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Magnetic anomalies on Io and their relationship to the spatial distribution of volcanic centers

Joshua Knicely [*,1], Mark E. Everett, David W. Sparks

Department of Geology and Geophysics, MS 3115, Texas A&M University, College Station, TX 77843-3115, United States

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ABSTRACT

Forward modeling of planetary-scale magnetic anomalies due to induced crustal magnetization of Io is developed. The approach involves finite difference modeling of a temporally- and spatially-averaged steady state geotherm superimposed by the thermal evolution of an instantaneously emplaced volcanic pipe with and without an underlying magma chamber. A slight adjustment to previous studies results in a preferred steady state geotherm. The crustal magnetization is based on the calculated distribution of temperature, the strength of an idealized Jovian magnetic field, and a temperature-dependent susceptibility. Magnetite is assumed to be the dominant magnetic mineral. Synthetic satellite flyby data are generated along selected meridional swaths of Io's surface, based on observed locations of volcanic centers, hotspots, and accumulations of ejected volcanic material.

This work produces a 1-D geotherm which remains at approximately the surface temperature to within a few kilometers of the thermal lithosphere/mantle boundary. This solution shows little dependence on porosity due to the depth at which rapid temperature change occurs. These conclusions hold for largely varying mantle temperatures. Silicate volcanic centers cool to the temperature of sulfur eruptions rapidly and become indistinguishable from sulfur volcanism within 10,000 years. The magnetic anomaly due to temperature variation is smaller than detectable for nominal conditions. The modeling herein requires a flyby altitude of ~25 km and a pipe radius of ~640 m for detection, or, for a more reasonable flyby altitude of 100 km, a pipe radius of ~6000 m. If a crustal anomaly is detected by future satellite missions, it would suggest different conditions at Io than modeled here.

1. Introduction

Io is the most volcanically active body in the solar system due to tidal heating. The intense heating experienced by Io is a tidal effect produced by a Laplace orbital resonance with Jupiter and the surrounding moons. The hundreds of volcanic edifices and mountains provide topographic information useful in constraining the predominant internal heating processes, the synchronicity of the moons rotation with respect to Jupiter, and the possible method by which mountains are constructed, but these structures provide limited information of the deep interior since they are only surface expressions. Resurfacing rates of 0.1–1 cm/yr obscure most topographic features under a veneer of sulfur within 1 Myr (Johnson, 1999; Lopes and Williams, 2005).

The magnetization of Io's iron-bearing crust, beneath the nonmagnetic sulfur layer, encodes further information about the fundamental geologic processes operating in its interior. Volcanic centers hidden by layers of sulfur have the potential to alter current theories of how geologic processes operate within this moon. Examination of the magnetic anomaly pattern due to crustal magnetization of Mars, for example, indicates the past presence of a powerful magnetic field and an early stage of plate tectonics, as inferred from observed magnetic stripes and apparent transform faults. The magnetic anomaly pattern on Mars contributes to the hypothesis that many of the extant great volcanic edifices on that planet were created by motion of the crust over two fixed hotspots that episodically broke through the surface (Connerney et al., 2005). Magnetic anomalies generated by the spatial variations in magnetization on Io could potentially be mapped by future satellite magnetometer missions and provide locations for previously unknown volcanic centers. As volcanoes on Io are used as a proxy for heat flow, a modification of their distribution would alter the depth at which models predict tidal heating to occur. The discovery and location of additional volcanic centers would provide more

* Corresponding author at: University of Alaska in Fairbanks, 903 N Koyukuk Drive, Fairbanks, AK 99709, United States.

E-mail addresses: knicely_joshua@yahoo.com (J. Knicely), everett@geo.tamu.edu (M.E. Everett), sparks@geo.tamu.edu (D.W. Sparks).

[1] Present address: 757 Chena Hills Drive, Fairbanks, AK 99709, United States.

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constraints on the statistical relationship between mountains and paterae and a potentially better understanding on the mode of mountain formation.

In this paper, we develop a synthetic magnetic anomaly map along swaths of Io as it would be observed by a magnetometer aboard a satellite flyby. A magnetic anomaly map displays the magnetic field intensity due to natural remanent magnetism (NRM) of crustal rocks. We limit the consideration to the thermoremanent magnetization (TRM) contribution and thus do not consider any past variation in the direction of the ambient Jovian field. As we assume the field direction and strength of the Jovian field at Io to be constant and uniform, the induced magnetization and TRM are equivalent components. Typically, induced and remanent magnetization are considered two distinct components that combine vectorially to form the total magnetization ($\vec{J}_{total} = \vec{J}_{induced} + \vec{J}_{remanent}$) (Butler, 1992). In this work, the magnetizing field is assumed constant and uniform. While this is very inaccurate on a short time scale such as part of an Ionian orbit, the periodic nature of the oscillation over the course of Io's orbit around Jupiter should be equivalent to a single magnetic direction over the long time periods required to produce a significant portion of the crust. Thus, the induced and remanent fields are treated as equivalent.

Radially-symmetric thermal modeling in 2-D cylindrical geometry is used to determine the likely thickness of the magnetized crustal layer around a recently-active volcanic center. We treat the recently-active volcanic center as an instantaneously emplaced pipe, first without a near surface magma chamber and then with one. Using the thermal modeling results to predict the magnetization of the crust, a standard technique of discretizing the region into prisms and summing the magnetic field of each prism (Blakely, 1995) is used to obtain the crustal magnetic anomaly map around a recent volcanic center. The mapping is conducted in meridional swaths so that Cartesian geometry may be used to simplify the analysis. Fig. 1 is a conceptual depiction of a volcano, magnetization, and satellite flyby.

2. Background

Io is the most volcanic body in the solar system due to tidal heating caused by the time-varying gravitational forces exerted on Io by Jupiter and its other moons (Johnson, 1999; Lopes and Williams, 2005; Moore et al., 2003; Peale, 2003). On a global scale, the volcanic output of Io continually buries the lithosphere in lava and ash, forcing it downward into the interior of the moon at a rate estimated to be ~1 cm/yr (Lopes and Williams, 2005; McEwen et al., 2004; McKinnon et al., 2001). As burial progresses, horizontal compressive stresses increase faster than vertical stresses, as a given volume of lithosphere becomes squeezed into a smaller volume. It is likely that the lithosphere breaks and portions of it tilt to accommodate the compression, forming mountains (Lopes and Williams, 2005; McEwen et al., 2004; McKinnon et al., 2001). The heights of these mountains provide an estimate of minimum lithospheric thickness of ~6–17 km based on the predominant hypothesis for their formation (Lopes and Williams, 2005; Williams et al., 2011). The foregoing estimates are lower limits of lithospheric thickness. Upper limits are poorly constrained and range from 25 to 100 km (McEwen et al., 2004; McKinnon et al., 2001). Along with many *Galileo* era scientists, we adopt a nominal lithospheric thickness value of 30 km (Lopes and Williams, 2005).

Both sulfur-based and silicate volcanism occur on Io. Whether sulfur volcanism can occur independently or is always linked to silicate volcanism is uncertain. The silicate volcanoes of Io are believed to behave similarly to those of terrestrial calderas. An intrusion of magma rises towards the surface as a dike until it reaches a point of neutral buoyancy. Due to the high porosity of the crust and interstitial sulfur reducing bulk density, the point of neutral buoyancy should be only a few km from the base of the lithosphere (Leone et al., 2011; Lopes and Williams, 2005). Because of this, the rising dike should stall until the magma density drops below that of the host rock by magmatic differentiation or the introduction of volatiles. A possible mechanism to introduce volatiles is via ingress from proximal sulfur and sulfur dioxide reservoirs. At a wide range of pressures of 0–200 MPa and relatively low temperatures of ~400 K and ~200 K, both sulfur and sulfur dioxide exist as liquids (Leone et al., 2011). These materials could become entrained in the crust and transported down along with it. The compressive stress regime of the crust creates numerous fracture pathways through which such a liquid could flow. The depth at which these fluid reservoirs would form is typically lower than the neutral buoyancy point of the magma (Leone et al., 2011). If the magma were to reach the level of these reservoirs, it would incorporate volatile sulfur and sulfur dioxide. The volatile content would greatly reduce the magma density and enables the magma to approach the surface (Keszthelyi et al., 2004; Leone et al., 2011; Lopes and Williams, 2005). The crust immediately beneath the surface is likely to be porous and low density. Such a layer

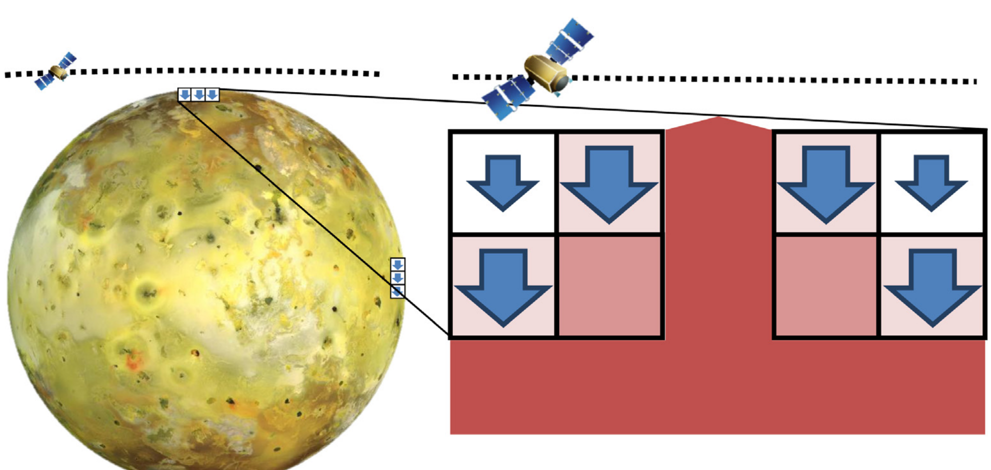

Fig. 1. Conceptual depiction of the satellite flyby and the magnetization around a volcanic center. Arrows depict the direction and strength of the magnetization adjacent to a volcanic pipe. The magnetic susceptibility (and hence magnetization) increase with temperature until the Curie temperature is reached, at which point the magnetization goes to zero. Image of Io courtesy of NASA/JPL (Boggs and Lavoie, 2014).