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Geologic mapping of the Hi'iaka and Shamshu regions of Io

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ABSTRACT

We produced regional geologic maps of the Hi'iaka and Shamshu regions of Io's antijovian hemisphere using *Galileo* mission data to assess the geologic processes that are involved in the formation of Io's mountains and volcanic centers. Observations reveal that these regions are characterized by several types of volcanic activity and features whose orientation and texture indicate tectonic activity. Among the volcanic features are multiple hotspots and volcanic vents detected by *Galileo*, one at each of the major paterae: Hi'iaka, Shamshu, and Tawhaki. We mapped four primary types of geologic units: flows, paterae floors, plains, and mountains. The flows and patera floors are similar, but are subdivided based upon emplacement environments and mechanisms. The floors of Hi'iaka and Shamshu Paterae have been partially resurfaced by dark lava flows, although portions of the paterae floors appear bright and unchanged during the *Galileo* mission; this suggests that the floors did not undergo complete resurfacing as flooding lava lakes. However, the paterae do contain compound lava flow fields and show the greatest activity near the paterae walls, a characteristic of Pele type lava lakes. Mountain materials are tilted crustal blocks that exhibit varied degrees of degradation. Lineated mountains have characteristic en echelon grooves that likely formed as a result of gravitational sliding. Undivided mountains are partially grooved but exhibit evidence of slumping and are generally lower elevation than the lineated units. Debris lobes and aprons are representative of mottled mountain materials. We have explored the possibility that north and south Hi'iaka Mons were originally one structure. We propose that strike-slip faulting and subsequent rifting separated the mountain units and created a depression which, by further extension during the rifting event, became Hi'iaka Patera. This type of rifting and depression formation is similar to the mechanism of formation of terrestrial pull-apart basins. With comparison to other regional maps of Io and global studies of paterae and mountains, this work provides insight into the general geologic evolution of Io.

1. Introduction

Io is the most volcanically active body in the Solar System. It has a Laplace resonance with Europa and Ganymede that induces tidal heating (Peale et al., 1979), which has resulted in more than 400 volcanic centers identified thus far on Io's surface, of which more than 150 are active (Radebaugh et al., 2001; Schenk et al., 2001; Lopes et al., 2004). *Voyager* and *Galileo* data show that Io exhibits multiple eruption styles and a variety of volcanic features (e.g., Smith et al., 1979a,b; McEwen and Soderblom, 1983; McEwen et al., 1998, 2000a; Lopes-Gautier et al., 2000; Keszthelyi et al., 2001; Lopes et al., 2004; Turtle et al., 2004; Lopes and Spencer, 2006; Davies, 2007). Many of the features have been mapped geologically (Schaber, 1980, 1982; Moore, 1987; Schaber et al., 1989; Greeley et al., 1988; Whitford-Stark et al., 1991; Crown et al., 1992; Williams et al., 2002, 2004, 2005, 2007). Complex interactions between sulfur, sulfur dioxide, and silicate materials produce an array of colorful explosive and effusive deposits (Geissler et al., 1999, 2004; reviewed by Lopes and Williams, 2005; Lopes and Spencer, 2006).

Previous studies have introduced the potential for relationships between volcanic and tectonic activity within small regions; for example, mountain formation is thought to have a tectonic influence on the location and morphology of some paterae and paterae are thought to be strongly influenced by regional tectonism (see Radebaugh et al., 2001; Turtle et al., 2001; Jaeger et al., 2003). This mapping effort focuses on a small area of Io that appears to have related volcano-tectonic features (Radebaugh et al., 2001). We attempt to address the following questions with detailed observations of a limited portion of the surface: Are mountains and paterae preferentially formed adjacent to each other or is their association random or coincidental? Is the topography of all mountains tectonically controlled? What are the roles of silicate and sulfur volcanism? How are volcanism and tectonism linked? How do volcanic processes on Io compare to those on Earth, specifically regarding lava lakes?

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The objective of this study was to investigate the geologic processes that formed the Hi'iaka and Shamshu regions by deriving a stratigraphy and geologic history of the regions through identification of flow units and surface features using planetary mapping techniques (e.g., Shoemaker and Hackman, 1962; Wilhelms, 1972, 1990; Tanaka et al., 1994). Mapping the surface of Io allows the identification of types of material units and structures that are present which can be interpreted to identify the geologic processes. The prevalence of and relationships between the materials and structures indicate the processes that dominate and control the formation of the surface of Io. Insights into these processes allowed us to assess the contribution of tectonic influences to paterae formation and explore ways in which volcanic materials can exploit tectonic features. We examine the morphology of the mountain units and associated scarps or faults to investigate the possibility that the Hi'iaka region was originally a single mountain structure and is controlled by tectonic movement and related volcanic exploitation of faults as originally proposed by Jaeger et al. (2000). To support this examination, we show reconstructive models of processes that could occur to form the current configuration of the Hi'iaka complex. We have interpreted the types and degree of activity of volcanism that are evident in this region and have compared them with overall activity on Io. We have compared the paterae in this study region with other larger Ionian paterae and terrestrial lava lakes. Our mapping allows the interpretation of gradational processes in the evolution of the landforms. We assess the degradational sequence proposed by Moore et al. (2001) and further interpret distinct feature changes that can occur during this process. We have examined seven mountain structures in detail to assess their differences and how those differences may be controlled by volcanic or gravitational interaction. Subsequently, we compare the Hi'iaka and Shamshu regions with other studied regions on Io to determine any significant differences in the geologic activity.

2. Background

The Hi'iaka region (~12°S–5°N, 75–87°W) and the Shamshu region (~15–5°S, 55–77°W) are located in Io's leading and antijovian hemispheres. The Hi'iaka region (Fig. 1) consists of Hi'iaka Patera, a large (60 km wide × 95 km long) caldera-like feature, the mountains of north and south Hi'iaka Mons (that border Hi'iaka Patera and are inverted L-shaped mirror-images of each other), west Hi'iaka Mons (a small isolated peak), and Mekala Patera (name submitted to the IAU) which is located west of the Hi'iaka Montes. The Shamshu region, located to the southeast of south Hi'iaka Mons (Figs. 1 and 2) consists of Shamshu Patera, three mountains, and Perun Patera (name submitted to the IAU), a small patera southwest of Shamshu Montes. Only the westernmost of the three edifices has been named. To facilitate descriptions, however, the three mountains are informally referred to as north, south and west Shamshu Mons.

Late in the extended *Galileo* Europa Mission (GEM), high resolution observations of the regions were obtained during the close Io flybys. The near-terminator observation of the Hi'iaka region (Fig. 1) obtained in November 1999 (orbit I25) has a spatial resolution of 260 m/pixel. An orthographic projection of this regional mosaic was used as a map base because it shows a surface area that includes portions of the Tawhaki and Shamshu regions. Analysis of the mosaic by Turtle et al. (2001) and Schenk et al. (2001) indicate that north Hi'iaka Mons extends 240 km in length and its highest peak is 11 km high; south Hi'iaka Mons extends 198 km in length and is 4.3 km high; west Hi'iaka Mons is only 25 km long and 3–4.5 km high. A study of the ridged textures on the mountains revealed that ridge formation may be dependent on local slope (Turtle et al., 2001); the steepest slopes on the mountains do not exhibit ridges. Jaeger et al. (2000) and McEwen et al. (2000a) proposed that the eastern scarp of north Hi'iaka Mons

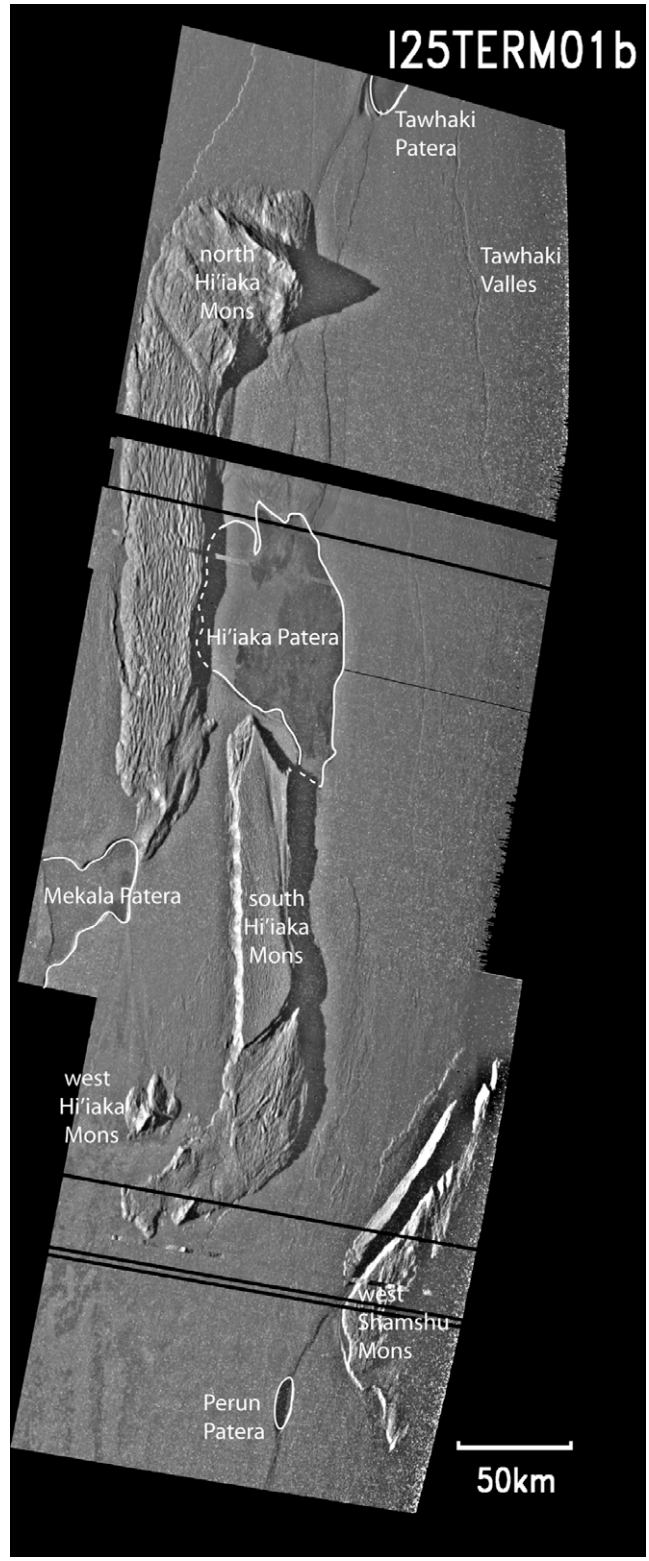

Fig. 1. Orthographic projection of *Galileo* SSI observation obtained during the orbit I25 flyby in November 1999 (observation I25ISTERM01b; PIA02540). Hi'iaka Patera is centered at 3.1°S, 79.8°W. Resolution is 360 m/pixel. North is up. Illumination is from the left. Major features in the Hi'iaka region are noted. This mosaic serves as the base for the geologic map of the Hi'iaka region.

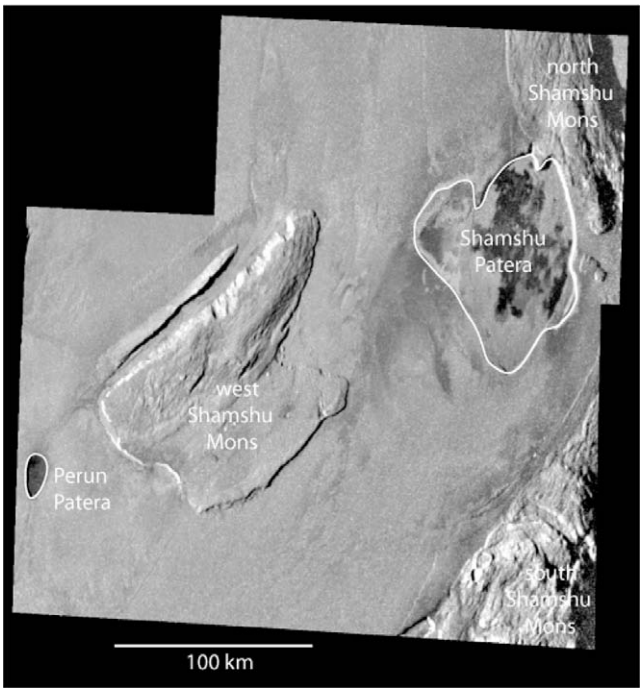

Fig. 2. *Galileo* SSI observation obtained during the orbit I27 flyby in February 2000 (I27ISSHMSHU01; PIA02555). Shamshu Patera is located at 9.8°S, 63.6°W. Resolution is 340–345 m/pixel. North is toward upper right. Illumination is from the left. Major features in the Shamshu region are noted.

may have been rifted away from the western scarp of south Hi'iaka Mons in both north–south and east–west motion; Turtle et al. (2001) supported that interpretation and determined that such motion indicates that the Hi'iaka Montes and Patera complex is an example of volcano-tectonic interaction on Io as described by Radebaugh et al. (2001). Mapping aided in further investigation of this hypothesis; the distribution of geologic units and the complementary morphology of the structures allowed us to reconstruct a possible arrangement of structures and a tectonic and volcanic modification process that would result in the current configuration of structures and deposits.

The near-terminator observation of the Shamshu region (Fig. 2) with a spatial resolution of 340–345 m/pixel was obtained in February 2000 (orbit I27). This mosaic is used as the base for the geologic map of the Shamshu region. Turtle et al. (2001) noted from an analysis of this mosaic that north Shamshu Mons stands ~3 km high. West Shamshu Mons is smaller than the two large Hi'iakan mountains, extending only 180.5 km and standing 2.9 km high (Schenk et al., 2001). The floor of the valley along the western margin of west Shamshu Mons exhibits streaks that suggest material flowed along it (Moore et al., 2001). The adjoining narrow ridge is ~1.4 km high. A "lineament" connects the valley with the small patera to the south. Turtle et al. (2001) also noted bright areas on the scarps of west Shamshu Mons that may indicate possible sapping activity. Shamshu Patera appears to cut into the mountain to its northeast; there is no obvious debris from the mountain on the patera floor indicating that it may have been obscured by subsequent volcanic resurfacing (Turtle et al., 2001).

Voyager coverage of this area was at much lower resolution than the *Galileo* coverage and does not reveal any small-scale differences from the more recent *Galileo* data. The limb views of this area also make assessing surface changes difficult. The only surface change noticeable over the period of observation of this region is a "dark flow-like deposit" that was emplaced at Hi'iaka in the interim between the *Voyager* 1 and 2 flybys (McEwen, 1988).

3. Mapping techniques

The geologic map of the Hi'iaka region was produced using the *Galileo* SSI orbit I25 mosaic (spatial resolution of 265 m/pixel: Fig. 1). The geologic map of the Shamshu region was produced using the *Galileo* SSI orbit I27 mosaic (spatial resolution of 340–345 m/pixel: Fig. 2). Interpretation of color units was made by examining the relevant portion of a global mosaic of images taken by *Galileo* (Fig. 3) and a low-phase angle (4°) color mosaic (in which mountains are not visible) covering the antijovian hemisphere obtained in June 1999 (orbit C21; McEwen et al., 2000a; Keszthelyi et al., 2001). These images were examined to ascertain the color differences of features and deposits so that the features could be mapped in detail; they remain the best global-scale color coverage obtained during the *Galileo* mission. Previous authors have established the importance of color in interpreting the composition of materials (see Section 4).

The geologic mapping approach and methodology of Wilhelms (1972, 1990) was employed for this study; it has been successfully applied to other small regions of Io (Williams et al., 2002, 2004, 2005, 2007; Bunte et al., 2008; Leone et al., 2009). Details on the mapping approach using *Galileo* data, including the constraints imposed by the multiple *Galileo* flybys, and previous interpretations of the *Galileo* color data (e.g., Young, 1984; Geissler et al., 1999, 2000, 2004) were described by Williams et al. (2002, 2004, 2005, 2007). In the absence of crater statistics and extensive stratigraphical constraints, material units are defined and characterized based on geomorphologic characteristics such as landform morphology, albedo, and color (i.e., composition); emplacement of the surface features and the stratigraphic relationships between the volcanic and structural features are interpreted. Contacts between units are inferred from color and albedo differences between units as well as changes in surface morphology.

Limitations on planetary mapping of Io include lack of full coverage high resolution images and wide range of phase angles of available images. Any maps produced solely from imagery rely heavily on interpreting surface morphology to define geologic units due to the lack of outcrop scale views that would facilitate examination of stratigraphy. The lack of rock samples prevents a definition of geologic units in the traditional sense, so we must look to the textures of surfaces to distinguish different units. The morphologies of some materials do allow the identification of superposition and cross-cutting relationships; our maps show the distribution of lithochronostratigraphic units to the extent allowable by available imagery but still must be assessed with caution regarding standard conventions for geologic analysis. The low number of images that cover these regions at high resolution somewhat limits the ability to map detailed features and structures. Also, identifying distinct units by color and texture alone is difficult because the color and grayscale images were taken at different resolutions. Materials within each geologic unit have similar ranges of compositions (combinations of silicates, sulfur, and sulfur dioxide); the units differ only by emplacement environment and mechanism, morphology, or alteration (e.g. Lopes and Williams, 2005; Geissler et al., 2004).

The lack of impact craters on Io prevents the stratigraphic correlation of map units by crater statistical methods. Johnson et al. (1979) estimated the extreme lower limit resurfacing rate of Io to be ~1 cm year^{-1}; McEwen et al. (2000a) estimated that the surface of Io is no more than a few tens of millions of years old. Whereas crater statistics cannot be used to suggest age relationships, relative stratigraphic correlations can be made using superposition, embayment, and cross-cutting relationships between material units. For example, younger lava flows superpose older lava flows; the superposition is indicative of multiple eruption events.

Fig. 3. Excerpt from USGS controlled photomosaic map of Io. Combination of best high resolution color images taken throughout the *Galileo* mission. North is up. Scale bar is 50 km. http://planetarynames.wr.usgs.gov/images/io_comp_color.pdf.

4. Map units

Following the convention used in *Voyager*-era maps (Schaber, 1980, 1982; Moore, 1987; Schaber et al., 1989; Greeley et al., 1988; Whitford-Stark et al., 1991; Crown et al., 1992) and our earlier *Galileo* SSI-based maps (Williams et al., 2002, 2004, 2005, 2007; Bunte et al., 2008; Leone et al., 2009), we define four types of geologic units for the Hi'iaka and Shamshu regions: mountain materials (i.e. tectonic massifs), plains materials, patera floor materials, and lava flow materials. A fifth type of unit used in previous maps, diffuse deposits, is not identifiable in these regions. Detailed descriptions and interpretations of the units found in both regions are given in Table 1. Fig. 4 shows images of the type localities of the units found in the Hi'iaka and Shamshu regions, respectively. Figs. 5 and 6 show the geologic maps of the material units and structural features in the Hi'iaka and Shamshu regions, respectively. These maps are consistent with SSI-based maps of other regions of Io (Williams et al., 2002, 2004, 2005, 2007; Bunte et al., 2008; Leone et al., 2009).

Based on previous interpretations of color as it appears in *Galileo* SSI and NIMS data (Simonelli et al., 1997; Geissler et al., 1999, 2000) and associated inferences of composition (Young, 1984; Geissler et al., 1999, 2001; Spencer et al., 2000; Williams et al., 2005), we attempt to use color as an identifying characteristic of surface materials. The many colors of surficial deposits on Io appear to not only indicate different material compositions but to also give clues to the different emplacement mechanisms of those materials. For example, dark or black materials are confined to paterae (Fig. 3); spectral analysis reveals that they exhibit an absorption feature due to magnesium-rich silicates (Geissler et al., 1999). The restriction of dark materials to paterae suggests that dark materials are generally extruded as the denser, silicate lavas that we see filling the paterae. Red deposits are located near hotspots and are often associated with plumes or high temperature sites of activity (e.g. Pele; Geissler et al., 1999). Red hued materials could be interpreted to be emplaced by plume fallout or to be the result of interaction with other high temperature materials. In the Hi'iaka and Shamshu regions, there is no obvious red diffuse material, though some of the paterae materials are tinted red, suggesting thermal interaction with warm materials; warm diffuse plume deposits may mantle the paterae or the substrate beneath the paterae may conduct heat to the overlying paterae floor materials. White materials correspond to areas of abundant coarse-to-medium-grained SO_2 (Carlson et al., 1997) and can occur as diffuse rings, presumably due to fine-grained SO_2 frost (Geissler et al., 1999). There are large bright white deposits adjacent to three of the mountains in this region (Fig. 3), suggesting that some SO_2 frosts were vented and condensed and mantle the surface. Yellow materials dominate the surface and appear to be linked compositionally or genetically to red and white materials (Geissler et al., 1999); we note that contacts between the yellow and white plains are poorly defined and that the yellow color of the mountains is less saturated than that of the plains.

Dark (low albedo) materials are mainly confined to patera interiors, appear in an array of colors from red to black, and are interpreted as silicate lava flows (Geissler et al., 1999). It is of interest to note that the darkest materials are associated with active volcanic centers or hotspots (Lopes-Gautier et al., 1997, 2000; Lopes et al., 2001, 2004). Bright (intermediate to high albedo) materials appear in an assortment of colors from gray–white to yellow and light red; the colors may be indicative of variations in composition of sulfur- and sulfur dioxide-rich materials and/or variations in age and degree of alteration due to radiation exposure (Geissler et al., 1999; Kargel et al., 1999). Elongate morphologic features with distinct lobate margins generally represent lava flows; bright colored flows have been interpreted as both sulfur-rich lava flows and degraded silicate flows (Williams et al., 2002). In general, dark-toned or low albedo paterae materials are considered to be younger than their light-toned or high albedo counterparts, which are interpreted to brighten through deposition of sulfurous plume materials. This relationship is seen at Zal Patera (Bunte et al., 2008) where bright patera materials are superposed by dark materials and a red diffuse deposit is concentrated over the area; it is also noted at other locations, including Amirani and Monan Paterae (Williams et al., 2007) where the patera materials are brighter where they are mantled by white diffuse materials. *Diffuse* materials (McEwen et al., 1998; Geissler et al., 1999; Carlson et al., 1997; Howell and Lopes, 2007) that are evident in other regions of Io (Williams et al., 2002, 2004, 2005, 2007; Bunte et al., 2008) are not evident in the Hi'iaka and Shamshu regions. This apparent lack of diffuse pyroclastic volatile material may simply be an artifact of viewing conditions; if diffuse material is present, it is most likely white diffuse

Table 1
Material units identified in the Hi'iaka and Shamshu regions of Io. Letter symbols refer to the keys from geologic maps of the regions (Figs. 5 and 6). Albedo from *Galileo* SSI I27 and I25 observations (Figs. 1 and 2). Color from *Galileo* SSI C21 observation and *Galileo* global mosaic (Fig. 3). Type locality images found in Fig. 4.

Material units	Description	Interpretation
Dark patera floor material (pf_d) subunits: 1–3	Surfaces are black or dark gray with some variation in albedo. The surfaces have distinct contacts with the surrounding terrain and are found within paterae. Material appears smooth with some variation in texture and often correlates with NIMS and/or SSI hotspots. Superposition indicates that subunit 3 is the darkest and freshest material	Dark floor materials are silicate lava flows that may be coated by sulfurous materials. Darker surfaces are likely warm and recently emplaced silicate flows
Bright patera floor material (pf_b)	Surfaces are bright red–orange and apparently smooth. The surfaces have distinct contacts with the surrounding terrain and are found within paterae but can occur beyond the rims of paterae	Bright floor materials are similar to those of dark floor materials. They may be cold and less active silicate flows coated by sulfuric materials. These materials may also have been produced as primary sulfuric flows or as plains materials that have been remobilized to flow into the patera's depression (Keszthelyi et al., 2004)
Bright flow material (f_b)	Surfaces are high albedo and appear bright yellow or white. Margins are lobate and lengths are greater than widths. Contacts with surrounding terrain are sharp. Flows extend into topographic lows. Albedo variations and superposition or cross-cutting relationships indicate relative age	Flows may be of sulfur or sulfur dioxide composition (Williams et al., 2001, 2002, 2005, 2007). Albedo variations indicate age differences in flows. Flows appear to be emplaced in the Promethean style (Keszthelyi et al., 2001)
Undivided flow material (f_u)	Terrain consists of bright and dark flows with a range of albedos. Contacts with surrounding terrain are not distinct so that individual flow units are not distinguishable	Lava flow types are unclear. They are older silicate and sulfur-rich flows which predate dark and bright flow materials
White bright plains material (p_{bw})	The surface is layered and exhibits colors of white or white–gray. Albedo varies but is higher than that of yellow bright plains. White plains may be mantled by white diffuse materials	White plains are the silicate crust mantled by dominantly SO_2-rich materials. The surface is possibly aged yellow bright plains material with sulfur dioxide snow that is recrystallized from plume fallout (Douté et al., 2001)
Yellow bright plains material (p_{by})	The surface is layered and exhibits colors in shades of yellow. Albedo varies but is intermediate between that of bright patera floors and bright flows. Plains are often mantled by diffuse materials and contain scarps and grooves	Yellow bright plains are the silicate crust mantled by sulfur-rich materials (Bart et al., 2004; Keszthelyi et al., 2004). Surface deposits may be formed by volcanic plume fallout flow deposits
Lineated mountain material (m_l)	Lineated mountains appear to be elevated blocks of bright plains but are separated from the plains by a bounding scarp. They contain well-defined grooves and ridges	Mountains appear to be uplifted crustal blocks. Lineated mountains exhibit little degradation or erosion by slumping and/or other processes (Moore et al., 2001)
Undivided mountain material (m_u)	Undivided mountains appear to be elevated blocks of bright plains but are separated from the plains by a bounding scarp. They contain few grooves, ridges, and lineaments and may contain lobes or dome-like hills	Mountains appear to be uplifted crustal blocks. Undivided mountains exhibit some signs of degradation and erosion by slumping and/or other processes (Moore et al., 2001)
Mottled mountain material (m_m)	Mottled mountains appear to be elevated blocks of bright plains but are separated from the plains by a bounding scarp. They generally do not contain grooves, ridges, and lineaments but do contain lobes and dome-like hills	Mountains appear to be uplifted crustal blocks. Mottled mountains exhibit lobes that result from slumping and mass wasting. Moore et al. (2001)
Plateau material (pl)	Mountains appear to be elevated blocks of bright plains but are separated from the plains by a bounding scarp. They contain grooves, ridges, and lineaments	Mountains appear to be uplifted crustal blocks. Plateaus exhibits depressions and grooves that result from sapping and scalloped boundaries that may result from contact with warm materials (Moore et al., 2001)
Layered plains material (p_1)	Layered plains appear to be other plains materials isolated into elevated structures. The plains may be lobate, digitate, unmodified, or with debris downslope (Moore et al., 2001)	Layered plains are the silicate crust mantled by sulfur-rich materials (Bart et al., 2004; Keszthelyi et al., 2004). They are exposed on local topographic highs as a result of degradational processes (see Moore et al., 2001)

material that corresponds to areas of SO_2 frost (Carlson et al., 1997) and concentrated in white bright plains materials.

It should also be noted that some materials appear to change hue as they age and are irradiated (Nash et al., 1986; Kargel et al., 1999). Dark materials tend to brighten if they are mantled by diffuse deposits (Nash et al., 1986). Bright materials may darken as a result of interaction with superposed or underlying materials (Williams et al., 2004). Red diffuse deposits appear to fade over a period of months (McEwen et al., 1998; Turtle et al., 2001; Geissler et al., 2004). Some dark patera floor materials may change from red to green hues as a result of interactions between sulfur-rich plume deposits and underlying warm silicate materials (i.e., Pillan Patera, Phillips, 2000; Keszthelyi et al., 2001). Each of these phenomena has been witnessed in different regions of Io (see Kargel et al., 1999); the same processes occur in the Hi'iaka and Shamshu regions. As color is a major distinguishing characteristic in defining material units, these kinds of surface changes are used to determine relative ages.

Phase angle affects the color and albedo appearance of different units. Some features that are visible at high phase angle are not visible at low-phase angle (Geissler et al., 2001); other features appear to change hue or relative albedo when viewed at different phase angles. Relative albedo of features is used as a qualitative descriptor to characterize units in addition to the color interpretations discussed

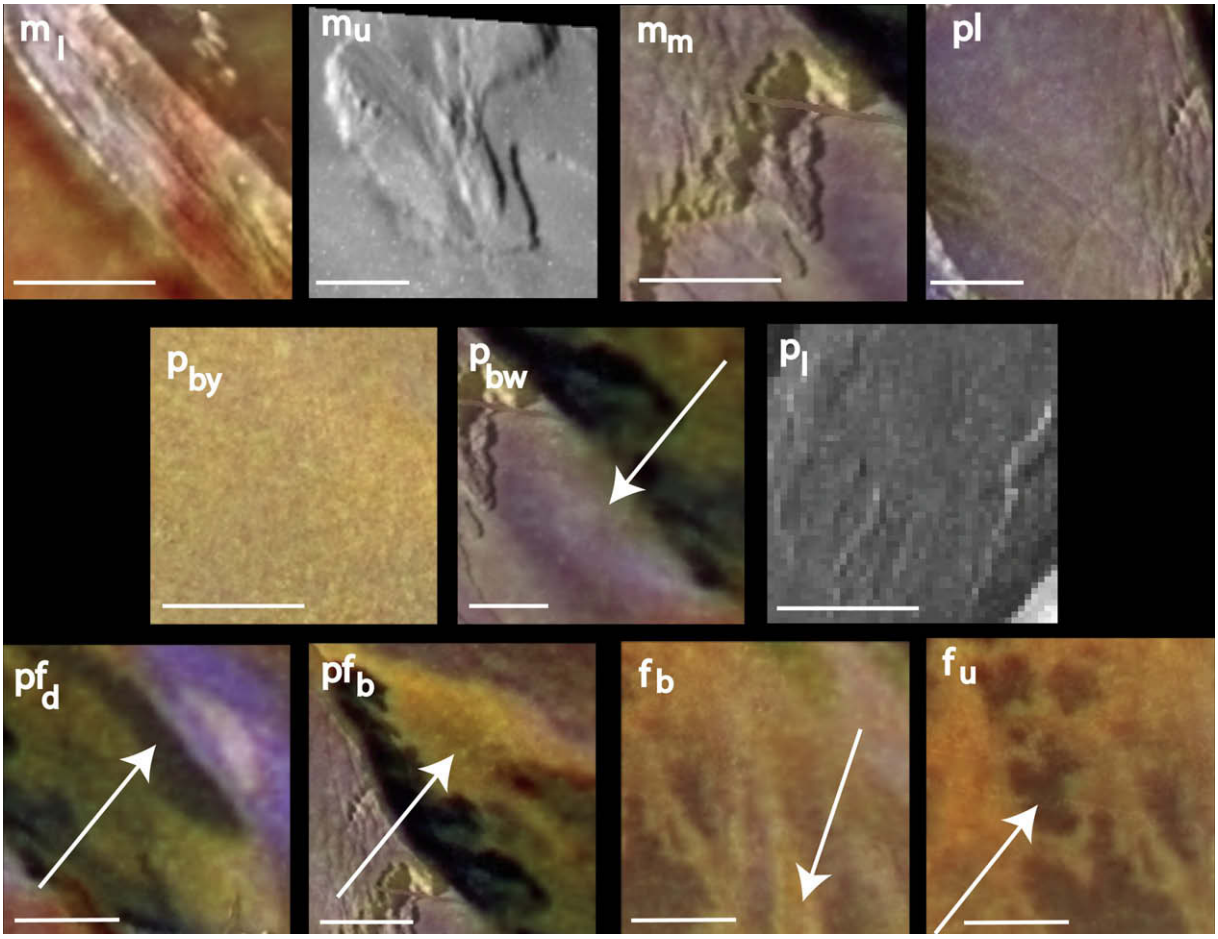

Fig. 4. Color type examples of material units found in the Hi'iaka and Shamshu regions of Io. Lineated mountain material (m_l), undivided mountain material (m_u), mottled mountain material (m_m), plateau material (pl), yellow bright plains material (p_{by}), white bright plains material (p_{bw}), layered plains material (p_l), dark patera floor material (pf_d), bright patera floor material (pf_b), bright flow material (f_b), undivided flow material (f_u). Excerpts taken from *Galileo* SSI image PIA02527, *Galileo* SSI mosaic I27ZALTRM01, or *Galileo* SSI mosaic I25ISTERM01b (Fig. 1). Scale bars are 25 km.

above. The most applicable interpretation of phase angle and related color and albedo can be made from NIMS spectral mapping (Carlson et al., 1997); areas that are bright (high albedo) at low-phase angles are characterized by coarse-grained SO_2.

4.1. Mountain/plateau units

Mountain and plateau materials generally appear similar to their surroundings and are often only visible in low-Sun angle images, where shadows highlight scarps, ridges, grooves, and peaks (Fig. 3; Schenk et al., 2001; Turtle et al., 2001; Jaeger et al., 2003). The bases of the mountain units appear to be partially obscured or covered by plains and flow materials. Four types of mountain morphologies are characterized (see Figs. 4–7): *lineated* (containing well defined ridges and grooves), *mottled* (containing lobes and dome-like hills), *undivided* (characterized by aspects of both the mottled and lineated units, but dominated by neither), and *plateau* (similar to the mottled map unit but occurs on flat-lying elevated topography).

Lineated mountain and plateau units are typically higher elevation than the other mountain types. Lineated units may exhibit isolated peaks at the highest elevations. For example, the peak at the northern end of the lineated mountain north Hi'iaka Mons is the highest elevation of the region. The average height of the lineated mountain materials is considerably lower than the isolated peaks. The heights of the eastern scarp of north Hi'iaka Mons and the eastern scarp of south Hi'iaka Mons are 3.5 and 3.6 km, respectively (Fig. 1; Turtle et al., 2001); this indicates that lineated and plateau units can be of similar elevations. Undivided mountains are generally of lower elevation than the lineated and plateau units. Mottled units are the lowest elevation of all mountain units, though the small shadow lengths do not allow for a precise estimate of elevation.

Lineated mountains generally have scarp contacts with other units. An exception to this generality is that lineated units can grade into undivided units, possibly due to gravitational downslope motion. Slumping or landslides can cause sharp contacts between undivided and mottled units. All mountain units except mottled mountains appear to have sharp contacts with plains units; the plains units embay the mountain units. Mottled material is only slightly elevated relative to the layered plains, suggesting that the mottled materials grade into the layered plains. There are no obvious structures that continue across unit boundaries. However, higher resolution images may reveal that furrows or ridges continue from lineated to undivided units. We have established unit boundaries such that they do not cut structures (Figs. 5 and 6); we note, however, that downslope movement, slumping, or sapping may have degraded structures such that they are not visible at the resolution of these images.

Lineations correspond to topographically distinct ridges, grooves, graben, or scarps. North Hi'iaka Mons and portions of south Hi'iaka Mons, north Shamshu Mons, and south Shamshu

Mons have lineations that are generally parallel to the downslope direction (Figs. 5 and 7a). South Hi'iaka Mons and west Shamshu Mons are plateaus with some mottled mountain unit characteristics (Figs. 7b and 8). South Hi'iaka Mons is relatively flat with a slight slope to the west. West Shamshu Mons exhibits lobes and debris aprons on the downslope edges (Figs. 6 and 8). Plateaus exhibit some lineations, though a lower concentration than on lineated mountain units (Fig. 7b). South and west Shamshu Mons have large lobes of mottled morphology that appear to have wasted from the main mountain structures (Fig. 8). North Hi'iaka

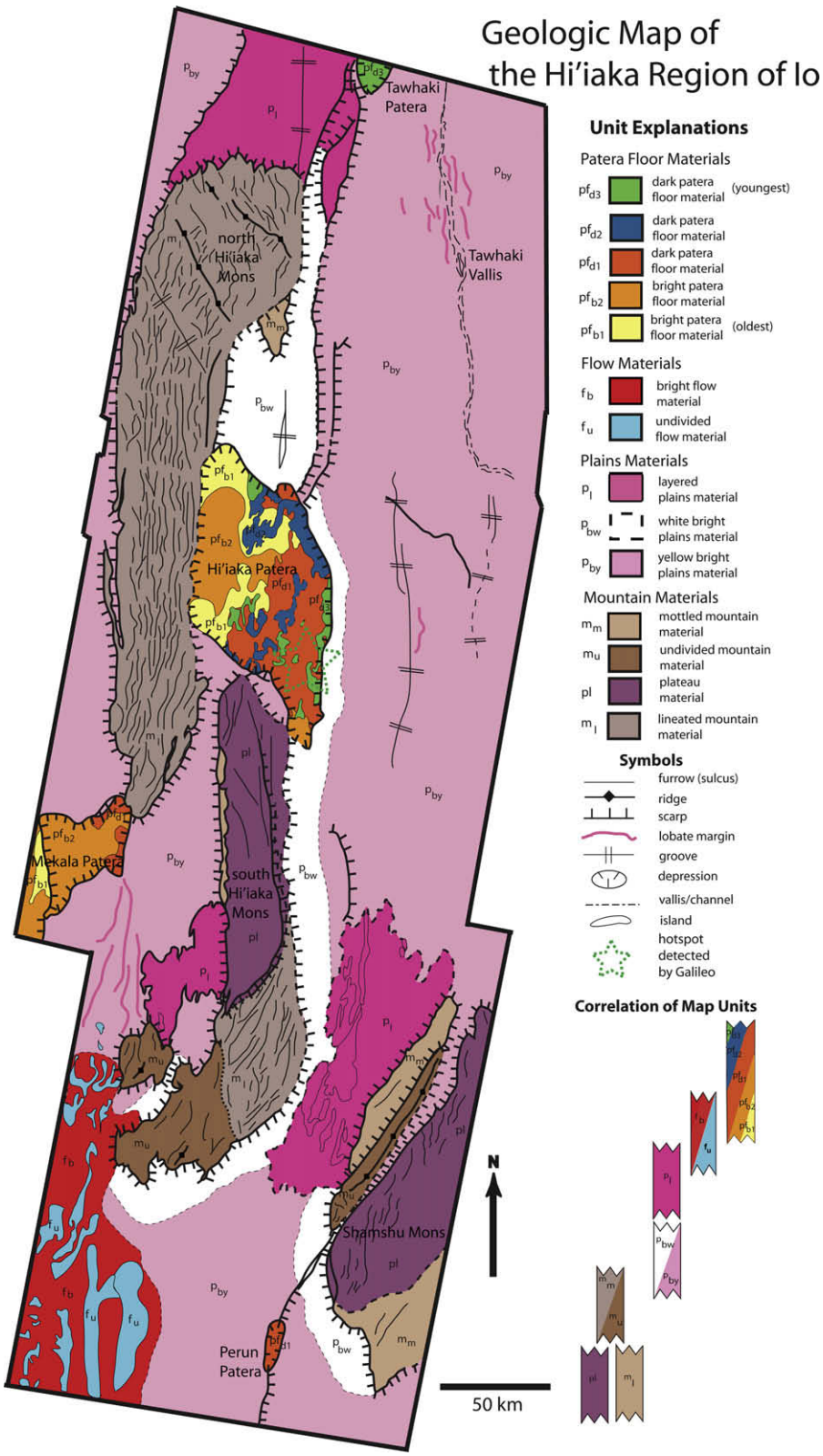

Fig. 5. Geologic map of the Hi'iaka region of Io. The map is based on observation I25ISTERM01b (Fig. 1) at a resolution of 260 m/pixel. Map covers 12°S–5°N, 75–87°W.

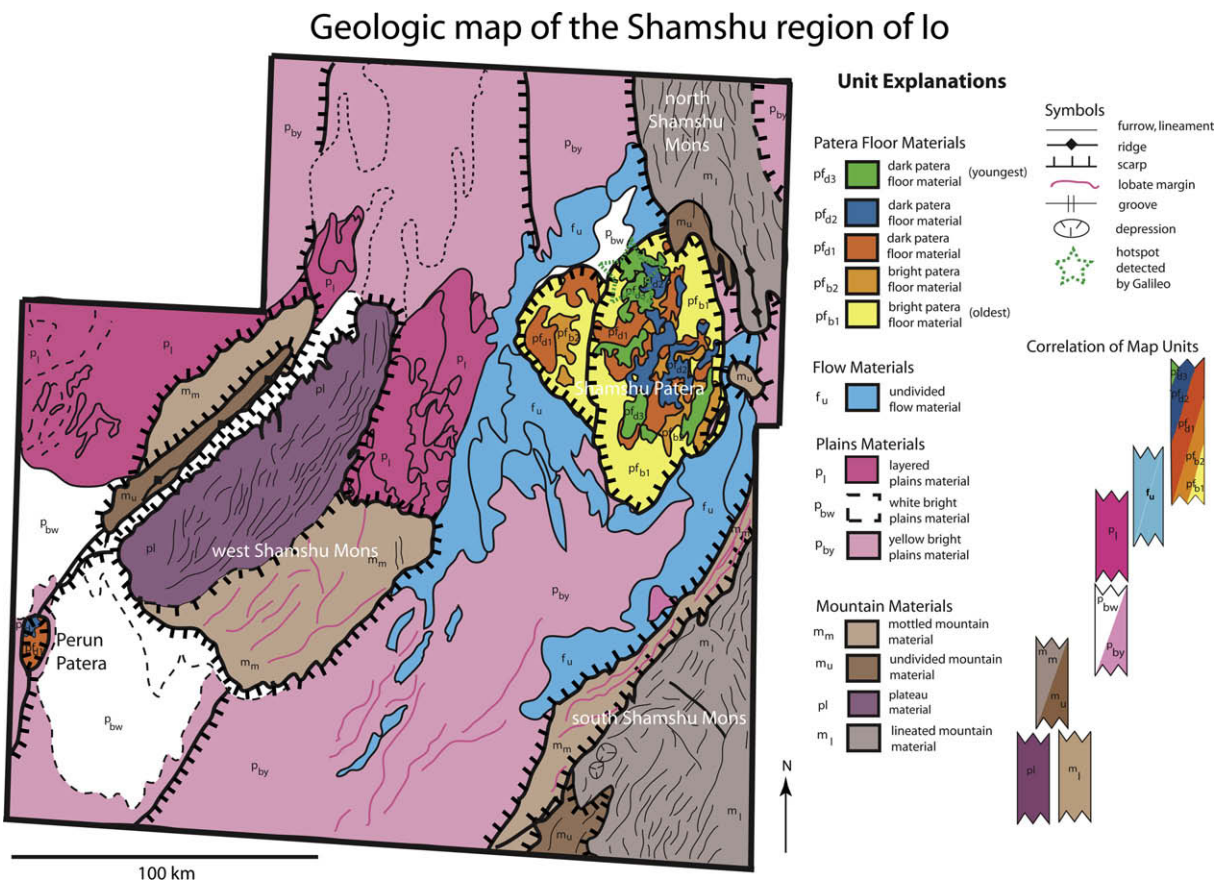

Fig. 6. Geologic map of the Shamshu region of Io. Map based on mosaic I27ISSHMSHU01 (Fig. 2) at a resolution of 345 m/pixel. Map covers 15–5°S, 55–77°W.

Mons and south Shamshu Mons exhibit several grooves and, in the case of south Shamshu Mons, depressions that are generally characteristic of undivided or plateau units; the concentration of lineations or furrows compels the designation of a lineated map unit. Lineated mountains are interpreted as tectonically modified uplifted crustal blocks, and mottled units are thought to be indicative of displacement of crustal materials by mass wasting processes (e.g., SO_2 sapping: Moore et al., 2001; Turtle et al., 2001). Undivided mountains have characteristics of both the lineated and mottled units, so they could be interpreted as uplifted blocks that have undergone some displacement by mass wasting, though not enough to qualify them as mottled. Plateaus, which are very similar to lineated mountains, are also interpreted as uplifted blocks; they are, however, not as extremely tilted.

4.2. Plains materials

Yellow, gray–white, and red to red–brown color units in SSI images are interpreted as plains materials (Fig. 3). Plains materials appear to partially obscure the bases of mountain units and to predate visible flow and patera floor materials (see Figs. 5 and 6). The Hi'iaka and Shamshu regions are dominated by yellow plains materials, although several local patches of white plains materials occur adjacent to the patera and mountains and in the northern part of the Shamshu region. Layered plains materials are also evident in both regions (Fig. 7b). Plains are interpreted as the silicate upper crust of Io with a mantle of sulfur- and/or SO_2-rich material (Bart et al., 2004; Keszthelyi et al., 2004) that formed by combinations of overlapping effusive flows, mass wasting of flow materials, SO_2 sapping, deposits from volcanic plumes containing SO_2 and sulfur frosts, and pyroclastic flows (McEwen et al., 2000b; Moore et al., 2001; Schenk et al., 2001). The layered plains materials appear to occur adjacent to highly degraded mottled mountain materials. In previous high resolution mapping (Williams et al., 2002, 2004, 2005, 2007), the units identified as layered plains were portions of the white and yellow plains material isolated by scarps onto local topographic highs. In those studies, some local topographic highs were identified as plateaus. We do not dispute this former classification, but we do use the term "plateau" to refer to a more extreme topographic expression and we infer a different formation mechanism. We identify plateaus as having the same composition, though not the same texture, as the plains and layered plains. We interpret that plateaus form as uplifted (and possibly tilted) blocks and degrade by downslope movement as opposed to the local topographic highs that might result from local degradation due to volcanic resurfacing. We classify plateaus as a mountain unit.

4.3. Lava flow materials

Three types of lava flow materials are recognized based on morphology, albedo, and color: bright flows, dark flows, and undivided flows. Lava flows can overlie low elevation mountain materials and all other material units, although previous mapping shows that they are typically constrained to inferred topographic lows based on mapping of scarps (Williams et al., 2002). The lava flow units are characterized by a lobate and elongated morphology, in which their flow lengths are greater than their widths (Williams et al., 2002, 2004, 2005, 2007; Bunte et al., 2008; Leone et al., 2009). Flows in the Shamshu region appear to emanate from a vent at or near Shamshu Patera (Fig. 6); the flows visible in the Hi'iaka region are not associated with a visible vent (Fig. 5). Bright flows

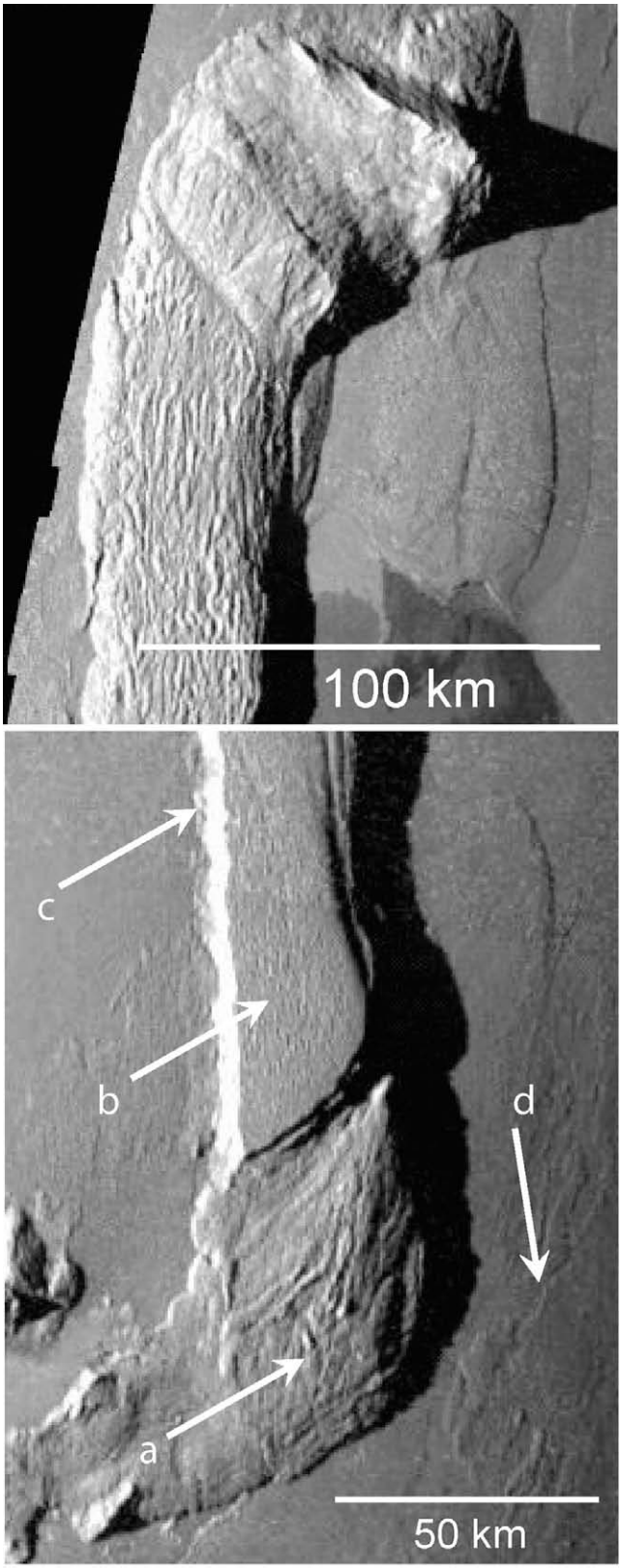

Fig. 7. Excerpts from *Galileo* observation I25ISTERM01b. Top: North Hi'iaka Mons. Note the grooved texture. Bottom: South Hi'iaka Mons. Arrows indicate the: (a) lineated mountain, (b) plateau, (c) mottled mountain, and (d) layered plains units. Lineated or plateau material would degrade to mottled mountain material. The layered plains material is a different expression of degradation by small scale mass wasting and only minor uplift, though they may be augmented in places by slumping of the mottled materials.

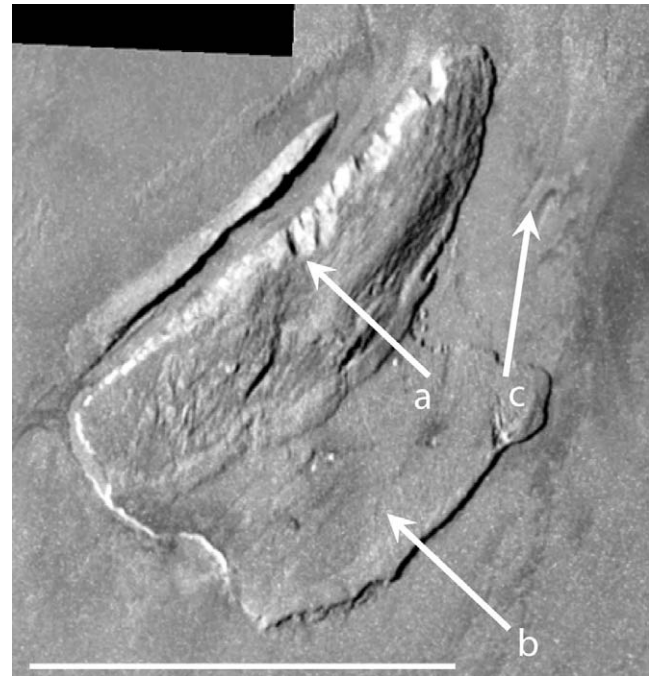

Fig. 8. Enlarged view of west Shamshu Mons. Excerpt from *Galileo* SSI mosaic I27ISSHMSHU01 obtained during the orbit I27 flyby in February 2000. Arrows indicate: (a) the scalloped scarps that likely result from erosion by warm silicate materials, (b) the lobed or mottled texture that is characteristic of severe degradation of the original tectonic structure, and (c) the layered plains, which may be included in the degradational process of materials to form the plains. Scale bar is 100 km.

exhibit a variety of colors from gray to orange and have a high albedo relative to the patera floor materials (Fig. 4). The albedo of bright flows is generally lower than the surrounding and underlying plains. Dark flows appear dark black and can have red, blue, and green tints; the albedo of dark flows is extremely low compared to all other units. No dark flows are evident in either region. Flows with intermediate albedo and undefined stratigraphic relationships with other units are classified as undivided flow materials. Bright flows are thought to be sulfur-dominated (Lopes et al., 2001, 2004; McEwen et al., 1997), dark flows are most likely silicate (Nash et al., 1986), and undivided flows may be either faded bright flows or mantled dark flows.

4.4. Patera floor materials

Quasi-circular features with irregular or scalloped boundaries are evident on Io; these features are paterae rather than impact craters (Radebaugh et al., 2001). The International Astronomical Union defines paterae as "irregular crater[s], or complex ones[s] with scalloped edges" (Gazetteer of Planetary Nomenclature, http://planetarynames.wr.usgs.gov, 2008). Radebaugh et al. (2001) further characterize these caldera-like features by their steep walls, flat floors, and arcuate margins; many paterae are irregular or angular in shape. Thermal emission is observed in these areas; thus any volcanic region (generally paterae) that exhibits low albedo is considered active (McEwen et al., 1985, 1997; Davies, 2007).

Patera floor materials have colors ranging from yellow–orange to dark black (see Fig. 3, Section 5.4). Two subunits of patera floor materials are defined: bright and dark materials. Patera floor materials have morphologies, colors, and albedos similar to flow materials; they are thought to be composed of the same materials as the flow units. Traditionally, flow and patera floor materials are

mapped separately (Schaber, 1980, 1982; Crown et al., 1992) because there is uncertainty regarding the emplacement mechanisms of patera floor materials (i.e., lava flows vs. lava lakes). Floor materials are emplaced effusively within the bounding scarps of paterae, whereas flow units are emplaced outside the bounding scarps of paterae but can flow downslope into paterae. The patera floor materials may be superposed by flow materials. Source vents for patera floor materials are not always evident.

Color differences are often considered to be indicative of variations in composition, including sulfur and silicate mixtures (e.g. Williams et al., 2002, 2004; Lopes et al., 2001). The Hi'iaka and Shamshu Paterae both contain compound flow fields which include units of several different colors but do not appear to be flooded by dark (i.e., fresh) flows (Figs. 5 and 6). Though neither NIMS nor SSI has sufficient spatial or spectral resolution to determine the difference in composition of the materials within the paterae, mapping supports that the dark units within each patera are likely of similar silicate composition due to location and color. The paterae floor materials are all confined within the paterae scarps and do not appear to be fed by a lava source outside of the paterae; the locations of concentration of dark materials suggest that the units within each paterae share a source within or at the boundaries of the paterae. The dark patera floor materials within Hi'iaka Patera are of a similar hue, suggesting that they are of comparable age. Materials erupted from the same source over a short period of time likely share similar composition. Color differences are attributed to differences in age between the units. The darkest units superpose the lighter units, suggesting that the darker materials are youngest. The lightest unit is the lowest unit, indicating that it was emplaced first.

Our mapping supports the theory that lighter patera floor units are inferred to be sufficiently aged to have brightened in albedo due to degradation and/or coating by sulfur-rich materials (Geissler et al., 1999; Douté et al., 2001) and to have changed hue by irradiation (Nash et al., 1986) to appear brighter and more yellow than other fresh lavas within the paterae. We note that the brighter patera floor materials do not exhibit morphologies (i.e. lobes, digitate, or elongated morphology) characteristic of fresh or undegraded lava flows. Only the darker materials exhibit the lobate morphology that suggests that the dark materials are younger than the bright materials. The superposition of dark units over bright units also suggests this age relationship. Units that have been exposed to the environment longer will have had more opportunity to be degraded, mantled, and irradiated. We also note that the bright materials are more likely to be red-toned than the dark materials; Nash et al. (1986) suggest that irradiation would most likely redden the materials. Mekala Patera is dominated by bright patera floor materials, thus it does not appear to be active. Tawhaki Patera appears to be covered with some of the freshest and darkest patera floor materials in our map region; it is also the location of a hotspot.

5. Discussion

Mapping results support the theory that mountain units can be uplifted and tectonically modified, then sloped, scalloped, and leveled by SO_2 sapping (Moore et al., 2001) and that morphology differences in mountains suggest a degradational sequence (Turtle et al., 2000, 2001; McEwen et al., 2000a). The progression of degradation of mountain materials allows for young lineated mountain materials or plateaus to degrade and waste into undivided and then mottled mountain material. Further sapping and slumping produces lobes and debris aprons which can potentially further waste into plains materials. Volcanism appears to exploit tectonic movement in order to form the paterae; the youngest volcanic materials are isolated in the paterae formed by tectonic movement, as shown in our mapping. Three out of five paterae in the Hi'iaka and Shamshu regions are adjacent to mountains (and three out of five major mountains are adjacent to paterae) and as many as four of the paterae remained active at the end of the *Galileo* mission. The relationship between paterae and adjacent mountains supports the theory that paterae are strongly influenced by regional tectonism, as suggested by Radebaugh et al. (2001). Volcanism also appears to play a minor role in the degradation of mountain structures by thermal interaction, though sapping is likely a larger contributor to degradation. In locations where mountain units are in contact with the volcanic plains, scalloped scarps are profuse. Though diffuse materials are not evident in this region, it is likely that some diffuse material has at some time mantled the mountain units and perhaps aided in degradation by thermal interactions and by contributing to the downslope movement of materials and formation or enhancement of furrows. Some form of strike-slip motion and/or rifting has likely taken place to separate north and south Hi'iaka Mons, which were probably once a single mountain edifice (Jaeger et al., 2000). A similar scenario is feasible (though not well supported by current images) for the edifices of Shamshu Montes as well. Multiple episodes of flow are evident in the graded hues of paterae floor deposits and flows; in many cases, these flows preferentially follow tectonic scarps or faults. For example, the freshest dark materials within Hi'iaka Patera are exposed along the southern and eastern scarps and generally flow along those scarps; the freshest materials within Shamshu Patera are exposed along the northern scarp, and the undivided flows of the Shamshu region flow preferentially outward from the bounding scarps of the patera and are confined by the mountain units. Degradation of the structures and units subsequently increases within the presence of volcanic materials.

5.1. Landforms, structures, and other features

A wide variety of structural features has been mapped, including lineaments and scarps thought to be the surface expressions of faults, ridges, grooves and furrows in mountain units, and the paterae depressions themselves (Figs. 4–8). Seven individual mountain structures were also mapped; each one has a differently textured surface. Scarps delineate both mountains and plains units. Most grooves, lineaments, and ridges are found in the mountain units (Fig. 7b). The plains contain several scarps interpreted to be evidence of tectonic and/or sapping activity. None of these features are found within the flow fields, indicating that the flows are younger than or unaffected by the activity. No positive relief volcanic constructs such as domes, cones, or shields are resolvable within the mapped region. A probable lava channel cuts the plains of the Hi'iaka region (Fig. 9; Schenk and Williams, 2004). The lava channel (Tawhaki Vallis) is 190 km long, 0.5–6 km wide, and 40–65 m deep and is possibly associated with the hotspot at Tawhaki Patera. It has a sinuous nature and exhibits several interior islands. The morphology of this channel is consistent with formation by erosion from a fluid flow, most likely a thermal erosion lava channel (Fig. 9; Schenk and Williams, 2004).

5.2. Mountain units

Multiple origins for mountain structures have previously been suggested. Originally, Io's mountains were thought to be volcanic constructs (Masursky et al., 1979; Schaber, 1980; Whitford-Stark, 1982). However, it soon became apparent that there was a large tectonic component to their formation (Heath, 1985). Schenk and Bulmer (1998) offered the first explanation for how such large mountains could be erected tectonically. They proposed that the crustal subsidence caused by volcanic resurfacing induced

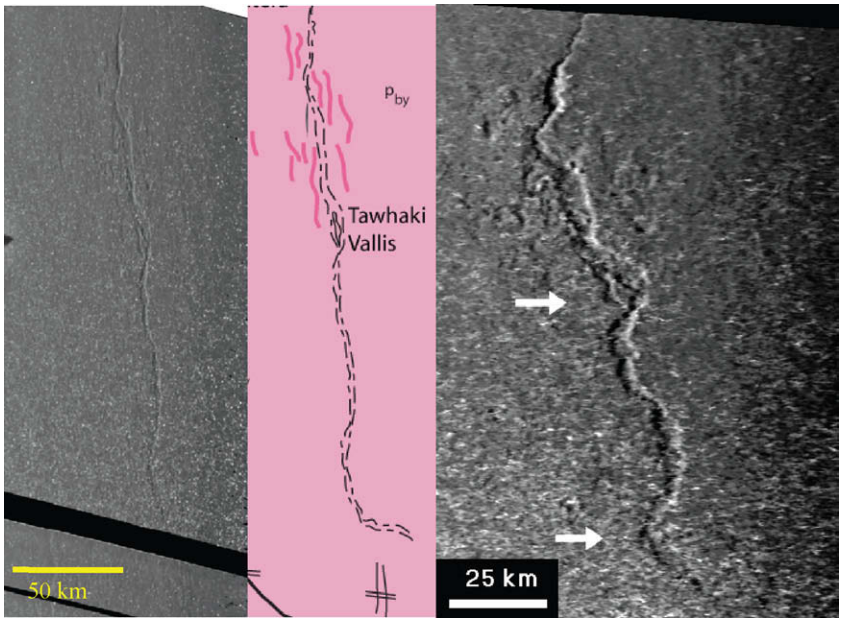

Fig. 9. Enlarged views of Tawhaki Vallis. Left: Excerpt from *Galileo* SSI observation I25ISTERM01b. North is up. Middle: Excerpt from geologic map of Hi'iaka region (Fig. 5). Right: Alternate projection of same area from Schenk and Williams (2004), shown to illustrate the sinuosity of the channel. Arrows indicate topographic "islands".

horizontal compression that drove thrust faulting. In contrast, McKinnon et al. (2001) hypothesized that Io's mountains formed in response to spatial and temporal variations in the temperature of the lower crust, such that repeated thermal expansion and contraction left coherent "rockbergs" standing in a matrix of disrupted crust in a process somewhat analogous to the formation of "chaos terrain" on Europa. Subsequently, Jaeger et al. (2003) compared the global effects of thermal and subsidence stresses on mountain formation and found that, while thermal stresses could potentially be important, subsidence stresses dominate mountain formation (in terms of global volumetric strain) for all reasonable values of lithospheric thickness.

The body of existing literature suggests that Io's mountains are composed of old surface materials that were buried as successively younger surface materials accumulated (Schaber, 1980, 1982; Moore, 1987; Greeley et al., 1988; Schaber et al., 1989; Schenk and Bulmer, 1998; Whitford-Stark et al., 1991; Crown et al., 1992). Thus, to first order, the mountains may be composed of materials similar to what the *Voyager* and *Galileo* spacecraft observed on the surface of Io. However, the composition of the crust probably does change with depth to a certain extent. Jaeger and Davies (2006) found that the large compressive stress in Io's crust confines most of its SO_2 (which fluidizes at a fairly low pressure) to the upper few kilometers. Therefore, the mountains are thought to be predominantly composed of a mix of silicates and elemental sulfur. We support the theory of Moore et al. (2001) that the mountains are tilted crustal blocks that were originally exposed as regions of the surface covered by multiple overlapping lava flows that continually resurface the satellite. If this is the case, the mountains would appear relatively flat after uplift and would likely have a detached or mobile surface layer that could easily be eroded.

The morphology of Io's mountains is influenced, not only by their formation mechanism, but also by their degradation process. Several well-defined grooves, lobes, terraces, and debris aprons that were mapped support the interpretation of Moore et al. (2001) that mountain units can be uplifted and tectonically modified, then sloped, scalloped, and leveled by SO_2 sapping (Figs. 5–8). Previous studies have also suggested that morphology differences in mountains such as contact sharpness, lobed texture, sulcus texture, and en echelon furrows may suggest a degradational sequence (Turtle et al., 2000, 2001; McEwen et al., 2000a). We further examine the features that may suggest degradation and interpret how they may be associated with a sequence of degradation.

Moore et al. (2001) discussed how scarps of mountain units have different features that result from degradation; these features include sapping pits and depressions, scalloped edges, and debris aprons. No sapping pits were found in these regions, though two apparently circular depressions were noted on south Shamshu Mons in lineated terrain. The depressions are located near an inferred contact between lineated, undivided, and mottled material (Fig. 6). We would expect such pits to be found in degraded material that may exhibit other signs of sapping. The fact that we find them at a gradational boundary between units suggests that the area is undergoing sapping in addition to slumping. West Shamshu Mons and south Hi'iaka Mons exhibit scalloped scarps (Fig. 5). The scalloped scarps (Moore et al.'s Type A or alcove morphology) are most evident on these two mountains due to illumination conditions, though we see evidence that suggests that the scalloping occurs on a majority of mountain scarps and is most evident where the mountains contact the surrounding plains. This contact relationship supports the theory of Moore et al. (2001) that the alcoves may be partially obscured by lava flows (i.e. the plains). Terracing is evident on the southeastern edge of north Hi'iaka Mons (Fig. 1); this morphology is consistent with coherent slumping and the formation of hummocky deposits. Both west and south Shamshu Mons exhibit substantial debris aprons and lobes. This lobe texture has been classified as a mottled texture (Fig. 4) and is consistent with drastic mass wasting by brittle slope failure or block release. The prominent surface texture of north Shamshu Mons and north Hi'iaka Mons is a series of ridges and grooves that is defined as a lineated or sulcus texture (Figs. 4 and 7). The ridges on mountain structures generally trend perpendicular to the downslope direction; Heath (1985), Turtle et al. (2001), and Moore et al. (2001) suggest that the ridges are generated by deformation of the near-surface layer that slides downslope under the influence of gravity. Bart et al. (2004) also note that some populations of ridges may be the result of tidal stresses. Ridges (perpendicular to the en echelon

crenulated surface) may also be the surface expression of folding (Turtle et al., 2001; Moore et al., 2001; Schenk et al., 2001). We see the grooved texture mainly on the highest elevation units and, in all cases, the grooves are most prominent on pronounced slopes. We agree with Moore et al. (2001) that this indicates gravity sliding of a detached or mobile surface layer.

The mapping results presented here support all of these previous findings. We interpret that the mountains form as tilted crustal blocks; because these blocks are resurfaced by lava flows, we infer that the blocks may have been relatively flat at the time of their formation and that the surface materials may not have been entirely cohesive thus allowing for a detached layer that is heavily affected by gravitational sliding. Older mountain units will exhibit more grooves as gravitational sliding removes the loose material; at low slopes, this material will accumulate as terraces or debris aprons or will obscure the mountain surface. Undivided units have lower slopes than the lineated or plateau units and exhibit fewer grooves but more slumped textures. The progression of degradation of mountain units explored here suggests that mountain structures exhibiting en echelon ridges will degrade into structures exhibiting massive downslope movement of material perpendicular to the original trend of the ridges (or furrows). The majority of ridges and furrows do appear to be parallel to the major topographic and tectonic features. Mottled units do not have pronounced slopes and exhibit the lowest density of furrows and the largest proportion of slumps and lobes. The mottled units appear to grade into the layered plains material, i.e. they slump onto preexisting layered plains, especially in the case of west Shamshu Mons. The layered plains units do not exhibit furrows, but they do exhibit some local topographic highs that may indicate multiple discrete episodes of mass movement due to warming and remobilization of the materials. The layered plains are likely the surface expression of degradation of volcanic materials that have undergone minor uplift and small scale mass wasting. As warm lava flows resurface the surrounding terrain, the layered plains units may be further degraded. Turtle et al. (2001) suggest that the differences in mountain characteristics may suggest differences in composition, volatile content, and material properties of the Ionian crust; Turtle et al. also suggest that these differences may reflect different formation mechanisms or thermal conditions. Our mapping and interpretations support the idea that the material properties of the crust may vary as in the case of mountains having a detached surface layer; we also support the theory that thermal conditions may vary as in the case of mottled materials being remobilized.

This study has shown that a degradational sequence is supported by morphological differences between mountain units. Degradation patterns and causes seem to be similar throughout the studied regions. In each case, the most degradation seems to occur as a result of gravitational sliding, although some degradation is evident near regions of volcanic activity. In all cases examined in this study, the highest elevation structures are more lineated, and presumably less degraded, than their lower elevation counterparts, which appear more degraded. For example, the high-

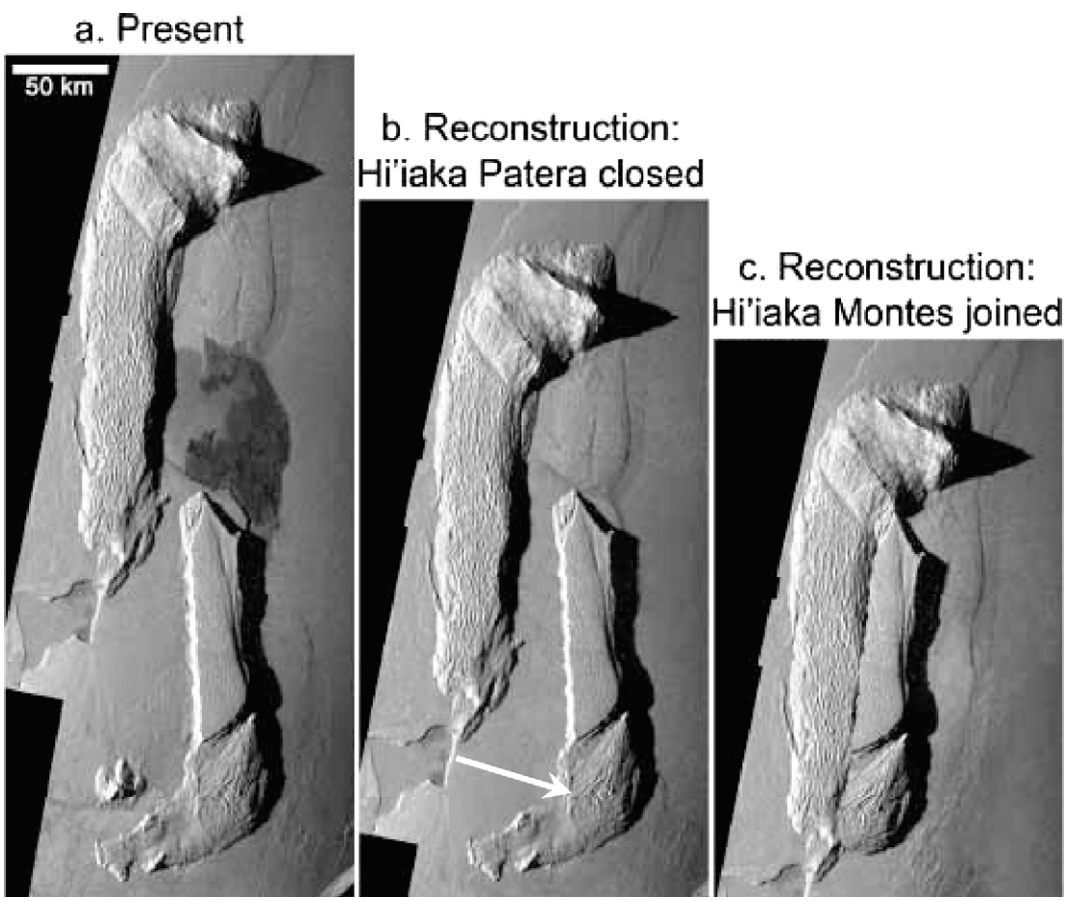

Fig. 10. From Jaeger et al. (2000). Approximate geometric reconstruction of possible strike-slip deformation through the Hi'iaka Montes shown in three stages: (a) the present configuration: *Galileo* SSI observation obtained during the orbit I25 flyby in November 1999 (observation I25ISTERM01b; PIA02540). Hi'iaka Patera is centered at 3.1°S, 79.8°W. Resolution is 265 m/pixel. North is up. Illumination is from the left. Image processing by Moses Milazzo, University of Arizona, (b) the geometry prior to the opening of Hi'iaka Patera, and (c) the original mountain. The northeastern peak of north Hi'iaka Mons may have been uplifted in response to the strike-slip faulting. The southern part of south Hi'iaka Mons appears to have been modified by a landslide that occurred sometime after the rifting took place (indicated by arrow).

est peak of north Hi'iaka Mons is surrounded by lineated material. The plateau portions of south Hi'iaka Mons and west Shamshu Mons have considerably lower elevations. The extreme oblique view of north and south Shamshu Mons prevents accurate shadow measurements of the mountain elevations; however, shadows do indicate that north and south Shamshu Mons are higher than west Shamshu Mons. We infer that with increasing degradation, mountain structures are reduced in elevation.

Among all of the mountain units in these regions, west Shamshu Mons may best illustrate the progression of the degradation effects that McEwen et al. (2000a) and Moore et al. (2001) describe (Figs. 7 and 8). Though west Shamshu Mons is mapped as a plateau due to its elevation and generally flat topography, it exhibits many lineations or furrows that are characteristic of the least degraded of the mountain units. Degradation causes the destruction of the lineated texture. Further degradation by mass wasting or by SO_2 sapping creates the debris aprons or lobes (i.e., Moore et al., 2001). The generally mottled appearance and the presence of debris aprons associated with south and west Shamshu Mons suggests that these mountain units have been severely degraded. This progression of degradation has previously been explored in the Zal region of Io (Bunte et al., 2008).

The level of degradation of each of the mountain and plateau units may be influenced by the proximity to active vents or warm materials. Moore et al. (2001) suggested that scalloped scarps may result from extended contact with warm silicate materials. It is possible that this degradation process continues after lobes and debris aprons form. Morphological similarities exist between the debris aprons and layered plains materials. The layered plains may be an expression of further degradation; degraded material could eventually waste into the plains materials where it would be indistinguishable from its original source or from other material units.

5.3. Tectonism

The high resurfacing rate of Io induces horizontal crustal compression, which drives thrust faulting intense enough to tilt and uplift mountain blocks (Schenk and Bulmer, 1998; Turtle et al., 2001; Jaeger et al., 2003). Mountain formation is thought to have a tectonic influence on the location and morphology of some paterae (Radebaugh et al., 2001). Thirteen percent of paterae catalogued at <3.2 km/pixel are adjacent to mountains (Radebaugh et al., 2001); in addition, ~42% of all identified mountains are adjacent to paterae (Jaeger et al., 2003). Radebaugh et al. (2001) concluded that >40% of paterae show strong influences of regional tectonics and that some paterae are likely influenced by rifting of the crust. The tectonic connection between mountains and paterae is probably that magma exploits fault planes (some associated with mountain formation) as it ascends towards the surface (Jaeger et al., 2003). In the mapped area, three out of five paterae are adjacent to mountains and three out of five mountains have adjacent paterae. This relationship suggests that paterae can preferentially form in regions of tectonism. All of the paterae are related to at least one scarp. Except in the case of Tawhaki Patera, the scarps are tectonic in nature. The scarp related to Tawhaki Patera may be the result of volcanic material movement. Only Tawhaki Patera does not have an associated mountain. In this region of Io, we see a strong connection between paterae formation and regional tectonics; however, we cannot associate this relationship with the global distribution of mountains and paterae because the mountains are often hard to identify in high-Sun images.

Previous studies have suggested that the Hi'iaka Montes may have once been a single mountain structure as shown in Fig. 10 and that the structure may have been rifted by strike-slip faulting (McEwen et al., 2000a; Jaeger et al., 2000; Turtle et al., 2001, 2004). This theory is supported by the inverted L shapes and similar elevations of north and south Hi'iaka Mons (Jaeger et al., 2000). One or multiple faults may have activated, moving the mountain units approximately 60 km apart in both north–south and east–west directions (Jaeger et al., 2000; Turtle et al., 2001). At least one fault is visible between the two mountain units (Figs. 5 and 11) and another may be obscured by the shadows on the eastern side of south Hi'iaka Mons. It is unclear whether motion in both directions occurred simultaneously, incrementally, or in distinct episodes. Associated rifting that separated the mountain units map have also opened conduits in the crust for magma ascent and created the depressions that became Hi'iaka Patera and Mekala Patera. Patera formation may have been influenced by a bend in the fault; a releasing bend could create a basin at the location of Hi'iaka Patera. In the case of Hi'iaka, strike-slip faulting with a bend would have resulted in a dextral pull-apart basin (i.e., Burchfiel and Stewart, 1966; Mann et al., 1983). It is assumed that volcanism would have activated immediately after the opening of a conduit. If the rifting occurred incrementally, continued motion could widen and stretch the basin while preventing young flows from covering the entire surface of the depression. A concept sketch of the progression of events shown in Fig. 11 is one possible way to explain the tectonic evolution of the Hi'iaka Montes and Patera complex. If this concept is correct, it implies that lithospheric compression is the most likely cause of faulting, translation, and rotation of crustal blocks. The mapping finds no evidence contrary to the strike-slip hypothesis, but neither does it reveal new supporting evidence.

The Shamshu region shows hints of tectonic influences as well. Perun Patera lies on a lineament that bisects west Shamshu Mons. It is likely that this lineament is the surface expression of a fault plane that acted as a conduit for magma flow. It may even be where the thrust fault that uplifted Shamshu Mons daylights. If that is the case, then Perun Patera lies at the point where compression gave way to shear offset along the margin of the thrust sheet. The valley that bisects Shamshu Mons along the inferred fault plane may have formed by tectonic and/or thermal activity along the fault. Fig. 12 illustrates a possible series of tectonic events to create the current morphology of the Shamshu complex.

5.4. Lava flow materials

The bright and undivided flow units in the Hi'iaka region appear to originate from a source that is not included in the mapped region. The undivided flow unit in the Shamshu region may originate at or near Shamshu Patera. Bright flows (including those mapped as undivided herein) have been interpreted as possible sulfur-rich flows (Williams et al., 2001, 2002, 2004, 2005, 2007). If the flow surrounding Shamshu Patera is a sulfur-rich flow, then the magma chamber that supplies the vent might have undergone change over time in order to supply both the sulfur lava that surrounds Shamshu Patera and the silicate lavas that fill Shamshu Patera. Alternatively, the sulfur flow may represent secondary sulfur volcanism (i.e., heat from silicate magma melts surrounding sulfur-rich country rock; Greeley and Fink, 1984). Of course, this flow may instead be an older altered silicate flow.

As stated above, previous studies have hypothesized that magmas preferentially rise along faults (Jaeger et al., 2003; Keszthelyi et al., 2004). This scenario appears to correlate well with the theory of rifting at Hi'iaka and with the mapping at Shamshu. In each region, the location of greatest activity or the location of source vents is tied directly to the location of lineaments that are inferred to be faults. For example, the lavas that flow into Hi'iaka Patera emanate from an inferred fault along which the mountain units moved in order to separate into their current configuration; the freshest flows are concentrated at the east and south paterae scarps (Figs. 5 and 13). In Shamshu Patera, the freshest materials appear to

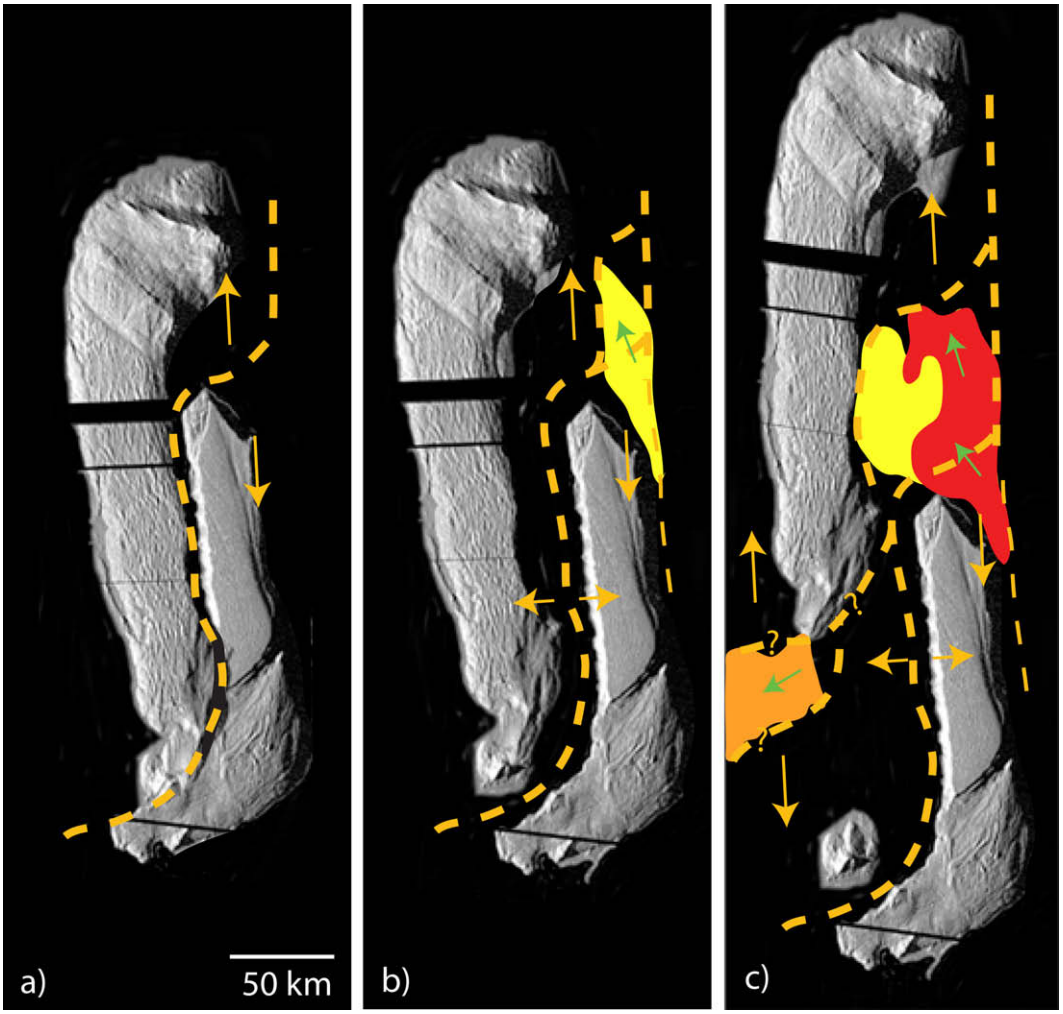

Fig. 11. Possible sequence of events to create the current configuration of mountain structures and shape of Hi'iaka Patera. (a) Strike-slip faults (orange lines) cause north–south separation of the mountain structures. (b) Fault results in opening of a pull-apart basin and opens a fissure vent (oblong yellow feature). East–west motion occurs during the faulting process. The rift also creates a depression into which lavas begin to flow; the depression expands westward. (c) Rift allows for expansion of the depression to its current dimensions; thus, the oldest flow materials (yellow) expand westward; young flows (red) erupt on the eastern side along the fissure. Secondary or additional faulting may similarly open the Mekala Patera (orange) basin. Green arrows show flow direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

emanate from the north and south east scarp boundaries and then to collect in the center of the patera at the greatest depth (Figs. 6 and 14).

5.5. Paterae

Dark patera floor materials are silicate-dominated whereas bright patera floor materials may be sulfur-dominated; the explanation that the bright floor materials have simply been altered from an original appearance similar to the dark floor materials to their present color by mantling of sulfurous materials from plume deposits is more likely in some cases (Nash et al., 1986). The latter explanation seems to be the more likely case for the Hi'iaka region. The materials that cover portions of the floor of the paterae appear to have emanated from the scarps created by rifting and faulting. This is similar to lava lake activity where activity is most intense at the paterae walls (Lopes et al., 2004) and to terrestrial fissure eruptions. The patera floor materials do not appear to be rifted or cracked, suggesting that they are younger than the formation of the patera itself. Flows appear to preferentially originate from the margins of the paterae, though some of the older patera floor materials appear to mainly occupy the interiors of the paterae as their sources are superposed by younger deposits. Within the active paterae, multiple distinct flows are evident. As many as six distinct flows are evident in Hi'iaka Patera. In each case where multiple flows are evident, a gradation in tone is distinguishable from dark young flows on top to light older flows that are, in some cases, partially overprinted. The paterae appear to have widened as the rifting events that formed them continued. Jaeger et al. (2000) examined the shape of Hi'iaka patera and determined that the north and south boundaries of the patera have similar curvatures and dimensions, strongly suggesting that the two walls could have been joined at one time (Fig. 10). North–south extension of the surface appears to have allowed the growth of the patera. This extension also served to move the patera floor materials to their current locations away from the vents (Figs. 11–14). The flows within Hi'iaka Patera appear to mainly emanate from the southern and eastern scarps of the patera and flow northwest. Shamshu Patera has fewer distinct flows than Hi'iaka Patera. The flow morphologies do not suggest an obvious origination point; it could be argued that the flows within Shamshu Patera originate from the interior of the patera. An origination point within the patera could support the theory of rifting between north and south Shamshu Mons in which the patera grew as the mountain units rifted apart. Flows within

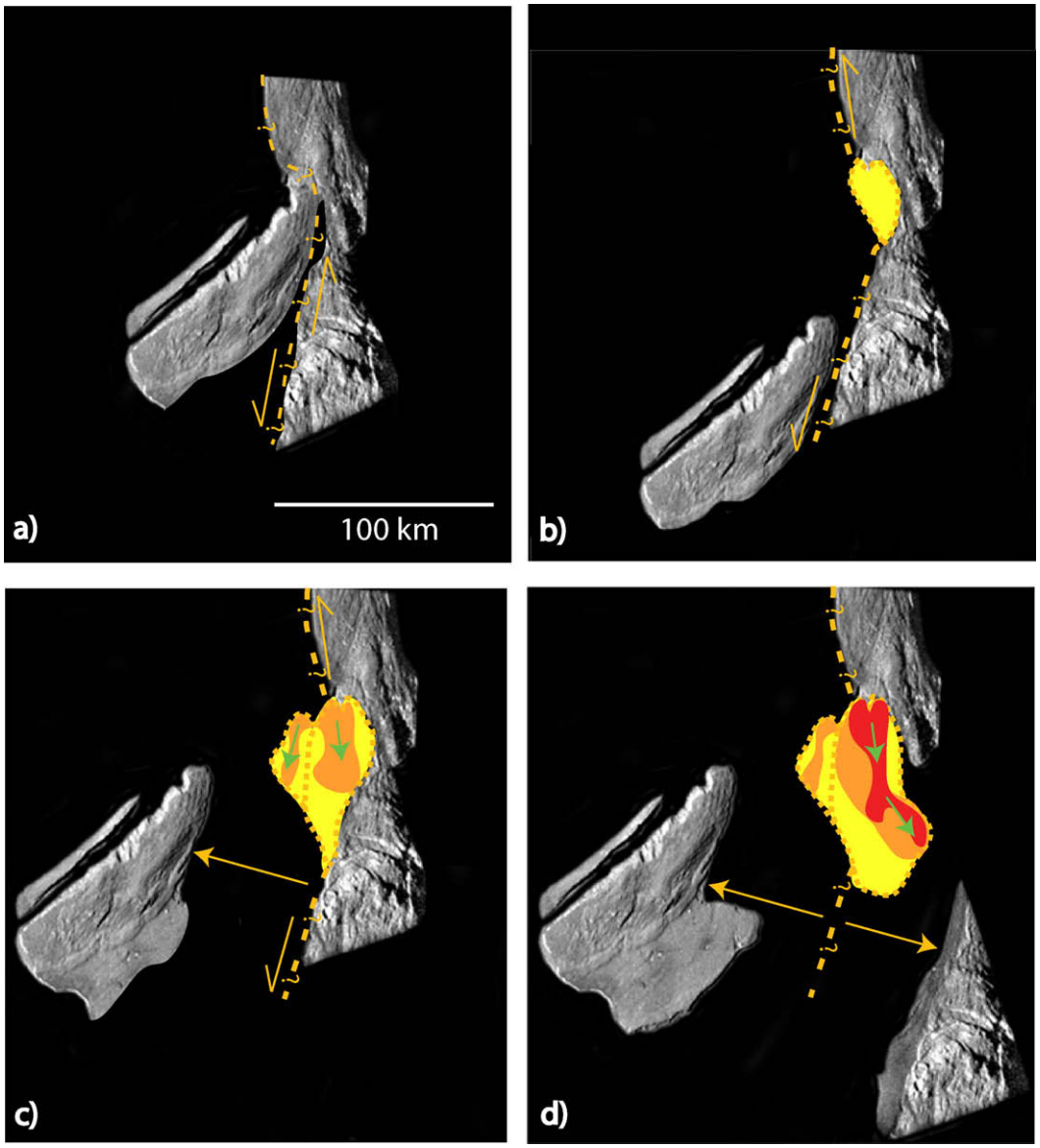

Fig. 12. Possible sequence of events to create the current configuration of mountain structures and shape of Shamshu Patera. (a) Faults (orange lines) separate the mountain units. (b) Strike-slip fault causes separation of west Shamshu Mons from the other mountain structures and opens a vent (yellow is lavas). The fault also creates a depression (pull-apart basin) into which the lavas begin to flow. (c) Rift allows for the separation of south and west Shamshu Mons and the expansion of the depression; thus, the oldest flow materials (yellow) expand southward. West and south Shamshu Mons begin to degrade; mottled materials slide downslope. (d) Rift expands Shamshu Patera to its current dimensions. The oldest flow materials (yellow) are now located on the southern side of the patera; young flows (orange and red) erupt on the northern side along the fissure. Degradation of the mountain units continues. Green arrows show flow direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Perun and Mekala Paterae are concentrated along the northern and eastern scarp boundaries, respectively. Shadowing effects may have made the flows within Perun Patera appear younger and darker than they truly are. Some degradation of mountain materials adjacent to the paterae is evident near regions of volcanic activity. A comparison of the level of degradation reveals that the mountain units adjacent to Hi'iaka Patera are less degraded than those adjacent to Shamshu Paterae; this comparison could be used to infer that Hi'iaka Patera may be younger than Shamshu Patera.

Hi'iaka Patera has been observed to be a persistent hotspot (Fig. 5; Spencer et al., 1997; Lopes-Gautier et al., 1999). It was detected by *Galileo's* Near Infrared Mapping Spectrometer (NIMS) during six orbits between June 1996 and September 1997; the hotspot was not detected in Solid State Imager (SSI) images. Its persistence may not indicate that its activity is continuous; activity may be intermittent (Lopes-Gautier et al., 1999). A thermal outburst seen in August 1999 by ground-based telescopic observers may have been induced by a hotspot at Shamshu Patera (Fig. 6); evidence of such a thermal increase could not be confirmed but may have originated at another patera (Keszthelyi et al., 2001). A hotspot was also detected at Tawhaki Patera in NIMS data in 1996 (Fig. 8; McEwen et al., 1998; Lopes-Gautier et al., 1999; Lopes et al., 2001). Tawhaki Patera is the only one of the five paterae that appears to be completely covered by materials of the same age. Previous studies of all paterae (Radebaugh et al., 2001; Lopes et al., 2004) suggest that fully covered paterae are not common; in general, most paterae exhibit some variation in color which may indicate multiple flows, rafts or crusts. We note that many small paterae such as Tawhaki Patera can appear to have entire surfaces of the same color and age simply because the materials must be confined within the patera depression. Additional surface changes have been evident during observations from other spacecraft; McEwen (1988) noted

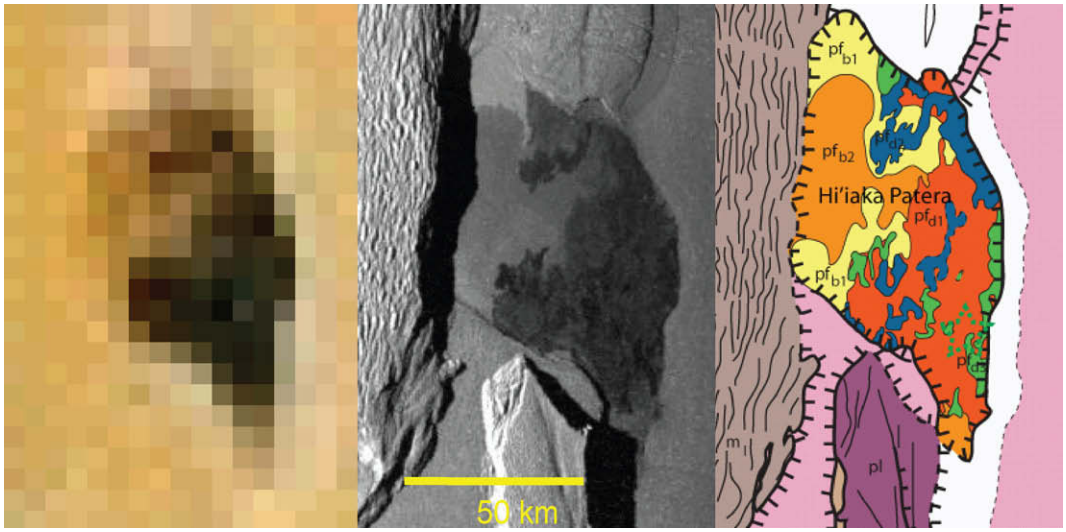

Fig. 13. Enlarged view of Hi'iaka Patera. Left: Excerpt from *Galileo* global mosaic (Fig. 3). Middle: Excerpt from *Galileo* SSI observation I25ISTERM01b. North is up. Right: Excerpt from geologic map of Hi'iaka region (Fig. 5). Multiple episodes of deposition of patera floor materials are mapped as the yellow, light and dark orange, blue and green units.

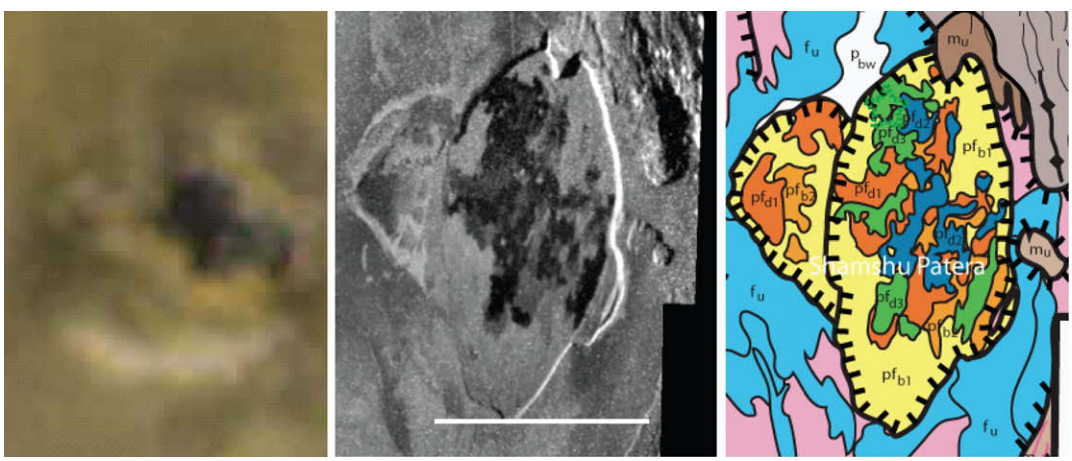

Fig. 14. Enlarged view of Shamshu Patera. Left: Excerpt from *Galileo* global mosaic (Fig. 3). Middle: Excerpt from *Galileo* SSI observation I27ISSHMSHU01. North is up. Right: Excerpt from geologic map of Shamshu region (Fig. 6). Multiple episodes of deposition of patera floor materials are mapped as the yellow, light and dark orange, blue and green units. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that, in the interim between the *Voyager* 1 and 2 flybys, a "dark flow-like deposit" was emplaced at Hi'iaka.

We have investigated the likelihood that the paterae in this region may be lava lakes. A lava lake is defined as a volcanic depression that contains exposed liquid lava, overlying and directly connected to a magma source (e.g., Rathbun et al., 2004). In general, lava lakes may have some periodicity to thermal output, can have iridescent flows, may resurface in waves by magmas propagating around the paterae, are likely most active at the paterae boundaries where chilled crusts break up against the patera walls, and may have fully or partially crusted surfaces that can crack and allow lava fountaining. Presently, Hi'iaka Patera and Shamshu Patera do not resemble active lava lakes as inferred for Loki (Rathbun et al., 2002; Lopes et al., 2004; Howell and Lopes, 2007) or Pele (Lopes et al., 2004; Rathbun et al., 2004). There is no *Galileo* data that indicates cracking or foundering of lava crusts and SSI images do not reveal a crusted surface, isolated islands, or incandescent flows. Thermal data for this region does not reveal any obvious periodicity or major temperature change. Materials of the same age (i.e., hue and intensity) do not cover the entire paterae floors; the concentration of fresh materials around the boundaries of the patera is similar to the Kupaianaha lava lake at Kilauea volcano, Hawaii (Lopes et al., 2004). The lack of complete resurfacing within the paterae may indicate that materials are not sufficiently mobile to cover the expanse of the paterae floors or simply that the paterae have only been partially filled by lava flows. Lava lakes do not necessarily require complete resurfacing by lavas, though one would expect that mobile materials would eventually fill a depression to some consistent level. The persistent activity at Hi'iaka Patera (Spencer et al., 1997; Lopes-Gautier et al., 1999) suggests that Hi'iaka may be a forming lava lake or one that is in a state of quiescence like that seen at Erta Ale in Ethiopia (Burgi et al., 2002). The thermal outburst seen at Shamshu Patera (Keszthelyi et al., 2001) hints at a short period of activity, but does not necessarily indicate periodicity of effusion.

Hotspots are generally correlated with paterae and fresh lava flows (Lopes-Gautier et al., 1999); the darkest and freshest materials on the surface tend to be confined within paterae, so it is likely that most activity can be found at paterae and that hotspots are centered at source regions. This region has multiple active paterae and several hotspots (see Figs. 5 and 6), as well as a lava flow, and is likely a persistently active region.

5.6. Comparison to other regions

The geologic history and progression of volcanic and tectonic and degradational activity is similar to that found in other regions of Io (Williams et al., 2001, 2002, 2004, 2005, 2007; Bunte et al., 2008; Leone et al., 2009). This similarity suggests that such evolutions in volcanic activity, characteristics of tectonic activity, and progression of mountain degradation are ubiquitous on Io.

6. Geologic history

The oldest materials in the mapped areas are the uplifted and tilted crustal blocks that comprise the mountains. The mountains sample a cross section of Io's crust, which typically increases in age with depth. Thus, the mountain bases are composed of older material than their tops. We hypothesize that, after the mountains formed, the faults along which they were uplifted were exploited by magma and, perhaps, tectonically reactivated. The hypothesized strike-slip motion at Hi'iaka may have occurred along one such reactivated orogenic fault. Volcanic vents along the fault planes, possibly coupled with tectonic "pull-apart" deformation in at least one instance, led to the formation of paterae. As of the end of the *Galileo* mission, volcanism remained active at four of the five paterae seen in the mapping area. Tectonic motion along reactivated faults may also continue into the present, but no direct evidence for such activity has been observed.

Since their uplift, the mountains have degraded, some more extensively than others. Landslide deposits at the southern margins of south Hi'iaka Mons and west Shamshu Mons are clear evidence of mass wasting (cf., Schenk and Bulmer, 1998). Subdued topography and morphology are another indication that the mountains have been altered from their original shapes. This probably happened through a combination of mass wasting (potentially triggered by seismic activity), thermal erosion of volatiles, accumulation of a volatile-rich mantling deposit, and SO_2 sapping. Only the northernmost peak of north Hi'iaka Mons looks relatively unmodified by these degradation processes. This observation is consistent with the hypothesis that the strike-slip fault geometry allowed the northern peak to continue to uplift as north and south Hi'iaka Mons rifted apart. Thus, it may be a relatively young addition to the mountain complex.

Like volcanism and tectonism, the formation of plains materials is an ongoing process. It is interpreted as the perpetual accumulation of eruption products and, to some extent, degradation products. The sapping scarps within the "layered" plains must postdate the materials they crosscut, making them among the younger features on the plains. Similarly, the bright and undivided flow materials that overprint the plains are relatively late-stage additions to the region. The undivided flow materials may represent bright flows that are older than the mapped bright flows. We interpret that the currently visible plains are younger than and have embayed the mountain units. We do not indicate that the plains form throughout the entire history represented in the Correlation of Map Units (Figs. 5 and 6) because the process of resurfacing is likely slower than the extrusion and alteration time of the freshest patera floor materials. Similarly, the materials that form as a result of degradation of the mountain and plateau units degrade on a comparable timescale to the plains.

The youngest features in the mapped area are the flows on the patera floors. Based on the albedo and color differences between the patera floor materials and on apparent cross-cutting relationships, multiple episodes of effusive flow on the patera floors may have occurred (e.g., Figs. 13 and 14). Variations in albedos suggest that the bright patera floor materials are older than all of the dark patera floor materials, some of which may still be active.

7. Summary and conclusions

This study has shown that geologic mapping reveals clues to the formation processes for the Hi'iaka and Shamshu regions of Io. These formation processes include tectonic activity, volcanic activity, and various forms of degradation. Each region appears to have been subjected to tectonic activity that facilitated volcanic activity. The styles of volcanic activity then progressed and were influenced by the tectonic structures (e.g., the degree of rifting may have influenced the volume of erupted lava). The volcanic materials then enhanced degradation of the mountains through thermal erosion and by obscuring their morphology with a volatile-rich mantling deposit. Mapping efforts have largely supported previous ideas about the materials and processes affecting this region, including the degradation of mountain structures (Moore et al., 2001) and possible tectonic movement (Schenk and Bulmer, 1998; Jaeger et al., 2000; Turtle et al., 2001). A geologic history was determined for each region; they can be compared to that of other regions and may be similar to global activity.

Geologic maps of both the Hi'iaka and Shamshu regions of Io were produced using *Galileo* images to better understand the volcanic activity of the regions. The primary types of material units (plains, flows, patera floors, and mountains) first identified from *Voyager* images continue to serve as mappable units. Each of these units occurs in the two regions, which are each dominated by large mountains and a patera. The smaller paterae in each region are considered to be inactive due to their overall lack of dark patera floor materials (McEwen et al., 1985, 1997; Davies, 2007).

The Hi'iaka and Shamshu regions exhibit various forms of volcanic activity. Both silicate and sulfur-rich lavas are likely present; individual deposits appear to be of different ages (i.e., in different stages of alteration) due to their differing albedos and colors. Both Hi'iaka Patera and Shamshu Patera include an active compound flow field rather than a flooding lava lake. The regions also shows evidence of tectonic activity; the mountain units appear to be related to one another although they each exhibit different degradation features indicative of SO_2 sapping and mass wasting.

Production, analysis, and comparison of these regional maps with maps of other regions based on both *Galileo* and *Voyager* imaging may offer additional details on geologic processes occurring on Io, a natural complement to the global mapping effort currently underway (Williams et al., 2008). The global map will identify the number, distribution, and type of eruptive centers across Io's surface. Regional maps provide greater detail on the spatial and temporal nature of geologic processes on Io. Detailed maps of other regions may also help to define emplacement and tectonic processes that may be active globally.

Future telescopic and spacecraft observations of Io should determine if hotspots are sporadic or periodic; this would require long term observations of Io from an Io- or Jupiter-orbiting spacecraft. Additional research is also necessary to determine if paterae growth induces mountain separation. We plan to observe and map paterae with associated mountain units to determine if there is an erosional or tectonic influence of one structure upon the other.

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