustal shortening
201 results in negative horizontal elongation whereas horizontal extension opens vertical accommodation
202 space into which magma can move (e.g., Byrne et al., 2018). A prevailing horizontally extensional
203 tectonic regime in its upper lithosphere is thus compatible with Io being almost entirely covered by
204 extensive lava flows and vast plains units, the latter of which mainly comprise buried lavas and
205 pyroclastic deposits (McEwan et al., 2000; Williams et al., 2002). Indeed, plains and lava flow units
206 occupy 66.6% and 27.8% of the surface, respectively (Williams et al., 2011).
207 Finally, Schenk and Bulmer (1998) proposed that uplifted blocks rise along deep-rooted thrust
208 faults, drawing a parallel between Io's mountains and basement-cored uplifts in the western United
209 States. In the latter case, those shortening structures moved along reactivated, high-angle normal faults
210 that originally formed via crustal extension (e.g., Reches, 1978). For horizontal compression, incipient
211 thrust faults form with low dip angles (Anderson, 1905). Therefore, should at least some mountain
212 blocks be bounded by high-angle reverse faults as suggested by Ahern et al. (2017), then those
213 bounding structures could have formed as normal faults that were later reactivated when horizontally
214 compressive stresses built at the base of the lithosphere from sustained burial of surface materials
215 (Bland and McKinnon, 2016).
216 We thus propose a model for Io whereby the upper lithosphere features a pervasive fracture network
217 formed by a combination of tidal, subsidence, and thermal stresses—with large, deep-seated thrust
218 faults and widespread normal faults dominant at lower and upper crustal levels, respectively (Figure 4).
219 Abundant extensional structures at shallow crustal levels serve as failure planes along which
220 undermined magma chamber roofs collapse, and are available for reactivation with a reverse or oblique
221 sense of slip if favorably aligned to local, subsequent stress fields. The apparent dearth of extensional
222 strain (beyond paterae and mountain block edges) on Io is probably a function of the moon's

extraordinary volcanic resurfacing rate, which likely obscures just how deformed the near surface actually is.

This stress state is in marked contrast to other terrestrial bodies in the Solar System. For instance, although there are major thrust fault-related landforms on Mercury as is the case on Io, those on the innermost planet are interpreted to have formed from secular interior cooling (Strom et al., 1975; Byrne et al., 2018). The resulting horizontally compressive stress field results in a dearth of extensional structures at the surface, and inhibits the ascent of magma to shallow depths in all but the weakest parts of the planet's crust (Byrne et al., 2018). The tectonic characteristics of Mercury are largely shared by the Moon (e.g., Byrne, 2020). Venus and Earth are replete with both extensional and shortening landforms, although each is in a different tectonic regime than that of Io (e.g., Byrne, 2020; Lourenço et al. 2020). Mars, too, has widespread extensional tectonics (e.g., Byrne, 2020), attributed at least in part to near-surface stresses associated with the Tharsis Rise (e.g., Anderson et al., 2001), as well as shortening structures reflecting both Tharsis-related loading stresses and global contraction (e.g., Nahm and Schultz, 2010). But none of the inner Solar System worlds has a tectonic inventory matching Io.

The Jovian moon is also distinctive among outer Solar System satellites in that it is the only such body without an icy exterior. Although tectonic structures including graben and thrust fault-related landforms are widespread on myriad other icy moons (e.g., Collins et al., 2010), none boasts the elevated mountain blocks nor visibly craterless surface of Io (Williams et al., 2011). Io's tectonic stress state is the result principally of its inordinate effusive volcanism, which in turn is driven by the dissipation of tidal energy in its interior (Peale et al., 1979). By this measure, Io's lithospheric stress state may be unique in the Solar System—but could be illustrative of tidally heated planets orbiting other stars (Barr et al., 2018; McEwen et al., 2020).

5 Conclusions

The distinctive, polygonal "island" in Loki Patera holds clues to Io's lithospheric stress state. This island may be a fractured crustal block, the remains of a portion of the crust undermined by a shallow magma body aided by widespread extensional deformation. A heavily extensionally deformed upper lithosphere, likely by a combination of subsidence, tidal, and thermal stresses, accounts for several seemingly disparate observations, including:

1) The polygonal, fractured appearance of the Loki Patera island;

2) A substantial number of other paterae with straight edges;

3) A globally youthful surface; and

4) The extensional strains so commonly seen within Io's enormous, uplifted mountains.

We therefore propose a scenario for Io under which the lower lithosphere is deformed by large, deep-seated thrust faults from the burial of surface materials, but that is also riven by extensional tectonics in the near surface.

The acquisition of image and topographic data at resolutions substantially greater than those returned by the Voyager and Galileo missions would enable the search for and measurements of joints, normal faults, and graben in the plains proximal to paterae and mountain blocks, and would also establish if the elevation of the upper surface of the island is in fact below that of the surrounding plains. Such data would also provide a valuable comparison for assessing whether the Loki island really has remained stationary since its discovery. Further, the detection of small-scale extensional structures undergoing burial by active volcanism would lend support to the hypothesis that the Ionian lithosphere is far more tectonically disrupted than previously recognized.

Open Research

No new data were created for this study. All Voyager and Galileo image data used in this paper are publicly available at the NASA Planetary Data System (PDS) at https://pds.nasa.gov. The photogeological data shown in Fig. 1a and used for preparing the structural sketch in Fig. 1b (and for

the surface texture of the block in Fig. 4) is the combined Voyager–Galileo SSI global 1 km/px mosaic, available at https://astrogeology.usgs.gov/search/map/Io/Voyager-Galileo/Io_GalileoSSI-Voyager_Global_Mosaic_1km. The data used to generate Figs. 2 and 3 are from the Galileo Solid-State Imaging (SSI) dataset (Thaller, 2000).

Acknowledgments

Part of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. This research made use of NASA's PDS and Astrophysics Data System.

References

Ahern, A. A., Radebaugh, J., Christensen, E. H., Harris, R. A., & Tass, E. S. (2017), Lineations and structural mapping of Io's paterae and mountains: Implications for internal stresses. *Icarus*, *297*, 14–32. doi:10.1016/j.icarus.2017.06.004.

Anderson, E. M. (1905), The dynamics of faulting. *Transactions of the Edinburgh Geological Society*, *8*(3), 387–402. doi:10.1144/transed.8.3.387.

Anderson, R. C., et al. (2001), Primary centers and secondary concentrations of tectonic activity through time in the western hemisphere of Mars. *Journal of Geophysical Research*, *106*, 20563–20585. doi:10.1029/2000JE001278.

Barr, A. C., Dobos, V., & Kiss, L. L. (2018), Interior structures and tidal heating in the TRAPPIST-1 planets. *Astronomy and Astrophysics*, *613*, A37. doi:10.1051/0004-6361/201731992.

Black, S. R. (2006). *The origin and evolution of islands in Ionian paterae* (Master's thesis). Retrieved from UMI ProQuest Digital Dissertations. (1436720). New York: State University of New York at Buffalo.

296 Bland, M. T., & McKinnon, W. B. (2016), Mountain building on Io driven by deep faulting. *Nature*
297 *Geoscience*, *9*, 429–433. doi:10.1038/NGEO2711.
298 Byrne, P. K, Whitten, J. L., Klimczak, C., McCubbin, F. M., & Ostrach, L. R. (2018), The volcanic
299 character of Mercury. *In* Solomon, S. C., Nittler, L. R., and Anderson, B. J. (eds.), Mercury: The
300 View after MESSENGER, 287–323. Cambridge University Press, Cambridge, UK.
301 doi:10.1017/9781316650684.012.
302 Byrne, P. K. (2020) A comparison of inner Solar System volcanism. *Nature Astronomy*, *4*, 321–327.
303 doi:10.1038/s41550-019-0944-3.
304 Carr, M. H., Greeley, R., Blasius, K. R., Guest, J. E., & Murray, J. B. (1977), Some Martian volcanic
305 features as viewed from the Viking Orbiters. *Journal of Geophysical Research*, *82*, 3985–4015.
306 doi:10.1029/JS082i028p03985.
307 Carr, M. H., Masursky, H., Strom, R. G., & Terrile, R. J. (1979), Volcanic features of Io. *Nature*, *280*,
308 729–733. doi:10.1038/280729a0.
309 Collins, G. C., et al. (2010), Tectonics of the outer planet satellites. *In* Watters, T. R., and Schultz, R.
310 A. (eds.), Planetary Tectonics, Cambridge University Press, 264–350.
311 Crumpler, L. S., Head, J. W., & Aubele, J. C. (1996), Calderas on Mars: characteristics, structure, and
312 associated flank deformation. *In* McGuire, W. J., Jones, A. P., and Neuberg, J. (eds.), Volcano
313 Instability on the Earth and Other Planets, Geological Society Special Publication No. 110, 307–
314 348.
315 de Kleer, K., Skrutskie, M., Leisenring, J., Davies, A. G., Conrad, A., de Pater, I., Resnick, A., Bailey,
316 V., Defrère, D., Hinz, P., Skemer, A., Spalding, E., Vaz, A., Veillet, C., & Woodward, C. E. (2017),
317 Multi-phase volcanic resurfacing at Loki. *Nature*, *545*, 199–202. doi:10.1038/nature22339.
318 Ernst, R. E., Grosfils, E. B., & Mège, D. (2001), Giant dike swarms: Earth, Venus, and Mars. *Annual*
319 *Review of Earth and Planetary Science*, *29*, 489–534. doi:10.1146/annurev.earth.29.1.489.

Howell, R. R., Landis, C. E., & Lopes, R. M. C. (2013), Composition and location of volatiles at Loki Patera, Io. *Icarus*, *229*, 328–339. doi:10.1016/j.icarus.2013.11.016.

Jaeger, W. L., Turtle, E. P., Keszthelyi, L. P., Radebaugh, J., & McEwan, A. S. (2003), Orogenic tectonism on Io. *Journal of Geophysical Research*, *108*, E8, 5093. doi:10.1029/2002JE001946.

Kargel, J. S., Delmelle, P., & Nash, D. B. (1999), Volcanogenic sulfur on Earth and Io: Composition and spectroscopy. *Icarus*, *142*, 249–280. doi:10.1006/icar.1999.6183.

Keszthelyi, L., Jaeger, W. L., Turtle, E. P., Milazzo, M., & Radebaugh, J. (2004), A post-Galileo view of Io's interior. *Icarus*, *169*, 271–286. doi:10.1016/j.icarus.2004.01.005.

Kirchoff, M. R., & McKinnon, W. B. (2009), Formation of mountains on Io: Variable volcanism and thermal stresses. *Icarus*, *201*, 598–614. doi:10.1016/j.icarus.2009.02.006.

Kirchoff, M. R., McKinnon, W. B., & Bland, M. T. (2020), Effects of faulting on crustal stresses during mountain formation on Io. Icarus, 335, 113326. doi:10.1016/j.icarus.2019.05.028.

Lipman, P. W. (1997), Subsidence of ash-flow calderas; relation to caldera size and magma-chamber geometry. *Bulletin of Volcanology*, *59*, 198–218. doi:10.1007/s004450050186.

Lopes, R. M. C., Guest, J. E., & Wilson, C. J. (1980), Origin of the Olympus Mons aureole and perimeter scarp. *The Moon and Planets*, *22*, 221–234. doi:10.1007/BF00898433.

Lopes-Gautier, R. M. C., Douté, S., Smythe, W. D., Kamp, L. W., Carlson, R. W., Davies, A. G., Leader, F. E., McEwan, A. S., Geissler, P. E., Kieffer, S. W., Keszthelyi, L., Barbinis, E., Mehlman, R., Segura, M., Shirley, J., & Soderblom, L. A. (2000), A close-up look at Io from Galileo's near-infrared mapping spectrometer. *Science*, *288*, 1201–1204. doi:10.1126/science.288.5469.1201.

Lourenço, D. L., Rozel, A. B., Ballmer, M. D., & Tackley, P. J. (2020), Plutonic-squishy lid: A new global tectonic regime generated by intrusive magmatism on Earth-like planets. *Geochemistry, Geophysics, Geosystems*, *21*, e2019GC008756. doi:10.1029/2019GC008756.

McEwen, A. S., Keszthelyi, L., Spencer, J. R., Schubert, G., Matson, D. L., Lopes-Gautier, R. M. C., Klaasen, K. P., Johnson, T. V., Head, J. W., Geissler, P., Fagents, S., Davies, A. G., Carr, M. H.,

345 Breneman, H. H., & Belton, M. J. S. (1998), High-temperature silicate volcanism on Jupiter's moon
346 Io. *Science*, *281*, 87–90. doi:10.1126/science.281.5373.87.
347 McEwen, A. S., Belton, M. J. S., Breneman, H. H., Fagents, S. A., Geissler, P., Greeley, R., Head, J.
348 W., Hoppa, G., Jaeger, W. L., Johnson, T. V., Keszthelyi, L., Klaasen, K. P., Lopes-Gautier, R. M.
349 C., Magee, K. P., Milazzo, M. P., Moore, J. M., Pappalardo, R. T., Phillips, C. B., Radebaugh, J.,
350 Schubert, G., Schuster, P., Simonelli, D. P., Sullivan, R., Thomas, P. C., Turtle, E. P., & Williams,
351 D. A. (2000), Galileo at Io: Results from High-Resolution Imaging. *Science*, *288*, 1193–1198.
352 doi:10.1126/science.288.5469.1193.
353 McEwen, A. S., et al. (2020), Tidal heating: Lessons from Io and the Jovian system; Relevance to
354 exoplanets. *Exoplanets in our Backyard*, *1*, abstract 3005.
355 McGovern, P. J., Kirchoff, M. R., White, O. L., & Schenk, P. M. (2016), Magma ascent pathways
356 associated with large mountains on Io. Icarus, 272, 246–257. doi:10.1016/j.icarus.2016.02.035.
357 McKinnon, W. B., Schenk, P. M., & Dombard, A. J. (2001), Chaos on Io: A model for formation of
358 mountain blocks by crustal heating, melting, and tilting. *Geology*, *29*, 103–106. doi:10.1130/0091-
359 7613(2001)029<0103:COIAMF>2.0.CO;2.
360 Nahm, A. L., & Schultz, R. A. (2010), Evaluation of the orogenic belt hypothesis for the formation of
361 the Thaumasia Highlands, Mars. *Journal of Geophysical Research*, *115*, E04008.
362 doi:10.1029/2009JE003327.
363 Peale, S. J., Cassen, P., & Reynolds, R. T. (1979), Melting of Io by tidal dissipation. *Science*, *203*, 892–
364 894. doi:10.1126/science.203.4383.892.
365 Radebaugh, J., Keszthelyi, L. P., McEwan, A. S., Turtle, E. P., Jaeger, W. L., and Milazzo, M. (2001),
366 Paterae on Io: A new type of volcanic caldera? *Journal of Geophysical Research*, *106*, 33,005–
367 33,020. doi:10.1029/2000JE001406.

368 Reches, Z. (1978), Development of monoclines: Part I. Structure of the Palisades Creek branch of the
369 East Kaibab monocline, Grand Canyon, Arizona. *Geological Society of America*, *Memoir 151*, 235–
370 271. doi:10.1130/MEM151-p235.
371 Riley, C. M., Diehl, J. F., Kirschvink, J. L., & Ripperdan, R. L. (1999), paleomagnetic constraints on
372 fault motion in the Hilina Fault System, south flank of Kilauea Volcano, Hawaii. *Journal of*
373 *Geophysical Research*, 94, 233–249. doi:10.1016/S0377-0273(99)00105-5.
374 Schenk, P. M., & Bulmer, M. H. (1998), Origin of mountains on Io by thrust faulting and large-scale
375 mass movements. *Science*, *279*, 1514–1517. doi:10.1126/science.279.5356.1514.
376 Schenk, P. M., Hargitai, H., Wilson, R., McEwan, A., & Thomas, P. C. (2001), The mountains of Io:
377 Global and geological perspectives from Voyager and Galileo. *Journal of Geophysical Research*,
378 *106*, 33,201–33,222. doi:10.1029/2000JE001408.
379 Strom, R. G., Trask N. J., & Guest J. E. (1975), Tectonism and volcanism on Mercury. *Journal of*
380 *Geophysical Research*, *80*, 2478–2507. doi:10.1029/JB080i017p02478.
381 Thaller, T. F. (2000), Galileo orbital operations Solid State Imaging raw EDR v1.0 [Data set]. NASA
382 Planetary Data System. doi:10.17189/1520425.
383 Turtle, E. P., Jaeger, W. L., Keszthelyi, L. P., McEwan, A. S., Milazzo, M., Moore, J., Phillips, C. B.,
384 Radebaugh, J., Simonelli, D., Chuang, F., Schuster, P., & the Galileo SSI Team (2001), Mountains
385 on Io: High-resolution Galileo observations, initial interpretations, and formation models. *Journal of*
386 *Geophysical Research*, *106*, 33,175–33,199. doi:10.1029/2000JE001354.
387 Walter, T. R., & Troll, V. R. (2001), Formation of caldera periphery faults: an experimental study.
388 *Bulletin of Volcanology*, *63*, 191–203. doi:10.1007/s004450100135.
389 Williams, D. A., Radebaugh, J., Keszthelyi, L. P., McEwen, A. S., Lopes, R. M. C., Douté, S., &
390 Greeley, R. (2002), Geologic mapping of the Chaac-Camaxtli region of Io from Galileo imaging
391 data. *Journal of Geophysical Research*, *107*, E9, 5068. doi:10.1029/2001JE001821.

392 Williams, D. A., Keszthelyi, L. P., Crown, D. A., Yff, J. A., Jaeger, W. L., Schenk, P. M., Geissler, P.
393 E., & Becker, T. L. (2011), Geologic map of Io: U.S. Geological Survey Scientific Investigations
394 Map 3168, scale 1:15,000,000, 25 p., available at https://pubs.usgs.gov/sim/3168/.

Figures

Figure 1. Loki Patera. (a) Combined monochrome Voyager 1 and color Galileo imagery at 1 km/pixel. The floor of the patera is dark, in contrast to the brighter polygonal island. We infer the dark, linear features crossing the island (green arrows) as extensional tectonic structures. Smaller patches of bright material dot the patera floor (blue arrows). The location of Loki Patera is shown with a purple diamond on the global Io mosaic (in Robinson projection). (b) A structural sketch of (a); the patera and main island are outlined in a solid blue and dotted black lines, respectively. The boundaries of the features we interpret to be extensional structures are shown with solid black lines. The units shown are from the Io global geological map (Williams et al., 2011). This scene is in azimuthal equidistant projection, centered at 13.2°N, 51.3°E.

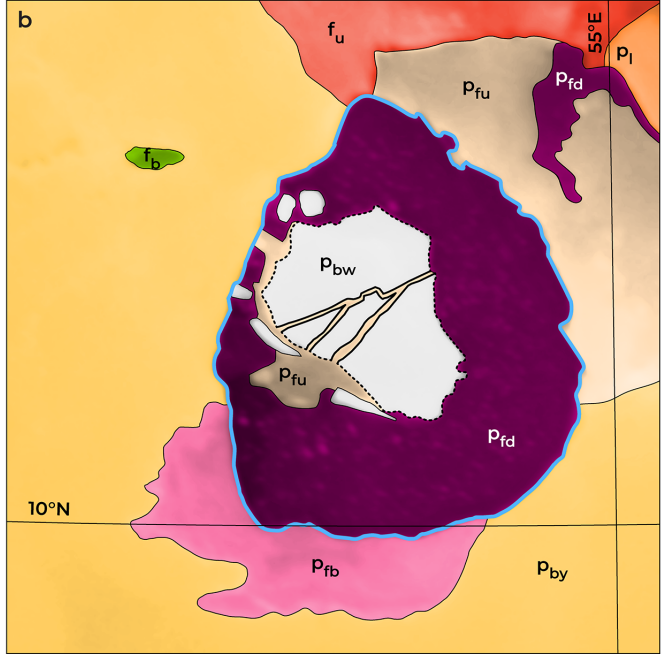
Figure 2. A portion of Emakong Patera, which has straight edges (green arrows) that terminate at sharp corners (Radebaugh et al., 2001). The location of Emakong Patera is shown on the global Io mosaic. The main scene comprises Galileo SSI images 5000r, 5139r, and 5140r, and is in azimuthal equidistant projection, centered at 3.5°S, 240.0°E.

Figure 3. Hi'iaka Montes, examples of thrust fault-bounded mountain blocks on Io that show substantial evidence for extensional deformation (pink arrows). The blue arrow indicates a lava flow. The position of Hi'iaka Montes is shown on the global Io mosaic. The main scene comprises Galileo SSI images 7465r, 7478r, and 7500r, and is in azimuthal equidistant projection, centered at 4.5°S, 279.0°E.

Figure 4. A schematic showing thrust faults (heavy black lines) dominating the lower part and extensional structures (thin black lines) throughout the upper part of Io’s lithosphere. Example kinematic indicators are shown, as are magma bodies (examples marked by white arrows) and where

magma is ascending along normal faults (yellow arrows). The principal compressive stresses for the upper and lower lithosphere are also shown; σ_H and σ_h are horizontal stresses, and σ_V is the vertical stress. Where mountains are present, deep-seated thrusts extend to the surface (not shown here).

2022JE007722 Figure 01.



UNITS

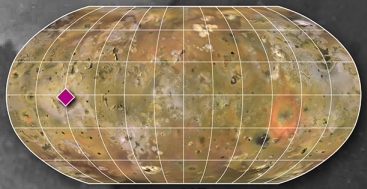
from Williams et al. (2011)

- p_{bw} white bright plains material
- p_{by} yellow bright plains material
- p_{fb} bright patera floor material
- p_{fd} dark patera floor material
- p_{fu} undivided patera floor material
- f_b bright flow material
- f_u undivided flow material
- p_l layered plains material

- patera outline
- patera island outline
- extensional structure

Note: Units are not shown here in stratigraphic order.

2022JE007722 Figure 02.

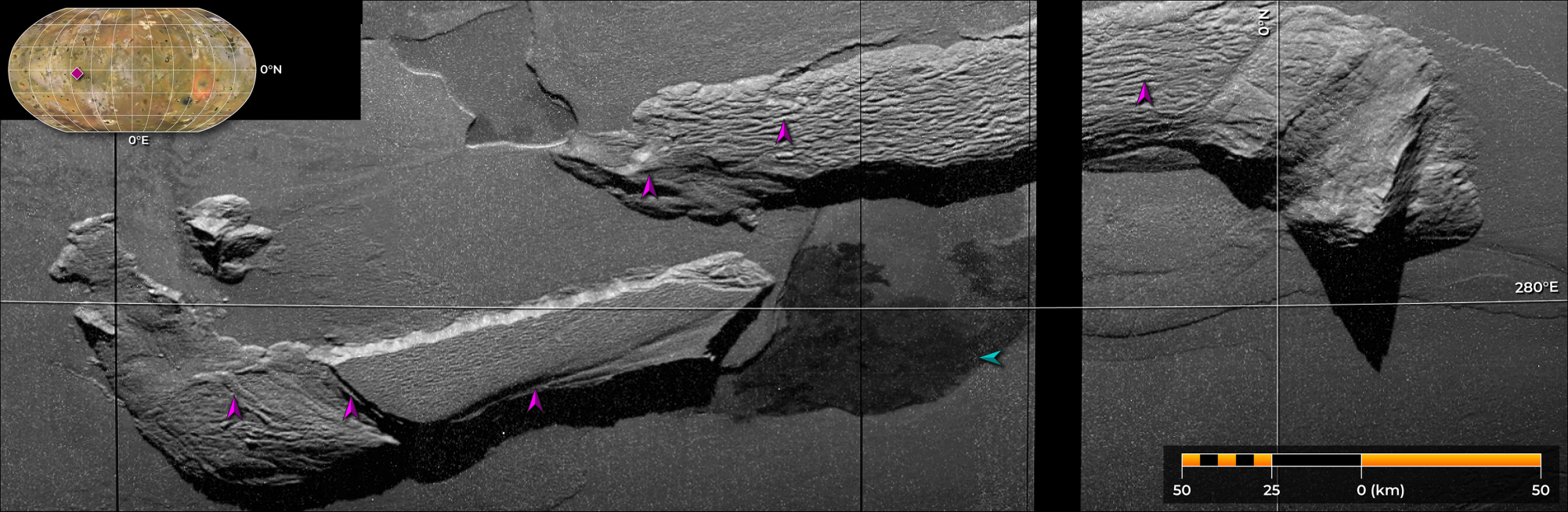


240°E

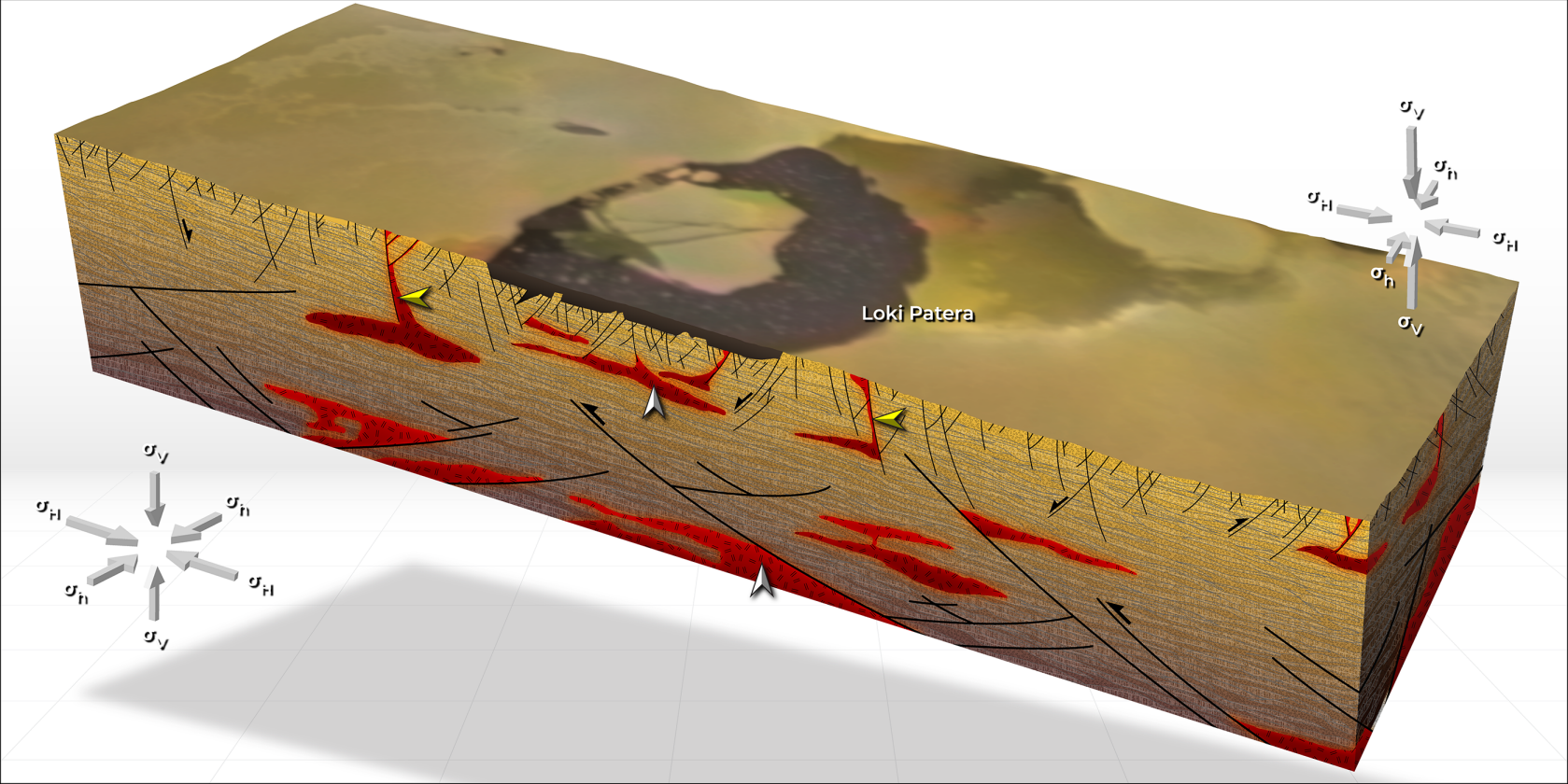
4°S

20 10 0 (km) 20

2022JE007722 Figure 03.


0°N
0°E
0°N
280°E
50
25
0 (km)
50

2022JE007722 Figure 04.


Loki Patera
σv
σh
σH
σH
σh
σv
σv
σH
σh
σh
σH
σv