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Geologic Map of Io

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Contents

Tables

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Introduction

Io, discovered by Galileo Galilei on January 7–13, 1610, is the innermost of the four Galilean satellites of the planet Jupiter (Galilei, 1610). It is the most volcanically active object in the Solar System, as recognized by observations from six National Aeronautics and Space Administration (NASA) spacecraft: Voyager 1 (March 1979), Voyager 2 (July 1979), Hubble Space Telescope (1990–present), Galileo (1996–2001), Cassini (December 2000), and New Horizons (February 2007). The lack of impact craters on Io in any spacecraft images at any resolution attests to the high resurfacing rate (1 cm/yr) and the dominant role of active volcanism in shaping its surface (Johnson and others, 1979). High-temperature hot spots detected by the Galileo Solid-State Imager (SSI), Near-Infrared Mapping Spectrometer (NIMS), and Photopolarimeter-Radiometer (PPR) usually correlate with darkest materials on the surface, suggesting active volcanism (McEwen and others, 1998a; Lopes and others, 2001; Williams and others, 2002). The Voyager flybys obtained complete coverage of Io's subjovian hemisphere at 500 m/pixel to 2 km/pixel, and most of the rest of the satellite at 5–20 km/pixel (Smith and others, 1979a,b). Repeated Galileo flybys obtained complementary coverage of Io's antijovian hemisphere at 5 m/pixel to 1.4 km/pixel (McEwen and others, 2000b; Keszthelyi and others, 2001; Turtle and others, 2004). Thus, the Voyager and Galileo data sets were merged to enable the characterization of the whole surface of the satellite at a consistent resolution. The United States Geological Survey (USGS) produced a set of four global mosaics of Io in visible wavelengths at a spatial resolution of 1 km/pixel (Becker and Geissler, 2005), released in February 2006, which we have used as base maps for this new global geologic map. Much has been learned about Io's volcanism, tectonics, degradation, and interior since the Voyager flybys, primarily during and following the Galileo Mission at Jupiter (December 1995–September 2003), and the results have been summarized in books published after the end of the Galileo Mission (Bagenal and others, 2004; Davies, 2007; Lopes and Spencer, 2007). Our mapping incorporates this new understanding to assist in map unit definition and to provide a global synthesis of Io's geology.

Base Map Data Products

Four distinct image products were created by the USGS and were used in this mapping project: (1) a global mosaic of SSI color images (hereafter referred to as "color mosaic"); (2) a global mosaic of the best resolution Galileo SSI monochrome images (hereafter referred to as "Galileo monochrome mosaic"); (3) a global mosaic of the best quality and highest resolution Voyager Imaging Science Subsystem (ISS) and Galileo SSI monochrome images (hereafter referred to as "combined monochrome mosaic"); and (4) a merged product combining Galileo color information with the higher resolution combined monochrome mosaic (hereafter referred to as "merged mosaic"). There are important technical details to consider regarding the production of the new global Io mosaics (fig. 1*A*–1*D*). Each of these products is described more fully below. An extensive set of ancillary data was developed for each mosaic to help users understand the various combinations of data from different sensors, filters, dates, and illumination and viewing geometries. These include footprint plots that show the identity of each of the component images (see appendix) and diagrams that show the incidence, emission, and phase angles, as well as the spatial resolutions of the individual frames used.

Color Mosaic

By the conclusion of the Galileo Mission, higher resolution color data and consistent phase-angle coverage by the SSI prompted a revision of the global color mosaics (fig. 1*A*) produced earlier in the mission (Geissler and others, 1999). The Galileo SSI GLOCOL01 sequence recorded during orbit I31 (August 2001) completed longitudinal coverage at an optimum phase angle near 4°, low enough to reveal subtle color variations with minimal topographic influences but high enough to exclude the opposition surge. The antijovian hemisphere was imaged in color during orbit C21 (June 1999) at a resolution of 1.3 km/pixel, revealing unprecedented detail (please see appendix for explanation of Galileo mission abbreviations). Archinal and others (2001) established a planet-wide control net, ensuring a much higher level of geometric fidelity than that achieved by Geissler and others (1999).

The global color mosaic that we used was constructed in two steps. First, the consistent phase angle (3.5–4.5°) 756 nm (NIR), 563 nm (GRN), and 411 nm (VIO) filter images from orbits G2 (September 1996), C9 (June 1997), C21 (June 1999), and I31 (August 2001) were calibrated using the best end-of-mission calibration information, coregistered to subpixel precision, and map-projected using the Archinal and others (2001) camera-pointing corrections. A Lunar-Lambert limb-darkening correction was next performed, after having first determined that a coefficient of 0.7 was adequate for all three colors. Finally, the images were mosaicked together to form a baseline estimate of Io's global color that was free of photometric effects caused by variations in phase angle but subject to spatial-resolution limitations and geometric distortions, especially in areas imaged near the limb.

The second step improved on the global color mosaic by including higher resolution images from orbit E6 (14° phase, February 1997), adjusted to match the color and contrast of the 4° phase angle data. The selected color images were processed as above, hand-edited to remove topographic shadows and bright or dark pixels too near the limb, and mosaicked using a numerical procedure (Soderblom and others, 1978) that reduces the mismatch at the seams. This mosaic represents our best understanding of Io's appearance during the Galileo Mission and is the only product of the current set that can be relied upon for photometric interpretations (such as deciding whether any given feature is brighter or darker than another). Users should keep in mind several limitations: the use of false color (NIR-GRN-VIO), required because of the limited wavelengths of the SSI filters; variations in incidence and emission angles; uncertainties in the limb-darkening correction, especially at the poles;

and mixed resolutions, ranging from 1.3 to 21 km/pixel at the equator, with the poorest resolution on the subjovian hemisphere of Io.

Galileo Monochrome Mosaic

A monochrome mosaic (fig. 1*B*) suited to studies of local and regional morphology was created by mosaicking the best quality global monitoring images taken by the Galileo SSI at a spatial resolution of 1 km/pixel. This mosaic is made up of 32 monochrome images taken at various phase angles and local times of day, so care must be taken to note the solar illumination direction when deciding whether topographic features display positive or negative relief. In general, the illumination is from the west over longitudes from 0° to 270° W. and from the east over longitudes from 270° W. to 360° W. The images were empirically adjusted in brightness and contrast to match one another in areas of overlap. Most of the images were taken using the clear filter (CLR, 663 nm), but GRN and NIR filter images were substituted when they had a larger digital number (DN) contrast than other available images. Image resolutions range from 1.3 to 10 km/pixel along the equator, and the poorest coverage is on Io's subjovian hemisphere.

Combined Mosaic

Although the subjovian hemisphere of Io was poorly seen by Galileo, superbly detailed Voyager 1 images cover longitudes from 240° W. to 40° W. and the nearby southern latitudes. A global combined mosaic (fig. 1*C*) of the best resolution images from both Galileo and Voyager 1 was assembled that includes 50 Voyager 1 images with spatial resolutions locally exceeding the 1 km/pixel scale of the final mosaic. These Voyager images were calibrated with an additional correction for dark current build-up during passage through the plasma torus, as described by McEwen (1988). Although most of these images neatly overlie the Galileo coverage, the Voyager 1 images of regions west of 0° longitude appear displaced from the positions predicted from the control net derived from the solution of the combined Galileo and Voyager data set. We suspect that the discrepancy arises from regional topography west of the subjovian point and have adjusted the positions of the Voyager 1 images (all acquired near the limb of Io) to match the best-fit geometry. Solar illumination of these longitudes was from the east during the Voyager 1 flyby. The one area not well imaged by either Galileo or Voyager is the north pole.

Merged Mosaic

To present the most information in a single view of Io, the global color, derived from the Galileo color images, was superimposed on the higher resolution combined mosaic to create a merged mosaic (fig. 1*D*). We calculated color ratio images from the Galileo data and applied them to the monochrome mosaic, which required that the color ratios of the composite images match the color ratios of the Galileo data. That is, the red brightness was computed as the product of the monochrome mosaic multiplied by the ratio of the Galileo NIR/GRN filters and the blue brightness as the monochrome mosaic times the Galileo VIO/GRN filter ratio. The Galileo SSI's silicon charge-coupled device (CCD) was sensitive to longer wavelengths than the vidicon cameras of Voyager, so distinctions between red and yellow hues can be more easily discerned. However, this approach suffers from an obvious disadvantage in areas where the surface appearance changed dramatically during the >20 year interval between the Voyager and Galileo eras, for example near Kanehekili (lat 18° S., long 34° W.).

Full-resolution TIFF and JPEG versions of the merged mosaic, as well as an MPEG (Quicktime compatible) animation, are available for free download from the NASA Planetary Photojournal (http://photojournal.jpl.nasa.gov), under PIA09257.

Mapping Techniques

Geologic mapping of Io has focused on specific types of geologic material units and structural features, as first recognized by Schaber (1980, 1982), because of (1) the quantity of concurrent volcanic activity on Io and (2) the variable quality of the global spacecraft data. These constraints mean that it is not practical to separate map units based on both age and lithology. The types of material units and structures that were defined served as a template for mapping four specific regions of Io's subjovian hemisphere, and the following maps were produced and published by the USGS during the Voyager era: Maasaw Patera, 1:1,000,000 (Moore, 1987); Ra Patera quadrangle, 1:2,000,000 (Greeley and others, 1988); Ruwa Patera quadrangle, 1:5,000,000 (Schaber and others, 1989); and Lerna region, 1:5,000,000 (Whitford-Stark and others, 1991). These maps were then synthesized to produce the first global geologic map at 1:15,000,000 (Crown and others, 1992). Although the relatively low resolution of the antijovian hemisphere imaged by Voyager inhibited the completeness of the global map, Schaber's (1980, 1982) early work and the Voyager-era maps continue to serve as templates of material units and structures on Io that are refined using later spacecraft data.

The material units described in the previously published USGS maps required only minor modification when applied to regional geologic mapping of Io using Galileo imaging data in the early 2000s. During the Galileo era, three regional maps (image spatial resolutions ~190–570 m/pixel) of sections of the antijovian hemisphere were produced and published in scientific journals: Chaac-Camaxtli Paterae region (Williams and others, 2002); Culann-Tohil Paterae region (Williams and others, 2004); and Zamama-Thor region (Williams and others, 2005). Since the end of the Galileo Mission, four additional Galileo-based regional maps have been produced: Amirani-Gish Bar region (Williams and others, 2007a); Zal region (Bunte and others, 2008); Hi'iaka-Shamshu region (Bunte and others, 2010); and Prometheus Eruptive Center (Leone and others, 2009).

Using the experience we gained from our past work on various Voyager- and Galileo-era maps, particularly the Amirani-Gish Bar map (Williams and others, 2007a), we developed the following five-step strategy for producing a new global map using the USGS mosaics (see also Williams and others, 2007a):

Step 1. Map diffuse deposits separately using color data only (color mosaic)

Step 2. Map mountains, plateaus, and layered plains (combined mosaic, supplemented with low-sun images)

Step 3. Map vents and paterae (combined and color mosaic)

Step 4. Map lava flows: first map those around each vent, then add more detail within flucti (combined and color mosaic)

Step 5. Map plains last (combined and color mosaic)

Map units were defined on the basis of their color characteristics, albedo, morphology, and surface texture, using primarily the global mosaics but with knowledge of characteristics revealed in individual Voyager and Galileo images. Descriptions of subunits or regions covered by high-resolution data have been included. The mapping strategy that we developed for the global map was initially tested through mapping of the polar regions with ArcGIS 9.3 software, which was then applied to the equatorial region. This was a stringent test of our strategy, given the difficulty in polar mapping, because of the widely varying resolution in the polar regions. Insights gained from the test for each of the steps of our mapping strategy are presented below:

Step 1. *Map diffuse deposits using color mosaic.* The SSI color data alone are sufficient to identify and map the five different colors of diffuse deposits on Io. In some cases, the context of the diffuse deposits is not clear, and we found it beneficial to switch from views of the color mosaic to the combined and merged mosaics to see the underlying morphology. This is especially true around positive- or negative-relief topographic features. With the exception of the green diffuse deposit centered on Culann Patera, all other green diffuse deposits observed in higher resolution Galileo SSI images are too small to be mapped on the global mosaics.

Step 2. *Map mountains, surrounding plateaus, and structural features using the combined mosaic.* Many of these features are easily visible in the combined and merged mosaics, where the mosaics include images that were obtained at low-sun angle to show the shadows associated with scarps, ridges, and other local relief. For areas of the mosaics where such images were not included, other data sources were consulted (for example, original Voyager or Galileo image products, Voyager-based shaded-relief maps, or other products). Additional stretching was also found to maximize viewing of the combined mosaic. The merged mosaic is also useful to map mountains, layered plateaus, scarps, and other structural features. Lineated, mottled, and undivided mountain materials were all mapped using these mosaics.

Step 3. *Map vents and paterae.* Bright, dark, and undivided patera floor materials were identified using all of the mosaics. However, we found that the merged mosaic was the best tool to identify these features.

Step 4. *Map lava flow fields.* Bright, dark, and undivided flow materials were identified using all of these mosaics. The merged mosaic was the ideal product to map these features (in terms of color and context), although switching views to the Galileo monochrome and combined mosaics was useful for robust mapping.

Step 5. *Map plains.* Plains include the regions that did not fit into the previous categories. The primary inter-patera plains materials have four subunits based on color and morphology (yellow, white, red brown, and layered). Lower resolution coverage and color variations in the polar mosaics make some identifications difficult, although all subunits are present. All four mosaics were reviewed to map these features. One region of the north polar plains is covered at particularly poor resolution in all mosaics, and, although we think it is probably red-brown plains material, we conservatively left it mapped as a zone of poor resolution.

The mosaics revealed various linear and point features that we were able to map. The linear features include scarps, ridges, grooves, graben, one sinuous channel, and lineaments (linear structures whose form cannot be interpreted). The point features include small positive-relief edifices (interpreted to be shields or cones), small dark spots (interpreted to be volcanic vents, either very small paterae or sources for outgasing), or small pits. Any feature <20 km diameter was mapped as a point feature, and the feature name in the map symbol explanation includes the word “small”. Most of these features have a width of a few pixels across in the mosaics when viewed at 100 percent zoom and, thus, are most appropriately mapped using lines and points. Linear features range in length from several pixels at 100 percent zoom to tens of kilometers in length. Point features and geomorphologic structures (linear features) were mapped as separate layers in the ArcGIS project. Note that not all detail is visible in the printed map at the print map scale. Please refer to the electronic version of the Io map for full detail.

Because the primary focus of the mapping was to determine the areal extents of the major material units, we produced material-unit polygons from which contact lines were generated later. Because of the distinctive colors of Io’s volcanic materials, most of the mapped material units have distinct contact relations that are shown as certain contacts. Mountains and patera floors have structural contacts, which are positive-relief edifices and closed topographic depressions, respectively. Thus their structural boundaries serve as contacts. Layered plains, by definition, are revealed by their bounding scarps. Flow materials are typically darker or brighter than the surrounding plains and have definite or gradational contacts. The three plains units have three different colors, and typically certain or gradational contacts can be identified. Some mountains grade into layered plains, and some undivided flow materials from specific volcanoes may grade into those from its neighbors. In these cases, gradational or approximate contacts are shown on the map.

General Geology

Io was recognized to have unusual spectroscopic characteristics in the 1970s, prior to the 1979 NASA Voyager flybys. Also prior to the Voyager flybys, Io's 4:2:1 Laplace orbital resonance with Europa and Ganymede was predicted to cause severe tidal heating, resulting in active volcanism (Peale and others, 1979). The Voyager flybys confirmed this prediction; not only was Io volcanically active, it is the most volcanically active body in the Solar System. Voyager showed that Io has an intensely colored surface, which suggests the presence of sulfur compounds, and a lack of impact craters, which is interpreted as evidence for a high resurfacing rate (1 cm/yr, Johnson and others, 1979) and a very young surface (Smith and others, 1979a,b). When navigation images showed a 260-km-high plume on Io's limb (Morabito and others, 1979), searches of other images revealed additional active plumes. The detection of SO_2 gas from the Loki plume and of surface hot spots by the Infrared Interferometer Spectrometer (IRIS) demonstrated that rampant volcanism was occurring on Io (Pearl and others, 1979).

Perhaps the greatest debate ignited by the Voyager data revolved around the composition of the active volcanism—sulfur or silicates? Advocates of the sulfur hypothesis pointed to a predominantly sulfur surface composition in Earth-based spectral data (Wamsteker and others, 1974) and the presence of SO_2 frost on the surface in Voyager data (Fanale and others, 1979; Smythe and others, 1979). Sagan (1979) and Pieri and others (1984) suggested that the observed surface colors indicated different allotropes of sulfur. However, the validity of color arguments was questioned, because the Voyager ISS did not accurately reproduce true color images (Young, 1984; Nash, 1987). Advocates of the silicate hypothesis pointed to Io's bulk density (~3,500 kg m^{-3}) and the topography of Io's mountains and volcanoes: slopes on Io's mountains and paterae required mechanically strong silicates (Clow and Carr, 1980; Moore and others, 1986). Although the temperatures measured by the IRIS suggested sulfur—molten sulfur pools and flows were expected to be in the range of 400–600K (sulfur vaporizes at ~718K at Io's surface), as opposed to temperatures of ~1,500K for molten basalts—cooling silicates pass through temperatures in the same range as sulfur. Thus, the temperatures of hot spots detected by IRIS (Pearl and others, 1979), which were below 650K, could be interpreted as either composition. The first strong evidence for silicate volcanism came from post-Voyager Earth-based telescopic observations that showed eruption temperatures >800K, which were definitely too high for sulfur (Johnson and others, 1986; Veeder and others, 1994). Galileo observations confirmed the presence of mafic silicate volcanism (Carr and others, 1998; McEwen and others, 1998b) and suggested that Io could erupt lavas with temperatures consistent with ultramafic silicates (McEwen and others, 1998b; Davies and others, 2001; Williams and others, 2001a). More recent reevaluation of Galileo temperature data, however, suggests that ultramafic compositions are not required to explain Ionian eruption temperatures (Keszthelyi and others, 2007). Although Io appears to be dominated by silicate volcanism at most active hot spots, there is some evidence, such as bright, lightly colored lava flows and low eruption temperatures, for active sulfur volcanism as well (Williams and others, 2001b, 2004).

Voyager detected a high heat flow from Io's surface, resulting from the many active volcanic hot spots that radiate Io's internal heat to space. The combination of Voyager IRIS measurements of thermal emission from hot spots and disk-integrated Earth-based telescopic observations enabled pre-Galileo estimates of Io's heat flow of ~1.5 W m^{-2} (Morrison and Telesco, 1980; Johnson and others, 1984; McEwen and others, 1985) to at least 2.5 W m^{-2} (Veeder and others, 1994). Additional Galileo observations, including the polar regions, suggest that current best estimates of Io's heat flow are ~3±1 W m^{-2} and ~1.3±0.4 x 10^{14} W (Veeder and others, 2004).

Io's extensive color palette is thought to result from a variety of sulfur-bearing compounds that mantle the surface and are produced by active volcanism (Geissler and others, 1999). Spectral detection of various sulfur species extends back to the 1970s (Johnson and McCord, 1971; Wamsteker and others, 1974). Voyager positively identified SO_2 on the surface (Smythe and others, 1979), and McCauley and others (1979) suggested that the agent responsible for the many erosional scarps observed on the surface was the explosive escape of sulfur dioxide from subterranean SO_2 aquifers. The idea of subterranean SO_2 reservoirs gained some support from the analysis of Galileo data of the movement of the Prometheus plume (Kieffer and others, 2000). Today it is well understood that sulfur compounds mantle the surface, although the exact composition of these sulfur compounds remains ambiguous. SO_2 is ubiquitous on Io, except at locations of hot spots (Douté and others, 2001). The yellow color observed in Galileo SSI images is thought to be either cyclo-octal sulfur (S_8) with or without a covering of SO_2 frosts deposited by plumes or, alternatively, polysulfur oxide and S_2O without large quantities of elemental sulfur (Hapke, 1989). The red materials are interpreted to be composed of short-chain sulfur molecules (S_3, S_4) resulting from either breakdown of cyclo-S_8 by charged-particle irradiation (in polar regions) or by condensation of S_2-rich volcanic gases in the plumes of active vents (in the equatorial region, Spencer and others, 2000). Greenish-yellow patches exist in or near several active vents and are thought to be an alteration product of silicate and sulfur that is perhaps composed of either sulfur compounds contaminated by iron from silicates or silicates such as olivine or pyroxene with or without sulfur-bearing contaminants (Geissler and others, 1999). White to gray materials are interpreted to be composed of concentrated, coarse- to medium-grained SO_2 resulting from plume fallout and subsequent recrystallization (Carlson and others, 1997; Douté and others, 2001, 2002). Black materials mostly correlate with active hotspots and occur as patera floors, as lava flow fields, or as dark diffuse materials near or surrounding active vents. These materials are most consistent with Mg-rich orthopyroxene (enstatite or bronzitehypersthene) and indicate silicate lava flows or lava lakes (within paterae) or diffuse silicate pyroclastic deposits of mafic to ultramafic composition (Geissler and others, 1999).

Mountains are the dominant structural landforms that are visible on Io and are recognized as steep-sided edifices rising more than ~1 km above the plains (Schenk and others, 2001). Approximately 150 mountains were identified and mapped by

Carr and others (1998), Schenk and others (2001), Jaeger and others (2003), McEwen and others (2004), and Turtle and others (2007). Io's mountains typically rise approximately 6 km in height; the highest (Boösaule Montes) rises >17 km above the surrounding plains. Galileo images show that many mountains are partly or completely surrounded by plateaus, layered plains, and debris aprons (Turtle and others, 2001). Various models have been proposed to explain the origin of the mountains (Schenk and Bulmer, 1998; Turtle and others, 2001; McKinnon and others, 2001; Jaeger and others, 2003). Their asymmetrical shapes suggest uplift along thrust faults, implying that compressional uplift is probably the dominant mechanism. McEwen and others (2000a) and Jaeger and others (2003) showed statistical evidence that far more paterae and mountains were in direct contact with each other than random chance would allow (probability ~0.1%). This result suggests a possible genetic link; perhaps the magma exploits the weakness in the lithosphere created by deep orogenic faults. Interestingly, Schenk and others (2001) showed a global anticorrelation between the areas with somewhat higher concentrations of observed mountains and the areas with somewhat higher concentrations of observed volcanic centers. However, the areas of low mountain concentration also correlate with areas with poor imaging for detecting topographic features (only medium resolution images and (or) high sun). Therefore, it is not yet confirmed that this anticorrelation is not an observational bias. Radebaugh and others (2001) found evidence that the concentration of observed paterae is slightly affected by observational bias.

Material Units

The original geologic mapping of Io using Voyager images by Schaber (1980, 1982) divided Io into geologic units of four principal classes: plains material, mountain material, patera floor material, and volcanic flows. Ephemeral diffuse deposits, an additional unit class, was also recognized in the Voyager data and mapped using stippled patterns superposed upon the other units (Crown and others, 1992). These five classes of material units continue to serve as useful designators for mapping Ionian materials even as higher spatial resolution and more accurate color data were obtained by later missions, particularly Galileo. These new data enabled additional subunits of these five classes to be defined and characterized, and spectral analysis of Galileo SSI and NIMS data allowed compositional information to be correlated with color and, to a lesser extent, morphological information. These data also enabled new studies of degradational features and the recognition of volcano-tectonic relations. Major results from the study of Galileo data of Io in terms of surface geology, composition, and volcanic activity can be found in McEwen and others (1998a,b) and Lopes-Gautier and others (1999) and in special issues of Science (Volume 288, 19 May 2000), the Journal of Geophysical Research (Volume 106, 25 December 2001), and Icarus (Volume 169, May 2004), as well as in review papers by Geissler (2003) and Lopes and Williams (2005) and in books by Bagenal and others (2004), Lopes and Spencer (2007), and Davies (2007). The distribution of material units as percentage of Io's surface area is given in the Results section (table 2). Below, we include brief descriptions of the major categories of Ionian material units to supplement the information provided in the Description of Map Units and figure 2, including initial descriptions from previous Voyager-based image analysis and mapping.

Mountain Units

Initial study of Voyager images first revealed the presence of mountains on Io. Schaber (1980) described mountains as isolated high massifs covering 1.9 percent of the total area of the first preliminary geologic map of Io (that map covered 26.5% of the surface at a spatial resolution of 1–10 km/pixel). At this time, mountains were interpreted to be the oldest geologic unit exposed on the surface, based on stratigraphic relations (Schaber, 1980). Their relief was estimated as at least 9±1 km high, and the mountains had a tectonically disrupted, topographically rugged surface (Schaber, 1980), probably composed of silicate volcanic material to support this significant relief (Carr and others, 1979; Masursky and others, 1979; Sagan, 1979; Clow and Carr, 1980). Mountains were associated with layered plains and paterae, and Schaber's description of some mountains containing pit craters and vents suggests that features we now recognize as tholus material (volcanic mountains) were initially lumped together with tectonic mountains. At this time, it was recognized that mountains were locally mantled by diffuse deposits of various colors, and in some cases high-albedo aureoles were identified surrounding the bases of some mountains, such as Haemus Montes. Lobate scarps just north of a mountain near Creidne Patera were recognized as having a morphology similar to landslides or lava flows (Schaber, 1980).

During the subsequent geologic mapping of Voyager-based quadrangles and specific areas, additional subdivisions of mountain units were made. Both Greeley and others (1988) in the Ra Patera quadrangle and Whitford-Stark and others (1991) in the Lerna Regio region separated mountain material from either dome material or cone material (respectively) to distinguish apparent volcanic mountains from tectonic ones. Schaber and others (1989) subdivided mountain materials in the Ruwa Patera quadrangle into three types: grooved, smooth, and undivided. The descriptions and interpretations of these units, including the presence of ridges and grooves on the grooved material and the evidence of down-slope movement in the smooth material, indicate that our units are the direct descendants of these mountain materials used in the Voyager-era maps.

As outlined earlier, there are two dominant theories on the formation and distribution of Io's mountains, and a good review is presented in Jaeger and others (2003). Mountain genesis is still not well understood. Schenk and Bulmer (1998) suggested that a horizontal lithospheric compressive stress is generated because of Io's rapid resurfacing rate, which results in uplift of crustal blocks via thrust faulting. Alternatively, McKinnon and others (2001) suggested that sustained reduction in Io's volcanic activity at local, regional, or global scales results in lithospheric heating that causes a large compressive stress at the base of the lithosphere. This stress causes, over time, fluctuating thermally induced stress as resurfacing rates wax and wane, leading to alternating episodes of tensile and compressive faulting. Such repeated episodes of normal and reverse faulting might produce coherent crustal blocks (mountains) that float in a matrix of highly disrupted material, similar to the chaos terrain of Europa (McKinnon and others, 2001). Through study of additional Galileo images, Jaeger and others (2003) cataloged 143 mountains and mountain-like features; of 92 mountains of sufficient resolution to infer a tectonic origin, 38 abut paterae. They proposed that orogenic faults associated with mountains act as conduits that feed magma to the surface, enabling patera formation near mountains. Lithospheric swells, produced by thermal diapirs impinging on the base of the lithosphere, may, in some cases, focus compressive stress and cause the formation of isolated mountains (Jaeger and others, 2003).

Our mapping shows that mountain material makes up ~3 percent of Io's surface, generally has colors and albedo similar to bright plains material, and is usually only visible in low-sun images where shadows highlight scarps, ridges, grooves, and mountain peaks. Layered plains, which include mesas and plateaus, make up another 4.4 percent of the surface and are often related to degrading mountains. We mapped 240 mountains and layered plains units on Io (121 mountains and 119 layered plains units), compared to the 143 mountains previously identified by Jaeger and others (2003). Additional mountains, interpreted from limb fits and stereo image analyses by Schenk, were included in our map. Note that, at the resolution of these mosaics, mountains typically grade into layered plains, which allows different mappers to interpret this boundary differently. All mountains identified on Io have heights between 1 and >17 km (see Schenk and Bulmer, 1998; McKinnon and others, 2001; Schenk and others, 2001; Turtle and others, 2001, 2007; Jaeger and others, 2003). We characterized three types of mountain materials (fig. 3) on Io: lineated (unit m_l, ~1.5%, containing well-defined ridges and grooves, interpreted to be tectonically modified, uplifted, autochthonous crustal blocks), mottled (unit m_m, ~0.2%, containing lobes and dome-like hills, interpreted to include materials displaced by mass-wasting processes), and undivided (unit m_u, ~1.3%, in which limited resolution prohibits classification as either lineated or mottled). The ten largest mountains (of all types) on Io, the ten largest lineated mountains, and the nine mottled mountains and all mountain areas are reported in table 3. In general, the lineated mountains (as a group) are higher than mottled mountains, which is consistent with the interpretation that mottled mountains have undergone degradation by mass wasting (figs. 4, 5). About 40 percent of mountains occur in close proximity to paterae (Jaeger and others, 2003), suggesting that at least some paterae and mountains have a genetic link. In several cases, volcanic vents are seen to preferentially form along the faults that bound mountains (McEwen and others, 2000a; Jaeger and others, 2003).

Plains Units

The initial geologic mapping of best-resolution Voyager images described three types of plains materials on Io's surface: inter-vent plains, layered plains, and eroded layered plains (Schaber, 1980, 1982). Plains units comprised approximately one-half of the 34.8 percent of the Ionian surface that was mapped, and inter-vent plains represent the dominant type (39.6% of the mapped surface). Plains are also recognized as the material type that has the largest areal extent in our global characterization, although the proportion of the surface identified as plains is higher globally than in the initial Voyager mapping. The plains were interpreted to be stratified materials from plume fallout interbedded with flow and fumarole deposits, and the different units were distinguished by the presence of bounding scarps (layered plains) and clusters of small erosional remnants of a once more continuous surface (eroded layered plains). The plains units in Voyager images showed a variety of colors attributed to the presence of sulfur. Mapping of 1:5M-, 1:2M-, and 1:1M-scale quadrangles all included intervent or interpatera plains units, as well as recognized layered plains (or plateaus) that have a higher concentration of structural features (Moore, 1987; Greeley and others, 1988; Schaber and others, 1989), similar to the 1:15M Voyager global map (Crown and others, 1992).

Our mapping shows that plains material covers ~67 percent of Io's surface and is subdivided into yellow (~18%), white (~9%), and red-brown (~35%) units. A fourth unit, layered plains (~4%), consists of any of the other types that are morphologically isolated into distinct layers separated from underlying plains by distinct bounding scarps indicative of erosional processes or mass wasting from mountains. In general, plains material is thought to consist of various combinations of silicate and sulfur-rich material in the form of buried lava flows, pyroclastic deposits, and frosts from condensed volcanic gases that make up the upper crust of Io, further mantled by sulfur-rich (yellow) or SO_2-bearing + contaminants (white) deposits traceable to one or more of Io's many active volcanoes (McEwen and others, 2000b; Williams and others, 2002). The color differences in the plains are due to variations in composition or alteration. White plains (unit p_{bw}) are dominated by coarse- to medium-sized grains of SO_2 snow and frost + contaminants (Carlson and others, 1997; Douté and others, 2001, 2002, 2004) due, in some cases, to the long-term accumulation of white diffuse deposits. Yellow plains (unit p_{by}) may be dominated by other sulfur-bearing compounds (S_8, S_nO and S_2O) and (or) SO_2 frosts mixed with these compounds (Hapke, 1989; Geissler and others, 1999) due, in some cases, to the long-term accumulation of yellow diffuse deposits. Red-brown plains (unit p_{rb}) in equatorial regions (<±30°) are colored by the long-term accumulation of red diffuse plume deposits containing short-chain sulfur (S_3, S_4) recrystallized from condensed S_2 gas (Spencer and others, 2000), some of which contain sulfur chlorides (Schmitt and Rodriguez, 2003). In middle to high latitudes (>±30°), extensive red-brown plains are thought to result from alteration of sulfur compounds in yellow plains by radiation exposure (Johnson, 1997; Geissler and others, 1999). Figures 6–8 include examples of white plains material at the highest resolution obtained by the Galileo SSI, in particular showing the poorly understood hummocky texture.

Patera Floor Units

Schaber (1980, 1982) mapped a vent wall and floor unit that included the wall and floor materials of pit craters, shield craters, and fissures. These materials were interpreted to be volcanic in origin and consist of lava flows and pyroclastic deposits. In Voyager data, extreme variations in color were noted, and complex wall and floor morphologies were described. The unit comprised 4 percent of the mapped region, which was slightly higher than, but comparable to, our new global characterization. Patera floor materials were divided into three types (bright, dark, and undivided) in subsequent mapping of the Ra Patera (Greeley and others, 1988) and Ruwa Patera (Schaber and others, 1989) quadrangles; these were subsequently grouped together in the Voyager global map (Crown and others, 1992). The detailed mapping of Maasaw Patera by Moore (1987) distinguished patera wall, rim, and floor materials and described slumping of the patera walls.

We mapped 425 paterae on Io, and our mapping shows that patera floor materials make up ~2.5 percent of Io's surface. By definition, this unit is restricted to the interiors of these caldera-like, volcano-tectonic depressions. At the resolution of our global mosaics, we do not map a patera wall unit, but we mapped the location of the patera walls with a bounding scarp symbol. Patera floors span the full range of colors from bright white to yellow-orange to black, often with multiple-colored deposits within one patera. This suggests that the compositions of patera floor materials include mixes of silicates and various sulfur-bearing compounds, including relatively pure sulfur dioxide deposits (either frost accumulations or flows: Williams and others, 2002, 2004). The processes that create this variety of materials during paterae formation and evolution are necessarily complex and are not well understood. Hypotheses for patera formation include caldera-forming collapses, tectonic basins filled with lava, and the exhumation of sills (Radebaugh and others, 2001; Williams and others, 2002; Keszthelyi and others, 2004). The spatial and spectral resolution of Galileo SSI images is generally sufficient to enable characterization of only three subunits of patera floor materials: bright (unit pf_b, 0.4%, possibly sulfur-dominated), dark (unit pf_d, 0.5%, presumably silicate-dominated), and undivided (unit pf_u, 1.6%, uncertain composition). The ten largest patera floor units and their areas derived from our mapping are reported in table 4. Although there is evidence of distinct lava flows in ~14 percent of patera floors, there is sufficient ambiguity regarding emplacement mechanisms in available imagery (ponded lava flows vs. lava lakes) to justify treating patera floor material as a separate material unit from flow material (Williams and others, 2004), which is consistent also with the Voyager-era mapping precedent. However, high-resolution SSI images (fig. 8) contain features morphologically similar to those found in terrestrial lava flow fields, and the compositions of patera floor materials and flow materials are expected to span the same range.

Flow Units

Early studies of best-resolution Voyager images of Io that cover 34.8 percent of the mappable surface identified four volcanic flow units associated with volcanic vents (paterae) (Schaber, 1980, 1982). These flow units composed 31.2 percent of the mapped region, compared to the ~28 percent determined in our global characterization. One, the crater cone unit, corresponds to what is now referred to as tholus material, and the other three (pit crater, shield crater, and fissure flows) were distinguished based on the associated vent geometry and setting. Pit crater flows included broad flow fields extending from large (~>80–100 km diameter) paterae (for example, Amaterasu Patera) in contrast to the typically more narrow and sinuous flow shapes within the shield crater flow unit (for example, Ra Patera). Formal 1:5M quadrangle mapping built upon this theme but also divided the patera and shield materials into light, dark, and undivided categories to emphasize albedo patterns and allow portrayal of individual lobes (Schaber and others, 1989; Whitford-Stark and others, 1991). Mapping in the Lerna Regio region followed this scheme but also subdivided flow materials into fissure, patera, young, old, undivided, and interpatera flows (no obvious source), and interpretations considered these to be either lava flows or pyroclastic flows (Whitford-Stark and others, 1991). Mapping at 1:1M scale of Maasaw Patera and 1:2M scale of Ra Patera included division of flow units by both albedo and geography, because flow materials were grouped and associated with a particular source vent/volcanic center. The Voyager global compilation applied these earlier themes to the 1:15M-scale mapping by defining a series of different flow materials, based primarily on morphology, linked to specific source vents (Crown and others, 1992). Separation of different flow units or subunits based on albedo alone was abandoned, because of the map scale and to better emphasize individual volcanic centers and the range of observed morphologies. The most abundant mapped flow units were lobate, plains-forming, patera, and undivided materials. The patera material generally corresponds to the shield crater material mapped earlier by Schaber (1980, 1982). A common stratigraphic relation was noted between younger lobate flows and older plains-forming flows, where they were in contact.

Our mapping shows that flow materials make up ~28 percent of Io's surface and are typified by their generally elongated planform shape (lengths >> widths) and sharp contacts with the other units (Williams and others, 2002, 2004). Like the patera floor materials, flow materials are generally characterized using color and albedo as bright (unit f_b, ~4%, possibly sulfur dominated), dark (unit f_d, ~3%, presumably silicate dominated), and undivided (unit f_u, ~21%, uncertain composition). The ten largest flow fields and their areas, derived from our mapping, are reported in table 5. Flow materials are interpreted to be the result of one or more outpourings of lava onto the surface. Albedo variations in the flows are generally thought to indicate age on the surface: the freshest dark flows are the darkest; the freshest bright flows are the brightest (McEwen and others 1998a; Williams and others, 2002). In other words, dark flows lighten with age and light flows darken with age toward an intermediate albedo with time. Correlation between NIMS and SSI data also shows that the darkest materials appear to correlate with active hot spots (Lopes-Gautier and others, 1999; Lopes and others, 2001, 2004), and only rarely does a hot spot correlate with a bright flow (Williams and others, 2004). Older flows have intermediate albedo and colors and ill-defined internal unit boundaries and are defined as undivided flow materials. These are likely either sulfur or silicate compositions mantled by various pyroclastic materials, which tends to homogenize the appearance of flows. This explains the relatively large abundance of undivided flow materials. Because of the generally lower resolution of the global mosaics, we did not attempt to subdivide flows based on fissure or point sources, although many undivided flow materials can be related to their likely source vent. The highest resolution SSI images of flow materials (fig. 6) suggest that they are morphologically and texturally reminiscent of terrestrial compound pahoehoe flow fields (for example, Kilauea, Hawaii) or platy ridged lava flows (for example, Laki, Iceland) (Keszthelyi and others, 2001).

Tholus Unit

We mapped bright tholus materials (unit t_b, ~0.1%), which are positive-relief domical edifices that are interpreted to be volcanic constructs, primarily shield volcanoes, or cones, depending upon morphology and flank slopes of the edifices. These features are relatively rare on Io at current spatial resolution, suggesting that the low-viscosity and (or) large volumes of Ionian silicate and sulfur lavas being erupted favor production of flow fields over constructs.

Diffuse Deposits

Diffuse deposits (figs. 5–8) mantle underlying topography in a manner characteristic of fine-grained fragmental material and typically occur on or near active volcanic centers. They cover ~18 percent of our map area, are superposed on all other units, and occur in five distinct colors (Williams and others, 2004): yellow (~2.1%), white (~6.9%), black (~0.6%), red (~8.6%), and green (~0.01%). These colors are interpreted to indicate the dominant chemical constituents: sulfur compounds, sulfur dioxide + contaminants, silicates, short-chain sulfur and (or) sulfur chlorides, and products of silicate-sulfur alteration, respectively. Although diffuse deposits can be ephemeral, long-term accumulation of red diffuse, yellow diffuse, and white diffuse deposits may lead to the formation of red-brown plains, yellow bright plains, and white bright plains materials, respectively. Whereas red diffuse deposits occur either as rings or asymmetric deposits around active volcanic centers, white diffuse deposits typically occur as irregularly shaped units surrounding lava flows. We map diffuse deposits only where they are distinct enough to discern their boundaries and, thus, constrain their sources. Note that this is only true if the gas vent was active during the Galileo era, because we use the Galileo SSI color mosaic to identify and map these deposits.

Structure

A wide range of structural features, including scarps, ridges, grooves, pits, mesas, and lineaments, are visible in the base-map mosaics, mostly in regions where images were obtained at low-sun angle. Scarps delineate layered plains, patera rims, and margins of mountains. Scarps in the plains appear to be largely degradational features. They are commonly associated with scarp-parallel fractures that are likely to be tension cracks that indicate incipient slope failure. There are also enigmatic grooves in the plains that suggest narrow grabens. These are likely to be shallow features, because compressional stresses rapidly increase with depth in Io’s lithosphere due to the weight of overlying material (Jaeger and others, 2003). In general, more structural features can be seen in higher resolution images than can be mapped from our base-map mosaics. Many structural features, particularly in the plains, are buried by extensive volcanic deposits. Schenk and Williams (2004) recognized the only sinuous lava channel, Tawhaki Vallis (east of Hi’iaka Montes, mapped as a sinuous lineament), identified to date on Io; it is interpreted to have formed by erosion of sulfur-rich country materials by flowing lava.

Shadow lengths and directions in low-sun images reveal that most paterae have depressed interiors, similar to terrestrial calderas, and that mountains are indeed positive relief edifices. As in all previous Io studies, no impact craters were detected or mapped on the surface, supporting the contention that Io’s average surface is very young and no substantial areas are less than a few millions of years old (Johnson and others, 1979; McEwen and others, 2000a). A suspiciously circular feature occurs within Heno Patera (lat 57.1° S., long 311.5° W.). This 71.1-km-diameter patera contains a dark floor and dark flows that surround a bright circular rim approximately centered on the patera floor. Although this feature was mapped by Whitford-Stark and others (1991), they did not comment on it. We propose that it could be a result of lava flooding in and around an impact crater (Williams and others, 2007b), but the existing data are ambiguous.

Stratigraphy

Stratigraphy on Io is difficult to determine for several reasons: (1) there are no impact craters visible in any image at any resolution, which prohibits the application of crater statistical techniques to determine crater retention ages or cratering model ages of surfaces; (2) the photometric properties and spatial resolution of images are quite variable at all scales (compare with orbiter images) and high-resolution images are limited in surface coverage; and (3) the ongoing active volcanism, particularly emplacement of condensed gases and tephra from plumes, leads to rapid resurfacing rates (Johnson and others, 1979), such that fresh volcanic deposits can mask older features or alter them beyond recognition. Nevertheless, our mapping has demonstrated that each of our map units has attributes that enable them to fit into a general stratigraphic correlation:

(1) Lava flow units tend to have distinctive albedos, colors, and lobate contacts with their surroundings and can, therefore, be easily distinguished from plains, patera floors, and mountains.

(2) Patera floor units by definition occur within paterae, which are assumed to be topographic depressions, and (because they are composed of similar material as lava flow units) have distinctive albedos and colors, as well as circular, elliptical, or partly curvilinear shapes that easily distinguish them from plains, lava flows, and mountains.

(3) Mountain and layered-plains units tend to have albedos and colors similar to plains materials, such that they can only be differentiated from plains if low-sun-angle images exist that produce shadows on scarps, ridges, grooves, or mass-wasting lobes; however, where these shadowed features exist, mountains can be easily mapped, and their albedos and colors are generally distinctive from lava flows and patera floors.

(4) Plains units can be easily distinguished from lava flows and patera floors, from mountains if low-sun images exist showing the mountains' scarps, and from one another if there is a sharp color difference; however, in some cases, distinct plains-plains contacts are gradational or difficult to detect.

(5) In many cases, diffuse deposits are the easiest to put in a local stratigraphic column, because they are clearly recently emplaced features (like some lava flows and patera floor units); in other cases, the stratigraphy is unclear, because diffuse deposits fade in time. Red diffuse deposits in the form of rings (except at Pele) and white diffuse deposits surrounding the perimeters of lava flow fields mark occurrences associated with distinctive eruptions; in contrast, many circular or ring-like yellow diffuse deposits (for example, Prometheus), red diffuse deposits at Pele, and white diffuse deposits represent ongoing, periodic to continuous eruptions. Additional analyses of discrete diffuse deposits at a regional scale could provide the potential for correlation across the surface.

Often at specific volcanic centers, it is possible to recognize the multiple styles of eruptions that are occurring (for example, explosive and effusive, or variation in types of effusive and explosive deposits, based on albedo-color differences), but it is not possible to recognize the order of eruptive products (without higher-resolution imaging) in ongoing eruptions. Where higher resolution (<1 km/pixel) images exist, regional mapping has demonstrated that a stratigraphic sequence of volcanic eruptions can be identified, for example, in the western Culann-Tohil region (Williams and others, 2004), from oldest to youngest: (1) presence of bright plains; (2) formation of a small shield, Tsũi Goab (TG) Tholus; (3) emplacement of a dark diffuse deposit on TG Tholus and surrounding plains; (4) emplacement of bright lava flows (TG Fluctus) overlying the dark diffuse deposit and plains.

Nevertheless, despite these challenges, a general stratigraphy of Io's surface materials can be recognized that offers insight into the role of various geologic processes as described in the Correlation of Map Units (map sheet). Figures 9–11 give three examples from the global geologic map that show the various stratigraphic relations that led to the development of the Correlation of Map Units (see also table 6).

Geologic History

How long has Io's rampant volcanism been occurring? This is an important question that has implications for Io's overall geologic evolution. Research by Keszthelyi and McEwen (1997) suggests that if Io has maintained its current level of activity since the formation of the Solar System ~4.6 Ga, then it should have completely melted its interior 40+ times, resulting in highly differentiated, highly silicic volcanic products. Yet, studies of the Galileo data over the last decade suggest that active volcanism is centered around eruptions of high-temperature, relatively undifferentiated, mafic to ultramafic material (McEwen and others, 1998b; Davies and others, 2001; Williams and others, 2001a; Keszthelyi and others, 2007), and no evidence of more evolved, more silicic material has been found. One possible explanation of these results is that Io only relatively recently (from a geologic perspective) entered into its Laplace resonance with Europa and Ganymede to trigger its tidally based volcanic activity. Alternatively, Io must have some mechanism to efficiently mix the crust back into the mantle. Further examination of the volcanism and tectonics of Io is required to more fully investigate hypotheses regarding the formation and evolution of Io, and further study of this new global map will aid in these studies.

With the completion of the global mapping, what insights can be gained about Io's geologic evolution? As indicated in the Correlation of Map Units (map sheet), the oldest materials exposed at the surface of Io are crustal materials that have been uplifted to form the various mountain units. Tectonic and geophysical arguments suggest that the upper crust of Io is ~20–30 km thick (Ross and others, 1990; Jaeger and others, 2003). Our mapping and other studies support the hypothesis of Schenk and Bulmer (1998) that the accumulation of volcanic materials on the surface causes compression of the upper crust, eventually leading to tectonic fracturing, faulting, and uplift of crustal blocks that form mountains (our lineated mountain material). Over time these materials are mantled and undergo gravitational collapse, forming mottled mountain materials that grade into layered plains. Surrounding the mountains are the various plains materials whose upper surfaces must be very young, based on the lack of impact craters, but whose lower layers are likely the same crustal materials that make up the mountains. The degradational scarps and other observations point to a significant thickness (up to a few kilometers) of volatile-rich materials mantling the plains (Moore and others, 2001). This volatile-rich material is probably largely confined to the uppermost crust as compression collapses pore space (Jaeger and others, 2003; Jaeger and Davies, 2006).

We suggest that volcanism on Io has been happening for at least the last few million years to build the stress necessary to form the mountains. We think volcanism has been going on for a much longer period of time, although the rapid reworking of the crust has obliterated any evidence of older activity. The currently visible paterae and lava flow fields (fluctus, pl. fluctüs) probably formed simultaneously or subsequently to the currently visible mountains. The oldest volcanic surfaces are related to centers that became inactive in the last decades to millennia and are mapped as undivided patera floor materials and undivided flow materials. More distinct volcanic constructs, including the bright tholus material, probably formed more recently. The visible surface of the plains is formed from the coalescence and homogenization of older eruptive products (pyroclastics and lavas).

The time frame of decades to years marks the period of spacecraft observations, from Voyager (1979) to Galileo (1996-

2001) to New Horizons (2007). While no new mountains or paterae have formed in this time interval, we have witnessed the formation of the Zamama flow field and possibly its cone-like constructs (Davies and others, 1997; Schenk and others, 2004; Williams and others, 2005) between Voyager and Galileo observations and ongoing emplacement of new flow fields at Pillan Patera and the Prometheus and Amirani Eruptive Centers, among others (McEwen and others, 1998a); lavas in patera floors at Pillan, Pele, Loki, and Gish Bar Paterae, among others (McEwen and others, 1998a; Keszthelyi and others, 2001; Rathbun and others, 2002; Lopes and others, 2004; Turtle and others, 2004); and various diffuse deposits at Pele, Pillan, and Thor Eruptive Centers, among many others (McEwen and others, 1998a; Geissler and others, 1999, 2004b; Keszthelyi and others, 2001; Turtle and others, 2004). These formations are the sources for the other geologic units, including bright and dark patera floor materials, bright and dark flow materials, and all five types of diffuse materials. The most recent spacecraft flyby (New Horizons, Feb. 28, 2007) recorded evidence of surface changes in both lava flow fields and diffuse deposits at several locations on Io (Spencer and others, 2007). Through the analysis of Galileo observations, we identified three types of eruptive styles on Io—flow-dominated or Promethean, explosion-dominated or Pillanian (Keszthelyi and others, 2001; Williams and Howell, 2007), and intra-patera or Lokian (Lopes and others, 2004; Williams and Howell, 2007)—that informed our interpretations of the mapped material units.

This global mapping project, despite use of the excellent quality 2006 USGS combined mosaics, was hampered by the nonuniformity of spatial and spectral resolution coverage of Io from the Voyager and Galileo missions. It is clear that the next phase of Io observation must include (1) long-term distant monitoring of Io to assess the variation in Io's volcanism at a range of time scales (minutes, hours, days, months, years) and (or) (2) collection of global data from the ultraviolet to the thermal-infrared at consistent resolutions and phase angles (for example, global visible color imaging at ~250 m/pixel or better, with multiple high-resolution spots at ~5–50 m/pixel). Because the harsh radiation environment at Io and propulsion requirements prohibit the use of an Io orbiter, we suggest that an Io-dedicated Jupiter orbiter, hardened against radiation and capable of ~50+ close Io flybys covering all longitudes in daylight, is an ideal choice for a future Io mission. This suggestion is consistent with the 2003 National Research Council (NRC) Planetary Decadal Survey and its supporting white paper (Spencer and others, 2002) and the Io exploration white paper submitted for the 2011 NRC Planetary Decadal Survey (Williams and others, 2009). Future mission concepts for the Jupiter system are also consistent with all or parts of this approach (Kwok and others, 2007). Only with long-term distant monitoring and (or) globally consistent high-resolution imaging at multiple wavelengths will Io reveal more of her hidden secrets.

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Appendix

The appendix for this map consists of four tables, tables 7–10. Table 7 contains a summary of the imaging coverage of Io from the Voyager, Galileo, Cassini, and New Horizons missions. Table 8 is a list of the Io global mosaics produced by the USGS in 2005, including the filters used and data sources of Galileo and Voyager images. Table 9 lists the image numbers of Galileo images used to make the SSI-only global Color Mosaic.

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Table 1. Latitude-longitude coordinates of type examples of map units shown in figure 2.

Unit label	Unit name	Number of outcrops[1]	Coordinates (lat, long)
	Diffuse deposits		
d_{by}	yellow bright diffuse material	16	19°, 141°
d_{bw}	white bright diffuse material	233	–37°, 163°
d_d	dark diffuse material	18	–40°, 272°
d_r	red diffuse material	70	–22°, 161°
d_g	green diffuse material	2	–20°, 160°
	Flow deposits		
f_d	dark flow material	203	23°, 115°
f_b	bright flow material	143	13°, 149°
f_u	undivided flow material	223	–37°, 165°
	Patera floor deposits		
pf_d	dark patera floor material	235	–28°, 160°
pf_b	bright patera floor material	84	13°, 142°
pf_u	undivided patera floor material	263	–26°, 158°
	Tholus deposits		
t_b	bright tholus material	7	0°, 163°
	Plains deposits		
p_{by}	yellow bright plains material	26	–25°, 175°
p_{bw}	white bright plains material	29	15°, 195°
p_{rb}	red-brown plains material	38	–55°, 135°
p_l	layered plains material	129	–7°, 165°
	Flow deposits		
m_l	lineated mountains material	39	–26°, 162°
m_m	mottled mountains material	9	–28°, 165°
m_u	undivided mountain material	73	–49°, 336°

[1]For some units, particularly the plains units, individually mapped outcrops have been merged in ArcGIS to larger, continuous outcrops.

Table 2. Distribution of geologic material units as percentage of Io's surface area.

[Diffuse deposits are superposed on all other materials and cover 18.2% of Io's surface. Io's surface area = 4.17 x 10^7 km^2]

Unit label	Unit name	Area (km^2)	Area (%)
	Plains deposits		
p_{rb}	red-brown plains material	1.41 x 10^7	33.4
p_{by}	yellow bright plains material	7.68 x 10^6	18.4
p_{bw}	white bright plains material	3.75 x 10^6	8.9
p_l	layered plains material	1.84 x 10^6	4.4
	region of poor resolution (likely red-brown plains material)	7.20 x 10^5	1.7
	Total plains	2.81 x 10^7	**66.6**
	Mountain deposits		
m_l	lineated mountains material	6.40 x 10^5	1.5
m_m	mottled mountains material	8.05 x 104	0.2
m_u	undivided mountain material	5.54 x 10^5	1.3
t_b	bright tholus material	5.25 x 10^4	0.1
	Total mountain material	1.33 x 10^6	**3.1**
	Patera floor deposits		
pf_b	bright patera floor material	1.84 x 10^5	0.4
pf_d	dark patera floor material	1.93 x 10^5	0.5
pf_u	undivided patera floor material	6.75 x 10^5	1.6
	Total patera floor material	1.05 x 10^6	**2.5**
	Flow deposits		
f_b	bright flow material	1.80 x 10^6	4.3
f_d	dark flow material	1.23 x 10^6	2.9
pf_u	undivided flow material	8.70 x 10^6	20.6
	Total flow material	1.17 x 10^7	**27.8**
	Diffuse deposits		
d_{by}	yellow bright diffuse material	8.76 x 10^5	2.1
d_{bw}	white bright diffuse material	2.90 x 10^6	6.9
d_r	red diffuse material	3.61 x 10^6	8.6
d_d	dark diffuse material	2.68 x 10^5	0.6
d_g	green diffuse material	4.09 x 10^3	0.01

Table 3. Locations, heights, and areal extents of the ten largest mountains, ten lineated mountains, and nine mottled mountains on Io.
[-, no data]

Feature name (dominant map unit)	Latitude (°)	Longitude (° W.)	Height (km)	Area (km²)
Mountains				
Carancho (lineated)	–1.37	318.07	8.5	42,064
Capaneus Mensa (undivided)	–16.45	121.11	9.5	38,102
Pan Mensa (lineated)	–51.83	31.16	5	33,540
Ethiopia Planum (lineated)	–45.38	24.79	4.5	31,331
Euboea Montes (undivided)	–47.85	335.83	13.4	30,729
Monan Mons (lineated)	15.22	104.55	6.5	30,200
Danube Planum (lineated)	–22.34	257.76	5.5	29,857
Unnamed (undivided)	–17.40	61.31	5.1	29,025
Unnamed (lineated)	–4.36	63.13	2.9	28,085
Euxine Mons (undivided)	26.24	126.44	7.7	27,444
Lineated mountains				
Carancho	–1.37	318.07	8.5	42,064
Pan Mensa	–51.83	31.16	5	33,540
Ethiopia Planum	–45.38	24.79	4.5	31,331
Monan Mons	15.22	104.55	6.5	30,200
Danube Planum	–22.34	257.76	5.5	29,857
Unnamed	–4.36	63.13	2.9	28,085
Skythia Mons	26.15	98.77	6	27,396
Haemus Mons	–69.95	43.19	10.8	24,712
Unnamed	–20.74	109.36	4.5	23,219
N. Nemea Planum	–65.65	248.78	6	22,982
Mottled mountains				
S. Tohil Mons	–28.08	163.49	<9	25,601
SE. Shamshu Mons	–12.07	71.21	2.9	17,732
Unnamed	8.34	261.64	4	14,021
Unnamed	-43.87	124.88	-	12,519
NW. Pan Mensa	-48.97	34.80	<5	4,929
Unnamed	7.07	284.38	4.5	3,173
NW. Shamshu Mons	–10.80	73.31	<3	1,632
Unnamed	–66.3	243.79	-	625
Unnamed	–7.08	278.16	-	263

Table 4. Locations and areal extents of the ten largest patera floors, ten dark patera floors, and ten bright patera floors on Io.

Feature name (dominant map unit)	Latitude (°)	Longitude (° W.)	Area (km^2)
Patera floors			
Unnamed (undivided)	–37.1	244.7	23,769
Loki Patera (dark)	12.8	308.4	21,204
Kinich Ahau Patera (undivided)	51.0	310.6	21,084
NE. of Loki (undivided)	15.2	305.1	19,082
Unnamed (undivided)	1.1	254.8	17,985
Unnamed (undivided)	31.5	132.3	12,653
Unnamed (undivided)	38.5	24.0	12,440
Outside Amaterasu Patera (undivided)	36.3	306.3	12,135
Horus Patera (bright)	–9.9	337.4	11,920
Itzamna Patera (undivided)	–15.8	99.2	10,581
Dark patera floors			
Loki Patera	12.8	308.4	21,204
Dazhbog Patera	55.1	301.5	8,968
Babbar Patera	–39.8	271.6	7,021
W. Gish Bar Patera	16.2	90.3	6,263
Unnamed	44.1	232.7	5,708
E. Hi'iaka Patera	–3.8	78.8	5,040
Tiermes Patera	22.4	350.2	4,854
Center Amaterasu Patera	38.1	306.5	4,658
N. Creidne Patera	–52.2	342.2	4,374
Emakong Patera	–3.3	119.9	3,675
Bright patera floors			
Horus Patera	–9.9	337.4	11,920
Tvashtar Catena	61.1	119.5	8,190
S. of Loki Patera	9.8	310.5	7,615
Cataquil Patera	–24.2	16.7	7,304
Unnamed	19.4	334.1	7,297
Asha Patera	–8.8	225.6	7,171
Unnamed	–7.6	85.0	6,418
Unnamed	25.3	281.2	6,220
Huo Shen Patera	–16.1	329.9	5,832
Mentu Patera	7.0	139.4	5,514

Table 5. Locations and areal extents of the ten largest lava flow fields, ten largest bright lava flow fields, and ten largest dark lava flow fields on Io.

Feature name (dominant map unit)	Latitude (˚)	Longitude (˚ W.)	Area (km^2)
Lava flow fields			
W. Girru Patera (undivided flows)	19.9	244.8	369,275
N. Mama Patera (undivided flows)	–10.1	353.9	276,264
S. Ukko Patera (undivided flows)	16.6	11.1	274,836
W. Pele (undivided flows)	–21.5	282.6	257,178
Ra Patera (undivided flows)	–8.5	325.4	232,819
Lei-zi Fluctus (undivided flows)	15.1	40.3	205,479
W. Isum Patera (undivided flows)	32.2	225.1	202,407
W. Emakong Patera (undivided flows)	–1.7	128.8	189,958
NW. Thor (undivided flows)	47.5	149.7	179,054
N. Ekhi Patera (undivided flows)	–19.4	84.4	175,180
E. Savitr Patera (bright flows)	45.0	108.9	173,987
Bright lava flow fields (surrounding undivided flow fields not included)			
E. Savitr Patera	45.0	108.9	173,987
NW. of Heiseb Patera	37.2	257.7	136,326
S. of Shakuru Patera	20.5	264.5	91,090
Bulicame Regio	34.8	191.0	81,484
SW. of Arusha Patera	–40.8	106.5	73,248
W. Chalybes Regio	49.0	96.9	57,446
N. Emakong Patera	3.1	118.5	53,911
North Polar 1	59.2	142.6	46,425
N. of Tvashtar Paterae	72.1	131.7	44,267
N. Tarsus Regio	–22.7	57.6	42,843
E. Illyrikon Regio	69.2	187.9	38,597
Dark lava flow fields (surrounding undivided flow fields not included)			
Isum Patera	28.6	208.6	85,162
S. of Mycenae Regio	–48.3	157.8	46,858
Lei-Kung Fluctus	40.3	206.3	45,610
S. of Gibil Patera	–24.8	292.6	40,915
SW. of Girru Patera	20.0	246.6	39,901
Daedalus Patera	19.6	274.5	39,276
Amirani	23.4	116.0	34,077
N. of Arinna Fluctus	42.1	142.6	31,069
N. of Wayland Patera	–25.2	223.5	30,476
NW. of Arinna Fluctus	40.8	149.1	26,832
W. of Wayland Patera	–31.9	230.3	26,759

Table 6. Stratigraphic justification of Io map units as displayed in the Correlation of Map Units.
[s/c, spacecraft]

Unit name (unit label)	Comment or justification
Yellow bright diffuse deposits (d_{by})	Top boundary: Present in Voyager and Galileo images, formation ongoing. May be locally older than d_{bw}, d_d, d_r, d_g. Bottom boundary: Likely started forming when Io became volcanically active. Possibly younger than or contemporaneous with d_{bw}, d_d, d_r, d_g, pf_d, pf_b, f_d, f_b. Younger than pf_u, f_u, m_l, m_m, m_u and younger than or contemporaneous with t_b, p_{by}, p_{bw}, p_{rb}, p_l. Long-term (decades) accumulation of d_{by} may transform to p_{by}.
White bright diffuse deposits (d_{bw})	Top boundary: Present in Voyager and Galileo images, formation ongoing. May be locally older than d_{by}, d_d, d_r, d_g. Bottom boundary: Likely started forming when Io became volcanically active. Possibly younger than or contemporaneous with d_{by}, d_d, d_r, d_g, pf_d, pf_b, f_d, f_b. Younger than pf_u, f_u, m_l, m_m, m_u and younger than or contemporaneous with t_b, p_{by}, p_{bw}, p_{rb}, p_l. Long-term (decades) accumulation of d_{bw} may transform to p_{bw}.
Dark diffuse deposits (d_d)	Top boundary: Present in Voyager and Galileo images, formation ongoing. May be locally older than d_{by}, d_{bw}, d_r, d_g. Bottom boundary: Likely started forming when Io became volcanically active. Possibly younger than or contemporaneous with d_{by}, d_{bw}, d_r, d_g, pf_d f_d, pf_b, f_d, f_b. Younger than pf_u, f_u, m_l, m_m, m_u and younger than or contemporaneous with t_b, p_{by}, p_{bw}, p_{rb}, p_l. Deposits eventually buried to become part of plains.
Red diffuse deposits (d_r)	Top boundary: Present in Voyager and Galileo images, formation ongoing. May be locally older than d_{by}, d_{bw}, d_d, d_g. Bottom boundary: Likely started forming when Io became volcanically active. Possibly younger than or contemporaneous with d_{by}, d_{bw}, d_d, d_g, pf_d, pf_b, f_d, f_b. Younger than pf_u, f_u, m_l, m_m, m_u and younger than or contemporaneous with t_b, p_{by}, p_{bw}, p_{rb}, p_l. Long-term (decades) accumulation of d_r may transform to p_{rb}.
Green diffuse deposits (d_g)	Top boundary: Present in Galileo but not Voyager images (likely due to imaging limitations); forms from alteration of d_r superposed on f_d, so is locally younger than d_r. Formation is likely ongoing. May also be locally older than d_{by}, d_{bw}, d_d. Bottom boundary: Likely started forming when Io became volcanically active. Possibly younger than or contemporaneous with d_{by}, d_{bw}, d_d, d_r, pf_d, pf_b, f_d, f_b. Younger than pf_u, f_u, m_l, m_m, m_u and younger than or contemporaneous with t_b, p_{by}, p_{bw}, p_{rb}, p_l. Deposits eventually transform to f_u or pf_u.
Dark flow material (f_d)	Top boundary: Present in Galileo images, among youngest flows, may not be present in Voyager images (although formation ongoing). Observed forming in Galileo images. Older than or contemporaneous with f_b, pf_d, pf_b, d_{by}, d_{bw}, d_d, d_r, d_g. Bottom boundary: Likely started forming when Io became volcanically active. Younger than f_u, pf_u, m_l, m_m, m_u and younger than or contemporaneous with t_b, p_{by}, p_{bw}, p_{rb}, p_l. Accumulation of superposed diffuse deposits eventually transforms this unit into f_u.
Bright flow material (f_b)	Top boundary: Present in Galileo images, among youngest flows, may not be present in Voyager images (although formation ongoing). None observed forming in Galileo images. Older than or contemporaneous with f_d, pf_d, pf_b, d_{by}, d_{bw}, d_d, d_r, d_g. Bottom boundary: Likely started forming when Io became volcanically active. Younger than f_u, pf_u, m_l, m_m, m_u and younger than or contemporaneous with t_b, p_{by}, p_{bw}, p_{rb}, p_l. Accumulation of superposed diffuse deposits eventually transforms this unit into f_u.

Table 6. Stratigraphic justification of Io map units as displayed in the Correlation of Map Units.—*Continued*

[s/c, spacecraft]

Unit name (unit label)	Comment or justification
Undivided flow material (f_u)	Top boundary: None observed forming in Galileo or Voyager images. Must be older than f_d, f_b, pf_d, pf_b, d_{by}, d_{bw}, d_d, d_r, d_g, contemporaneous with pf_u, and older than or contemporaneous with t_b. Bottom boundary: Likely started forming when Io became volcanically active. Younger than or contemporaneous with p_{by}, p_{bw}, p_{rb}, p_l (any older f_u buried by ongoing plains formation) and younger than or contemporaneous with m_l, m_m, m_u. Long-term accumulation of superposed diffuse deposits eventually buries this unit, transforming it into plains.
Dark patera floor material (pf_d)	Top boundary: Present and observed to form in Galileo images, among youngest patera floors, may not be present in Voyager images (although formation ongoing). Older than or contemporaneous with pf_b, f_d, f_b, d_{by}, d_{bw}, d_d, d_r, d_g. Bottom boundary: Likely started forming when Io became volcanically active. Younger than pf_u, f_u, m_l, m_m, m_u and younger than or contemporaneous with t_b, p_{by}, p_{bw}, p_{rb}, p_l. Accumulation of superposed diffuse deposits eventually transforms this unit into pf_u.
Bright patera floor material (pf_b)	Top boundary: Present in Galileo images, among youngest patera floors, may not be present in Voyager images (although formation likely ongoing). None observed forming in Galileo images. Older than or contemporaneous with pf_d, f_d, f_b, d_{by}, d_{bw}, d_d, d_r, d_g. Bottom boundary: Likely started forming when Io became volcanically active. Younger than pf_u, f_u, m_l, m_m, m_u and younger than or contemporaneous with t_b, p_{by}, p_{bw}, p_{rb}, p_l. Accumulation of superposed diffuse deposits eventually transforms this unit into pf_u.
Undivided patera floor material (pf_u)	Top boundary: None observed forming in Galileo or Voyager images. Must be older than pf_d, pf_b, f_d, f_b, d_{by}, d_{bw}, d_d, d_r, d_g, contemporaneous with f_u, and older than or contemporaneous with t_b. Bottom boundary: Likely started forming when Io became volcanically active. Younger than or contemporaneous with p_{by}, p_{bw}, p_{rb}, p_l (any older pf_u buried by ongoing plains formation) and younger than or contemporaneous with m_l, m_m, m_u. Long-term accumulation of superposed diffuse deposits eventually buries this unit, transforming it into plains.
Bright tholus material (t_b)	Top boundary: Present in Voyager and Galileo images. Older than or contemporaneous with d_{by}, d_{bw}, d_d, d_r, d_g, pf_d, pf_b, f_d, f_b. None observed forming during Voyager or Galileo missions, but formation may be ongoing. Bottom boundary: Likely started forming when Io became volcanically active. Younger than or contemporaneous with pf_u, f_u, p_{by}, p_{bw}, p_{rb}, p_l, m_l, m_m, m_u. Long-term accumulation of superposed diffuse deposits eventually buries this unit, transforming it into plains.
Yellow bright plains material (p_{by})	Top boundary: Plains formation is ongoing, but visible surface typically underlies units pf_d, pf_b, pf_u, f_d, f_b, f_u, t_b, d_{by}, d_{bw}, d_d, d_r, d_g (these units usually superposed on plains). Bottom boundary: Likely started forming when Io became volcanically active. Younger than or contemporaneous with p_l, p_{bw}, p_{rb}, m_l, m_m, m_u.
White bright plains material (p_{bw})	Top boundary: Plains formation is ongoing, but visible surface typically underlies units pf_d, pf_b, pf_u, f_d, f_b, f_u, t_b, d_{by}, d_{bw}, d_d, d_r, d_g (these units usually superposed on plains). Bottom boundary: Likely started forming when Io became volcanically active. Younger than or contemporaneous with p_{by}, p_l, p_{rb}, m_l, m_m, m_u.
Red-brown plains material (p_{rb})	Top boundary: Plains formation is ongoing, but visible surface typically underlies units pf_d, pf_b, pf_u, f_d, f_b, f_u, t_b, d_{by}, d_{bw}, d_d, d_r, d_g (these units usually superposed on plains). Bottom boundary: Likely started forming when Io became volcanically active. Younger than or contemporaneous with p_{by}, p_{bw}, p_l, m_l, m_m, m_u.

Table 6. Stratigraphic justification of Io map units as displayed in the Correlation of Map Units.—*Continued*

[s/c, spacecraft]

Unit name (unit label)	Comment or justification
Layered plains material (p_l)	Top boundary: Layered plains degradation is ongoing. Typically older than or contemporaneous with units pf_d, pf_b, pf_u, f_d, f_b, f_u, t_b, d_{by}, d_{bw}, d_d, d_r, d_g (these units usually superposed on layered plains). Bottom boundary: Likely started forming when Io became volcanically active. Younger than or contemporaneous with p_{by}, p_{bw}, p_{rb}, m_l, m_m, m_u.
Lineated mountain material (m_l)	Top boundary: No evidence of m_l formation since s/c observations began, but likely is ongoing. Unit degrades to form m_m (and possibly p_l), therefore must be locally older than m_m. Bottom boundary: Likely started forming when Io became volcanically active. Older than or contemporaneous with t_b, pf_u, f_u, p_{by}, p_{bw}, p_{rb}, p_l.
Mottled mountain material (m_m)	Top boundary: No evidence of m_m formation since s/c observations began, but likely is ongoing. Derived from m_l, therefore must be locally younger than m_l. Bottom boundary: Likely started forming when Io became volcanically active. Older than or contemporaneous with t_b, pf_u, f_u, p_{by}, p_{bw}, p_{rb}, p_l.
Undivided mountain material (m_u)	Top boundary: No evidence of m_u formation since s/c observations began, but could be ongoing. Could consist of units m_l or m_m, but limited by s/c resolution constraints. Bottom boundary: Likely started forming when Io became volcanically active. Older than or contemporaneous with t_b, pf_u, f_u, p_{by}, p_{bw}, p_{rb}, p_l.

Table 7. Imaging coverage of Io from the Voyager ISS, Galileo SSI, and New Horizons instruments. From Smith and others (1979b), Galileo Team records (unpub.), and Spencer and others (2007).

Mission[1]	Flyby/orbit[2]	Date	Coverage/resolution (km/px)
Voyager	Voyager 1	March 5, 1979	Regional grayscale & color, ~35% of moon @ 0.5–2; global color @ 10–125
Voyager	Voyager 2	July 9, 1979	Global color: 80% of moon @ 10–45
Gal-NOM	G1	June 29, 1996	Global color @ >30
Gal-NOM	G2	Sept. 6, 1996	Plume monitoring @ 10–31
Gal-NOM	C3	Nov. 6, 1996	Grayscale global @ 2.5–4
Gal-NOM	E4	Dec. 18, 1996	Eclipse observations @ 18–35; Global color @ 6–12
Gal-NOM	E6	Feb. 20, 1997	Regional color @16–21
Gal-NOM	G7	April 3, 1997	Eclipse @ 33; Grayscale @ 6; Global color @ 12
Gal-NOM	G8	May 7, 1997	Eclipse @19; Regional color @ 10–23
Gal-NOM	C9	June 27, 1997	Eclipse @ 13–15; Regional color @ 6–17
Gal-NOM	C10	Sept. 18, 1997	Eclipse @ 13; Global color @ 5–13
Gal-NOM	E11	Nov. 7, 1997	Regional color @ 8–19
Gal-GEM	E12	Dec. 16, 1997	Eclipse @ 12
Gal-GEM	E14	Mar. 29, 1998	Regional color @ 3
Gal-GEM	E15	May 31, 1998	Eclipse @ 11–13
Gal-GEM	C21	June 30, 1999	Global color @ 1.4
Gal-GEM	C22	Aug. 14, 1999	Plume monitoring @ 10–17
Gal-GEM	I24	Oct. 11, 1999	High-res grayscale @ 0.01–0.63; Regional color @ 0.22; Global color @ 6–13
Gal-GEM	I25	Nov. 26, 1999	Regional grayscale @ 0.14–0.2; Regional color @ 0.2
Gal-GEM	E26	Jan. 4, 2000	Regional color @ 3–4
Gal-GMM	I27	Feb. 22, 2000	High-res grayscale @ 0.01–0.02; Regional grayscale @ 0.2–0.9; Global color @ 3
Gal-GMM	G29	Dec. 28, 2000	Global color @ 10–17
Gal-GMM	I31	Aug. 6, 2001	Global color @ 19–20
Gal-GMM	I32	Oct. 16, 2001	High-res grayscale @ 0.013–0.4; Regional color @ 0.22; Global color @ 5–13
Cassini	Jupiter Flyby	Jan. 1–2, 2001	Color & grayscale timelapse movies @ 60–120
New Horizons	Jupiter Flyby	Feb. 28, 2007	190 grayscale images @ 14–22; 17 color nighttime & eclipse images @ 50–60; 7 near-IR image cubes @ 140–170

[1]Gal-NOM, Galileo Nominal Mission (1996–1997); Gal-GEM, Galileo Europa Mission (1998–1999); Gal-GMM, Galileo Millennium Mission (2000–2002).

[2]For the Galileo mission, the orbit letter designates primary remote sensing target: I, Io; E, Europa; G, Ganymede; C, Callisto.

Table 8. List of the new Io global mosaics produced by the USGS, combining Galileo and Voyager images. All mosaics have a spatial resolution of 1 km/pixel. The versions shown in this report (fig. 1) are simple cylindrical projections centered on the antijovian point (long 180° W.).

Mosaic	Filter-wavelengths used	Phase angle (°)	Data sources	Comments
Galileo SSI-only low-phase color	765nm-GRN-VIO	4	57 images from Galileo orbits G2, E6, C9, C21, I31	Use for mapping colorful diffuse deposits
Galileo SSI-only monochrome	CLR, GRN, 756nm	Various	32 images from Galileo orbits G1, G2, C3, E6, G7, C9, C10, E11, C21, C22, I24	Use for mapping surface morphology—antijovian hemisphere
Combined Galileo-Voyager monochrome	GLL: CLR, GRN, 756nm; VGR: CLR, BLU	Various	50 Voyager 1 images, 32 Galileo images (see above)	Use for mapping surface morphology—subjovian hemisphere
Merged Galileo-Voyager monochrome and SSI low-phase color	See rows 1 and 3 above	Various, Color = 4	See rows 1 and 3 above	Use for correlating mapped features with color—compositional relations

Table 9. Image numbers of Galileo and Voyager images used to make the Combined Mosaic.
Io Global Mosaic: Galileo SSI and Voyager 1 Combined for Best Resolution, December 2005.

Galileo SSI (all SSI images are Clear filter unless otherwise specified)			Voyager 1 (all Voyager 1 images are Clear filter & Narrow Angle (NA) camera unless otherwise specified)			
OBSERVATION	**IMAGE_NUMBER**	**NOTE**	**v-#**	**IMAGE_NUMBER**	**v-#**	**IMAGE_NUMBER**
1 – G1ISGLOMON05	0349746300	Green	v-2	1639133 (WA)	v-30	1639152
2 – C22ISIOGEOD01	0512336700	Green	v-3	1638227 (Blue)	v-31	1639144
3 – E11ISTOPO__01	0420669000		v-4	1638858	v-32	1639158
4 – G2ISSRFMON01	0359986578	Green	v-5	1638906	v-33	1639156
5 – C9ISSRFMON01	0401785378		v-6	1638954	v-34	1639150
6 – C10ISIOTOPO02	0413659700		v-7	1638946	v-35	1639154
7 – G7ISTOPMAP03	0389771978		v-8	1639239 (WA)	v-36	1639148
8 – G7ISTOPMAP02	0389752400		v-9	1639104	v-37	1639146
9 – C3ISTOPMAP05	0368641300		v-10	1638918 (Blue)	v-38	1639110
10 – E6ISTOPMAP01	0383694100		v-11	1638914	v-39	1639108
11 – C3ISTOPMAP01	0368558239		v-12	1639024	v-40	1639130
12 – C21ISALBEDO01	0506406726	Green	v-13	1639026	v-41	1639124
13 – C3ISTOPMAP03	0368599800		v-14	1639042	v-42	1639112
14 – I24ISSTEREO01	0520821326		v-15	1639028	v-43	1639114
15 – C3ISTOPMAP04	0368620000		v-16	1639018 (Blue)	v-44	1639132
16 - C3ISTOPMAP03	0368599813		v-17	1639012 (Blue)	v-45	1639126
17 - C3ISTOPMAP01	0368558252		v-18	1639006 (Blue)	v-46	1639116
18 – C21ISALBEDO01	0506406839	Green	v-19	1639044	v-47	1639122
19 – C21ISCOLOR_01	0506406007	7560	v-20	1639002	v-48	1639120
20 – C21ISALBEDO01	0506406739	Green	v-21	1639034	v-49	1639118
21 – C21ISSTEREO01	0506431239		v-22	1639036	v-50	1639128
22 – I24ISSTEREO01	0520821213		v-23	1639038	v-51	1638938
23 - I24ISSTEREO01	0520821200		v-24	1639056		
24 - I24ISSTEREO01	0520821226		v-25	1639134		
25 - I24ISSTEREO01	0520821265		v-26	1639136		
26 - I24ISSTEREO01	0520821278		v-27	1639138		
27 - C21ISSTEREO01	0506431313		v-28	1639140		
28 - C21ISSTEREO01	0506431300		v-29	1639142		
29 - C21ISSTEREO01	0506431339					
30 - I24ISSTEREO01	0520821326					
31 - I24ISSTEREO01	0520821339					
32 - I24ISSTEREO01	0520821352					

Table 10. Image numbers of Galileo images used to make the SSI-only global Color Mosaic.

OBSERVATION	IMAGE_NUMBER	FILTER
1 – C9ISPHOTOM01	0401740711	7560
	0401740700	GREEN
	0401740707	VIOLET
2 – G2ISSRFMON01	0359986607	7560
	0359986578	GREEN
	0359986604	VIOLET
3 – E6ISSRFMON02	0383758511	7560
	0383758500	GREEN
	0383758507	VIOLET
4 – C21ISCOLOR_01	0506405700	7560
	0506405735	
	0506405770	
	0506405814	
	0506405849	
	0506405884	
	0506405928	
	0506405963	
	0506406007	
	0506406042	
	0506406077	
	0506406121	
	0506406156	
	0506406200	
	0506406235	
	0506406484	
4 – C21ISALBEDO01	0506406626	GREEN
	0506406639	
	0506406652	
	0506406665	

Table 10. Image numbers of Galileo images used to make the SSI-only global Color Mosaic.—*Continued*

OBSERVATION	IMAGE_NUMBER	FILTER
	0506406678	
	0506406700	
	0506406713	
	0506406726	
	0506406639	
	0506406752	
	0506406765	
	0506406778	
	0506406800	
	0506406813	
	0506406826	
	0506406839	
4 – C21ISCOLOR_01	0506405688	VIOLET
	0506405732	
	0506405767	
	0506405811	
	0506405846	
	0506405881	
	0506405925	
	0506405960	
	0506406004	
	0506406039	
	0506406074	
	0506406118	
	0506406153	
	0506406188	
	0506406232	
	0506406481	