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VOYAGER AND GALILEO SSI VIEWS OF
VOLCANIC RESURFACING ON IO
AND THE SEARCH FOR GEOLOGIC ACTIVITY ON EUROPA

By
Cynthia Baya Phillips

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A Dissertation Submitted to the Faculty of the
DEPARTMENT OF PLANETARY SCIENCES
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
In the Graduate College
THE UNIVERSITY OF ARIZONA

2000
As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Cynthia Baya Phillips entitled Voyager and Galileo SSI views of Volcanic Resurfacing on Io and the Search for Geologic Activity on Europa and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

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SIGNED: [Signature]
ACKNOWLEDGMENTS

A thesis is necessarily a collaborative effort, yet the final product is claimed by a single author. This is a rare occurrence in science. As such, I would like to acknowledge just a few of the many people who have influenced the direction of my scientific career leading up to this point. My parents, as well as my high school teachers Norton Levy and Peter Atlas, encouraged me to become a scientist. As an undergraduate at Harvard, Carl Agee first interested me in Planetary Science, John Wood began my real scientific training, and Emily and Diane were supportive roommates and friends. In graduate school, Clark Chapman, Jay Melosh, Rick Greenberg and Bob Strom provided invaluable insight, guidance, support, and fascinating scientific discussions. Terry Wallace and Clem Chase were patient with me as I learned geophysics. And Alfred McEwen has been a supportive and inspiring advisor and mentor.

I’d also like to thank the members of the Galileo Imaging Team for allowing me to participate in one of the most exciting, and successful, spacecraft missions ever. Mike Belton, Liz Alvarez, Bob Pappalardo. Jeff Moore, Beth Clark and Tammy Becker all were helpful and supportive.

LPL has been an amazing place to be a graduate student, not just because of the expertise of the faculty, but also because of the wonderful sense of camaraderie among the graduate students, researchers, staff, and others. I’d like to thank Zibi. Laszlo, Chris, Jen, Andy, Barb. David T., Greg, Nancy, Bill M., Bill B., Kim, Josh, Rachel, Paul G., Maria, and Moses for being classmates, friends, housemates, and colleagues. I’d also like to thank Joe Plassman and Linda Hickcox for making PIRL the best computer facility around.

I would like to thank my parents, brother and sister, and grandfather for being supportive, helpful, and inspirational.

And finally, Shana has made this all possible, and Zoecyn has made it worthwhile. I can never thank them enough.
DEDICATION

This thesis is dedicated to Shana, my partner in life and love.

and to Zoecyn, who lights up my life with her smile.

It is also dedicated to my grandmother.


I hope to have scientific opportunities that were not available to her

as a physicist in the 1930's.
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ABSTRACT

Observational evidence and theoretical arguments suggest that Jupiter's satellite Europa could be geologically active and possess an "ocean" of liquid water beneath its surface at the present time. We have searched for evidence of current geologic activity on Europa in the form of active plumes venting material above the surface and by comparison of Voyager and Galileo images to look for any changes on the surface. So far, we have observed no plumes and have detected no definitive changes. The lack of observed activity allows us to estimate a maximum steady state surface alteration rate of 1 km$^2$ y$^{-1}$ in the regions analyzed, assuming alterations will cover contiguous areas of at least 4 km$^2$ over a period of 20 years. Assuming this as a constant, globally uniform resurfacing rate leads to a minimum average surface age of 30 million years.

Lava flows and plumes are the two main types of volcanic activity that resurface Io. We have used the Galileo Io dataset to observe the detailed sequences of interconnected plume activity, hotspot activity, and new surface deposits at a number of volcanic centers on Io. Red material has faded on a timescale of less than a year, and a green coating has formed on a caldera over a time period of about 3 months. Change detection maps can illustrate the percentage of the surface newly covered by plume deposits and lava flows, and constrain volume and mass resurfacing rates. Areal resurfacing is dominated by plume deposits, but volume resurfacing is dominated by lava flows. Estimates of resurfacing from these change maps range from 0.4 to 12.9 cm/year, assuming a flow thickness of 1 to 10 meters. The minimum resurfacing rate
required for the lack of impact craters on Io's surface is about 0.02 cm/year. If high-magnesium (komatiitic) lavas dominate the observed Io heat flux, the maximum resurfacing rate is about 0.69 cm/year. Basaltic lavas could produce a rate of 1.3 cm/year. The komatiitic rate produces an average flow thickness of about half a meter. Thus, we suggest that the average resurfacing rate of Io is between 0.1 and 1 cm/year.
Forward

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

-T. S. Eliot. Four Quartets. Little Gidding, IV

This thesis is an exploration of the processes taking place on two of the most exotic moons in the solar system, Io and Europa. These tidally tortured worlds, located five times further from the sun than the Earth, are dominated by the giant planet Jupiter which looms in the sky above their surfaces. Yet the basic physical processes taking place on these satellites are the same as those elsewhere in the solar system. Io’s dramatic volcanic activity could be similar to eruptions that took place here when the Earth was young. The frozen, icy world Europa could harbor a liquid water ocean beneath its crust, where simple life could exist. The study of such life would have dramatic implications for our views of how life began on Earth, and how it has evolved. Thus, in exploring such seemingly-different bodies in our solar system, we can in fact shed new light on our own world, and eventually know this place for the first time.
Part 1: The search for current geologic activity on Europa


Overview. Observational evidence and theoretical arguments suggest that Jupiter's satellite Europa could be geologically active and possess an "ocean" of liquid water beneath its surface at the present time. We have searched for evidence of current geologic activity on Europa in the form of active plumes venting material above the surface and by comparison of Voyager and Galileo images to look for any changes on the surface. So far, we have observed no plumes and have detected no definitive changes. The lack of observed activity allows us to estimate a maximum steady state surface alteration rate of 1 km² y⁻¹ in the regions analyzed, assuming alterations will cover contiguous areas of at least 4 km² over a period of 20 years. Assuming this as a constant, globally uniform resurfacing rate leads to a minimum average surface age of 30 million years. We also suggest that the lack of obvious circular albedo patterns on the surface due to plumes, coupled with the presence of bright-rayed craters such as Pwyll and the predicted sputtering erosion rate, implies that no large-scale plume activity has taken place over at least the last few thousand years. We thus conclude that if Europa's surface is currently active, any changes must be relatively small in spatial scale or episodic in nature rather than continuous. To detect potential small-scale
surface changes, we need high-resolution comparisons between the Galileo data and future Europa Orbiter images.

1.1. Introduction

Jupiter's satellite Europa is currently the focus of much scientific excitement. Voyager images showed a surface covered with a complex set of intersecting linear features, interspersed with regions of dark mottled terrain and very few impact structures (Smith et al., 1979; Lucchitta and Soderblom, 1982; Malin and Pieri, 1986). Higher-resolution Galileo observations have shown other types of surface features and revealed that the mottled areas consist largely of chaotic terrain where portions of the surface seem to have been disrupted, broken, and "rafted" into new positions (Carr et al., 1998). The variety of surface features, coupled with the relative lack of impact craters (only 28 larger than 4 km in diameter have been detected to date (Turtle et al., 1999)), indicates that Europa's surface is most likely geologically young (based on impactor-flux models (Zahnle et al., 1998)) and perhaps currently active. Europa's surface is not as young as Io's, which seems to have no impact craters at all due to continuous volcanic resurfacing, but is certainly much younger than the surfaces of Ganymede and Callisto, which are densely covered with craters in most areas. The possibility of current activity on Europa is supported by thermal and tidal models suggesting that there may be enough heat dissipated in Europa's interior, mostly from tidal flexing due to Europa's resonances with Io and Ganymede, to maintain a layer of liquid water beneath the surface (Cassen et al., 1979, 1980; Reynolds et al., 1983;
Squyres et al., 1983; Ojakangas and Stevenson, 1989). The presence of a subsurface liquid layer would affect the rate of endogenic activity on the surface, but the existence, thickness, and depth to such a layer are hotly debated (Pappalardo et al., 1999).

The interpretation that Europa has a young surface prompts a search for current activity. However, what kind of activity might we expect, and how might we detect it? One type of unequivocal evidence of current activity would be the detection of active plumes of material venting from Europa’s surface. Plumes have been detected on Io and on Neptune’s satellite Triton (Smith et al., 1979, 1989). We have reexamined a controversial Voyager image and the Galileo images but have found no evidence of plumes on Europa. We have also compared Galileo images to those taken by Voyager to search for changes on Europa due to surface geologic activity. Careful coregistering and ratioing of overlapping areas has revealed no differences due to geologic activity, but we are hindered by the low resolution of the Voyager data set and the limited overlap area with similar-resolution Galileo images. The lack of detectable surface changes allows us to place constraints on the surface age and resurfacing rate and style of Europa, given certain assumptions.

1.2. Plume Detection

Plumes on Europa are a possible consequence of a near-surface body of liquid water. If a thin ice shell overlying a liquid water “ocean” or isolated water pocket is cracked open by tidal or other stresses, any liquid water which is exposed will immediately boil and create a substantial vapor cloud. Dissolved volatiles, if present, could exsolve and
drive an even larger gas-rich spray. This process will tend to deposit dissolved materials such as salts or organics near the vent site (Squyres et al., 1983), but the water vapor could travel up to hundreds of kilometers before recondensing (Reynolds et al., 1983). However, cracks which open at the surface may have difficulty propagating down far enough to reach liquid water before they are closed by hydrostatic pressure (Crawford and Stevenson, 1988). An alternative scenario is that cracks propagate upward from the liquid water layer, with water eventually reaching the surface. This is hampered by the negative buoyancy of water with respect to ice unless the water contains dissolved gases such as CO$_2$ or SO$_2$ (Crawford and Stevenson, 1988), which can help drive the eruption. Such eruptions would likely follow ballistic trajectories and could reach heights up to 100 km if the plume gas content were as high as 30 wt% (Fagents et al., 2000). Thus these plumes could be large enough to detect in Voyager or Galileo images of Europa.

A single Voyager image of Europa has been cited as evidence of an active plume over Europa's bright limb by Cook et al. (1982, 1983) and Helfenstein and Cook (1984). We have reanalyzed that image (Pappalardo et al., 1999, Figure 17) and have shown that the supposed plume was more likely a distortion at the edge of the image. The feature is observed only in this single low-resolution frame (Table 1.1), is only five gray levels above the background, and is located in the corner of the image where distortion and noise were at maximum levels in Voyager's vidicon camera (Gaskell, 1988). Similar distortions are visible in corners of other images in the Voyager sequence located far
from the disk of Europa. Thus it seems most likely that the putative plume is an observational artifact.

Table 1.1. Voyager and Galileo Plume Search Images

<table>
<thead>
<tr>
<th></th>
<th>Voyager</th>
<th>Galileo C10</th>
<th>Galileo E19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>1979</td>
<td>1997</td>
<td>1999</td>
</tr>
<tr>
<td>Image number(s)</td>
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<td>s0416073126-</td>
<td>s0484889800-</td>
</tr>
<tr>
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<td></td>
<td>s0416073165;</td>
<td>s0484889842</td>
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<td></td>
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<td>s0416110126-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>s0416110165</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>44 km pixel$^{-1}$</td>
<td>73 km pixel$^{-1}$</td>
<td>72 m pixel$^{-1}$</td>
</tr>
<tr>
<td>Phase angle, deg</td>
<td>143</td>
<td>178</td>
<td>149</td>
</tr>
<tr>
<td>Filter(s)</td>
<td>clear</td>
<td>clear</td>
<td>clear</td>
</tr>
<tr>
<td>Longitude of limb, deg</td>
<td>345</td>
<td>60, 70, 80</td>
<td>215</td>
</tr>
<tr>
<td>Latitude range, deg</td>
<td>-90 to +90</td>
<td>-90 to +90</td>
<td>-2 to +15</td>
</tr>
</tbody>
</table>
To follow up on the Voyager observations, several global-scale and small-scale images of Europa were taken by Galileo specifically to search for plumes (Table 1.1). The first set, taken in October 1997 on orbit C10 at low resolution (73 km/pixel) and high phase angle, revealed no large-scale plumes. A higher-resolution series of images targeting the bright limb of Europa at a high phase angle was acquired in February 1999 on Galileo orbit E19. This observation, consisting of a series of 30 images at an average resolution of 72 m/pixel, was intended to search for small-scale plumes. One swath of 15 images paralleled the limb, and the second followed the dark sky just off the limb. These images covered a longitude of about 215° and spanned a latitude range from 2°S to 15°N. A mosaic of some of these images is shown in Figure 1.1. Careful analysis of these images has revealed no bright, diffuse glows off the bright limb of Europa and no anomalously bright regions on the surface. We thus conclude that no plumes were visible in this series of images.
Figure 1.1.
Mosaic of 13 of the E19 plume images following the limb, which is visible in the upper-right corner. The mosaic includes only those images which could be mosaicked; many of the images including the limb had long exposure times which saturated the surface, and some of the images missed the surface completely, including only dark sky. These images were impossible to include with the rest of the mosaic, although they have also been examined for the presence of plumes with a negative result. The mosaic is in an orthographic projection around the subspacecraft point (20°N, 281°W), at a resolution of 74 m/pixel and covers a range from -0°-15° N latitude, and -150° to -130° longitude (see Table 1.1 for more information). No plumes or anomalously bright surface regions are visible.
Figure 1.2. (a) The raw "limb haze" image, in its original form, is shown. The suspicious feature is visible in the upper right corner as a bright, diffuse structure paralleling the limb. Image number s0484888253. (b) Cutout over the limb of Figure 1.2a, corresponding to the white box in Figure 1.2a, stretched for maximum enhancement of the "limb haze." This results in saturation of the surface. Note how the brightness of the "haze" can be seen to parallel the brightness of the surface (best visible in Figure 1.2a). In this stretch, subtle radiation noise in the dark sky off the limb is also enhanced. (c) This image demonstrates how the suspected "limb haze" can be formed in a double exposure. This is a synthetic double exposure made from Figure 1.2b, with the bright limb at 7% of its full brightness, shifted off the planet by 16 pixels. The synthetic double exposure reproduces Figure 1.2b (the real image) well, except for the random radiation noise in the real image.
Hoppa et al. (1999a) suggested that the E19 plume search opportunity occurred at a time and longitude combination unfavorable for activity associated with Europa's diurnal tides. Over the 85 hour tidal cycle, regions of the surface undergo both tension and compression. Thus cracks may form along favorable stress orientations, and such cracks would subsequently be pulled open and closed over the diurnal tidal cycle. Active plumes and venting of material would most likely be associated with cracks perpendicular to the orientation of the maximum tensile stress, as they opened up and potentially exposed liquid water to a vacuum. Hoppa et al. (1999a) showed that the region targeted for the E19 plume search would be predominantly under compression at the time the images were taken, but orbital trajectory constraints did not allow the observations to be moved to a more favorable location and time.

An interesting side note is that one of the images taken in another imaging sequence on orbit E19 had what appeared upon initial inspection to be a limb haze just off the bright limb of Europa. Frame s0484888253 is shown in its raw, unprocessed (just contrast-enhanced) form in Figure 1.2a, and a cutout of just the limb, with a hard stretch, is shown in Figure 1.2b. The potential limb haze is visible in Figures 1.2a and 1.2b as a bright feature paralleling the limb ~100 km above the surface, at a brightness level ~7% of the average surface brightness. There was originally much guarded excitement when this image was received on the ground, but the fact that the "haze" brightness seemed to exactly parallel the limb brightness, and that the "haze" was not visible in immediately adjacent images, led the Galileo engineering team to search for another possibility. The match between haze and limb brightness patterns suggests the
possibility of a double image or "ghost image." This possibility is demonstrated in Figure 1.2c, which shows a simulated ghost image constructed by offsetting and adding a dimmer version of the actual image in 1.2b, shifted 16 pixels to the left.

Examination of the imaging sequence and the operation of the SSI camera itself reveals a likely cause. The image was taken in the AI8 camera mode, which has a fast frame time and thus does not reset the charge-coupled device (CCD) detector by performing a full light flood and erasure cycle in between exposures (Klaasen et al., 1997). This mode also has a reset of the shutter blades 0.2 seconds before the exposure begins. In all other imaging modes, the light flood and erasure take place between the shutter reset and the exposure, but since this particular mode has no light flood, this does not occur. The location and brightness of the offset "ghost image" in frame s0484888253 are consistent with a small light leak equivalent to about 0.5 ms of exposure during the shutter reset stage of image acquisition, which occurred during a slew from the position of the previous image to this position. The direction and speed of the slew are consistent with the position of the "ghost image." The light leak would not be noticeable unless the many conditions of this image were met, namely, the platform slewed from one position to the next; the exposure time was short enough that the slight light leak was visible next to the full image; and the image contained a high-contrast feature (the limb) against which the ghost image is obvious. The last two frames of the first swath of plume search images (s0484889846 and s0484889849) also show a ghost image off the limb that is consistent with the shutter reset light leak theory. Only four other images taken during the Galileo orbital mission have the
characteristics necessary (camera mode, high-contrast boundary, short shutter time, platform slewing) to detect ghost images produced during the shutter reset; of these, ghost artifacts consistent with this theory were detected in three of them.

Another possible way to detect material vented above the surface of Europa would be to see it glowing in eclipse as can be seen on Io (McEwen et al., 1998a). An image of Europa in eclipse was taken in April 1997, on orbit G7, and analysis of that image showed a diffuse glow across almost the whole disk. This is most likely due to illumination of the disk of Europa by scattered light refracted through Jupiter’s atmosphere, rather than being evidence for active venting of material from Europa (P. Geissler, personal communication, 1999; Pappalardo et al. (1999)). A Europa eclipse observation was repeated on orbit C20 and again detected no obvious glowing plume material above the disk of Europa. However, detailed analysis of these images is still pending.

Thus the results from the Voyager and Galileo plume search and eclipse observations are negative to date: we have found no evidence of active plumes venting material above the surface of Europa. When we compare the appearance of Europa’s surface to that of Io, which has well-documented plume activity, it is clear that Europa’s surface also lacks the characteristic surface traces of large recent plume activity. Io is covered with many circular, diffuse plume deposits (~100-1000 km in diameter) which are due to eruptions of particles and SO$_2$ gas. In the simplest model of these features, the material follows ballistic trajectories until it intersects the surface, creating a characteristic circular shape (Kieffer, 1982; Strom and Schneider, 1982). A study of
potential cryovolcanism on Europa by Fagents et al. (2000) considers the possibility that various low-albedo features on the surface of Europa, such as lenticulae and ridges with diffuse margins, could be the result of cryoclastic plume deposits from either point-source or linear eruptions. They suggest that Europan plume deposits composed of pure water or CO$_2$ ice would be bright, but note that as little as 0.5% areal coverage by dark contaminants could significantly reduce their visible and near-IR reflectance (Clark and Lucey, 1984). However, the paper concludes that a more likely explanation for the dark diffuse deposits is heating of the surface by a subsurface heat source, which drives off volatiles and concentrates nonice components. Thus we must look elsewhere for evidence of plume activity.

Purves and Pilcher (1980) showed that water molecules on the Galilean satellites could have ballistic jump distances of tens to hundreds of kilometers. Thus if a large enough quantity of water molecules were emitted from an active region on Europa’s surface, we would see a large-scale bright plume deposit up to hundreds of kilometers in radius. Even if the initial bright plume deposit coverage was quite thin, cold-trapping might take place over time and brighten the surface even more, assuming that competing processes such as sputtering and impact gardening did not dominate (Spencer, 1987; Section 1.4.1). Since no large-scale, diffuse, circular features are readily apparent on the surface of Europa, we can conclude both that there has been no observable plume activity during the Voyager/Galileo era and that it is likely that no such activity has occurred in the time period that such albedo features would persist on Europa. An estimate of this time period is made in Section 1.4.1.
1.3. Change Detection

1.3.1. Types of Changes

Depending on which model for surface feature formation one chooses, surface changes on Europa could take a variety of forms (Figure 1.3). If, for example, ridges are built by diurnal stresses as suggested by Greenberg et al. (1998), over a 20 year period it might be possible to see increases in height and width as more material is added, although at the rate estimated by Greenberg et al., only 1 to 10 cm of material would be added in 20 years. There could also be the formation of new cracks in the surface, or strike-slip style offset, potentially aligned to the preferred tidal stress orientations as calculated by Hoppa et al. (1998). If cycloidal cracks are formed by the diurnal tides, with a 3.55-day period, then new instances of such cracks should be possible in certain preferred locations (Hoppa et al., 1999b), though the formation of actual cycloidal ridges would presumably take longer. Alternatively, if ridges are formed by a cryovolcanic process (Kadel et al., 1998), in addition to plumes over ridges, one might expect changes in ridge albedo as new frost and particle layers are deposited.
Figure 1.3. Predominant feature types on Europa’s surface having potential for geologic activity. As described in the text, fracture and ridges could form, widen, or increase in offset. Bands could widen, and new diffuse material or smooth dark plains deposits could be emplaced. Lenticulae could form or widen, and chaos blocks could move. These are some of the types of potential geologic activity that we attempted to find on Europa’s surface.
For features such as domes and disrupted areas, perhaps formed by solid-state convection (Pappalardo et al., 1998), one might expect formation of new areas or increases in the sizes of existing features. Regions of chaotic terrain, if currently active, might be expected to show block motion, either in translation, rotation, tilting, or submersion. If regions of fresh ice or frost are currently being deposited, one might expect them to change in albedo as they darken and weather with time, due to magnetospheric ion implantation and micrometeorite gardening, changing their photometric properties (Nelson et al., 1986).

One area thought to be a prime candidate for current or recent activity was Agenor Linea, which has an unusual photometric function, and is bright, in contrast to most of Europa's ridges and bands which have dark margins. One possibility for Agenor's bright appearance was recent frost deposition (Geissler et al., 1998). Recent, high-resolution observations of Agenor, however, have revealed that it is not as young as expected; it is overprinted by a series of small obliquely trending fractures as well as regions of disrupted terrain and clumps of small secondary craters (Prockter et al., 1999a). Thus Agenor no longer seems a prime location for current geologic activity.

Detection of all these possible changes is, of course, dependent on image resolution. When comparing Galileo images to Voyager images taken 20 years before, the resolution problem is particularly striking. Europa, unfortunately, was imaged poorly by both Voyager spacecraft, which observed only ~20% of the surface at the best resolution of 1.9 km/pixel. Not only did the Voyager images have an inherently lower spatial resolution than the Galileo images (Table 1.2), but the vidicon technology of the
Voyager camera introduced geometric distortions and other artifacts which combined to lower the apparent resolution of the images (Gaskell, 1988). To reduce this limitation, we have developed an iterative coregistration procedure which attempts to show changes at subpixel scales (Section 1.3.3).

1.3.2. Change Detection: Data Sets Used

The data sets used for the change detection analysis include a series of Voyager 2 high-resolution images obtained in 1979 and a series of Galileo images obtained from 1996 through 1998. The Voyager data set (Tables 1.2 and 1.3) consists of 20 images of five adjacent regions, taken in four color filters. They were taken at a phase angle of 86°, through filters with central wavelengths in the UV, violet, blue, and orange. These images represent Voyager’s best view of Europa and cover ~20% of the surface (Plate 1.1, left).
**Table 1.2. Voyager / Galileo Image Comparisons**

<table>
<thead>
<tr>
<th></th>
<th>Voyager</th>
<th>Galileo G1</th>
<th>Galileo E14</th>
</tr>
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<tbody>
<tr>
<td><strong>Date</strong></td>
<td>1979</td>
<td>1996</td>
<td>1998</td>
</tr>
<tr>
<td><strong>Image numbers</strong></td>
<td>c2064910 s0349875100 - 139; s0349875152 - 139; s0440984852 - 19; s0440985139</td>
<td>- 31</td>
<td></td>
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<tr>
<td><strong>Resolution, Km/pixel</strong></td>
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<td>1.6</td>
<td>1.4</td>
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<tr>
<td><strong>Phase angle, deg</strong></td>
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<td>37</td>
<td>78</td>
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<tr>
<td></td>
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<td>violet</td>
<td>green</td>
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<tr>
<td></td>
<td>blue</td>
<td>green</td>
<td>red</td>
</tr>
<tr>
<td></td>
<td>orange</td>
<td>red</td>
<td>1 micron</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 micron</td>
<td></td>
</tr>
<tr>
<td>Voyager 2 Filters (Narrow-angle camera)</td>
<td>Galileo Filters</td>
<td>Central Wavelengths, micron</td>
<td></td>
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<tr>
<td>---------------------------------------</td>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Near-IR</td>
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<td>0.990</td>
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</tr>
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</table>

Voyager numbers are solar radiance values averaged from Smith et al. (1977, 1979), Danielson et al. (1981), and Johnson et al. (1983). Galileo solar radiance values are averaged from Klaasen et al. (1997, 1999) and Clark et al. (1998).
Plate 1.1. (left) Reprocessed versions of the Voyager high-resolution color images which overlap with Galileo coverage. The image is composed of orange, blue, and violet filters displayed as red, green, and blue. The Voyager images were taken in 1979 at a resolution of 1.9 kilometers per pixel. See Table 1.2 for more information. (right) Mosaic of images taken on Galileo’s fourteenth orbit through the Jupiter system (E14). The image is composed of near-IR, green, and violet filters displayed as red, green, and blue. See Table 1.2 for more information.
The Galileo data used for comparisons consist of images from two separate orbits, G1 and E14 (Tables 1.2 and 1.3). The E14 data provide the best comparison, but the G1 case will also be discussed to demonstrate effects due to photometric geometry. The appearance of Europa's surface is highly sensitive to photometric angles (illumination, emission, and phase angle (see Malin and Pieri, 1986; McEwen, 1986, 1991; Domingue and Hapke, 1992; Phillips et al., 1997; Clark et al., 1998; Helfenstein et al., 1998)), and features are known to change dramatically in brightness and contrast with changes in viewing geometry. Thus matching the photometric angles of comparison images is important for detecting true surface changes due to geologic activity.

The G1 images (Figure 1.4 shows the clear-filter mosaic) were taken through the Galileo clear, violet, green, red, and 1 micron filters, and overlap the northern part of the Voyager mosaic, at a resolution of 1.6 km/pixel. They differ greatly in phase angle from the Voyager images, and the differences in illumination result in changes in the appearance of shadows near topographic features. The E14 images (Plate 1.1, right) were taken through the Galileo violet, green, red, and 1 micron filters, at a phase angle, viewing geometry, and resolution (1.4 km/pixel) relatively close to those of the Voyager images. The Voyager and Galileo violet filters are similar in central wavelength and bandpass (Table 1.3), and as the contrast on Europa's surface is greatest at this wavelength they were selected for the comparison. The clear filter was also used for part of the G1 comparison, as the overlap area in the violet filter is quite small.
Figure 1.4. Mosaic of clear-filter images taken on Galileo's first orbit through the Jupiter system (G1). See Table 1.2 for more information.
1.3.3. Change Detection Technique

The change detection technique is described below, using one image set from Voyager and Galileo orbit E14 as an example. First, overlapping pairs of Voyager and Galileo images were identified. Mosaics were not used to avoid artifacts such as edge effects or smoothing which might be introduced in the mosaicking process and because the photometric geometry varies from frame to frame. For the E14-Voyager comparisons, 10 different pairs of overlapping images were identified. The processing steps for each pair of images were approximately the same, so a single image pair will be used as an example (the original images are shown in Figure 1.5). See the appendix for a detailed documentation of the steps used to process an image pair in the Integrated Software for Imagers and Spectrometers (ISIS) software package written and maintained by the United States Geological Survey (Torson and Becker, 1997). These steps included calibration, geometric control, image alignment, reprojection, photometric correction, iterative subpixel coregistration, and ratioing. The photometric correction adjusts for brightness variations with illumination and viewing geometry. Figures 1.6a and 1.6b show the images from Figure 1.5 after the reprojection and masking stage. Figures 1.6c and 1.6d show a pair of images after coregistration, demonstrating how this procedure degrades the sharpness of the Galileo image to better match the Voyager images. Figure 1.6e shows a sample ratio image, where the Galileo image is divided by the Voyager image. The ratio image was used to search for changes.
Figure 1.5. (a) Example of a raw Voyager violet-filter image which was used in the change detection analysis described in the text. The black rectangles are reseaux, which were used for rectification of the Voyager images to remove distortion. The bright horizontal feature is a bad line in the Voyager data. Image number c2064913. (b) Example of a raw Galileo violet-filter image from orbit E14 which covers some of the same area as Figure 1.5a. The white dots are radiation noise. Image number s0440984939.

Figure 1.6. (a,b) Raw Voyager and Galileo images from Figure 1.5, reprojected to the same viewing geometry and masked to show only overlapping areas. The structure at the far right of the Galileo image is due to that observation's proximity to the terminator. (c,d) Images from Figure 1.6a and 1.6b after the iterative coregistration procedure. Note that the sharpness of the Galileo image has been reduced to better match the lower-resolution Voyager image. (e) Ratio of the Voyager and Galileo images from Figure 1.6c and 6d. To first order, the image is a flat gray, indicating that no substantial changes have occurred in this region of the surface over the 20 year time period between the observations. The ratio image has been stretched to bring out the subtle structure visible (the actual data range is very small), most noticeably near the lower-right corner. Recall that the Galileo image was very close to the terminator in this area; hence the apparent changes are merely due to the difference in illumination between the Voyager and Galileo images. Note that bright linear features trending vertically, i.e. north-south, also appear in the ratio. These are due to the changes in illumination between the two images.
The resulting ratio image should indicate any areas of the surface which have changed in size, shape, location, or albedo over the 20-year time span between the Voyager and Galileo images. In the ratio image, if a particular feature has darkened in appearance, with respect to the rest of the surface, it will appear dark in the ratio; conversely, a region which has brightened with respect to the rest of the surface will appear brighter than the average background value in the ratio. If a feature has changed in shape or size, the feature will not ratio out completely and an area of bright or dark corresponding to the changed area will appear in the ratio image. Similarly, if a feature has changed in location with respect to the rest of the features in the image, perhaps due to motion either parallel or perpendicular to a fault, it should appear in the ratio image as an apparent "ghosting," where the old location of the feature and its new location do not cancel each other out but rather appear as the feature and its negative in the old and new positions. The geometric corrections performed on the images to improve their alignment to subpixel accuracy should not interfere with the validity of a detection of surface motion, since the corrections applied were predominantly simple translations and rotations of the whole image and would not alter the position of one particular feature with respect to other features in the scene. A more complicated subpixel registration procedure was also used on some image pairs. This procedure can potentially alter the position of one pixel with respect to another but was run with a correlation box size of 30 pixels. This allows a minimum 30 by 30 pixel area of the surface to be moved around, preserving small-scale interpixel relationships.
These techniques of coregistration and ratioing have been used successfully on images of Io (Figure 1.7) taken on sequential orbits by the Galileo spacecraft (Part 2). Io is the perfect testbed for such techniques, since changes there are frequent and widespread. For example, volcanic eruptions resulting in new plume deposits and surface flows are clearly detectable in ratio images taken on orbits spanning a 1-year period, as seen in Figure 1.7. Clearly, if the technique cannot successfully detect changes on Io, it has no hope of finding them on Europa. The coregistration and ratioing technique has proven an excellent method of detecting changes that are not readily apparent on visual inspection of the images.
Figure 1.7. Illustration of the change detection technique on Jupiter's satellite Io. The grid shows the appearance of the active volcanic center Kanehekili during orbit G1, in 1996, and orbit E6, in 1997, over about a 9-month time period. The first row shows Kanehekili on orbit G1 in three individual filters, and the second row shows its appearance during orbit E6. The third row consists of the ratios of each of the three color filters. Note that the ratio images in the bottom row clearly show evidence of current volcanic activity; a new bright halo is visible around the vent, as well as several dark lava flows. The violet ratio image tracks the movements of volatile SO2 frost on the surface. Thus the change detection technique can easily detect changes when they are present.
1.3.4. Change Detection Results

The results of our Europa analyses are shown in Figures 1.6, 1.8, 1.9, 1.10, and 1.11. There is some structure visible in the ratio images, especially in Figure 1.9. There are two possible explanations for this structure: either there have been widespread changes on the surface or the ratios contain artifacts due to the differences in photometric geometry and filter wavelength between the images. Work on the photometric behavior of various terrain types on Europa has shown that the appearance of features on Europa can change substantially with photometric angles, and the photometric correction we applied to these images does not take into account the phase functions of different terrain types. Also, the illumination of topography at different angles can result in dramatic changes in the appearance of features with and without shadows. This is especially obvious as lineaments which seem flat near the center of the image appear to change to ridges as they approach the terminator, as is visible in Figure 1.4 (Lucchitta and Soderblom, 1982).

**Figure 1.8.** Comparison of violet-filter images from Galileo orbits G1 and E14. (a,b) The raw, unreploject text's views of the surface on these two orbits, demonstrating the differences in illumination and viewing geometry are shown. (c,d) The regions of overlap between the two images, after they have been reprojected to the same viewing geometry, are shown. (e) The ratio of the two images is shown. The features visible in the ratio image demonstrate the changes in appearance of the surface due to the phase function of different feature types and the movement of shadows due to changes in illumination.
a. Original G1  
b. Original E 14 

c. Masked G1  
d. Masked E 14 

e. G1 / E 14 ratio
To demonstrate more directly the effects of photometric angles on the appearance of surface features, we performed a comparison between images of the surface from Galileo orbits G1 and E14, taken ~2 years apart. Only a small area of the surface was covered by violet filter images on both Galileo orbits. The comparison is shown in Figure 1.8. Figures 1.8a and 1.8b show the raw appearance of the surface on each of the two orbits, and Figures 1.8c and 1.8d show the images reprojected to the same viewing geometry and masked to show only the overlapping areas. The same methods of coregistration and ratioing described in the preceding section were used on this pair of Galileo images, and the final ratio image is shown in Figure 1.8e. This ratio image demonstrates the need for well-matched photometric angles: Even in this best-case scenario, where we have used images taken by the same camera with the same filter at similar resolutions, features appear in the ratio image due to the almost 40° difference in phase angle (Table 1.2). Since these images were taken only 2 years apart, at widely different phase angles, we do not believe that this structure in the ratio image is a result of actual surface changes. The change in contrast between the dark lineaments and the surrounding bright plains with changes in illumination and viewing geometry is quite striking, especially in the northern part of the overlap area. This is due to the different phase function of the lineaments as compared to the bright plains. Another effect of the changing illumination is visible in the change in appearance of the small dark spots visible in the lower right of Figures 1.8c and 1.8d. These spots are clearly visible in the ratio image as features which distinctly alternate from bright to dark, the signature of topography. These features are most likely pits which are illuminated differently in the
two images, and thus the changing position of shadows results in structure in the ratio image. We conclude that no actual surface changes are visible in the ratio image of Figure 1.8e and that the visible structure is due to the difference in photometric angles between the two images.

Figure 1.9 demonstrates the problem of comparing Voyager and Galileo images with different photometric angles. These images have almost a 50° difference in phase angle (Table 1.2), and the comparison is complicated further because we are comparing the Galileo clear filter images to Voyager violet filter images (Table 1.3). On the basis of our observations from Figure 1.8, the Galileo-Galileo comparison, we conclude that the structure visible in the ratio image is due solely to the changes in photometric angles and again is not a real surface change. The contrast reversal visible in Figures 1.9a and 1.9b, where the dark linear features trending approximately north-south in Figure 1.9a have changed to bright features in Figure 1.9b, is a particularly striking illustration of the differing appearance of the surface at different photometric angles. These features are visible as the bright vertical stripes in the ratio image in Figure 1.9c. Similarly, the change in appearance of lineaments in Figure 1.9a to ridges in Figure 1.9b as they approach the terminator on the right side of Figure 1.9b is another illustration of changes due to illumination. Thus we conclude that the most important criterion for successful change detection is carefully matched photometric angles.
Figure 1.9. Voyager and G1 coverage of Europa, reprojected to the same viewing geometry, ratioed and masked to show only overlapping areas. (a) This is the Voyager violet image (from Plate 1, left). (b) This is the G1 image (from Figure 1.4). (c) This is the ratio of the two images from Figure 1.9a and 1.9b. Most of the structure in Figure 1.9c is due to the differences in photometric angles between the images, rather than actual surface changes. For example, the bright white linear features trending from the upper right to the center of Figure 1.9c indicate a dramatic difference in brightness. These features are parallel to the terminator, so their brightness change is merely due to the differing illuminations of the two images. See the text for a more detailed discussion.
Figure 1.10. This is a Voyager-E14 comparison image, located near the South Pole. As seen in Figure 1.9, the ratio image shows slight structures due to the differences in illumination between the images, but no changes which are clearly due to surface geologic activity. In the ratio in Figure 1.10c, Thrace and Thera Macula (the two dark oblong features in the center of the images) ratio out completely. This means that the whole-image photometric correction compensates well for their behavior with changing illumination. In contrast, the gray band Libya Linea, trending South through the lower center of the images, shows up as bright in the ratio image, and therefore is not compensated for adequately by the applied photometric function. Also note the two topographic features clearly visible at the upper right of the ratio image in Figure 1.10c. These are trenches on the surface which are apparent near the terminator in the Galileo image (but not in the Voyager), and thus appear in the ratio image.
Figure 1.11. This is another Voyager-E14 comparison image, similar to Figure 1.10. The ratio image in Figure 1.11c shows Agenor Linea, the horizontal feature at the lower center, as bright. Agenor has an anomalous photometric function which is also not compensated for adequately by the full-disk photometric correction.
The results of such a comparison are visible in Figures 1.6, 1.10, and 1.11. Although these Voyager–El4 comparisons are much better matched in filter and photometric angles than the Voyager–Gl comparison described above (Table 1.2), some phase function effects are still visible. In Figure 1.6, note that most of the large albedo variations visible in the original images (Figures 1.6a-1.6d) are removed almost completely from the ratio image in Figure 1.6e, leaving only a few small linear features visible. In Figure 1.10, the large dark features in the center of the Voyager and Galileo images are Thrace and Thera Maculae. Wilson et al. (1997) had proposed that these might be cryovolcanic surface flows, and thus a good place to look for surface changes. However, Thrace and Thera completely disappear in the ratio image, showing that not only have no changes taken place there, but also that the photometric function applied to this image properly accounts for this terrain type. High-resolution Galileo images of Thrace and Thera have also revealed that they are unlikely to be surface flows, and rather are more similar to regions of chaotic terrain elsewhere on Europa.

Just below Thrace and Thera is a gray band called Libya Linea. Libya is an unusually smooth and flat linear feature, and its appearance as a bright region in the ratio image, and as a red area in the color composite, shows that the photometric function applied to this image does not fully account for this type of feature. We assume this because the brightening of the whole feature is not consistent with incremental formation models (Prockter et al., 1999b; Sullivan et al., 1999), and thus is unlikely to represent a real surface change. Similarly, Agenor Linea, which is visible in Figure 1.11, appears as a bright feature in the ratio image. Agenor is known to have an
anomalous photometric function (Geissler et al., 1998), and it is clear from this ratio image that the full-disk function does not fully account for its scattering behavior.

Figures 1.6, 1.10, and 1.11 also show some structure in the ratio images due to changes in illumination of topography. The difference in subsolar longitude is much smaller in this comparison than in Figure 1.9 but still results in the terminator being much closer to the right edge of the Galileo images than in the Voyager images. Thus features such as ridges which are parallel to the terminator, with a topographic expression of a few hundred meters, are illuminated at a smaller angle in the Galileo images, which will tend to make them appear brighter than in the Voyager images. So the appearance of bright linear features trending north-south in the ratio images can, again, be explained by the differences in illumination between the two data sets, rather than as a real geologic change on the surface. Topography is clearly visible at the far right in the ratio image in Figure 1.6e and can be understood when the original Galileo image in Figure 1.6b is examined. The far right edge of Figure 1.6b is very close to the terminator, and ridges appear there which are invisible under less sharp lighting conditions in Figure 1.6a. These ridges thus appear in the ratio image of Figure 1.6e. Similarly, Figure 1.10 is particularly interesting in that the ratio image highlights a pair of trenches which are revealed in the Galileo image due to their proximity to the terminator. These features are practically invisible in the Voyager images but stand out in the ratio image.

Thus we find that all the features visible in the ratio images of Figures 1.6, 1.9, 1.10, and 1.11 can be explained by differences in photometric angles between the image sets.
The full-disk photometric functions used to correct the images do not account for differences in photometric behavior of different terrain types or of sloping surfaces and thus result in some features being incompletely "ratioed out." The G1 comparison illustrates the problems of comparing images taken at widely different photometric angles, and even the E14 case, which is much more closely matched, has problems due to differences in illumination and phase angles. We conclude that there are no strong candidates for surface changes that have taken place over the 20 years between the two image sets.

1.4. Discussion

1.4.1. Implications of Lack of Plumes or Bright Plume Deposits

No plumes have been detected on Europa, and no features have been found on the surface which can be unambiguously identified as plume deposits. Most likely no plume activity has taken place during the era of Voyager/Galileo observations of Europa. We might extend our observational timeframe; however, if we consider the nature of a potential plume deposit on Europa's surface. We can assume that an active plume venting material above Europa's surface would produce a diffuse deposit of surface material, bright in albedo if pure frost or dark if contaminated. Such a plume deposit would likely consist of small particles ballistically emplaced on the surface in a thin surface veneer of frost and other particles (Fagents et al., 2000) and could be hundreds of kilometers in diameter.
How long might a thin, bright frost deposit remain recognizable on Europa? Sputtering (Cheng et al., 1986; Ip et al., 1998; Johnson et al., 1998) and micrometeorite bombardment (Spencer, 1987) are probably the primary sources of erosion at Europa's surface. Ip et al. (1998) suggested that the sputtering erosion rate at Europa is ~10-20 m over 100 million years. The potential thickness of plume deposits on Europa is unknown, but Clark (1981) suggested that a 1 mm thick frost deposit is the minimum thickness to obscure a dark surface. At the erosion rate of Ip et al. (1998), a 1 mm thick plume deposit would last ~10,000 years. The surface erosion rate due to micrometeorite bombardment at Europa is poorly known. Estimates based on the flux of particles detected by Pioneer 10 (Galileo-era measurements are still pending) suggest that the top 1 mm of the surface could be mixed by impact gardening over a timescale of ~1000 years (Spencer, 1987), about 10 times the sputtering erosion rate from Ip et al. (1998). This material is not eroded as in the sputtering case, but merely redistributed over a lateral length scale of ~10 times the vertical depth, in this case centimeter scales over 1000 years. The addition of the micrometeorite mixing rate to the sputtering erosion rate would reduce the lifetime of plume deposits, down to a minimum lifetime for a 1 mm thick plume deposit of ~900 years if we assume that all material affected by micrometeorite bombardment is removed from the deposit. A more realistic intermediate scenario has sputtering erosion dominating, with a smaller contribution from lateral and vertical mixing from micrometeorite impact gardening, resulting in a surface lifetime for a millimeter-thick plume deposit of a few thousand years. Thus the fact that we have detected no obvious plume deposits on the surface of Europa could
mean that no large millimeter-thick plume deposits have formed in the last few thousand years, if other processes such as cold-trapping (discussed below) do not intervene.

Another way of estimating how long potential plume deposits might last on Europa is to compare them to the rays observed around the youngest large impact craters. Crater rays on the Moon are thought to be created when secondary ejecta impacts and stirs up the matured surface. However, rays on icy satellites may be bright because they consist of fine-grained frost (Chapman and McKinnon, 1986). The rays of the crater Pwyll on Europa extend for thousands of kilometers away from the impact site but, in high-resolution images, are seen to produce minimal disruption of the underlying surface material aside from the change in albedo (Moore et al., 1998). We thus posit that these crater rays, while clearly different in initial formation mechanism, might be similar to a thin deposit created by an active plume venting water and gas at Europa’s surface.

If we assume that plume deposits are similar in thickness and composition to crater rays, then such deposits would likely last for similar amounts of time on Europa’s surface. Since Pwyll, which is judged to be the youngest large impact crater on Europa based on its stratigraphic position and preservation state, has the best-developed ray system (Moore et al., 1998), it is reasonable to assume that such ray systems fade and eventually disappear over time, probably due to micrometeorite bombardment and sputtering as discussed previously. So if plume deposits are similar to crater rays, they might fade over the same timescale.
Zahnle et al. (1998, 1999) predicted that craters with diameters larger than 20 km, such as Pwyll, should form on Europa at a rate of once every 1.4 Myr; this estimate was later revised to once every 3.2 Myr (Pappalardo et al., 1999). Only three of the seven craters larger than 20 km in diameter, which have been identified on about half the surface of Europa, have detectable ray systems (Pwyll, Manannán, and Taliesin). If such craters form once every 3.2 Myr (or once every 6.4 Myr on half of Europa), the three youngest craters would have formed over ~20 Myr. This implies that crater rays have a lifetime of ~20 Myr on Europa. Thus if plume deposits have approximately the same thickness and fade at the same rate as crater rays, then no plume deposits large enough to be seen by Galileo have formed for the last few million years.

One problem with this estimate is that the sputtering erosion rate from Ip et al. (1998) implies that over 10 million years about 1 m would be eroded from the surface. At this rate, crater rays would need to be a few meters in thickness to endure for the 20 million year lifetime estimated above. Thus the fact that we observe crater rays but not plume deposits on Europa could just mean that crater rays are substantially thicker and that thin plume deposits might be removed relatively quickly from the geologic record. However, both crater rays and bright plume deposits might sustain themselves on Europa’s surface through cold trapping, as sputtered frost is preferentially deposited on bright areas (Spencer, 1987). Thin, bright plume deposits and crater rays with similar albedoes would be expected to take advantage of cold trapping with similar effectiveness and thus remove the age constraint on each feature type due to sputtering and micrometeorite erosion. We therefore conclude that the fact that we see a 20 Myr
history of crater rays, but no plume deposits, could imply that no large bright plume deposits have formed over approximately the last 20 Myr.

1.4.2. Implications of Change Detection Results

On the basis of the change detection analysis described in section 1.3 we conclude that there is no convincing evidence for geologic activity occurring on Europa in the last 20 years. This result can be used to estimate a maximum surface alteration rate and a minimum surface age for Europa. The surface alteration rate, or areal resurfacing rate, is the rate at which the surface is noticeably altered or destroyed through any of the geologic processes described in section 1.3. We note that this is not a resurfacing rate in the sense of burial of surface features by new material erupting or being otherwise deposited, as the term has been used on bodies such as Io and Mars. We determined the maximum surface alteration rate for Europa using the minimum size of a detectable change, i.e., one Voyager pixel, which is \(2 \times 2 \text{ km}^2\). The area of the surface studied in the E14/Voyager comparisons was approximately 20% of the total surface of Europa. This yields a maximum areal resurfacing rate of less than \(4 \text{ km}^2\) over 20% of the surface over 20 years. Applying this areal resurfacing rate to the entire surface of Europa yields an areal resurfacing rate of \(< 20 \text{ km}^2\) over Europa's surface over 20 years, or \(< 1 \text{ km}^2 \text{ y}^{-1}\). Thus the maximum areal resurfacing rate in this simple analysis is \(1 \text{ km}^2 \text{ y}^{-1}\), assuming that resurfacing occurs across large contiguous areas rather than at a scale smaller than the \(4 \text{ km}^2\) Voyager pixel size.

This maximum surface alteration rate can be used to estimate a minimum resurfacing timescale for Europa, assuming that resurfacing took place at a constant rate and that it
proceeded in an orderly fashion, such that one square block of the surface was
resurfaced at a time without covering any regions again until the entire surface had been
covered once. The surface area of Europa is \( \sim 30 \) million square kilometers, so at a rate
of \( 1 \text{ km}^2 \text{ y}^{-1} \), this results in a minimum surface age for Europa of \( \sim 30 \) million years.
This is roughly consistent with the dynamical cratering studies by Zahnle et al. (1998, 1999) described above which suggest that a 20 km crater forms every 3.2 million years.
The seven detected craters with diameters larger than 20 km on Europa would imply a
surface age of more than 22 million years, since there are still regions of Europa’s
surface (up to half) that could contain undetected 20 km or larger craters.

There are of course limitations to this estimate. One is that it assumes that surface
changes take place in 4 km² patches on the surface. If, instead, resurfacing took place
in much smaller increments, such changes could occur within many individual pixels on
the surface, resulting in a much higher resurfacing rate which still could not be detected
by this method. Another potential problem is that this method assumes that resurfacing
is slow and steady, proceeding at a constant rate. However, another potential method of
resurfacing is via large catastrophic events, where much of the surface is changed
simultaneously, followed by long quiescent periods which could last for hundreds or
thousands of years. Such episodic resurfacing could be caused by periodic changes in
Europa’s eccentricity and tidal heating (Ojakangas and Stevenson, 1986). If this is in
fact the resurfacing pattern on Europa, no changes would be expected to be seen in this
analysis over a twenty-year time period, but the average surface age of Europa could
still be much younger than we have derived.
Clearly, more research is required on this topic. The methods of change detection used in this work are based on purely visual inspection of the coregistered ratio images. A more quantitative method would be to inspect the residuals from the coregistration procedure, looking, for instance, for regions of the surface which are shifted in a coherent pattern, suggesting that an entire area of the surface had moved with respect to other features, for example in strike-slip motion along a fault. Another possibility would be to use stress field models to predict the preferred orientations and locations of currently active features (e.g., Hoppa et al., 1998). The coregistration procedure could then be modified to preferentially look for any changes or misalignments which occur in these directions. These more advanced techniques would be worth the time and effort if we had detected any actual changes in the current data set; however, since we have no features which are even potential surface changes, we feel the situation does not currently warrant this more detailed analysis.

1.4.3. Implications of Other Methods of Detecting Activity

Other theoretical and observational methods have been used to search for evidence of activity on Europa. The theoretical work of Van Cleve (1999) shows that the thermal signature of recently-erupted regions of liquid water or warm ice should be visible for up to 400 years, under the right conditions. Spencer et al. (1999) have analyzed the Galileo photopolarimeter-radiometer (PPR) thermal measurements and have not detected any endogenic hot spots on the surface of Europa. Their observations place a maximum size on hot spots which could have escaped detection, ranging from a diameter of 16.8 km at a temperature of 130 K to a diameter of 2.0 km at 350 K. A
variety of ground-based observations have suggested potential changes in Europa's thermal properties (Tittemore and Sinton, 1989) and UV signature (Domingue and Lane, 1998), but these have not been seen in subsequent observations. Thus no definitive evidence has been found for current or recent activity on the surface of Europa.

1.5. Summary

The negative results of the plume search, change detection search, and other methods of detecting activity lead us to believe that if Europa's surface is currently geologically active, it must change the surface primarily in an incremental manner over small areas at a slow rate. Alternatively, the surface may undergo periods of activity and quiescence, with a quiescent period underway at present. If frequent large-scale venting of material occurs, evidence for it should have been found in the Voyager and Galileo plume search observations. If such venting is rare, transparent, or takes place only under optimum tidal stress conditions, it could remain undetected. The lack of visible plume deposits, coupled with the presence of bright crater rays and the predicted sputtering erosion rate, allow us to infer that no plume activity with kilometer-scale surface deposits has taken place in at least the last few thousand years and perhaps up to 20 million years. Again, if such activity took place on a small enough scale, the deposits could be sufficiently small or diffuse to escape notice. The lack of changes between the Voyager and Galileo images allowed us to estimate that no changes larger than 4 km² in size had taken place in the area analyzed over that 20 year period, which
we extrapolated to a 1 km$^2$ y$^{-1}$ maximum areal resurfacing rate and a 30 million year minimum surface age. However, this technique would not detect small changes which were below the limit of the Voyager resolution. The lack of localized thermal anomalies on Europa's surface leads us to believe that no large eruptions of water or warm ice have taken place in the last few centuries, but such anomalies could exist below the limit of resolution of the PPR data.

Thus we conclude that the most likely scenario is that venting via large plumes on Europa is not currently occurring. If any activity does in fact exist, it is on a relatively small scale. Episodic resurfacing is a feasible alternative scenario. Higher-resolution data are clearly needed to more accurately quantify the chances for current activity on Europa, especially in terms of change detection. Since formation timescales might be short for tectonic features tied to the diurnal tidal cycle (Hoppa et al., 1999b), we will search the Galileo data set for possible small-scale changes over shorter timescales. The Europa Orbiter will provide better opportunities for change detection. Planned for launch in the next decade, this mission should obtain global, high-resolution data which can be compared to the Galileo data set to search for changes.
Part 2: Volcanic Resurfacing of Io as seen by Galileo SSI


Overview. Lava flows and plumes are the two main types of volcanic activity that resurface Io. We have used the Galileo Io dataset to document these changes at a number of Io's active volcanic centers, using an iterative coregistration and ratioing technique. Our 3.5 years of sporadic global-scale observations have allowed us to observe the interconnections between plume activity, hotspot activity, and new surface deposits at a number of volcanic centers on Io. We have detected activity at previously unknown locations, and established timescales for the formation and alteration of various color units, such as red plume deposits and green coatings on caldera floors. We have seen red material fade on a timescale of less than a year, and seen a green coating form on a caldera over a time period of about 3 months. We estimate that the average lifetime of an active hotspot is about 40 years. We have used these observations to create change detection maps illustrating the percentage of the surface newly covered by either plume deposits or lava flows. These estimates of areal resurfacing rates are then used to constrain volume and mass resurfacing rates. Areal resurfacing is dominated by plume deposits, but volume resurfacing is dominated by
lava flows. Estimates of the global average resurfacing rate from these change maps range from 0.4 to 14 cm/year, assuming a flow thickness of 1 to 10 meters. The minimum average resurfacing rate required for the lack of impact craters on Io's surface is about 0.02 cm/year. We can also calculate the maximum average resurfacing rate by high-magnesium (komatiitic) lavas, if they dominate the observed Io heat flux, which is about 0.69 cm/year. Basaltic lavas would produce a rate of 1.3 cm/year, and sulfur flows 12.5 cm/year. The komatiitic rate can then be used to infer an average flow thickness of half a meter. Thus, we suggest that the average resurfacing rate of Io is between 0.1 and 1 cm/year. Our results include a new understanding of the volcanic histories of Kanehekili, Lei-Zi, Masubi, Prometheus, Pillan, Culann, and Zamama, as well as a few smaller features.
2.1. Introduction:

Active volcanism was first detected on Io by Voyager 1 in 1979: plumes were seen (Smith et al., 1979), hotspots were detected (Hanel et al., 1979; Pearl and Sinton, 1982), and many surface changes were observed in the four months between the Voyager 1 and 2 flybys (McEwen and Soderblom, 1983; McEwen, 1988). Active volcanism had been predicted from theoretical models of energy dissipation due to the tidal flexing of Io (Peale et al., 1979), and from ground-based, near-infrared observations of an enhancement of Io's brightness between 2 and 5 microns (Wittebom et al., 1979). Since the two Voyager flybys, telescopic observations of hot spots have documented Io's continued volcanic activity (Spencer and Schneider, 1996; Spencer et al., 1997a). The arrival of the Galileo spacecraft in the Jovian system and its images of Io, beginning in 1996, have allowed us to observe almost four years of Io's volcanism.

Many questions remain about the composition and style of Io's volcanic activity, even after the past four years of observations. IR measurements have shown that temperatures at most of Io's hot spots are too high to be sulfur volcanism and must be silicate (Lopes-Gautier et al., 1997). The highest temperature flows have temperatures similar to ultramafic flows present earlier in Earth's history such as komatiites (McEwen et al., 1998b). Spectral information from ground-based and spacecraft observations of Io's surface has only revealed the presence of SO₂, but elemental sulfur and sodium compounds are strongly suspected from observations of the Io torus and neutral sodium cloud. Spectral measurements, though, are only sensitive to the top few microns of Io's surface (Nash et al., 1986). Gravity measurements have shown that Io's
bulk density is consistent with a silicate composition, with a large metallic core. Theoretical models of Io's interior have suggested a variety of possible internal configurations and compositions, including the possibility of a fluid or partially-crystalline magma ocean (Schubert et al., 1986; Keszthelyi et al. 1999). While our understanding of the processes shaping and coloring Io's dramatic surface has certainly increased in the 20 years since the Voyager observations, there are still many questions left unanswered.

This work addresses some of the remaining questions about the rate and style of Io's volcanic activity. Io's surface must be covered at a rapid rate, since even the highest-resolution Voyager and Galileo images of Io have revealed no impact craters. The lack of craters, combined with the predicted cratering rate, can be used to estimate a minimum resurfacing rate (section 2.5.4). The main resurfacing methods seem to be advancing lava flows and surface deposits (pyroclastics and condensing volatiles) from Io's many active plumes. Plume deposits are formed when material is blown out of a vent in a continuous, geyser-like, high-velocity eruption, with the material then falling back to Io's surface under the influence of gravity where it usually forms symmetric rings surrounding the plume vent.

We have tracked the changes occurring at a number of active volcanic centers on Io over four years of Galileo observations, extending the comparisons back to Voyager images when possible. These observations have been used to develop a detailed picture of the types of activity taking place on Io's surface. We have calculated the net changes in the appearance of Io's surface in a number of different areas, partitioning these
changes by type (plume deposit vs. lava flow) and assigning the appropriate resurfacing rate to each. This method has been used to estimate the current resurfacing rate of Io. We have compared this result to the constraint from the lack of craters, and the estimate obtained from the hotspot heat flow.

2.1.1: Global styles of activity

One important caveat when comparing the Voyager and Galileo images, which will be elaborated on in the upcoming sections, is that much of Io’s resurfacing and heat loss seems to occur in a few small, dark regions of Io’s surface which are covered again and again. The number of substantial changes that occurred on Io’s surface in the four months between the two Voyager flybys of Io (McEwen and Soderblom, 1983) suggested that by the time of the Galileo flybys, Io’s surface features would be entirely unrecognizable. Observations of Io made in the intervening years by Hubble Space Telescope (Spencer et al., 1997a) showed that this was not the case, and Galileo’s first images of Io in 1996 confirmed that while there were substantial new lava flows on Io’s surface, for the most part the large-scale color and albedo patterns have remained similar in appearance.

However, we have also seen regions of Io’s surface change due to a new eruption, and then change back to their previous appearance. For example, a bright region to the north of Surt during the Voyager 1 flyby was covered by dark material at the time of Voyager 2 from an eruption at Surt, but returned to its previously-bright appearance when observations were made by Hubble Space Telescope (Spencer et al., 1997a) and
confirmed by Galileo. Since we have no high-resolution observations of the plume deposits in the intervening 20 years, it is possible that the plume deposit has changed shape many times during this time interval, or that it reverted to the Voyager 1 appearance sometime after the Voyager 2 encounter and has remained unchanged since then. We have seen other locations, such as Pillan (section 2.3.4), where the initial large dark pyroclastic deposit has faded dramatically over a 2-year period and previously-existing features such as red and white areas have returned as the deposit faded. The ephemeral nature of some plume deposits, and the ability of pre-existing color and albedo patterns to re-assert themselves after burial by a new deposit, will be discussed in more detail in the following sections. Since the Galileo observations of Io are unevenly spaced over the 4-year period the spacecraft has been in orbit, it is possible that we have missed short-period changes where the surface has reverted to its previous appearance at other locations, as well. In particular, few observations of Io were obtained during the Europa phase of the Galileo Europa Mission, between orbits E14 (March 1998) and C21 (July 1999). Thus the estimates of portions of the surface that have been changed and covered with new plume deposits are necessarily minimums.

2.1.2 The Data Set

Observations of Io have been taken at a variety of wavelengths, resolutions, and phase angles by the Galileo SSI (Solid-State Imaging) Camera. Table 2.1 has a listing of the Galileo orbits, and the date of closest approach to Io on each. The orbits are numbered sequentially, with the first letter indicating which satellite was targeted with
the closest flyby of the orbit (G=Ganymede, E=Europa, I=Io, C=Callisto). All of the Io images from Galileo's nominal mission through orbit C22, and on orbit E26, were relatively low in resolution due to the large distance between Io and the spacecraft. These images, taken from 1996 to mid-1999, ranged in resolution from a few kilometers to tens of kilometers per pixel (Table 2.2). Beginning in the fall of 1999 and continuing through early 2000, observations were made on orbits I24, I25, and I27 at much higher resolutions with approach distances as close as a few hundred kilometers (McEwen et al., 2000). This work focuses on the distant, surface monitoring observations of the nominal mission and Galileo Europa Mission (GEM) phases, although high-resolution images will be discussed in some places where they shed light on processes that were only speculated upon based on the low-resolution views. We have also compared the Galileo views of the surface to Voyager images for some of the features, to track changes over a longer time period (with the caveats described above). Table 2.2 has a list of the images used in this study, sorted by feature, date, phase angle, and sub-spacecraft longitude. A few active regions of the surface which have been well-imaged on at least two separate occasions at similar phase angles and viewing geometries have been chosen for analysis, and we have documented the changes which have occurred at these locations over almost four years of observation. I have used a coregistration and ratioing technique on these images to map out changes on Io’s surface (Section 2.2). Changes at the features Kanehekili, Lei-Zi, Masubi, Prometheus, Pillan, Culann, and Zamama will be described in detail, and smaller changes at a few other locations will also be shown. Figure 2.1 shows the locations of these features on a global map of Io.
Table 2.1: Galileo and Voyager Io orbits or flybys and dates

<table>
<thead>
<tr>
<th>Orbit or Flyby</th>
<th>Date of closest approach to Io</th>
<th>Orbit or Flyby</th>
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</tr>
</thead>
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<td>7/20/98</td>
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Note: the first letter in each Galileo orbit denotes the satellite to which the closest approach was made. C=Callisto, G=Ganymede, E=Europa, I=Io.
Table 2.2: List of Io images studied, by feature

<table>
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<td>1997-04-04</td>
<td>s03897782000, 04, 07, 11</td>
<td>275</td>
<td>37</td>
<td>5</td>
<td>7rgv</td>
</tr>
<tr>
<td>C10</td>
<td>1997-09-19</td>
<td>s0413744178, 200, 204, 207</td>
<td>230</td>
<td>61</td>
<td>5</td>
<td>97rgv</td>
</tr>
<tr>
<td>E14</td>
<td>1998-03-29</td>
<td>s04408887900</td>
<td>215</td>
<td>36</td>
<td>2</td>
<td>c</td>
</tr>
<tr>
<td>C21</td>
<td>1999-07-02</td>
<td>s0506501100, 04, 08</td>
<td>240</td>
<td>32</td>
<td>12</td>
<td>rgv</td>
</tr>
<tr>
<td>I24</td>
<td>1999-10-11</td>
<td>s0520873426, 39, 52, 65, 78, 500</td>
<td>260</td>
<td>31</td>
<td>6.7</td>
<td>987rgv</td>
</tr>
<tr>
<td>E26</td>
<td>2000-01-04</td>
<td>s0532939900, 13, 26, 39, 52</td>
<td>260</td>
<td>26</td>
<td>3.4</td>
<td>987rgv</td>
</tr>
<tr>
<td>Prometheus</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VGR1</td>
<td>1979-03-04</td>
<td>c1636830</td>
<td>169</td>
<td>15</td>
<td>7.5</td>
<td>c</td>
</tr>
<tr>
<td>C3</td>
<td>1996-11-06</td>
<td>s0368558239</td>
<td>140</td>
<td>31</td>
<td>2</td>
<td>c</td>
</tr>
<tr>
<td>E6</td>
<td>1997-02-20</td>
<td>s0383655100, 04, 07, 11</td>
<td>165</td>
<td>24</td>
<td>5</td>
<td>7rgv</td>
</tr>
<tr>
<td>E14</td>
<td>1998-03-29</td>
<td>s0440873539 - 700</td>
<td>170</td>
<td>36</td>
<td>2</td>
<td>987rgv</td>
</tr>
<tr>
<td>C21</td>
<td>1999-07-02</td>
<td>s0506405732 - s0506413639</td>
<td>135</td>
<td>5</td>
<td>2.6</td>
<td>7rgv</td>
</tr>
<tr>
<td>C21</td>
<td>1999-07-02</td>
<td>s0506431239 - s0506431352</td>
<td>155</td>
<td>22</td>
<td>1.4</td>
<td>c</td>
</tr>
<tr>
<td>I24</td>
<td>1999-10-11</td>
<td>s0520821200 - s0520821352</td>
<td>180</td>
<td>24</td>
<td>1.5</td>
<td>c</td>
</tr>
<tr>
<td>I24</td>
<td>1999-10-11</td>
<td>s520795742</td>
<td>153</td>
<td>19</td>
<td>0.1</td>
<td>g</td>
</tr>
<tr>
<td>I27</td>
<td>2000-02-22</td>
<td>s0539936100</td>
<td>155</td>
<td>22</td>
<td>0.2</td>
<td>g</td>
</tr>
<tr>
<td>Zamama</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-------</td>
<td>------------------------</td>
<td>-------</td>
<td>-------</td>
<td>-----</td>
<td></td>
</tr>
</tbody>
</table>
| E6           | 1997-02-20 | s0383655100, 04, 07, 11 | 165   | 24   | 5   | 7rgv  
| E14          | 1998-03-29 | s0440873539 - 700       | 170   | 36   | 2   | 987rgv  
| C21          | 1999-07-02 | s0506405732 - s0506413639 | 135   | 5   | 2.6 | 7rgv  
| C21          | 1999-07-02 | s0506431239 - s0506431352 | 155   | 22   | 1.4 | c  
| I24          | 1999-10-11 | s0520821200 - s0520821352 | 180   | 24   | 1.5 | c  
| Culann       |       |                        |       |       |     |  
| VGR1         | 1979-03-04 | c1636830                | 169   | 15   | 7.5 | c  
| C3           | 1996-11-06 | s0368558252              | 140   | 31   | 2   | c  
| E6           | 1997-02-20 | s0383655100, 04, 07, 11 | 165   | 24   | 5   | 7rgv  
| E14          | 1998-03-29 | s0440873539 - 700       | 170   | 36   | 2   | 987rgv  
| C21          | 1999-07-02 | s0506405732 - s0506413639 | 135   | 5   | 2.6 | 7rgv  
| C21          | 1999-07-02 | s0506431239 - s0506431352 | 155   | 22   | 1.4 | c  
| I24          | 1999-10-11 | s0520821200 - s0520821352 | 180   | 24   | 1.5 | c  

Notes: Central Longitude is the apparent central longitude of the visible part of Io’s disk in each observation. Reprojected resolution is the resolution used in the comparison case: images were reprojected into three resolution bins, at 5, 11, or 15 km/pixel. The resolution was increased in this resolution to avoid losing data in the coregistration/resampling stage. Thus, images with resolutions worse than 15 km/pixel were reprojected to 15 km/pixel; image with resolutions between 15 and 11 were reprojected to 11, etc. Any different listed resolutions are therefore the actual resolution of the image. Filters: 9=0.968 micron; 8 = 0.889 micron; 7=0.756 micron. r=red, o=orange, g=green, b=blue, v=violet, c=clear. See Table 1.3 for Voyager/Galileo color filter comparisons.
Figure 2.1. Global map of Io with features discussed in text labeled, in a Lambertian equal-area projection. The left hemisphere is centered on 0 degrees longitude, showing the sub-Jupiter hemisphere, and the right hemisphere is centered on 180 degrees longitude, showing the anti-Jupiter hemisphere.
Io’s surface has a complicated photometric function, and the same area of the surface can appear very different depending on lighting and viewing conditions (Simonelli et al., 1997). In fact, in some areas lava flows and other features seem to disappear when viewed under certain lighting conditions, only to reappear on the next orbit. This complicates our change detection analysis significantly. Simonelli et al. (1997) documented the changes in the color and albedo patterns on Io under different lighting and viewing geometries. This implies that different regions on Io’s surface have very different photometric (light-scattering) behavior, for example due to differing particle sizes in the surface coating. Even after correcting the surface for Io’s average light-scattering behavior, significant variations remain. These variations are most strongly dependent on phase angle, although incidence and emission angles also have an effect.

To minimize the problems from the differing photometric behaviors of different terrain types, we have limited our analysis of change detection to images taken at comparable phase angles. In some cases, we have views of the surface which are at comparable phase angle and resolution, but at opposite viewing geometries (a morning view vs. an evening view, for example). These comparisons complicate the change detection process, but allow for the detection of topographic features on Io’s surface which are illuminated from opposite sides in the two image sets. This will be demonstrated in section 2.3.2. Many “real” changes can be recognized from a change in morphology as well as color. Complicating any understanding of Io’s photometric function is the fact that some features on Io’s surface seem to change dramatically in color over time without any change in morphology or an associated new deposit. While
we cannot rule out a purely photometric variation, we believe that in some cases, such as the Pillan caldera, true color changes have occurred.

2.2. Change Detection Technique:

Once suitable pairs or groups of images had been chosen that match as closely as possible in phase angle and viewing geometry, and which cover a region of interest on Io's surface, we began the change detection process. To map out the changes that had occurred on Io between subsequent views of the surface, we used an iterative coregistration and ratioing technique described in Phillips et al. (2000) and used on images of Europa. A set of images documenting the processing steps are visible in Figures 2.4, 2.5, and 2.6. The processing steps and coregistration technique are described in more detail in the appendix. Briefly, we first reprojected the images to a common viewing geometry and pixel scale. The images were then photometrically corrected, using a Lunar-Lambert function with L=0.8. This compensates for brightness differences due to distance from the terminator, but does not account for the potentially different photometric behaviors of different terrain types. The parameter L in the Lunar-Lambert function describes what proportion of the behavior of the surface is lunar-like, and what proportion is Lambertian (McEwen, 1991). A purely lunar-like behavior would have no limb darkening at all at zero phase, like a full moon. L is dependent on phase angle, but we have found that the value L=0.8 produces the best result for most Io images, and averages out brightness variations to produce flat ratio images between different observations.
Once the images had been matched in brightness and viewing geometry as closely as possible, we began an iterative coregistration procedure to align the images to subpixel accuracy. Match points were first found between the images to perform a first-order correction to the raw spacecraft geometry. Then, single-filter image pairs from sequential orbits were coregistered iteratively until the correlation coefficient for each image pair was maximized, thus aligning them geometrically to sub-pixel accuracy. This technique also matches the effective resolutions, via incremental resampling. Appendices A and D have a more detailed description of the commands and software packages used.

Once the images were aligned through this subpixel registration technique as whole-disk images, they were ratioed to identify regions where changes had taken place. A similar ratioing technique was used by Spencer et al. (1997a) to map out changes on Io between Voyager images and low-resolution images from the Hubble Space Telescope. An example of these whole-disk ratio images is shown in Figure 2.5. For the most part, the ratios are a flat gray, which shows that most of the surface did not change. However, in certain areas changes are clearly visible: areas where the surface has brightened over time show up as bright in the ratios, and areas which have darkened are darker than the background gray. Once an area of interest has been identified in the whole-disk ratio, a cropped version of the image is made which contains only that area in each filter. The cut-out regions are again coregistered and ratioed, so that the coregistration is more accurate for small areas. Significant changes were found at the volcanic centers
Kanehekili, Lei-Zi, Masubi, Prometheus, Culann, Pillan, and Zamama. These are described in turn in the following pages.

2.3. Detailed observations of specific volcanic centers on Io

2.3.1: Kanehekili

Kanehekili is a volcanic center located at -17° N, 36° W on the Jupiter-facing hemisphere. The observations and changes at Kanehekili are summarized in Table 2.3. Kanehekili was first seen as a hotspot in 1989 by Spencer et al. (1990) from telescopic observations. Changes were found in the Kanehekili region in 1994 in the Spencer et al. (1997a) Voyager - HST comparisons. Kanehekili exhibited continued activity in ground-based observations in 1996, just prior to the first Galileo observations in G1 (Spencer et al., 1997b). Kanehekili could also have been the site of an outburst detected in ground-based observations in 1986 (Veeder et al., 1994; Lopes-Gautier et al., 1999).

A persistent hot spot has been detected at Kanehekili in Galileo SSI eclipse images and NIMS images, and activity has continued throughout the extended mission (Table 2.3). The SSI eclipse images on orbit E4 revealed that the Kanehekili volcanic center consists of two hot spots (McEwen et al., 1998a). Since the Kanehekili region was poorly observed by the Voyager IRIS instrument, it is possible that a hot spot could have been missed.
<table>
<thead>
<tr>
<th>Observation</th>
<th>Date</th>
<th>Appearance or changes</th>
<th>Plume?</th>
<th>Hotspot?</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voyager 1</td>
<td>1979</td>
<td>Dark central region, red diffuse area surrounding center</td>
<td>No</td>
<td>No (but not well-observed)</td>
<td>Veeder et al. 1994</td>
</tr>
<tr>
<td>Ground-based</td>
<td>1986</td>
<td>-</td>
<td>-</td>
<td>Yes?</td>
<td>Spencer et al. 1990</td>
</tr>
<tr>
<td>Ground-based</td>
<td>1989</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>Spencer et al. 1990</td>
</tr>
<tr>
<td>HST</td>
<td>1994</td>
<td>Changes as compared to Voyager</td>
<td>-</td>
<td>-</td>
<td>Spencer et al. 1997a</td>
</tr>
<tr>
<td>Ground-based</td>
<td>6/02/96</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>Spencer et al. 1997b</td>
</tr>
<tr>
<td>Galileo G1</td>
<td>6/25/96</td>
<td>Voyager central red material darkened</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galileo E4</td>
<td></td>
<td>Glow in eclipse</td>
<td>Yes - 2</td>
<td></td>
<td>McEwen et al., 1998a</td>
</tr>
<tr>
<td>Galileo E6</td>
<td>2/19/97</td>
<td>New bright plume deposit as compared to G1, new dark central lava flows, changes centered on southern hot spot</td>
<td>Not seen, but must have been active</td>
<td>Not observed</td>
<td>Phillips et al., 1999</td>
</tr>
<tr>
<td>Galileo G7</td>
<td>4/03/97</td>
<td></td>
<td>Yes - 2</td>
<td>High temp</td>
<td></td>
</tr>
<tr>
<td>Galileo G8</td>
<td>5/07/97</td>
<td>yes</td>
<td>Yes - 2</td>
<td></td>
<td>McEwen et al., 1998a</td>
</tr>
<tr>
<td>Galileo C9</td>
<td>6/27/97</td>
<td></td>
<td>Yes - NIMS</td>
<td></td>
<td>Lopes-Gautier et al., 1999</td>
</tr>
<tr>
<td>Galileo C10</td>
<td>9/18/97</td>
<td>New dark spot to NE of central flow complex, fading of red E6 deposit, plume ring fading</td>
<td></td>
<td>Yes - 2</td>
<td></td>
</tr>
<tr>
<td>Galileo E11</td>
<td>11/07/97</td>
<td>yes</td>
<td>Yes - 2</td>
<td></td>
<td>McEwen et al., 1998a</td>
</tr>
</tbody>
</table>
SSI provided additional evidence for active volcanism at Kanehekili by observing plumes. A diffuse glow around the Kanehekili area was visible in the E4 eclipse images, and plumes were seen at Kanehekili against black sky on orbits G8 and E11 (McEwen et al., 1998a). The double Kanehekili hot spot was also observed on a number of orbits (Table 2.3), with the G7 observation suggesting very high temperatures. The two hot spot locations both fall within the large dark central region described above. Significant surface changes, described below, occurred between orbits G1 and E6, and more subtle changes occurred between orbits E6 and C10.

Most of the observations of Kanehekili by both Voyager and Galileo are at a relatively low resolution, no better than five kilometers per pixel. There are a few oblique views of Kanehekili at a resolution of about 1 km/pixel from Voyager 1. Morphologically, Kanehekili has a large dark central region, probably composed of lava flows, perhaps confined to a caldera. The dark area at Kanehekili lacks the sharp margins seen at other volcanic centers with calderas, but this could be because of a) low resolution images, b) small lava flows overflowing the caldera walls, or c) pyroclastics. (As will be shown later, Ionian calderas often have associated lava flows and pyroclastics). The dark central region at Kanehekili is surrounded by bright, yellow-white areas which resemble the bright equatorial plains of Io in color, and lack any distinguishing morphologic features. Low spectral resolution studies of Kanehekili using the SSI visible wavelengths from violet to 1 micron have shown that Kanehekili has an absorption in the .89 micron band (Geissler et al., 1999). This absorption has been seen elsewhere on Io, associated with recently active dark deposits. The
absorption is suggestive of the mineral orthopyroxene, which would indicate a magnesium-rich silicate composition (Geissler et al., 1999). Kanehekili also has a decreased reflectance at wavelengths shorter than 0.6 microns, indicative of a sulfur absorption. Thus, the dark materials are probably silicate in composition, but most likely are covered with a thin veneer of SO2 frost, S, or another sulfur compound. Again, this is a common association at Ionian volcanic centers.

The changes observed at Kanehekili are summarized in Table 2.3, and will be described in the following section. Figure 2.2 shows one of the Voyager views of Kanehekili, in its original near-limb viewing geometry and reprojected. This view shows the lobate nature of the edges of Kanehekili, supporting the interpretation that the dark central region is composed of a number of coalesced lava flows. Figure 2.3 shows a comparison of the appearance of Kanehekili on Voyager 1 and on orbit G1. In comparing these images, it is important to note the differing filters which are displayed for Voyager and for Galileo. The Voyager filters are orange, clear, and violet, displayed as red, green, and blue. The Galileo filters used here are red, green, and violet, displayed as red, green, and blue. Thus, the violet filter images provide the only direct comparison. The Voyager orange filter is fairly close to the Galileo green filter (Table 1.3), and thus can also be compared, but only with caution. For example, the dark lobe to the right of Kanehekili visible in the Voyager orange image most likely corresponds to a bright red deposit which appears bright at wavelengths of red and longer, but dark at shorter wavelengths. A similar deposit is visible to the right of Kanehekili in the G1 images.
Figure 2.2: This image is our highest-resolution view of Kanehekili. It is an oblique view from Voyager at a resolution of about 1 km/pixel. The view on the left is the original near-limb appearance, and the view on the right has been reprojected to the same viewing geometry as in Figure 2.4.
Figure 2.3: This image grid compares the Voyager and Galileo G1 color views of Kanehekili. See the text for caveats about the differing filters. The grid shows the original appearance of Kanehekili in a 3-color composite, and in the individual filters, from Voyager and from Galileo. The Voyager composite combines the orange, clear, and violet filters, and the Galileo composite uses the red, green, and violet filters. The last row has ratios of the two bands which were closest in wavelength, which were the Voyager orange and Galileo green, and the two violet filters.
Comparison of the Voyager and G1 violet images indicates that much of the area surrounding Kanehekili appears to have darkened substantially in the intervening years. A bright halo of material also seems to surround Kanehekili on G1, but little trace of this halo is visible in the Voyager image. However, as indicated in Table 2.2, the Voyager image was taken at a phase angle of 11 degrees, while the G1 image was taken at 48 degrees phase. This large difference in phase angle results in many changes in the appearance of Io's surface which are not due to geologic activity, but solely to the differences in the illumination of different surface units. In this case, the apparent darkening in the violet filter image is probably just due to this phase function effect. This example illustrates the need for well-matched images in terms of both filters and phase angle.

The Galileo observations of Kanehekili include a set of images taken at similar phase angles on three orbits from 1996 to 1997. These images are shown in Figure 2.4 as color composites made from the NIR, green, and violet data. Figure 2.5 shows the whole-disk ratios for the Kanehekili hemisphere from orbits G1 and E6. The three bands are the NIR (.756 microns), green, and violet. Recall that in these ratio images, regions of the surface which have brightened over the 8 months between the two observations appear bright in the ratio image, and conversely regions which have darkened between the two appear dark. Note that most of the surface appears a flat gray, which indicates that most of the surface remains unchanged over the 8-month interval. The bright arc at the right of the image is due to the 2 degree difference in phase angle between the observations. While most of the ratio images appear gray, changes are visible around
Kanehekili, near the bottom center of the image, and also near the North and South Poles. The changes visible near the North Pole may be related to a transient high-temperature event seen in ground-based observations on October 6, 1996 (Spencer et al., 1997b, Stansberry et al., 1997). The changes near the South Pole may be related to continuing activity in this region, and will be discussed in a later section on Masubi.

After examination of the ratios in Figure 2.5, areas which exhibited substantial changes in the whole-disk ratio images were then cut out of the global images into subareas which were again coregistered and ratioed to produce the best possible image alignment over these smaller areas. Such images are shown in Figure 2.6. The figure shows the Kanehekili area as seen on orbits G1 and E6, in the color composite and in the three individual bands. Ratios are then shown in all three bands. For scale, the top left G1 image is about 1300 km wide.
Figure 2.4: This image shows full-disk color views of Kanehekili from orbits G1, E6, and C10. The pink and green boxes are due to missing data in one or more filters.
Figure 2.5: This image shows the full-disk ratios from orbits G1 and E6 in the Near-Infrared, green, and violet filters. Regions that brightened from G1 to E6 appear bright in the ratio images, and regions that darkened from G1 to E6 appear dark. Note that most of the surface is a flat gray, indicating that it remains unchanged, but that substantial changes are visible near Kanehekili, as discussed in the text.
Figure 2.6: This image shows a grid of cutout windows over the Kanehekili area in three filters from G1 and E6. The cutout areas in each filter were coregistered individually, and the ratios in each of the three bands are shown in the bottom row. These ratios reveal the detailed nature of the activity which took place at Kanehekili between G1 and E6. The NIR and green ratio images show a new bright ring, which is the result of a plume deposit, and a dark central area, which is due to new lava flows on the surface. Thus, these images document an eruption which took place from the southernmost of the two hotspots observed at Kanehekili. A new bright red diffuse deposit is also visible near the northernmost of the two hotspots. The complexity of the violet ratio image is due to the mobility of SO$_2$ frost.
Examination of the two 3-color images of Kanehekili in Figure 2.6 shows that the dark central region has changed shape, and is more pointed near the northern end in the E6 image than it was in the G1. Visual inspection alone, therefore, can often indicate that a change has taken place, but the ratio images are able to illustrate the details of that change. New features are clearly visible near Kanehekili in the last row of Figure 2.6. First, a bright ring is visible surrounding the lower end of the dark central region. This appears to be a new plume deposit. An umbrella-shaped plume of freezing gas deposits snow onto the surface in a ring due to the ballistic trajectories of the ejected particles. The ratio images also reveal new, dark, lobe-shaped central features, which could be new surface flows. These changes indicate that the plume imaged on orbit G8 began erupting sometime between G1 and E6. Since Kanehekili has two associated hot spots, this plume deposit shows that the most recent eruption occurred from the more southern of the two.

A new bright red linear deposit is also visible at the northern end of the dark central flow complex, and a more diffuse red deposit is visible to the east of Kanehekili. Red surface deposits are associated with recent or current volcanic activity on Io (McEwen et al., 1998a), and are thought to be composed of short-chain sulfur (S$_3$ or S$_4$, Spencer et al., 1997a). This material is known to be unstable, and is thought to eventually transition to stable S$_8$ and appear yellowish, similar to the background plains of Io. Red deposits seem to endure for timescales of months to years before fading away, unless they are continually replenished (Section 2.5). The red linear feature is clearly visible in the color composite ratio image, which is located in the lower left box of Figure 2.6.
This composite is created by superimposing the ratio images in the NIR, green, and violet images, and displaying them as the red, green, and blue channels of the image. Thus, areas of the image which are bright red, such as the linear feature mentioned previously, indicate regions which have brightened in the red filter between G1 and E6. Regions which are bright blue have brightened in the violet filter.

Kanehekili seems to have a very similar appearance to Prometheus and Zamama, which will be discussed in later sections. We observe two hot spots, a large one associated with new dark lava flows and an active plume, and a fainter hotspot associated with diffuse red deposits. The fainter hotspot with the red diffuse material is most likely associated with the location where the magma reaches the surface, becoming lava. The lava then travels through a flow with an insulating crust to the flow front, which is the second, larger hotspot. The larger hotspot has an associated plume located near the active end of the lava flows. It is speculated that the active silicate lava vaporizes volatiles such as SO₂, which then erupt through a vent near the end of the flow, forming a stable umbrella-shaped plume (Kieffer et al., 2000). We see a similar dual hotspot configuration, with the larger hotspot associated with a plume vent within the active flows and a smaller hotspot associated with red diffuse material, at both Zamama and Prometheus. This structure will be discussed in more detail in the sections describing Zamama and Prometheus, and in section 2.5 on plumes.

The complexity of the Kanehekili violet ratio image shows the mobility of volatiles such as SO₂, which are seen to affect a much larger area than just the immediate vicinity of the vent. This is consistent with eclipse observations, which show a much larger
plume than is visible in reflected sunlight. Such stealth plumes are described by Johnson et al. (1995). Careful inspection of the G1 and E6 violet images reveals that the bright halo surrounding the dark central region of Kanehekili on orbit G1 has disappeared due to the new eruption seen on orbit E6. Such halos have been seen surrounding many dark, flow-like features on Io, and were first recognized in Voyager images (Nash et al., 1986). Bright halos could be formed by remobilization of plume fallout that is emplaced on dark, hot, surface areas. This fallout could be re-vaporized on contact with the hot material and condense in a bright ring surrounding the dark lava (McEwen et al., 1998a).

Observations of the Kanehekili region were repeated on orbit C10, seven months after the E6 observations. Figure 2.7 shows the comparison cut-out regions for these two orbits. The ratio images indicate that, while the bulk of the new plume deposit has begun to fade, there are also some new features that have appeared in this time interval. First, a new dark spot is visible to the northeast of the main dark flow complex, as visible in the NIR and green ratio images. This dark spot could be a new small lava flow issuing from the northern hot spot (thought to be the main lava vent), or it could be a dark, diffuse plume deposit. Visible in the color ratio image is a pair of red and green spots to the east of Kanehekili. Examination of the color E6 and C10 images reveals that the diffuse red deposit to the east of Kanehekili in the E6 image has faded, and a new red deposit is visible much closer to the central dark complex. The bright, ring-shaped plume deposit which was so visible in the G1/E6 ratio images of Figure 2.6 can be seen to be fading, as shown by the dark ring surrounding Kanehekili in the green
ratio image. Also note that the violet ratio image reveals the return of a bright halo surrounding the dark central complex. Perhaps the bright halo indicates a reduction in plume activity, but not a complete cessation, as a plume was observed at Kanehekili on orbit E11.

The observations of Kanehekili from orbits G1, E6, and C10, thus indicate that a substantial volcanic eruption took place in this time period. A new bright, ring-shaped plume deposit and dark surface flows formed between G1 and E6, and the plume deposit began to fade between E6 and C10. We are still not sure where the vent for the silicate flows is located — it seems to be between the two hot spots. If the red deposits are “blown out” from a different vent than the silicate one by the stronger bright SO$_2$ plume, then the fact that the red diffuse deposit in the C10 image is closer to the vent than the red deposit in the E6 image could indicate that the main SO$_2$ plume has decreased in strength between E6 and C10.

**Figure 2.7:** This image compares the appearance of Kanehekili on orbit E6 with that on C10. Note the continuing activity at Kanehekili, and the change in location of the red plume deposit. A new dark deposit is also visible near the northern end of Kanehekili.
2.3.2: Lei-Zi

Images of the Kanehekili hemisphere were also acquired on orbit C9. These images were taken at a similar phase angle, but at the opposite illumination from the G1 and E6 images (Table 2.2; Figure 2.8). This makes change detection more difficult, but also allows identification of topographic features on Io's surface. Kanehekili was located just off the terminator of the C9 images, but other nearby features are visible. The opposite illumination of C9 means that features which exhibit topographic relief above the surface will be illuminated from opposite sides. Examples of such features are visible in the ratio images in Figure 2.9 (full-disk ratios) as features that are bright on the left and dark on the right.

Figure 2.10: This image shows a cutout around the Lei-Zi area. Note the dark ring visible in the violet ratio image surrounding Lei-Zi. This is the first detection of activity at this feature. The opposite illumination geometry also reveals a mountain in the top part of the image, and a plateau at the lower center.
Figure 2.8: This image compares the full-disk color views from orbits E6 and C9. The C9 image has the same phase angle, but is illuminated from the opposite direction. Kanehekili is too close to the terminator in the C9 image for useful comparisons.
Figure 2.9: This image shows the full-disk ratio images from orbits E6 and C9, in the overlap areas. Note the bright-dark signatures in the ratio images which indicate the presence of topography which is illuminated from opposite sides.
Figure 2.10
Figure 2.10 shows a coregistered subarea for comparison between orbits E6 and C9. The top left E6 image is about 1350 km wide. The features visible in the ratio images are mostly topography: note especially the mountain at the upper left and the elongated plateau near the center of the image. The latter in particular is barely visible in the individual images, but is clearly identified as relief in the ratios. It leads down to the active hot spot Shamshu, the dark feature in the lower left of the image. Shamshu does not show any evidence of new plume deposits in these ratio images, but the violet ratio clearly shows a new circular plume deposit surrounding a volcanic center named Lei-Zi at the upper right. This is the first direct evidence we have of any activity at this location. The Lei-Zi plume deposit appears as a dark ring in the violet filter. This type of plume deposit has also been seen elsewhere on Io, such as at Masubi, described in the next section. It could indicate that a different type of eruption is taking place than that associated with Kanehekili. No plume or hot spot has been seen at Lei-Zi.

2.3.3: Masubi

The changes at Masubi are summarized in Table 2.4. Masubi, located at -44° N, 54° W, was observed as an active plume by both Voyagers 1 and 2 (Strom and Schneider, 1982), and changes in the appearance of Masubi and the surrounding area were reported by Spencer et al. (1997a) based on comparisons between Voyager and Hubble Space Telescope images. The increase in the albedo of the region surrounding Masubi was first observed in 1993 (Sartoretti et al., 1995), and was attributed by Spencer et al. (1997a) to a buildup of \( \text{SO}_2 \) frost from the active plume. The bright area also changed
shape as well as increasing in albedo. No plume activity was detected at Masubi during the Galileo nominal mission, but a plume was seen during the extended mission on orbits C21 and C22 (Figure 2.11).

Table 2.4: Table of observations and changes seen at Masubi and Haemus Mons

<table>
<thead>
<tr>
<th>Observation</th>
<th>Date</th>
<th>Appearance or changes</th>
<th>Plume?</th>
<th>Hotspot?</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voyager 1</td>
<td>1979</td>
<td>Plume vent seemed to be near dark &quot;v&quot; in center of flow</td>
<td>yes</td>
<td>-</td>
<td>Strom &amp; Schneider, 1982</td>
</tr>
<tr>
<td>Voyager 2</td>
<td>1979</td>
<td>Dark, orange ring surrounds central part of Masubi, white halo</td>
<td>yes</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ground-based</td>
<td>1993</td>
<td>Increase in albedo in area surrounding Masubi</td>
<td></td>
<td></td>
<td>Sartoretti et al., 1995</td>
</tr>
<tr>
<td>HST</td>
<td>1994</td>
<td>Bright area changed shape and albedo due to frost buildup?</td>
<td></td>
<td></td>
<td>Spencer et al. (1997a)</td>
</tr>
<tr>
<td>Galileo G1</td>
<td>6/28/96</td>
<td>Voyager ring is gone, no bright halo in SE quadrant, new halo surrounding Haemus Mons</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>12/18/96</td>
<td>-</td>
<td>Plume-like feature seen in eclipse image; could have been Haemus Mons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E6</td>
<td>2/20/97</td>
<td>Haemus Mons halo darkened, new bright arc SE of Haemus and Masubi</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C9</td>
<td>6/27/97</td>
<td>Opposite viewing geometry to E6. Topography evident. No major changes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C10</td>
<td>9/18/97</td>
<td>New dark ring surrounding central portion of Masubi flow. South of Voyager location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E11</td>
<td>11/07/97</td>
<td>-</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E15</td>
<td>5/31/98</td>
<td>No trace of ring-shaped plume deposit from C10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground-based</td>
<td>8/29/98</td>
<td>Yes</td>
<td>Goguen and Davies, 1999</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C21</td>
<td>7/2/99</td>
<td>-</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C22</td>
<td>8/11/99</td>
<td>New ring-shaped plume deposit, larger and north of C10 location. Also return of SE bright halo</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.11: This image shows the appearance of the Masubi plume on Galileo orbit C22. The left image shows the surface, and the right is the same image stretched to reveal the plume structure.
Images of Masubi from Voyager 2 and from Galileo were analyzed. All these images are at relatively low resolution, and are at a variety of phase angles (Table 2.2). The Voyager 2 image, in Figure 2.12, includes images taken through the orange, green, and violet filters. A dark, orange-colored ring is clearly visible surrounding the dark linear flow-like feature named Masubi Fluctus. The orange tint of the ring comes from it being dark in all three filters: the ring is darkest in the violet, intermediate in the green, and blends into the background in the orange image. Note, however, that the orange frame is smeared with respect to the other two frames, reducing its effective resolution. The ring has approximately the same color and albedo as the orange background plains surrounding the bright central region. Outside of the orange ring is a bright white halo, visible most prominently in the southeast quadrant.

Figure 2.12: This image shows a comparison of the appearance of the Masubi area from Voyager to Galileo G1. Despite the difference in color filters, a ring is visible surrounding part of Masubi during Voyager which is gone in the Galileo image.
When the Voyager 2 appearance of Masubi is compared to the first Galileo images of this feature, taken in 1996 on orbit G1, several changes are apparent (Figure 2.12). The G1 images were taken at a much lower phase angle than the Voyager 2 images (Table 2.2). The G1 images also use the Galileo red, green, and violet filters. The green and violet filters of Galileo are at very similar wavelengths to those used on Voyager; however, the red filter is at a significantly longer wavelength than the Voyager orange filter (Table 1.3). Thus, we have only performed direct comparisons on the green and violet filters. The appearance of Masubi in the G1 color image (Figure 2.12) is quite similar to its appearance during Voyager, but the orange ring is missing. Also note that the bright halo visible in the southeast quadrant of the Voyager image is gone as well; this area appears the same red-orange color as the background polar plains elsewhere in this image. The G1 image also reveals the appearance of an increased bright halo surrounding the 10-kilometer high mountain Haemus Mons, to the south of Masubi. This halo could be the result of a fresh deposit of SO$_2$ from sapping at the base of the mountain. The ratio images show this bright halo, as well as the brightening of the former dark plume ring in the Voyager image.

Comparison of images taken on orbit E6 with the G1 images (Figure 2.13) shows that the formerly-bright halo around Haemus Mons has darkened, but that a new bright arc of material is visible in the green filter to the southeast of Masubi and Haemus. The G1 and E6 images were very closely matched in phase angle and viewing geometry (Table 2.2); thus the darkening of the halo and brightening of the arc are unlikely to be solely due to photometric effects. This could suggest that sapping at the bases of
mountains is episodic rather than continuous, perhaps related to landslides or small explosive collapses.

Comparison of images taken on orbit C10 with the images from orbit C9 (Figure 2.14) reveals that there has been a new plume deposit emplaced at Masubi. The C10 red and violet images (the green image was truncated to the east of Masubi) both show a new dark ring surrounding the central portion of the dark Masubi linear feature. This dark circular feature is again dark in both the red and violet filters, and appears strikingly similar to the Voyager ring deposit. The ratio images both clearly show the new dark ring, as well as the brightening of the halo surrounding it to the southeast, again very similar to the Voyager appearance. Note, however, that the C10 ring is located to the south of the Voyager ring. The center of the C10 ring, and thus the potential plume source, is located to the west of the linear Masubi feature, and is visible in the red and violet images as a spot of similar albedo to the plume deposit itself. The center of the Voyager ring was located further to the north, near the V-shaped bend in Masubi.

Our next view of Masubi was 8 months later, on orbit E15. Comparison of the E15 images to the C10 (Figure 2.15) reveals that the new ring-shaped plume deposit is completely gone – no traces remain, and the surface has reverted to its appearance on orbit C9. Not only is the dark ring gone, but the bright halo surrounding it has also disappeared. The violet ratio image clearly shows the brightening due to the removal of the dark ring, and the darkening as the bright halo faded. This dramatically demonstrates the ephemeral nature of these plume deposits.
Figure 2.13: This image compares the appearance of the Masubi area on orbit G1 with that on E6. A new dark halo is visible in the green and violet ratio images surrounding Haemus Mons, near the bottom of the image.
Figure 2.14: This image shows Masubi on orbits C9 and C10. The C10 images show a new dark ring surrounding the central portion of Masubi, and this appears as a dark ring in the ratio images as well. This is a new plume deposit from Masubi.
**Figure 2.15:** This image shows the appearance of Masubi on C10 and E15. Note that in the E15 images, the dark ring from C10 has completely disappeared, showing that plume deposits can fade in 8 months or less.
Figure 2.16: This image shows the appearance of Masubi on orbits E15 and C22 in the violet filter. Note the new dark plume deposit in the C22 image.
Figure 2.17: This image compares the violet filter images of Masubi from Voyager and the Galileo orbits discussed previously. The Voyager 2, C10, and C22 images show similar dark ring-shaped plume deposits. Their locations and sizes are different, however, suggesting that they are separate eruptions from related sources.
The next observation of Masubi came on orbit C22. Figure 2.16 shows a comparison of the violet filter images from these two observations (only a violet filter was obtained on orbit C22). The C22 violet image reveals that a new plume deposit has been emplaced, most likely associated with the vigorous plume observed at Masubi on orbits C21 and C22 (Figure 2.11). The time span between E15 and C22 is a little over one year. Not only has the dark ring returned in the C22 observation, but the bright halo surrounding it to the southeast has also reappeared. Both are visible in the ratio image. The new plume deposit is similar to the one seen on orbit C10, but the center has moved about 125 kilometers to the northwest. The new C22 plume deposit is also larger than the ones seen during Voyager or on C10.

Figure 2.17 shows the violet filter images of Masubi from all seven observations. Note the striking similarity in appearance between the 1979 Voyager image and the 1999 C22 image. However, the C22 plume deposit is located further north than either the C10 or Voyager deposits, and is also larger in diameter. The center for the C22 ring is located to the west of the V-shaped bend in Masubi. This series of observations clearly shows both the ephemeral nature of surface plume deposits such as the dark Masubi ring, and the cyclical nature of such deposits. In the case of Masubi, there appears to be a repeated style of eruption that produces similar deposits every few years in slightly different locations. We have observed these eruptions in 1979, 1998, and 1999, and we can infer from Spencer et al. (1997a) that a similar eruption occurred in 1993. The eruptions seem to involve Prometheus-style, umbrella-shaped plumes such as that observed on orbit C22 (Figure 2.11). The plume deposit is a transient feature in
this case, present only while the associated plume is active and for a brief time afterwards. The diameter of the plume in Figure 2.11 is about 250 kilometers, which is the same as the diameter of the new dark ring observed on the surface on orbit C22 (Figure 2.17). Since the plume deposits from Voyager, C10, and C22 are all approximately the same size, this implies that the eruptions observed or inferred from Voyager and Galileo are all of plumes of approximately the same shape, size, and composition. However, it is interesting that while the surface deposit from each eruption is remarkably similar, the location of the plume vent at the center of each ring is different. The distance between the plume vent on orbit C10 and that on orbit C22 is about 125 kilometers. If the plume vents are related, then the plume vent migrated this distance over less than two years.

The ordered structure of the plume deposits, with a dark ring surrounded by a bright halo, is quite similar to the long-lived Prometheus plume deposit. In the case of Prometheus, which is continuously erupting, the plume deposit is a long-lived feature. However, since Masubi appears to have only periodic eruptions, the plume deposit has time to fade between eruptions. If the plume is the result of new hot lava interacting with cold plains, where it vaporizes the condensed SO₂ frost, as has been suggested (McEwen et al., 1998a; Kieffer et al., 2000), then the plumes should form near the fronts of newly-active flow fronts. In the case of Masubi, we lack the required resolution to infer the detailed morphology of the plume vents; however, we can speculate that each plume and resulting plume deposit is the result of a new breakout of lava from the active region of Masubi, which appears to be the central region near the
V-shaped bend. An interesting comparison can be made between the Masubi plume system, which is located at relatively high latitudes and has intermittent eruptions, and the Prometheus plume system, which is located in the equatorial regions, and has a long-lived, continuous eruption. Perhaps there is a more plentiful supply of volatiles able to be vaporized at lower latitudes for Prometheus, while features at higher latitudes, where the temperatures are colder, do not have a reservoir of volatiles that is as easily vaporized. Speculations have been made that in the extreme polar regions, the eruptions are even shorter-lived (such as Tvashtar, McEwen et al. 2000), but such an eruption has never been seen to produce a large SO₂ plume.

No hot spots were detected at Masubi by NIMS (Lopes-Gautier et al., 1999) up through orbit C10, or by SSI in eclipse images. However, a hotspot was seen at Masubi by NIMS on orbit E11, and Masubi was also observed by ground-based observers on 8/29/98 as a high temperature hot spot (Goguen and Davies, 1999). The Voyager IRIS instrument also failed to detect a hot spot at Masubi in 1979 (Lopes-Gautier et al., 1999). However, faint diffuse glows have been observed around the location of Masubi in eclipse images of that hemisphere (McEwen et al., 1998a), probably indicating plume activity.
2.3.4: Pillan

The changes at Pillan are summarized in Table 2.5. Pillan, located at −12° N, 242° W, was first identified based on Voyager and early Galileo images as a 50 kilometer diameter caldera with some associated linear cracks or flows, located just outside Pele's bright red plume deposit. Galileo observations revealed that the caldera at Pillan darkened significantly between orbits G1 and G2, and then brightened again when observed on orbit C3 (McEwen et al., 1998a). This was originally attributed to anomalous scattering properties of the caldera, rather than volcanic activity, but observations on orbit E6 which matched the G2 ones in phase angle still indicated that the caldera was bright. There was also evidence for a darkening in the Pillan caldera between Voyager 1 and Voyager 2 observations (McEwen, 1988). Since Pillan is located beneath the red ring of Pele's plume deposit, it is likely that surface changes such as the G2 caldera darkening, if real, would be obscured quickly due to the rain of material from Pele (McEwen et al., 1998a).

**Table 2.5: Table of observations, changes seen at Pillan**

<table>
<thead>
<tr>
<th>Observation</th>
<th>Date</th>
<th>Appearance or changes</th>
<th>Plume?</th>
<th>Hotspot?</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voyager 1</td>
<td>1979</td>
<td>Small set of linear fractures or flows, caldera</td>
<td>no</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Voyager 2</td>
<td>Year</td>
<td>Description</td>
<td>McEwen 1988</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>-------------</td>
<td>--------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>Galileo G1</td>
<td>6/28/96</td>
<td>Similar to Voyager 1</td>
<td>No - SSI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>9/06/96</td>
<td>Caldera darkened significantly</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>11/06/96</td>
<td>Caldera brightened to G1 appearance</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>12/18/96</td>
<td>Caldera still bright and greenish, even at G2 phase angle; darker than Voyager appearance; bright white patch to north</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E6</td>
<td>2/20/97</td>
<td>Caldera still bright and greenish, even at G2 phase angle; darker than Voyager appearance; bright white patch to north</td>
<td>Yes - NIMS, no SSI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G7</td>
<td>4/03/97</td>
<td>Greenish caldera appearance on E6 has faded – caldera brighter than E6</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G8</td>
<td>5/07/97</td>
<td></td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C9</td>
<td>6/27/97</td>
<td>Yes – large plume</td>
<td>Yes – NIMS and SSI, intense hotspot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HST</td>
<td>7/4/97</td>
<td>Yes</td>
<td>Spencer et al., 1997c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C10</td>
<td>9/18/97</td>
<td>New dark diffuse deposit surrounding Pillan, diameter 400 km; new dark flows; brightening of Reiden; dark deposit has bright halo; bright patch to North covered</td>
<td>Yes – NIMS and SSI, less intense, two separate locations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Code</td>
<td>Date</td>
<td>Description</td>
<td>Notes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E11</td>
<td>11/07/97</td>
<td>yes</td>
<td>Yes – faded, 2 locations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E12</td>
<td>12/16/97</td>
<td></td>
<td>Yes – northern spot barely visible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E14</td>
<td>3/29/98</td>
<td>Dark flows, fading diffuse deposit; white deposit on plateau</td>
<td>Yes – only southern spot visible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E15</td>
<td>5/31/98</td>
<td></td>
<td>Yes – NIMS, fading</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E16</td>
<td>7/20/98</td>
<td></td>
<td>Yes – NIMS, fading</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C20</td>
<td>5/02/99</td>
<td></td>
<td>Yes – NIMS, fading</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C21</td>
<td>7/2/99</td>
<td>Dark deposit fading. lava flows same size, new eruption to east at Kami-Nari, white patch to north reappears: Pillan and Pele plumes active simultaneously</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I24</td>
<td>10/11/99</td>
<td>Red Pele material covers Pillan deposit, less interaction between plumes; high-resolution strip shows platy texture</td>
<td>Yes? SSI eclipse, marginal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E26</td>
<td>1/4/00</td>
<td>Diffuse Pillan deposit mostly gone, .9 micron abs. in Pillan flows, caldera; caldera appears greenish</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.18: This image shows Pele and Pillan from orbits G7, C10, C21, and I24. The new eruption at Pillan is visible in the C10 image, and the fading of the dark deposit and its interaction with the bright red Pele plume deposit are visible in the C21 and I24 images.
No hot spot was seen at Pillan in the G1 SSI eclipse images, but one was seen at Reiden, slightly to the east of Pillan. A hot spot was observed at Pillan by NIMS beginning on orbit G2 and continuing through orbit C20 (Lopes-Gautier et al., 1999, Davies et al., 2000; Table 2.5). SSI observations on orbit C9 revealed an intense hot spot and a plume 120 kilometers high. A plume was also seen at Pillan in an observation by HST a week after the C9 image (Spencer et al., 1997c). Observations of Pillan on orbit C10 showed that a new dark deposit had been emplaced around the volcano, with a diameter of approximately 400 kilometers (Figure 2.18). Outside the main dark deposit is an outer ring of material that is dark in the violet filter, similar to that seen at Kanehekili, which again suggests that the visible plume and plume deposit do not indicate the entire size of the altered region. IR observations of the Pillan eruption indicate magma temperatures between 1700 K and 2000K (McEwen et al., 1998b).

An eclipse image on orbit C10 showed that the hot spot intensity at Pillan had been reduced significantly, and continuing NIMS observations tracked the cooling history of the area (Davies et al., 2000). The C10 hot spot seen by SSI could be resolved into two separate centers, separated by about 75 kilometers. These two locations could indicate the vent and perhaps the front of the active surface flows (McEwen et al., 1998a), or where the flows cascade over the caldera wall. The southern hotspot was brighter than the northern one. Hotspot observations on orbit E11 showed that Pillan had further faded in intensity. Two hotspots were still visible on E11, with the southern one brighter than the northern one (Table 2.5). A plume was also seen at Pillan on orbit E11.
By orbit E12 the northern hotspot was just barely visible, and by E14 only the southern hotspot remained. NIMS has tracked the cooling of the Pillan hotspot through orbit C20 (Table 2.5; Davies et al., 2000). The Pillan hotspot may have been seen by SSI on orbit I24, but the detection is marginal. The following section will document our views of continuing activity at Pillan beginning with Voyager and continuing through orbit E26.

Figure 2.19 shows the appearance of Pillan Patera in Voyager 1 images, as well as its appearance on Galileo orbit E6. The Voyager 1 image shows what appear to be three linear flows or fissures intersecting at the northern end. Below these dark linear features is the Pillan caldera, which appears to be an orange color similar to the rest of the nearby plains. Note that Pele, just off the bottom left of these images and visible in Figure 2.18, has probably been a continuous source of substantial plume fallout for the past 20 years (Spencer et al., 1997d). The red arc visible from the top left to the bottom center of the images is part of the bright red Pele plume deposit, and this deposit can be seen to be covering the Pillan caldera in the Voyager image. The dark feature to the lower right of Pillan is Reiden Patera. Also note that a bright white patch of material appears to the north of the linear Pillan features. A possible explanation for this anomalous white patch will be discussed later.
Figure 2.19: This image compares the appearance of Pillan in Voyager with its appearance in Galileo orbit E6. In both these images, Pillan is composed of a triple junction of fractures above a caldera. The Voyager color is composed of orange, blue, and violet filter images, while the Galileo image has red, green, and violet images. The Voyager orange and Galileo green are closest in central wavelength and bandpass, and have been compared, as well as the violet filters.
Figure 2.20: This grid of images compares the appearance of Pillan on orbits G7, C10, and C21. The new eruption is visible in the ratio images from G7 to C10, and its disappearance due to covering from material from Pele is visible in the C10 / C21 ratios. The C21 image also shows a new eruption at Kami-Nari, to the right of Pillan.
The E6 images of Pillan in Figure 2.19 were taken at a similar phase angle (Table 2.2) to the Voyager images, but through the Galileo red, green, and violet filters as opposed to the Voyager orange, blue, and violet filters. Thus the surface appears more red and less orange than it did in the Voyager color images. Despite the differences in filters, the change in the appearance of the Pillan caldera is striking. The caldera appears dark in the red filter and bright in the green and violet filters, leading to its blue-green appearance in the E6 color image. A greenish tint is visible around the linear Voyager features to the north of the caldera. The white patch is also visible. The ratio images in the bottom row of Figure 2.19 show the darkening of the Pillan caldera and the region surrounding the linear flows or fissures. The bright white patch to the north of Pillan has also darkened somewhat.

Figure 2.20 shows the appearance of Pillan on orbits G7, C10, and C21. The G7 appearance of Pillan is very similar to that on orbit E6, except that the dark, greenish caldera from orbit E6 seems to have changed by orbit G7. The caldera still has a greenish appearance, but is brighter than it appeared during E6. The C10 image of Pillan is strikingly different from the G7 appearance. Clearly, a large, 400-kilometer diameter, dark deposit has appeared surrounding the caldera. This new deposit, with its diffuse margins and interior, appears to be a pyroclastic surface coating associated with a single, large eruption of material from near Pillan. Also visible within the new dark deposit are a series of new dark flows on the surface, similar to the new flows seen at Kanehekili as described previously, but larger in area. The new C10 dark deposit covers the red Pele plume deposit. Also visible in the ratio images is the brightening of
Reiden Patera, to the east of Pillan – this could be due to volatile outgassing from Reiden associated with the Pillan eruption. Note that the C10 violet image reveals that the new dark deposit has a halo which is bright in the violet filter, as seen previously for Masubi and Kanehekili, and a dark outermost ring. The G7/C10 ratio images also show the darkening of the bright patch to the north of Pillan – this area has darkened substantially as it was covered by the new Pillan deposit.

The C21 image of Pillan at the bottom of Figure 2.20 shows our next look at this area. Almost two years after the Pillan eruption, the dark deposit is beginning to fade away. Already, the red Pele plume deposit has begun to cover the western edge of the dark Pillan deposit. Also note that the Pillan caldera has darkened substantially in C21 from its C10 appearance. If Pillan has continued its volcanic activity, then the darkening of the caldera could be due to the draining of lava flows into the depression, darkening it with new dark flows. The darkening could also be thermal in nature – the caldera could darken as it heats up and drives off the volatile plume deposits that had settled out on it. The C21 violet image shows that the dark deposit no longer has a bright margin as it did in C10, and the violet ratio shows a substantial darkening in the violet filter that is either due to more yellow material being deposited on top of the dark Pillan deposit, or due to transformation of the dark deposit itself into a brighter, yellower appearance. The C21 images also show a new small eruption to the east of Pillan, at a newly-recognized volcanic center with the name Kami-Nari. The central region of Kami-Nari has darkened substantially, as seen in the ratio image, and the dark central deposit has a new ring of bright material surrounding it.
As mentioned before, the small white patch to the north of Pillan, which was visible in the pre-eruption G7 images, was covered by the dark pyroclastic deposit in the C10 post-eruption images. This bright patch can be seen to begin to reappear in the C21 images after much of the dark deposit has either been removed from the surface or covered over by the red Pele plume deposit. It is possible that this white deposit is associated with a mountain to the north of the Pillan caldera. In this case, either the dark Pillan deposits have been removed from this portion of the surface, or new white frost deposits have returned to this region, and have covered over the dark deposit, returning the surface to its pre-eruption appearance. The local topography surrounding this white area will be discussed in more detail later. A similar occurrence was noted by Spencer et al. (1997a) at the volcanic center Surt, where a region bright during Voyager 1 was darkened 4 months later for the Voyager 2 flyby by dark pyroclastic deposits from Surt. However, HST and later Galileo images showed that the bright spot north of Surt had returned to its Voyager 1 brightness. Spencer et al. (1997a) attributed this to either sublimation which removed the dark pyroclastic covering, or continued condensation of SO2 at the site of the previous SO2 concentration, which covered over the dark Surt material.
Figure 2.21: This figure compares the C21 and I24 views of Pillan, and shows the continued covering of the Pillan plume deposit by material from Pele.
Figure 2.21 shows a comparison of the C21 and I24 views of the Pillan area. There have been no large changes over the three months between these observations, but a few subtle variations in the appearance of the surface are visible. First, note how the bright red Pele plume is continuing to cover the dark Pillan deposit. This material is bright in the red filter, and dark in the green and violet filters. The green and violet ratio images show a new dark arc of material covering the western portion of the dark Pillan deposit. The interaction between the Pillan deposit and the Pele deposit is most obvious in the southwest quadrant of the Pillan deposit. As shown in the ratio images, in this region it appears as if the two plumes are active simultaneously, with the interaction of their plumes resulting in the region of mixed red and black material visible in this quadrant. The boundary between the Pele and Pillan deposits in the I24 image is much smoother than that in the C21 image, and the red Pele material has encroached almost to the margin of the dark Pillan flows, covering most of the yellowish material present between them in the C21 image. It is possible that the Pillan plume has turned off between C21 and I24, and the I24 image shows the dominance of the Pele plume. Also visible in the violet ratio image is a newly-bright arc of material on the eastern edge of the Pillan deposit, most likely due to continued plume activity at Kami-Nari.

Orbit E26 provided our best-resolution color view of the Pillan deposits of the Galileo tour. Figure 2.22 shows a comparison of the I24 view to the E26 view of Pillan. We not only have color, but we have a full five filters (Pillan was at the very edge of the frame, and is partially cut off in some of them). The E26 images show that the dark Pillan deposit has faded away almost completely, leaving behind the new dark lava
flows and the darkened caldera. Perhaps the most interesting aspect of these new E26 images is the change in color of Pillan's caldera. The Pillan caldera, even in its pre-eruption days, was the site of a number of interesting contrast reversals, as described previously. Following the C10 eruption, the C21 images show that the Pillan caldera has darkened substantially.

The E26 images, however, show that the caldera appears to have changed color and has become greenish rather than just dark black (Figure 2.22). Green materials have been found elsewhere on Io, and one possible explanation is that they represent a surface coating on recently active lava flows and calderas, perhaps related to the cooling of the dark material (Geissler et al., 1999). If the Pillan caldera has actually turned green between C21 and E26, this is the first estimate of a timescale of such an event, and the change occurred over less than 6 months. This observation provides evidence that the greenish tints are in fact due to coatings of sulfur compounds deposited on lavas. Pillan presents an excellent example, because we know there is a large amount of red sulfurous material deposited on the caldera and the surrounding area by the Pele plume. If this red material falls on a hot lava flow, it evaporates and the flow or caldera remains dark. However, we can speculate that if the red sulfur compound falls on warm lava, it is transformed into a greenish material (Kargel et al., 1999), perhaps iron contaminated sulfur. If the red material falls onto cooled lava, or onto the plains, it remains red, as seen in the bright red ring of material surrounding Pele.
Figure 2.22: This image compares the I24 and E26 appearance of Pillan. Note the brightening of the caldera, which has also turned greenish.
The color change in the Pillan caldera is apparent in Figure 2.22 as the brightening of the caldera in the 0.756 micron and especially the green filters. The 0.889 micron filter, the only one in which we have full coverage of the Pillan caldera, reveals that the entire caldera has not turned green: only the portion to the northeast appears to have brightened. Perhaps this was the last part of the caldera to have active flows on its surface. Spectra of the Pillan caldera, flows, and surrounding plains are displayed in Figure 2.23. Figure 2.24 shows the location of each colored spectrum with a dot of the same color. Figure 2.23 clearly shows a dip in band 2 (the 0.889 micron band) in the dark purple and blue profiles, which are both located in the caldera. The apparent 0.889 micron absorption is approximately 10% lower than the brightness in the 0.756 micron band. This 0.889 micron absorption has been seen in other dark flows on Io by Geissler et al. (1999), and is hypothesized to represent orthopyroxenes in ultramafic silicate lava flows.

**Figure 2.23:** This image shows spectra of the Pillan caldera, lava flows, and surrounding plains. Note the characteristic absorption at 0.889 microns due to silicates, probably orthopyroxenes, in the flows and caldera.

**Figure 2.24:** This figure shows the location of each colored spectrum from Figure 2.23 with a dot of the same color.
Figure 2.25: This image combines a view of the topography at Pillan from orbit E14 with a view of the color from orbit E26. The E26 color image combines the .889 micron, green, and violet filters. The 0.889 micron filter is the only filter which covers the whole caldera in this observation, and the data gaps in the other two filters appear red in the color image. The two are combined in the third image, which shows the relationships between the new flows, the returning white area, and the mountain and plateau.
Another observation was made by Galileo after the C10 eruption, on orbit E14. This image was taken through the clear filter when Pillan was located on the terminator, to allow for detection of topography surrounding the caldera and flows. This image is shown in Figure 2.25, which has the E14 clear image next to the E26 color image. Some fading of the Pillan plume deposit has clearly occurred between orbits E14 and E26, as the dark plume deposit is scarcely visible in the E26 image. The E14 clear-filter image reveals that a rather large mountain is present just to the northwest of Pillan. The mountain may consist of an upthrust faulted block, as is believed to be the case for many mountains on Io (Turtle et al. 2000). Also visible to the north of the main mountain is a lower, flat plateau. The two images can be combined, and the merged product is visible at the right of Figure 2.25. This product is a bit misleading because it combines images taken over a year apart; however, it is instructive because it reveals the relationship between the topography and the E26 color.

Careful inspection of the merged image product shows that the bright red linear feature visible in the E26 color connects with one of the main fissures running through the mountain. This red linear feature is aligned with the original Voyager flows or fissures which were visible in Figure 2.19. Most likely, they are an expression of the tectonic weakening and faulting of the crust in this area which allowed the formation of the mountain, and provided a conduit for lava to reach the surface at this location. Turtle et al. (2000) have noted a striking association between some mountains and calderas on Io, which suggests a genetic relationship. The red fissure could mark the vent for the flows. The dark, Voyager-era, linear features perpendicular to the fissure
can be seen to be aligned with the base of the mountain, and could be flows left from a previous eruption that lapped up against the base of the mountain. The new flows seem to have flowed down away from the mountain, toward and into the caldera.

The puzzling white patch to the north of Pillan, which disappeared when it was covered by the C10 dark Pillan plume deposit, only to reappear again in the same location, becomes more understandable when observed in the combined image of Figure 2.25. The white patch corresponds to the flat plateau to the north of the mountain. Perhaps the white patch is formed by outgassing of SO$_2$ due to sapping at the base of a cliff. The source for this SO$_2$ could either be the northern scarp of the mountain, or the northwestern scarp of the plateau itself. The white patch may be slightly sheltered from the competing red Pele plume deposit by the mountain, but it is also possible that the prevailing pressure from Pele has blown the white material radially away from Pele, causing it to cover the plateau.

A high-resolution strip of images of the new Pillan lava flows was acquired on orbit 124. Unfortunately, these images suffered from the scrambling that affected most of the 124 high-resolution images, but a clever reconstruction algorithm (McEwen et al. 2000) has managed to restore many of these images. The scrambled images were taken at a resolution of 19 meters per pixel. A single, partial, full-resolution (unscrambled) frame was also taken at Pillan, at a resolution of 9 meters per pixel. Since the best context for these images is the 2 km/pixel E14 image in Figure 2.25, it has proven extremely difficult to mosaic these high-resolution images into context. Figure 2.26 shows the original targeting plan for this observation. It is unlikely that the pointing was off by
more than a frame in any direction, so this provides an approximate guide to the location of these images within the context. Figure 2.27 shows a preliminary mosaic of most of the 124 high-resolution Pillan images.

The PPR scan of the same observation (Spencer et al., 2000b) shows that the material in the central, darker region is significantly warmer than the brighter material to the right, suggesting that the warm, dark material is the most recent flow. The dark, central region has the right size to be a transect across the new flows, and appears to have channel-like margins. The texture of the flows is hummocky and platy, with areas of large pits and other areas with smooth channels, lava tubes, or flow margins. The jumbled, incoherent nature of this flow is consistent with its extremely rapid formation, likely over days or weeks. This type of flow is not obviously related to any type of terrestrial lava flow, but there are some possible similarities to the flood lavas on Mars and the most rapidly emplaced parts of the Laki Flow Field in Iceland (Keszthelyi and McEwen, 2000; Keszthelyi et al., 2000). These analogs suggest an open sheet flow, which is supported by the platy-ridged texture of the high-resolution images.
Figure 2.26: This is the targeted location for the high-resolution strip of images of Pillan taken on I24. The images were targeted to cover the region of new lava flows, north of the caldera. Pointing and targeting uncertainties could result in the actual location of the image mosaic (Figure 2.27) being off by as much as a frame in any direction.
Figure 2.27: This image shows a preliminary mosaic of most of the 124 high-resolution Pillan images. Note the dark central region surrounded by linear features, which is interpreted to be an open lava channel. This dark central region was found to be warm in the PPR data (Spencer et al., 2000b). The mosaic is composed of inverse scrambled 124 images, and the dark vertical stripes, sharpness, and brightness variations are artifacts which remain from the scrambling. See the text for more details.
The diffuse nature of the dark Pillan deposit, and the fact that it has the same size and location as the plume observed on orbit C9, suggests that the deposit consists of plume fallout. Given the dark nature of the deposit, a thickness of only a few microns of dark material is needed to produce the observed coloration. The deposit could be made up of silicates, or monatomic sulfur, both of which could appear black. However, the extremely high temperatures observed for the Pillan eruption, between 1700K and 2000K, are much higher than the boiling point of sulfur in a vacuum, suggesting an ultramafic silicate composition (McEwen et al., 1998b). This was confirmed by Geissler et al. (2000) who measured the .889 micron absorption in the Pillan dark pyroclastics, suggesting silicates rather than sulfur.

Given the Pillan deposit’s location in the fallout zone of the Pele plume, it is likely that much of the observed disappearance of the deposit is due to burial from the Pele plume and the new plume at Kami-Nari which flank the Pillan deposit. The fact that the plume deposit has almost completely faded by E26, but that the new dark flows remain clearly visible, could indicate that the flows have remained warmer (perhaps because they are thicker), and thus resist burial by volatile plume fallout. This was confirmed by the Spencer et al. (2000b) PPR measurements of the Pillan flows, which showed them to be warmer than background areas. The timescales for various removal processes will be discussed in a later section.
2.3.5: Prometheus

A consistently bright plume has been seen at Prometheus, located at $-2^\circ$ N, $153^\circ$ W, dating back to the Voyager observations in the late 1970's. The first Galileo images of Prometheus on orbit G2 revealed that in the intervening years, a large, new, dark surface flow had appeared, and that the plume source location changed to a new location approximately 85 km west of its 1979 position. No continued motion in the location of the plume source or the end of the lava flow has been observed during the Galileo tour. The Prometheus plume is especially bright, and has been imaged successfully on every attempt to observe it by Galileo. Hot spots have been seen by both SSI and NIMS at Prometheus on various orbits (Table 2.6; Lopes-Gautier et al. 1999). New Galileo images have shown a continued sequence of activity at Prometheus, and new, high-resolution images have begun to reveal the detailed workings of this volcano. The changes at Prometheus are summarized in Table 2.6.

Table 2.6. Table of observations, changes seen at Prometheus

<table>
<thead>
<tr>
<th>Observation</th>
<th>Date</th>
<th>Appearance or changes</th>
<th>Plume?</th>
<th>Hotspot?</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voyager 1</td>
<td>1979</td>
<td>Prominent plume with dark arms, bright / dark halo</td>
<td>yes</td>
<td></td>
<td>McEwen 1988</td>
</tr>
<tr>
<td>Voyager 2</td>
<td>1979</td>
<td>Plume similar to VGR1</td>
<td>yes</td>
<td></td>
<td></td>
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<tr>
<td>Galileo G1</td>
<td>6/28/96</td>
<td>Yes – SSI eclipse</td>
<td>Yes –</td>
<td>Yes – NIMS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Observations</td>
<td>Yes/No</td>
<td>System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
<td>----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/6/96</td>
<td>New dark lava flow; plume vent migrated 70 km west of Voyager position; Voyager plume vent at &quot;elbow&quot; of new flow</td>
<td>yes</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11/6/96</td>
<td></td>
<td>yes</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/18/96</td>
<td></td>
<td>yes</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/20/97</td>
<td>Red deposit visible to east of Prometheus</td>
<td>yes</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/3/97</td>
<td></td>
<td>yes</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/7/97</td>
<td></td>
<td>yes</td>
<td>no</td>
<td></td>
<td></td>
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<tr>
<td>6/27/97</td>
<td></td>
<td>yes</td>
<td>Yes - NIMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/18/97</td>
<td></td>
<td>yes</td>
<td>Yes - NIMS, not SSI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11/7/97</td>
<td></td>
<td>yes</td>
<td>Yes - SSI Eclipse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/29/98</td>
<td>Red deposit less diffuse than E6. darker, closer to vent</td>
<td>yes</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/2/99</td>
<td>Highest-resolution to date, 3 small flows at Northern end</td>
<td>yes</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10/11/99</td>
<td>Caldera at NE corner of flow; new dark material at N. edge of central flow region; new plume material from source vent on eastern edge, no .9 micron abs.</td>
<td>yes</td>
<td>NIMS high-res: 3 hotspots W. plume vent, E. lava vent, central deposit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/22/00</td>
<td>Changes in dark patches on surface of flow since 124 hires</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.28: This image shows the appearance of Prometheus and Culann in Voyager and in Galileo. The Galileo colors have been synthesized to match the Voyager wavelengths. A new dark lava flow has been emplaced at Prometheus, and the plume vent has moved 70-90 km west of the Voyager location. A new dark flow has been emplaced at the northern part of Culann as well, and the distribution of red material (which appears brown at these wavelengths) has also changed.
Figure 2.28 shows the Voyager and Galileo views of Prometheus, with the Galileo color synthesized to match the Voyager wavelengths. The new, dark flow which has appeared in the intervening 20 years extends west from the Voyager-era plume center to the center of the current plume deposit, about 70-100 kilometers. We believe that the flow originated at the eastern end and flowed to the west. This is consistent with the creation of the Prometheus plume by the movement of the lava flow over the bright, SO₂-rich plains. Kieffer et al. (2000) suggested that the lava melts and vaporizes the volatiles beneath it, which escape in a stable plume through a rootless conduit located about a kilometer back from the active flow front.

Figure 2.29 shows the clear-filter Voyager and Galileo C3 images of Prometheus. Care must be taken when comparing these images because of the very different bandpasses of the Voyager and Galileo clear filters: the Voyager clear filter is weighted to much shorter wavelengths than the Galileo clear filter. These images are useful geometrically, however, to compare the locations of features. Careful inspection of the ratio image in Figure 2.29 indicates that the source of the Voyager-era plume (the center of a circle fit to the plume deposit) is located near the "elbow" of the Galileo-era dark surface flow. There is no evidence of the Voyager-era, dark, linear feature extending below this "elbow" in the Galileo image, so either the southern portion of the linear feature is a dark plume spoke (similar spokes are visible in the Galileo image), or it was a surface deposit which has been completely obliterated by plume deposits in the 20 intervening years.
Figure 2.29: This image shows the Voyager and Galileo C3 clear-filter views of Prometheus. Although the central wavelengths of the two clear filters are quite different, geometric registration can be used to compare the location of the Voyager and Galileo plume vents. The Voyager plume vent is located just above the "elbow" in the new dark Galileo flow, at the southeastern corner. The plume vent has moved 70-90 km over the 17 years between these observations.
Figure 2.30: This image shows a sketch map of the Voyager and Galileo plume vent and lava flow locations. The image on the left shows the Voyager-era plume vent, lava flow, and plume deposit. The image on the right shows the new Galileo plume vent, lava flow, and plume deposit. The plume deposit has a very similar shape and size to the Voyager one, but has changed location. The new Galileo flow extends west from near the Voyager plume vent location. The image in the center superimposes the two stages in the appearance of Prometheus, to illustrate the relationships.
Figure 2.30 shows a schematic diagram comparing the Voyager appearance of Prometheus to the Galileo appearance. The Voyager image, on the left, shows the dark lava flows, the plume source, and the plume deposit. The Voyager plume source is near the end of the lava flows. The Galileo view, on the right, shows that the new lava flows have proceeded west from the Voyager location, and that the new plume vent is located near the end of the new flows. This is consistent with the Kieffer et al. (2000) plume model, for in both cases the plume source location is near, but not at, the active flow front. We believe that the lava ponded in the Voyager location due to a topographic obstacle, and that enough lava built up at some point in the 17 years between Voyager and Galileo for the lava to resume flowing to the west. The Galileo appearance of Prometheus shows that the lava has again ponded due to topography, and has built up a stable reservoir of volatiles to drive a plume very similar to the Voyager one.
Figure 2.31: This image shows the appearance of the area including Prometheus, Culann, and Zamama on orbits E6 and E14.
Figure 2.32: This image shows the ratios in all three bands of the images from orbits E6 and E14 from figure 2.31. Note that substantial changes are apparent near Prometheus and Zamama, but that little change is apparent near Culann.
Comparisons of color images of Prometheus taken on Galileo orbits E6 and E14 show a concentration of the red material venting from the eastern end of Prometheus, as visible in Figure 2.31. Figure 2.32 shows the ratios of these cutout regions. Note that substantial changes have occurred at Prometheus and Zamama, and lesser changes have occurred at Culann. Zamama and Culann will be discussed later. Figure 2.33 shows ratios of the three individual bands for a cutout region over Prometheus, and illustrates how the red material is less diffuse in the E14 images: it is darker than in the E6, and is also concentrated closer to the vent location. A brightening of the area to the southeast of the main dark flow is also visible in the ratios, as is the appearance of a bright circle in the violet image surrounding the main circular plume deposit. A bright lobe in the violet ratio image is visible to the northeast of Prometheus. This could be a new SO$_2$ deposit, perhaps associated with the same increased plume activity which resulted in an increased concentration of red material closer to the vent. The source for the red material is the vent located at the eastern end of the Prometheus flow complex, north of the Voyager-era plume vent. The red material, when vented from this location, is blown to the east by the prevailing pressure of the main Prometheus plume. We believe that the red material marks the lava vent, where silicate lavas reach the surface and then flow through channels to the active front, where they drive the main SO$_2$ plume (McEwen et al., 2000). This vent is marked with a * in Figure 2.30. A caldera is located at the northern end of the Voyager and Galileo flows, and will be discussed later in this section. The lava vent is located to the south of the caldera.
Figure 2.33

3-color  NIR  green  violet

E6

E14

t ratio
Figure 2.33: This image compares the appearance of Prometheus on orbits E6 and E14. Changes are apparent in the location of the deposit of red material, and in the structure of the plume deposits. There is also a 12-degree difference in phase angle between the two observations, which could influence the appearance of various surface features.
Comparisons of the color E14 and C21 images reveal a variety of new features not visible in the lower-resolution E14 view of the area. Figure 2.34 compares the E14 and C21 views of Prometheus. Visible first is the change in plume deposit structure. Inside the bright outer plume deposit, the E14 plume deposit has a distinct dark inner ring, which is bounded on the inside by a bright region. In the C21 image, the dark inner region remains mostly dark, without the bright areas close to the flows that were visible in E14. Also visible for the first time in the C21 image are three small, finger-like flows extending from the top, right, dark region of the Prometheus flow. Examination of the E14 image reveals that these flows were likely present in that image as well, but were close to the limit of resolution. In the E14 image, the eastern portion of the flow is surrounded with a bright halo of material that could be a plume deposit; this bright region is not present in the C21 image. The red deposit visible in the E14 image is also visible in the C21 image, but has moved closer to the main Prometheus flow, and slightly to the north. The C21 image also shows a diffuse region in the center of the eastern part of the flow, which could be the source vent for the red material. The combination of less structure in the plume deposit and the red material closer to the vent suggest that the Prometheus plume could have been less active in C21 than it was in E14.
Figure 2.34: This image compares the appearance of Prometheus on orbits E14 and C21. The large difference in phase angle (Table 2.2) makes direct ratios misleading, but general differences in the distribution of red material are obvious.
Figure 2.35: This image compares clear-filter views of Prometheus from orbit C21 with I24. A new dark diffuse deposit of material is visible in the I24 image and in the ratio images near the top central portion of the flows. A similar dark region is also visible to the right of Prometheus, some of which could be airborne plume material and some of which could be a new plume deposit.
Comparisons of clear-filter images taken on orbits C21 and I24 also show continued activity at Prometheus (Figure 2.35). A new dark deposit is visible just north of the central part of the dark lava flows in the ratio image, where it appears as a dark hump. This material is interesting because it does not seem to originate at either the plume vent or the eastern red vent. It could be a breakout of new material from the edge of the main lava flow, but the diffuse appearance of the material suggests that it is a new dark plume deposit. A new dark wing of material is also visible in the I24 image east of the caldera and flow. This material could be part of an active plume rather than a surface deposit. The source of this material seems consistent with the source of the red material mentioned in the E6/El4 comparisons in Figure 2.33. Thus, this material is ejected from the lava vent. The C21 image is also the first high-resolution image of Prometheus to resolve the three small finger-like lava flows emanating from the caldera. These flows are also present in the I24 image, but are covered by the active plume (or plume deposit).

Orbit I24 also produced a number of high-resolution observations of Prometheus. Unfortunately, many of those images were scrambled, as in the case of Pillan (as discussed previously). However, the few unscrambled images revealed that the northern lobe of the Prometheus flow is in fact a caldera (Figure 2.36). The caldera is the dark bean-shaped feature at the top of the high-resolution images, and is 28 kilometers long and 14 kilometers wide. The sharp albedo boundary suggests a scarp at the edges of the caldera. The three small finger-like flows first resolved in the C21 images are clearly visible in the high-resolution image, and could have been formed
when the caldera filled up with lava which then spilled out over the western rim. The probable vent location for the red material is just to the south of the high-resolution image, so we have not directly imaged a plume vent in this observation. The new region of dark material noted in the low-resolution C21 – I24 comparisons in Figure 2.35 is also visible at the lower left corner of the high-resolution image as a dark, diffuse deposit.

**Figure 2.37:** This image shows the NIMS high-resolution I24 data on top of the I24 images. There are three visible hotspots: one at the western plume vent, one at the eastern lava vent, and a third, fainter hotspot at the new deposit of material at the top central, as seen in Figure 2.35.
Figure 2.36: This image shows the Prometheus caldera in merged .756 and .889 micron images from orbit 124. The caldera is located at the top right part of the Prometheus flow complex. Small flows are visible which seem to originate at the caldera. The suspected source of the red material (and the potential lava vent) is located just off the bottom edge of this image.
NIMS data from orbit 124 provided a high-resolution view of the hot spots at Prometheus. Three hot spots are visible in Figure 2.37, which has the NIMS data overlain on the high-resolution 124 data merged with the lower-resolution 124 context image. The brightest, main hot spot is located at the western end of the flow, at the main plume source. This hot spot, and the vigor of the sustained Prometheus plume from this location, suggests that the lava at this end is the site of continued activity, or at least continued heating. Two other hot spots are also visible, one associated with the lava vent below the caldera which is the source of the red material, and the second located near the new dark deposit described above.

Near-infrared high-resolution color observations of the Prometheus caldera on orbit 124 have revealed no sign of the 0.889 micron absorption seen at so many other dark hotspots and calderas on Io (Geissler et al., 2000). This is consistent with earlier spectra from orbit E14, but since the E14 images were at a much lower resolution, the possibility of a spatially-smaller region with the 0.889 micron absorption was still possible until the 124 images were analyzed. The lack of a 0.889 micron absorption implies that the magnesium-rich orthopyroxene seen elsewhere on Io is not exposed within the caldera. Geissler et al. (2000) suggest that this could either be due to a compositional heterogeneity, meaning that the Prometheus lava is compositionally distinct from lavas elsewhere on Io, or that the caldera is coated with a veneer of material which masks the characteristic absorption. Since the caldera is not the site of a current hotspot, it could be cool enough for a thin layer of SO₂ frost to stick, masking the absorption.
A synthesis of these different datasets has resulted in a new understanding of the processes occurring at Prometheus. Most likely, the magma is stored in an underground chamber beneath the caldera at the northeastern end of Prometheus. The lava reaches the surface about 15 kilometers south of the caldera, at a point marked by the blue, eastern hot spot in the temperature map and by the bright red deposit visible in Figure 2.33. This location is marked with a * in Figure 2.30, and is also marked in Figure 2.38. From this volcanic vent, the lava travels almost 100 kilometers through lava tubes or insulated sheets to the front of the flow. The exposed liquid lava produces the large, high temperature area on the western end of Prometheus. The source of the 100 kilometer tall Prometheus plume is somewhere within this western end. A plume source midway along the tube forms the faint (purple) hot spot visible in Figure 2.37, which could be associated with a breakout from the middle of the lava tube. This breakout appears to have taken place within the three month period between C21 and I24, spreading a new dark diffuse deposit to the north of the older lava flows. It also appears that the gas discharge from the volcanic vent at the eastern end of the flow has increased between C21 and I24, as visible in Figure 2.35. There is a new fan of dark material streaming out from this location. Furthermore, the new, bright, crescent-shaped deposit across the middle of Prometheus suggests that the main (western) plume has been pushed aside by the increased gas release to the east. A geologic map of the Prometheus area, which combines the synthesized views of Prometheus from SSI and NIMS, is visible in Figure 2.38 (by Laszlo Keszthelyi).

We also have a new high-resolution image of Prometheus from orbit I27 which
supports the interpretation that small breakouts of new, dark lava form on the surface of the main flow complex. When we compare the I27 image to a mosaic of the scrambled high-resolution I24 images of the same area, taken 4 months earlier (Figure 2.39), we see significant changes in the distribution of the dark patches within the main flow complex. These dark patches are interpreted to be the youngest, hottest flows, which are warm enough that volatiles from the Prometheus plume are not stable on their surfaces, keeping their albedos dark. The changes in the locations of the dark patches indicate that over this 4 month period, the Prometheus lava flows have continued growing by the process of repeated small breakouts of lava at various locations within the flow complex. Patches which were dark in the I24 image can be seen to have faded in the I27 image, probably as a result of cooling of the flows, allowing volatiles to remain on their surfaces which raises their albedo. The new dark patches in the I27 image appear to extend from the fading I24 flow patches, indicating that the formerly-active flows have extended.

These changed dark patches are concentrated near the western end of the main Prometheus flow, near the plume source. Interestingly, we do not see any evidence in the I27 image of a plume vent or source. One possibility is that this source, if it is similar to the pseudocraters described in Kieffer et al. (2000), is small enough not to be visible in this image. Since the image resolution in I27 is about 200 meters per pixel, a source up to 500 or so meters in diameter could be missed.
Map of *Prometheus* Volcano and Surroundings, Io

**Figure 2.38:** This is a geologic map of the Prometheus flow complex by Laszlo Keszthelyi. The image presents a combined view of the Galileo appearance of Prometheus, from our combined SSI and NIMS observations. The two separate vents are visible, each of which corresponds to a NIMS hotspot. The western vent is the source of the active plume, and the eastern vent is thought to be the vent for the lava and the source of the diffuse red deposits.
Figure 2.39: This image compares the appearance of Prometheus in a mosaic of two scrambled frames from Orbit 125, and in a single frame from 127. Both observations are in the green filter; the 125 at 110 m/pixel and the 127 at 200 m/pixel. Artifacts are visible in the 124 mosaic resulting from the inverse scrambling process. These artifacts include the brightness variations and the smooth gray smeared regions. Changes are visible in the appearance of some of the dark flows within the flow complex: dark, active regions in 124 have likely cooled and been covered with plume materials, and new extensions of these dark areas are visible in the 127 image.
With this new understanding of the morphology of the Prometheus flow and caldera, we can reexamine the Voyager appearance of this area. Figure 2.29 reveals that the caldera was present during Voyager as well – it is the dark rounded feature at the northern end of the dark Voyager-era flow. Figure 2.30 shows our interpretation that at the time of Voyager, there was a caldera to the north, and a southern plume source. The Voyager flow could have originated at or near the Galileo lava vent, flowing north to fill the caldera, and flowing south until it eventually ponded and produced the stable plume observed during Voyager. This configuration is visible on the left in Figure 2.30. Sometime during the 17 years between Voyager and Galileo, the lava flow overcame its topographic obstacle and continued flowing, this time to the west. It ponded again, producing the necessary conditions to form the stable plume seen during Galileo.

2.3.6: Culann

The changes at Culann are summarized in Table 2.7. Culann is located at −20° N. 160° W. No plume was seen at Culann by Voyager, but a darkening was observed near Culann in Voyager – HST comparisons from 1994 (Spencer et al., 1997a). Tentative plume detections were made at Culann on orbits G1 and G2, but no plume was seen on later orbits, suggesting that plume activity might have decreased over this time period. Hot spots have been seen at Culann by NIMS on various orbits, but no hot spot has been seen at Culann in the SSI eclipse images (Table 2.7; Lopes-Gautier et al., 1999). Significant surface changes are visible when comparing Voyager and Galileo images of the area, and the bright red material is indicative of recent activity. Comparisons of
Galileo images taken throughout the mission show subtle changes, and a high-resolution color observation from orbit 125 has revealed the complexly colored morphology of its flows and plume deposits.

**Table 2.7. Table of observations and changes seen at Culann**

<table>
<thead>
<tr>
<th>Observation</th>
<th>Date</th>
<th>Appearance or changes</th>
<th>Plume?</th>
<th>Hotspot?</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voyager I</td>
<td>1979</td>
<td>Diffuse central region</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HST</td>
<td>1994</td>
<td>Darkening in Culann area</td>
<td></td>
<td></td>
<td>Spencer <em>et al.</em> 1997a</td>
</tr>
<tr>
<td>Galileo G1</td>
<td>6/28/96</td>
<td></td>
<td>maybe</td>
<td>Yes -</td>
<td>NIMS</td>
</tr>
<tr>
<td>G2</td>
<td>9/06/96</td>
<td></td>
<td>maybe</td>
<td>Yes -</td>
<td>NIMS</td>
</tr>
<tr>
<td>C3</td>
<td>11/06/96</td>
<td>Southern Voyager-era red deposits have faded? Clear-filter only</td>
<td></td>
<td>Yes -</td>
<td>NIMS</td>
</tr>
<tr>
<td>E6</td>
<td>2/20/97</td>
<td>Color obs. confirms fading of red voyager deposits</td>
<td></td>
<td>No? (poor obs)</td>
<td></td>
</tr>
<tr>
<td>G7</td>
<td>4/3/97</td>
<td></td>
<td>no</td>
<td>No?</td>
<td></td>
</tr>
<tr>
<td>G8</td>
<td>5/7/97</td>
<td></td>
<td>no</td>
<td>Yes -</td>
<td>NIMS, no SSI</td>
</tr>
<tr>
<td>C9</td>
<td>6/27/97</td>
<td></td>
<td>no</td>
<td>Yes -</td>
<td>NIMS</td>
</tr>
<tr>
<td>C10</td>
<td>9/18/97</td>
<td></td>
<td></td>
<td>Yes -</td>
<td>NIMS, no SSI</td>
</tr>
<tr>
<td>Code</td>
<td>Date</td>
<td>Description</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E14</td>
<td>3/29/98</td>
<td>New deposits of red material at western and eastern ends of red deposit.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C21</td>
<td>7/2/99</td>
<td>Fading of red material near Tohil, and to northeast; new red material to north.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I24</td>
<td>10/11/99</td>
<td>Brightening to NW and SE could be fading of red material; only clear filter comparisons.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I25</td>
<td>11/26/99</td>
<td>High-resolution color shows lava tube. greenish caldera. central region was much darker and redder in Voyager. continued motion of western edge of red lobe. new red deposits north of caldera. eastern red deposits faded substantially.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.28 shows the appearance of Culann in Voyager and Galileo color images, with the Galileo color synthesized to better match the Voyager wavelengths. The regions that have a dark, diffuse appearance in the Voyager color view correspond to deposits of bright red material, probably a pyroclastic deposit (McEwen et al., 1998a), which Voyager was not sensitive to. The Voyager-color views show that this material covered much of the central part of Culann during Voyager, and that now this material is located below the Culann flow complex. It also appears that a new dark flow has formed at Culann between Voyager and Galileo, located in the northwestern portion of the Galileo flow complex.

Figure 2.40 compares the appearance of Culann in Voyager 1 and Galileo C3 clear-filter images. Recall that the clear filter images are poorly matched in wavelength, but at least allow geometric comparisons. In the C3 image, the southern part of the dark, diffuse (red) Voyager deposit has faded, resulting in the bright region in the ratio image. A new dark linear flow is visible at the northwestern part of Culann. This region appears dark in the ratio image. The dark flow at the southern end of the Voyager image of Culann appears absent in the Galileo image, but could be covered by the plume deposit. We will reexamine this missing flow in the higher-resolution I25 view of Culann.
Figure 2.40: This image compares the appearance of Culann from Voyager and Galileo C3 clear-filter images. Despite the difference in wavelength, changes are visible in the distribution of flows. A new dark flow is visible at the northwest corner of the Culann flow complex.
Figure 2.31 and Figure 2.32 show the appearance of Prometheus, Zamama, and Culann on orbits E6 and E14. These images were taken at 24 and 36 degrees phase, respectively (Table 2.2), and the difference in phase angle could result in photometric variations in the appearance of the surface. Note also the resolution difference apparent in these two views of Culann. The changes at Culann are less obvious than those at Zamama and Prometheus, but the ratios do show changes in the lobe of red material to the south of Culann. Figure 2.41 shows a cutout around Culann on orbits E6 and E14, and the ratios of each of the three bands. Some apparent changes visible in the ratio images are simply due to the resolution difference: the coregistration procedure resamples the images to reduce the resolution, but in this case even after coregistration there is a clear resolution difference. Some changes, however, are real. Most obvious in the ratio images are the changes in the appearance of the bright red deposit to the south of Culann. New deposits of red material are visible at the western and eastern edges of the red deposit, and these are shown clearly in the color composite ratio image. The two red arcs show where the surface has darkened in the green and violet filters, as a result of the new red material. The central portion of the deposit has remained relatively unchanged. Despite the difference in phase angle, we believe that these are real changes in the appearance of Culann's red deposits, as only the outer portions of the deposit have changed.
Figure 2.41: This image shows a cutout around Culann from orbits E6 and E14. New lobes of red material are visible in the E14 image, and appear in the color composite ratio image.
Figure 2.42: This image compares the appearance of Culann from orbits E14 and C21. Despite the large difference in phase angle, some new deposits of red material are visible at the top of the C21 image, and fading of the eastern lobe of red material is also visible in the C21 image.
Figure 2.42 shows the appearance of Culann on orbit E14 as compared to orbit C21. The phase angle difference (Table 2.2) between these two observations is clearly visible in the differing appearance of the surface; however, again some real changes are also apparent. The red material between Culann and Tohil, at the lower right, has begun to fade in the C21 image, which shows a decreased concentration of red material in between the two features. The C21 image also shows that the red material to the northeast of Culann is fading as well, and is newly-concentrated closer to Culann itself. New wisps of red material are visible to the north of Culann, as well. Thus, we have evidence for the emplacement of new red deposits, and the fading of deposits which were present on previous orbits. The apparent contrast reversals of several features in the northwest corner of the image are likely just due to the differences in phase angles between the two observations. Also note the difference in the appearance of the red plume located at the small dark caldera to the southwest of Culann.
Figure 2.43: This image compares the clear-filter appearance of Culann from orbits C21 and I24. A darkening is visible in the region at the top right of the flow complex, and could represent the location of active flows.
Figure 2.43 shows a comparison of the appearance of Culann on orbits C21 and I24 in clear-filter images. The red material which is so prominent in the color images just appears as an intermediate gray in these clear-filter images, making determination of changes more difficult in this case. The ratio image does show some brightening in the dark flows to the northwest of Culann, but this could also just be a slight calibration error. Since dark regions of the surface have very low DN’s, when they are ratioed very small differences in calibration are amplified could result in large apparent differences. We also see the brightening of a region to the southeast of Culann in the formerly red plume deposit. This could be due to the fading of the red material in this region. This fading was confirmed in the next color view of Culann on I25 (Figure 2.44). Also visible in the ratio image is a diffuse darkening to the north of the central Culann flows. This is likely a new plume deposit, as there is no apparent change in the shape or size of the dark flows themselves.
Figure 2.44: This image shows a high-resolution color view of Culann from orbit 125. The caldera is visible as the greenish region in the center of the flows. Old flows have been covered with red material, and fading and motion of the red plume deposits is also visible. North is to the left in this view, and the gray areas are missing data.
Figure 2.44 shows a high-resolution color view of Culann from orbit I25. This view, acquired in the red, green, and violet filters, is the highest-resolution color view of Io’s surface. It clearly reveals the complex morphology of the flow features at Culann. Discernible for the first time is the Culann caldera, which appears as the greenish feature at the center of the image. The irregular shape of the caldera suggests a series of collapse events. The western margin of the caldera is smooth, suggesting a scarp, while the eastern edge blends into a series of dark flows that could have resulted from an overflow of lava from the caldera. Leading to the north from the caldera, into the dark flow complex, is a dark, sinuous feature interpreted to mark the top of a lava tube feeding the dark western flows. The lava tube is dotted with red, wispy material which could be sulfur venting from the tube. The dark northwestern flows exhibit complex mottling and convoluted lobes which could indicate a series of breakouts.

Comparison of the I25 high-resolution color image to the appearance of Culann in the Voyager and E14 images reveals many changes. In comparing the Voyager appearance of Culann to that during I25, we see that the lobes of dark and bright flows to the southeast of the Culann caldera on I25 were part of the dark central region in Voyager. Either this flow area was covered with red material after Voyager and before 1996, or these flows were significantly darker at that time. Careful analysis of the Voyager and I25 images reveals that the location of the missing dark Voyager flow is covered with red material in the I25 image, but subtle traces of the old flow are visible just to the south of Culann within the red deposit. The Voyager-era dark western flow has also been covered with material in the intervening years, and is visible as the fainter
flow beneath the new dark flow lobe to the west. Comparison of the E14 and I25
Culann images reveals a continuation of the motion of the red lobe to the west, as seen
in the E6 / E14 comparisons in Figure 2.41. Red material is also visible just to the north
of the caldera in the I25 image, where no red material appears in the E14 view. The red
deposits to the east of Culann in the E14 image appear to have faded substantially – that
region of the surface appears yellow-orange in the I25 view rather than the bright red
appearance it had in E14.

Culann does not possess a bright, structured, circular plume deposit like Prometheus
and many other active volcanic centers. There is a vaguely circular, bright, yellowish
deposit visible to the northeast and southwest of the caldera in the E6 and E14 views
(Figure 2.41). The substantial red deposit could be vented from near the central caldera,
and pushed out mostly to the southeast by a larger SO$_2$ plume (if it existed). The motion
of the red deposits could indicate variations in the size, strength, or direction of the
potential SO$_2$ plume, and of the venting of the red material itself. The fading of the red
deposit to the east of Culann between orbits E14 and I25 suggests that the red material
can fade over a timescale of less than a year if not constantly replenished. The burial of
the Voyager-era flow to the south of Culann over 20 years implies that at least a meter
of plume material was deposited in that time period, requiring a rate of at least 5
cm/year. This is consistent with some of the plume depositional rates discussed in
Section 2.5.
2.3.7: Zamama

The changes at Zamama are summarized in Table 2.8. A new plume and hotspot were first seen at Zamama, located at 18° N, 173° W, on Galileo orbit G1, and surface changes including a new dark flow complex were seen on orbit G2 (McEwen et al. 1998a). Figure 2.45 compares the appearance of the Zamama region during Voyager to Galileo, again in synthesized Voyager colors. The new dark linear feature is about 150 kilometers long, and could be a fissure-fed flow complex. A plume and SSI eclipse hotspot were also seen at Zamama on orbit E11 (Table 2.8).

Table 2.8. Table of observations and changes seen at Zamama

<table>
<thead>
<tr>
<th>Observation</th>
<th>Date</th>
<th>Appearance or changes</th>
<th>Plume?</th>
<th>Hotspot?</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voyager 1</td>
<td>1979</td>
<td>Featureless plain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galileo G1</td>
<td>6/28/96</td>
<td>New surface flow, 150 km long, since Voyager</td>
<td>yes</td>
<td>Yes - NIMS</td>
<td>McEwen et al. 1998a</td>
</tr>
<tr>
<td>G2</td>
<td>9/6/96</td>
<td>Red material to west of flows</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>11/6/96</td>
<td>Red material to west of flows</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>12/18/96</td>
<td>Red material to west of flows</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E6</td>
<td>2/20/97</td>
<td>Red material to west of flows</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G7</td>
<td>4/3/97</td>
<td>Red material to west of flows</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G8</td>
<td>5/7/97</td>
<td>Red material to west of flows</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C9</td>
<td>6/27/97</td>
<td>Red material to west of flows</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C10</td>
<td>9/18/97</td>
<td>Red material to west of flows</td>
<td>yes</td>
<td>Yes - SSI</td>
<td></td>
</tr>
<tr>
<td>E11</td>
<td>11/7/97</td>
<td>yes</td>
<td>Yes - SSI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Event</td>
<td>Details</td>
<td></td>
<td></td>
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<td>------</td>
<td>-------</td>
<td>---------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E14</td>
<td>3/29/98</td>
<td>Red material moved closer to flow at W. end, new bright plume deposit to NW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C21</td>
<td>7/2/99</td>
<td>Western end has radial flows</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I24</td>
<td>10/11/99</td>
<td>New bright arc-shaped plume deposit to north formed since C21, brightening in western end of flow. High-res obs reveal flow margins</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.45: This image compares a color view from Voyager and Galileo (in synthesized Voyager colors) of the Zamama region. Note that what was featureless plains during Voyager was the site of a new lava flow sometime over the 17 years between the two observations.
Figure 2.46: This image compares Zamama on orbits E6 and E14. Increased plume activity is evident in the E14 image as the diffuse, blue-colored region in the center of the flows. Motion in the location of the red deposit to the west of Zamama is also apparent.
Figure 2.46 shows a grid of images comparing the appearance of Zamama on orbit E6 with that on E14. Changes are visible in the distribution of red material at the western end of the flow complex, where the red material appears more concentrated close to the flow. The ratio images reveal a darkening in the lobe at the western end, which could be the source of the red material. Also visible is a brightening in the green and violet filters that could be a new plume deposit to the northwest of Zamama. If the red material is entrained in this plume, the source of both could be the newly darkened lobe at the western end of Zamama. The diffuse nature of the appearance of the central portion of the Zamama flows indicates that we could be viewing the surface through an active plume, which is obscuring the details of the flows.

Figure 2.47 compares the appearance of Zamama during orbit E14 with that during orbit C21. The phase angles of the two images are quite different (Table 2.2), which results in some of the contrast reversals visible on the surface. If the E14 image had a fuzzy appearance from viewing the surface through an active plume, this plume is no longer active at the same level in the C21 image. The radial spokes of material pointing south from the main dark flow in the E14 image appear to be spokes of the plume: there is no trace of these features as surface deposits in the C21 image. The C21 view of the surface also reveals that the red material is much more copious, extending almost all the way to the end of Volund. The strong E14 plume could have distributed this material over a large area.
Figure 2.47: This image compares Zamama on orbits E14 and C21. Despite the large difference in phase angle (Table 2.2), some changes in the location and appearance of the red deposit are likely real. The diffuse blue-colored region in the center of the E14 image, which could represent the active plume vent, is not visible in the C21 image.
The appearance of the red material in the C21 image of Zamama is quite similar to that in the E6 view in Figure 2.46. The E6 image is at a phase angle of 24 degrees, the C21 image is at a phase angle of 5 degrees, and the E14 image is at a higher phase angle of 36 degrees. Thus, it is possible that the similarities between the E6 and C21 appearance of Zamama are just due to their lower phase angles, and that the E14 appearance was an artifact of the higher phase angle on that observation. However, since the plume was visibly active at Zamama on orbit E14, it is more likely that the E6 and C21 views of Zamama show its appearance during a period of lesser plume activity, and that the E14 appearance, particularly of the western red deposit, is simply due to plume activity. Once the plume decreased its activity between E14 and C21, the red material returned to its usual position to the west of Zamama, extending up to near Volund. The bright yellow-white region to the southeast of Zamama on orbit C21 could also be a new plume deposit from the E14 period of activity.

Zamama was also observed in a set of matched stereo observations through the clear filter on orbits C21 and I24. Figure 2.48 shows a comparison of the region surrounding Zamama on the two orbits. The new bright arc of material visible in the I24 image to the northwest of the main dark flow appears to be a new plume deposit, perhaps due to continued or renewed plume activity at Zamama. The ratio image shows the brightening of this plume deposit area, as well as darkening of a lobe of material near the center of the flow. The diffuse nature of this newly-darkened area suggests that it could be the vent for the plume which has produced the new bright deposit. This area also corresponds to a warm region seen in the PPR data from orbit I24 (Spencer et al.,
2000b). Also visible in the ratio image is a brightening in the western end of the flow, at the lobe discussed earlier. No change in flow morphology has been seen in either the E6/E14 or the C21/I24 comparisons, suggesting that these flows, similar to Prometheus, were emplaced in a similar fashion to terrestrial compound pahoehoe flows. The waxing and waning of plume activity could be due to either new breakouts or new infusions of hot lava beneath the crust of the inflated flows.
Figure 2.48: This image compares clear-filter images of Zamama from C21 and I24. Changes are visible in the central portion of the flow complex, as a darkening near the potential plume vent, and near the western end, which is the source of the lava flows.
Figure 2.49: This image shows a context view of Zamama from the scrambled I24 images. Note the radial flows at the western end of Zamama, which is interpreted to be the main lava vent.
The medium-resolution 124 Zamama observation, in Figure 2.49, showed that the dark knob at the western end of Zamama is surrounded by a number of thin, dark radial flows which seem to radiate from that point. Thus, the western end of Zamama is likely the silicate lava vent which appears similar to a terrestrial volcano (McEwen et al., 2000), and is the source of the radial lava flows and the diffuse red material seen to the west of Zamama. High-resolution images of the Zamama area were obtained on orbit 124, but they were scrambled like the Prometheus and Pillan images. The margins of the flows visible in these images are crenulated, suggesting an inflated pahoehoe sheet flow (McEwen et al., 2000). Analysis of the preliminary mosaic (Figure 2.50) has not yet revealed the detailed morphology of the plume vent, but the PPR data show a peak in temperature near the western end of the flows visible in Figure 2.50, at the same location where surface detail is obscured in the mosaic (Spencer et al., 2000b). This could correspond to the plume vent location, which is located within the flow field and does not correspond with the vent for the silicate lava, located at the far west.
Figure 2.50: This image shows a preliminary mosaic of some of the scrambled high-resolution 124 images of Zamama. The crenulated flow margins suggest an inflated pahoehoe-style eruption.
2.4. Major Change Detection Results

The major results of the four years of monitoring of Io's surface by Galileo, coupled with the Voyager images, can be summarized as follows.

**Kanehekili:** A new plume eruption occurred between orbits G1 and E6; hot spot observations suggest that increased eruption of lava continued through orbit G7, when very high temperatures were observed. A new circular plume deposit and dark central lava flows are visible in the E6 images. We see red material associated with the northern of the two hotspots, while the majority of the new lava is located near the southern hotspot, which is also the location of the SO$_2$ plume vent. This is consistent with the structure seen at Prometheus, Culann, and Zamama.

**Lei-Zi:** A new circular plume deposit was noted in comparisons of E6 and C9 images of this area. This is the first sign of activity at this feature, at which no hot spot has been detected.

**Masubi:** This feature presents a fascinating story of spatial and temporal plume variability. A circular plume deposit is visible in Voyager images of the area. This deposit is gone in early Galileo images through orbit C9, but a similar deposit reappears on orbit C10. The deposit has disappeared again by orbit E15, and a new deposit reappears on orbit C22. The sizes and shapes of the deposits are strikingly similar, but the central vent location is slightly different in each case, and the sizes of the dark circular deposits also vary slightly. This observation gives us a timescale of no more than 8 months for the fading of a plume deposit.

**Pillan:** A major eruption occurred at Pillan around orbit C9, and surface changes
were first observed by SSI on orbit C10. The new 400-km-diameter, dark, diffuse deposit surrounds a dark central flow complex. Observations of Pillan on orbits C21, I24, and E26 have shown the covering over of the dark deposit by new red and yellow plume deposits. The C10 and C21 images show the interaction of the Pele and Pillan plumes, which appear to be active simultaneously. The C21 images also show a new eruption at a volcanic center east of Pillan, named Kami-Nari. Kami-Nari was also observed by NIMS as a hotspot on orbit I24. By the time of the E26 images, most of the dark deposit had faded, leaving only the dark central lava flows. The thermal signature of Pillan detected by NIMS is consistent with the cooling of rapidly emplaced, relatively thin lava flows.

Prometheus: A new dark area was emplaced at this consistently active plume site between orbits C21 and I24. The new region of material is visible as a hotspot in high-resolution NIMS data, and could represent a new deposit of material from the middle of the main insulated flow. Comparisons of the Voyager and Galileo images show that the Voyager-era plume vent was located near the right-angle bend in the current flow, below the current source of red material and below the caldera. This supports the Kieffer et al. (2000) model which suggests that plume vents are located in the active flow field. Again, we have two separate vents, one a lava vent associated with a red surface deposit, and the other a plume vent located within the inflated flow field and associated with an SO₂ plume and deposit.

Culann: The red diffuse plume deposits have faded and changed location as observed on orbits E6, E14, C21, and I24, suggesting that red material can fade over
timescales of less than one year. The high-resolution 125 color image reveals the caldera, a lava tube feeding the northwestern flows with red material vented from its roof, and the continued fading of the southeastern portion of the red plume deposits. The green coating on the Culann caldera supports the idea that green material is the result of an altered red plume deposit.

**Zamama:** No changes in the shape or size of the dark flows have been noted during Galileo, but changes in plume activity are visible. The active plume can be seen in E14, and changes in the red and yellow-white plume deposits are evident. A dark diffuse region visible in the 124 view could be the plume vent itself, which is consistent with the bluish region seen in E14.

### 2.5. Discussion

The previous observations describe the series of events taking place at a variety of active volcanic centers on Io over a period of 4 years, and extending back 20 years to Voyager. These observations shed light on physical volcanology on Io, and illustrate the many different styles of volcanism. The change detection technique of iterative coregistration and ratioing can reveal a variety of different kinds of changes, including new plume deposits, new lava flows, and darkened hotspots which could indicate new flows or resurfacing within a caldera. We can use these changes to calculate rates of activity, surface change rates, and global average resurfacing rates.

In order to convert measurements of areal surface changes into mass and volume resurfacing rates, estimates of the thickness and density of the observed deposits must
be made. The surface changes can be divided into two main types: plume deposits and lava flows. Plume deposits are thought to be thin surface veneers of volatiles such as $S_2$ and $SO_2$, with possible entrained droplets or pyroclasts of silicate material. Dark lava flows are most likely silicate, and while they cover smaller areas than plume deposits, are likely to be much thicker and denser and therefore contribute more substantially to the resurfacing rate. For this study, we will assume that the observed darkenings of calderas known to be hotspots are due to coverage with new lava flows with the same average thickness as lava flows on the plains of Io.

One important endmember in this analysis is Loki, which outputs as much as 20% of Io's net heat flow, yet has had only relatively minor surface changes between Voyager and Galileo, or during the Galileo mission. Clearly, since especially active thermal periods have been observed at Loki every few years, including two during the Galileo mission, resurfacing is ongoing. We suspect that it must be confined to the low-albedo region which resembles a caldera floor, and the new flows have a similar visible albedo to the older flows (or cooled lava lake surface). Thermal measurements by Galileo NIMS and PPR, have verified that the dark material only is hot, and have located more active regions (Lopes-Gautier et al., 2000; Spencer et al., 2000b).

The following sections will review the literature on plume deposit and lava flow thickness considerations on Io, and choose average values to use in this work. The global average resurfacing rate will then be computed in two different ways. First, we will take the ratio images described previously, and define threshold levels to partition the surface changes into plume deposit and lava flow categories. We will define these
categories not only on the appearance of the area in the ratio image, but also based on
the original and new albedo of the feature, so that we can avoid mixing the fading of
bright plume deposits with actual darkenings at lava flows or calderas. We will then
estimate the percent of the area changed over various time periods by each of these two
processes, estimate an average area per time resurfaced by each, and use the thickness
and density estimates to convert this into vertical resurfacing and mass resurfacing
rates. The second method, as an independent check on the first two, will be to revisit
cratering rates and the lack of observed impact craters on Io to calculate a minimum
required resurfacing rate. We will also consider the implications that Io's global
average hotspot heat flow has on the maximum possible resurfacing rate, and use
observations of hotspot longevity to estimate their average lifetime.

2.5.1: Resurfacing rates from plume deposits

A variety of theoretical and observations studies have been made of Io's plumes in
attempts to measure or calculate the mass flow rates and volume resurfacing from the
plumes. Johnson and Soderblom (1982) provide an overview of Voyager-era studies, as
an extension of Johnson et al. (1979). Voyager-era studies were divided into two
classes: some, such as Johnson et al. (1979) and Johnson and Soderblom (1982) focus
only on small optically-detectable particles, whose diameters are comparable to the
observational wavelength. These particles range in size from 0.01 μm to 1 μm. They
used the observed plume brightnesses, radii, and heights to calculate ballistic
trajectories for the plume particles, and computed the total mass of particles in the
plumes. The resurfacing rate was then calculated from the total mass and the flight times of the particles. The total resurfacing from these small particles from the 8 plumes active during Voyager 1 was about $3.5 \times 10^{-4}$ cm/year, averaged globally (Johnson et al., 1979). The net mass flux from these small particles was about $9 \times 10^6$ g/sec. Johnson and Soderblom (1982) also calculate a separate rate from the Loki plumes of about $10^{-2}$ to $1$ cm/year. The Loki mass flow rate was $10^9$ g/sec.

Lee and Thomas (1980) studied slightly larger particles, in the size range from 0.1 to $10 \mu$m, carried in the Pele gas plume. Analysis of streaks of material near Pele required mass flow rates between $10^7$ and $10^9$ g/sec. If the plume is actively depositing material for about 1/3 of the time, and deposits are $1.5$ g/cm$^3$ in density over an area surrounding Pele that is 500 km in radius, this produces a mass flux of solids of about $2 \times 10^7$ g/sec. The flow of smaller gas particles may be much higher, but since the particle sizes are much smaller, the mass flow rates for gas are likely within 1 or 2 orders of magnitude of the $2 \times 10^7$ g/sec solid mass flux.

Wilson and Head (1981) studied the emplacement of larger particles from the Prometheus plume, again using a ballistic model. They use the observation of optical thickness of the Prometheus plume during Voyager, the plume height, and an estimated average particle radius of 0.1 mm to calculate a mass flux of $1.6 \times 10^7$ kg/sec, or a volume flux of about 7000 m$^3$/sec. This is about 3 orders of magnitude greater than the flux found by Johnson et al. (1979) for small particles. James and Wilson (1998) reanalyzed the ballistic model of Wilson and Head (1981), and found mass eruption rates of up to a factor of 10 lower than the previous estimates. They suggest that a
volume flux between 100 and 1000 m³/sec is more consistent with the observations. Since the radius of the Prometheus plume deposit is about 200 km, this gives a resurfacing rate in the deposit of between 2.4 cm/year and 24 cm/year, assuming continuous activity at the plume.

More recently, observations from the Hubble Space Telescope and Galileo have been used to put better constraints on the resurfacing rates from volcanic plumes on Io. Spencer et al. (2000) detected S₂ gas in the Pele plume for the first time, using the Hubble Space Telescope, and measured the column densities of both S₂ and SO₂ gas in the plume. They calculated a resurfacing rate in the Pele plume deposits of 1.7x10⁻³ cm/year from S₂ and 1.1x10⁻² cm/year from SO₂ frost, assuming a deposit density of 1 g/cm³ and a deposit radius of 350 km. For a more realistic deposit radius of 500 km, the resurfacing rate of S₂ would be 1.2x10⁻³ cm/year and the resurfacing rate of SO₂ would be 7.7x10⁻³ cm/year.

Kieffer et al. (2000) studied the production of the Prometheus plume with a theoretical model of the Prometheus lava flowing over a reservoir of SO₂-rich material on the ground, which is then vaporized and escapes from beneath the flow in a stable plume. The plume vent in this model is located near the active flow front, about a kilometer back from the toes of the flow. Their theoretical mass flux is about 5x10⁶ kg/sec, which is equivalent to a volume flux of about 3x10³ m³/sec (3000 m³/sec). This theoretical result is consistent with the theoretical estimate of Wilson and Head (1981). Again using 200 km for the radius of the Prometheus plume deposit, this gives a resurfacing rate within the deposit of 72 cm/year, assuming the plume is continuously
active. This is a very high resurfacing rate, but new high-resolution Galileo images of the plains surrounding Prometheus show evidence for frost deposits that could be consistent with this estimate.

The main difference between the studies of the Pele and Prometheus plume deposits discussed in the preceding sections seems to be the particle size considered. The studies of Pele by Johnson et al. (1979) and Spencer et al. (2000) both consider small particle sizes, and result in resurfacing rates within the plume deposit between $10^{-4}$ and $10^{-2}$ cm/year. The resurfacing at Prometheus by larger particles was studied by Wilson and Head (1981), James and Wilson (1998) and Kieffer et al. (2000), and resulted in resurfacing rates within the Prometheus plume deposit ranging from 2.4 to 72 cm/year. Since the Pele plume deposit appears fundamentally different from other plumes on Io due to its bright red coloration, and the Pele plume itself is larger and fainter than other plumes on Io, we will treat Pele as a special case. We will assume that the resurfacing by large particles within a plume deposit will dominate the resurfacing rate, and that the values estimated for Prometheus can be extrapolated to other plume deposits on Io. We thus conclude that the range of resurfacing rate within a plume deposit on Io is probably between 2.4 and 72 cm/year, but could be smaller if dominated by Pele-style small particles.

We can use this estimate to calculate a global average resurfacing rate by plume deposits if we take the number of active plumes seen by Galileo, which is 11 (Lopes-Gautier et al., 1999). If we assume that these plumes are all active continuously and simultaneously, and assume an average radius of 200 km for a plume deposit, we get a
global average resurfacing rate from plume deposits between 0.08 cm/year and 2.4 cm/year.

2.5.2: Resurfacing rates from lava flows

Numerous studies have attempted to model the thermal IR observations of Io's hotspots as due to cooling lava flows (Carr, 1986; Davies, 1996; Howell, 1997; Keszthelyi and McEwen, 1997). The observed flux is due to a combination of various areas of Io's surface at various temperatures. The models which best fit the IR data over a range of wavelengths require two or more temperatures and areas. Typically this consists of a small area at a high temperature, and larger areas at lower temperatures. The small area is usually interpreted as an active source or flow, and the larger areas as cooling flows and perhaps pyroclastics. Given the cooling rates and other parameters, the average flow thickness can be estimated.

When attempting to study the thermal signatures of lava flows on Io, a distinction must be made between gradual resurfacing at sites of continuing thermal activity such as Prometheus, and high-temperature thermal outbursts such as Pillan which most likely erupt large amounts of lava in a short period of time, and then largely turn off. The timescales, and likely also the methods of lava emplacement, are very different for these two types of eruptions. Lava flow complexes like Prometheus probably consist of compound inflated pahoehoe flows, which could have been emplaced in a thin flow which has built up to much larger thicknesses over time (McEwen et al., 2000). Repeated injections of hot lava may keep the flow surfaces warm, but most areas not
hot enough for detection by NIMS (Lopes-Gautier et al., 2000). Flows like Pillan, on the other hand, are likely emplaced over a very short period of time in an open channel, and then cool with or without continuing injections of new material (Davies et al., 2000). Thus, we will attempt to distinguish between these two eruption styles in this analysis.

A variety of flow thickness estimates and guesses have been published in the Io literature. Terrestrial basaltic lava flows have thicknesses of 1 to several 10s of meters (Blaney et al., 1995). Carr (1986) suggested a flow thickness of about 10 m. Blaney et al. (1995) suggested a flow thickness of 1.9 meters from estimates of the amount of silicate lava that could provide the observed heat flux. Such estimates will be revisited in section 2.5.5. Davies (1996), in a detailed model of lava flow cooling on Io, considered a flow which varied in thickness from 0.4 m at the margins to 13.4 m at the center, for an average thickness of about 7 m. Howell (1997) modeled a 14 m thickness for a flow at Loki. Kieffer et al. (2000) studied a flow range between 1 and 100 meters thick, and assumed a 30 meter compound flow thickness for the inflated Prometheus flow. Spencer et al. (2000b) inferred a flow thickness of less than 13 meters for the Pillan flow, using the PPR temperatures. One caveat is that most of these studies have considered laminar flows, but the high temperatures observed for some of the Io hotspots suggest an analog with terrestrial komatiites, which were emplaced in a turbulent regime. Williams et al. (2000) consider a komatiitic model for Io's lava flows, and assumed an average flow thickness of about 10 m, consistent with the above estimates.
For the purposes of this work, we therefore will consider a range of average flow thickness between 1 and 10 meters, to represent both open channel flows and inflated compound flows. We will use this flow thickness range to compute the volumes of material emplaced at new lava flows observed on Io, and also to estimate the amount of new material emplaced on dark, active caldera hotspots. Later on, we will attempt to use the inferred resurfacing rate from Io's net heat flux to calculate the maximum flow thickness.

2.5.3: Use of thresholded ratio images to partition surface changes

To calculate the net resurfacing rate from plume deposits and lava flows as seen in our images, we have developed a ratio threshold technique to separate out different types of changes from our studies of various features and regions of Io's surface during the Galileo mission. I took the ratio images, over as large an area as possible, and studied the pixel values in detail to determine bins of darkening or brightening. This was done individually for each ratio image. Since the ratio images are dimensionless, areas that remained unchanged should have pixel values of 1. For most images, however, changes in illumination and viewing geometry result in imperfect matches in absolute albedo levels between images. In most cases, therefore, I defined ratio levels between .95 and 1.05, or in some cases between .90 and 1.10, as regions which have remained unchanged. Regions below .95 or .90 are defined as having darkened, and regions above 1.05 or 1.10 are defined as having brightened. We binned the pixel values in the ratio images into one of those three categories, and stretched each to a
single brightness level (0.5 = darkened, 1 = constant, 1.5 = brightened). The area of each image at each of these three pixel values could then be measured. We have also compared the pixel values in the ratio image to those in the original image to further classify a particular region as new dark material (probably lava). This allows us to segregate out plume activity, which usually brightens the surface, but sometimes darkens it. In this measurement, if a feature in the new image has a low albedo, and if that feature darkened, we would count that change as due to lava flow activity. However, if a bright region darkens but still remains brighter than the lava / plume threshold at an albedo of about 0.4, the ratio image would still show that area as a darkened region. The comparison with the original albedo of the region allows us to eliminate cases like that from the aggregate totals.

To perform this analysis, we have selected two of the comparison cases that had the best match in resolution and phase angle. The first case is visible in Figure 2.51, which shows the thresholded ratio images for the G1 / E6 Kanehekili comparison, in three filters. These are the same ratio images from Figure 2.5. About 10 degrees has been trimmed off the terminator and bright limb of these images, and they have been photometrically corrected (Lunar-Lambert function, L=0.8). The ratios in Figure 2.5 clearly show the emplacement of a new bright plume deposit and dark lava flows surrounding Kanehekili, as well as the darkening of several calderas in the same hemisphere. Thus we can use the area of bright material that brightened or darkened to estimate the area of new plume deposits, and the new dark area to estimate the area of new lava flows and resurfaced calderas, based also on the original albedo of each area.
As measured in the red filter, about 1.3% of the pixels are classified as new plume deposits and about 1.13% are classified as new lava flows, and in the green filter, about 3.2% are classified as new plume deposits and 0.96% as new lava flows. The differences between the red and green filter brightening percentages are mostly because the green filter includes coverage of the south polar area, where a new bright area (a possible plume deposit) is located. This region was cut off in the E6 red image. The violet ratio image is primarily sensitive to plume deposits, but its appearance is complicated by the mobility of SO$_2$ frost. Since the motion of frost results in both bright and dark areas associated with plume activity, this thwarts the analysis described above. Thus, the violet images will not be considered for this part of the analysis. It is possible that future analysis of the violet ratio images will provide a better way to track plume activity on Io, however.
Figure 2.51: This image shows the thresholded ratio images from figure 2.5, as described in the text. The ratios from the NIR, green, and violet filters have been stretched and compared with the original and new images to classify portions of the surface into new lava flow and plume deposit categories.
Thus, in the G1 / E6 comparison area, an average of 2% of the surface is classified as new plume deposits, and about 1% is classified as new lava flows. The G1 / E6 comparison covers about 1/4 of the surface of Io, or about $1 \times 10^7$ km$^2$. Thus, in this comparison area, about 200,000 km$^2$ is covered by new plume deposits, and about 100,000 km$^2$ is covered by new lava flows. The time period between these two observations is about 9 months, so at a resurfacing rate in a plume deposit between about 2.4 and 72 cm/year, from section 2.5.1, we can estimate a thickness of the new deposits between 1.9 and 57 cm. This gives a total volume of new plume deposits of between 3.8 km$^3$ and 114 km$^3$, assuming that the plumes are active for the whole observational period. For the new dark lava flows, using the range of flow thickness of 1 to 10 meters from section 2.5.2 yields a volume of 100 to 1000 km$^3$ of new lava flow material. If we combine the contributions from lava flows and plume deposits, and extrapolate the rates over the entire surface of Io, we would get between 415 and 4456 km$^3$ of new material emplaced over a 9 month period, for a net resurfacing rate from combined plumes and lava flows of between 1.35 and 14.5 cm/year. Assuming an average density of 1000 kg/m$^3$ for the plume deposits and 2680 kg/m$^3$ for the lavas, the mass resurfacing rate is between $1.4 \times 10^{15}$ kg/year and $1.5 \times 10^{16}$ kg/year. This estimate also shows that even though plume deposits cover a large area of Io's surface, and result in substantial albedo changes, their small thickness and low density means that they count for less than 10% of Io's resurfacing as compared with lava flows.

The rate of approximately 1.4 to 14 cm/year as derived in the previous estimate is necessarily crude. It assumed that all the new dark areas in the ratio image were due to
new active lava flows on Io's surface, and that those flows all had a thickness of between 1 and 10 m. However, even though the two images used in this comparison were well-matched in terms of phase angle, resolution, and other geometric parameters, there are small variations in illumination geometry which could result in some of the dark patches being artifacts. There is likely a similar problem with the identification of all the bright patches as new plume deposits, but the error in the dark patches contributes most to the errors in this measurement due to the dominance of lavas. Thus, the actual resurfacing rate by lava flows on Io's surface is likely less than 14 cm/year, and could be less than 1.4 cm/year.

A similar analysis is shown in Figure 2.52 for a different area of Io's surface. This image shows a comparison between images taken on orbits C21 and I24, through the clear filter. These images were subjected to a similar thresholding process as described previously, and the percentages of the surface which were classified into new plume deposits and new lava flows were measured. These images were closely matched in viewing geometry, and their resolution was higher than the G1 / E6 case above. There are also substantial artifacts in the form of horizontal dark bands visible in the image seams in the ratio image. These correspond to areas where the bottom of one of the C21 images happened to line up with the top of one of the I24 images, and vice versa. There is a noise gradient present in Galileo images related to how long the image is resident in the CCD chip before being read out, and in the high radiation environment near Io, substantially more noise can accumulate in an image between the time the top is read out and the time the bottom is read out. This is discussed in more
detail in the appendix. This noise gradient therefore results in an apparent darkening of large areas of the surface that is not real. Thus, in these images, rather than just assigning bins to each group of ratio values, each section of the image was considered individually to remove artifacts caused by the background variations.

Our analysis of the C21 / I24 comparisons indicates that 0.093% of the surface can be classified into new lava flows, and 0.39% can be classified into new plume deposits. The time interval between these observations is 3 months, and the area covered is about 1/8 of Io's surface. This gives a total area of new lava flows of $5 \times 10^3$ km$^2$, and a total area of new plume deposits of $2.1 \times 10^4$ km$^2$. For the lava flow regions, again assuming a 1 to 10 meter thick flow, we get between 5 and 50 km$^3$ of lava. For the plume deposit regions, assuming a plume deposit rate between 2.4 and 72 cm/year, we get between 0.13 and 5.2 km$^3$ of plume deposit materials. We can add these to get a range of 5.13 to 55.2 km$^3$ of material. Averaged over a 1 year period over the whole surface of Io, this gives a resurfacing rate between 0.4 cm/year and 4.3 cm/year. The net mass flux in this analysis is between $4.3 \times 10^{14}$ and $4.3 \times 10^{15}$ kg/year. This is within a factor of 3 of the G1/E6 comparison case discussed above, and given the higher resolution of these images, could be more accurate. However, the C21 / I24 case is over a shorter time period, perhaps reducing the accuracy when extrapolated over an entire year.
Figure 2.52: This image shows a similar thresholding for the C21 / I24 image comparison. The first two images are the appearance of the Prometheus hemisphere in clear filter images from C21 and I24; the lower left image is the ratio image, and the lower right is the thresholded ratio.
Thus, our thresholding analysis suggests that the maximum combined resurfacing rate from plume deposits and lava flows on the surface of Io is between 0.4 and 14 cm/year, and is likely less than 4 cm/year. The net mass flux from lava flows and plume deposits is between $4 \times 10^{14}$ kg/year and $1 \times 10^{16}$ kg/year, and is probably around $10^{15}$ kg/year. We have also shown that while plume deposits are important in the changing appearance of Io's surface, and in fact cover a larger area than do lava flows, they are probably inconsequential in an analysis of Io's net resurfacing rate, which is dominated by the thicker and denser lava flows.

2.5.4: Independent estimate of resurfacing rate from cratering

The previous sections have used observations of changes on Io's surface to estimate the resurfacing rate. We can make an independent estimate of the Io resurfacing rate from the observation that no impact craters, of any size, have been observed on Io's surface. Although small craters are more frequent, they are also harder to identify. Also, we have an uncertain size-frequency distribution of small primary craters. Thus, we have chosen a crater size of 20 kilometers to consider, as we can be reasonably sure that no recognizable 20-kilometer-diameter craters are currently present on Io's surface.

Zahnle et al. (1998) reanalyzed the impactor populations expected to be important in the Jovian system. They found that impacts in that region were dominated by short-period, Jupiter-family comets, a population which is relatively unimportant in the inner
solar system. The impact rate on Io is also enhanced due to gravitational focusing from Jupiter. The revised numbers from Zahnle et al. (1999) estimate that a 20-kilometer diameter crater is formed on Io approximately every 10 million years, with a factor of 5 uncertainty in this timescale. We thus assume that a 20-kilometer crater formed on Io 10 million years ago, and estimate the resurfacing rate, in depth per year, which would be required to completely remove such a crater from Io's surface.

The depth of an impact crater can be related to its diameter by the relation \( d = 0.2D \), where \( d \) is the depth and \( D \) is the diameter (Melosh, 1989). Thus, a 20 kilometer diameter crater has a depth of about 4 kilometers. To remove this crater from view, we estimate that if it were filled halfway with new material, the crater's impact origin would be unrecognizable. Buried halfway, a crater might still be observed as a circular depression, but given that Io has numerous calderas and other circular features of volcanic origin, we believe it unlikely that a half-buried crater would be recognized as such. Thus, a burial depth of 2 kilometers is required to remove the crater from view.

We thus require a 2 kilometer thick global average layer of material to completely remove the single 20-kilometer-diameter crater considered in this simple analysis. If we assume that this layer was emplaced over 10 million years, this gives a minimum average resurfacing rate of 2 km / 10 million years, or 0.02 cm/year (2x10^{-2} cm/year). The factor of 5 uncertainty in the cratering rate leads to a range between 0.2 cm/year and 0.004 cm/year. This is a minimum average resurfacing rate: such a crater could have formed more recently than 10 million years, requiring a faster resurfacing rate to remove it from view, or the resurfacing rate could be much faster, removing craters
many times over in this time period. This estimate is similar to the technique used by Johnson and Soderblom (1982), except that it uses the more modern estimates of impactor flux from Zahnle et al. (1998, 1999), and it assumes that a crater burial of only half the crater depth is required for removal from view, rather than twice the crater depth. Even given these differences, this estimate is similar to the Johnson and Soderblom estimate of 0.1 cm/year. Lee and Thomas (1980) suggested that the required crater burial depth could be as little as the rim height, which is 0.04 D. For a 20-kilometer diameter crater, this requires a burial depth of 0.8 kilometers, requiring a resurfacing rate of only $8 \times 10^{-3}$ cm/year. However, we believe that the half-burial criterion gives a more robust answer.

2.5.5 Resurfacing rate and heat flow

Another possible check on the resurfacing rate is to calculate the amount of energy required to bring enough lava to the surface to accomplish the resurfacing. Reynolds et al. (1980) calculated the minimum energy requirement, assuming that resurfacing is accomplished by transporting liquid lavas to the surface of Io. Their equation was:

$$h = (dl/dt) \rho (H_f + C_p \Delta T)$$

where $h$ is the average planetary heat flux density at the surface, $dl/dt$ is the resurfacing rate, $\rho$ is the density, $H_f$ is the heat of fusion, $C_p$ is the heat capacity of the material which is mobilized, and $\Delta T$ is the temperature difference between the melting point of the material and the surface temperature. This formula gives a lower limit, since it ignores heat conducted through the lithosphere, but this is expected to be a minor
component due to the rapid resurfacing rate (O'Reilly and Davies, 1981: Carr et al. 1998). Reynolds et al. (1980) used average values for basalts, and found that for a resurfacing rate of 0.1 cm/year (the nominal rate from Johnson et al. (1979) to ensure crater burial), a minimum heat flow of 0.18 W/m² was required.

We can apply the same analysis as Reynolds et al. (1980) to estimate the heat flux required to sustain the resurfacing rates obtained in section 2.5.3. Rather than just the values used by Reynolds et al. for basalts, we also consider the values for komatiites found in Williams et al. (2000). For the Commondale komatiites, which Williams et al. suggest as the closest analog to at least some Ionian lava flows, the heat of fusion is 6.84 x 10⁹ ergs/g; the density is 2.68 g/cm³; the liquidus temperature is 2084 K; and the specific heat is 1.78 x 10⁷ ergs/g K. For the nominal resurfacing rate of 0.1 cm/year required to remove all the visible impact craters, this gives a minimum heat flow of 0.36 W/m², twice the value obtained by Reynolds et al. (1980) for basalts. Our minimum resurfacing rate from the new cratering rate studies of 0.02 cm/year requires a heat flow of 0.072 W/m². Our average resurfacing rate of 1 cm/year would require a heat flow of 3.6 W/m² if produced solely by komatiites, and our maximum resurfacing rate of 14 cm/year would require a heat flow of 50 W/m².

We can compare these heat flows to the best available estimate of Io’s total hot spot heat flow, which is about 2.5 W/m² (Veeder et al., 1994). Clearly, a resurfacing rate of 14 cm/year, if accomplished solely by komatiitic lavas brought to the surface as liquids, would dwarf Io’s current observed heat flow. We can also calculate the maximum resurfacing rate possible, given a heat flow of 2.5 W/m². This calculation gives a
maximum resurfacing rate of 0.69 cm/year. The maximum resurfacing rate of Io by purely basaltic lava is about 1.33 cm/year (Blaney et al., 1995). The higher resurfacing rates estimated in section 2.5.3 would require resurfacing by a material such as sulfur. Due to sulfur's lower melting point, a resurfacing rate as high as 12.5 cm/year could be sustained by pure sulfur flows and still produce the observed heat flux at Io. However, the hot spot evidence suggests the dominance of silicate volcanism on Io (McEwen et al., 1998b), and sulfur flows, if present, must be a minor component. Thus, Io's resurfacing rate is likely close to 1 cm/year or less.

We can also use the maximum resurfacing rate by komatiitic lavas of 0.69 cm/year derived above, based on Io's observed total heat flow, to estimate the maximum thickness of lava responsible for the resurfacing observed on Io's surface due to lava flows. Assuming that an area of 100,000 km² of new dark lava flows has been emplaced on Io's surface over the 9 month time period discussed in section 2.5.3, we can solve for the thickness of flows required to produce a resurfacing rate of 0.69 cm/year. This thickness is about 52 cm. This flow thickness is consistent with the lower end of the 1 to 10 meter range used to estimate resurfacing rates from changes. The small thickness also suggests that the flows were very fluid.
2.5.6: Estimates of lifetimes of hotspots

We can continue our study of hotspot activity on Io by considering the aggregate observations of hotspot activity on Io seen during the Voyager and Galileo missions, as summarized in Lopes-Gautier et al. (1999). An updated version of Table 1 from Lopes-Gautier et al. (R. Lopes-Gautier, personal communication, 2000) reveals that 59 active hotspots on Io have been seen during Galileo by either SSI, NIMS, or both, during the Galileo mission from orbit G1 through C20. This can be compared to the 27 hotspots seen by the Voyager IRIS instrument. IRIS viewed only a limited portion of Io's surface, and had only a small time period to make its observations. Therefore, we would not expect it to observe as large a range of hotspots as Galileo can. However, the converse is also true: given Galileo's long time period of observations in the Jovian system, we would expect that any hotspots able to be observed by Voyager certainly could be seen by Galileo.

When we compare the lists of hotspots observed by Voyager and Galileo, we find that there are 12 hotspots observed by Voyager that have not been seen by Galileo. The most likely explanation for this is that the hotspots have become inactive. Another possibility is that the hotspots are just at much lower temperatures than Galileo can detect, since IRIS was sensitive to longer wavelengths than NIMS and thus older, and cooler, flows. In this case, however, they likely would have continued cooling between Voyager and Galileo, and would have become inactive. Thus, close to half the hotspots observed by Voyager may have turned off over the 20 years between Voyager and Galileo. This suggests an average hotspot lifetime of approximately 40 years for the
persistently-active, lower-temperature hotspots. The lifetime of the high-temperature IR outbursts is much shorter, as seen in the cooling of Pillan (Davies et al., 2000) which has cooled significantly over only 2 years.

If we assume an average hotspot lifetime of 40 years, we would expect that during the 4 year Galileo mission to date, about 10% of hotspots would have become inactive. Since there are 59 active hotspots, we would expect that 5 or 6 would have turned off, and perhaps a similar number turned on, during those 4 years. When we inspect the hotspot data from Lopes-Gautier et al. (1999), we can find evidence of a decrease in activity at Ra, Fo, Rata, Lei-Kung, Kuradalagon, Reiden, and Daedalus. We also have seen increases in activity at Shamshu, Pillan, Kami-Nari, and a few other potential new hotspots. Thus, we have evidence for decreases in activity at 7 volcanic centers, and increased activity at at least 3, over a 4-year period. This is roughly consistent with the changes we would expect over 4 years if the average hotspot had a lifetime of about 40 years.

Of course, this estimate does not take into account such persistently active hotspots as Pele, Loki, Kanehekili, Marduk, Mulungu, Isum, Amirani, Prometheus, and Hi’iaka, which were active most or all of the time they were observed over the 4-year Galileo observational period. Many of these features were also active during Voyager. Due to observational constraints, both in the small area of the surface observed by the Voyager IRIS instrument and the large distance from Io on many Galileo flybys which results in very low-resolution NIMS observations, there are probably other persistent hotspots which we have missed, and other fluctuations. This estimate also disregards
the high-temperature, short-period IR outbursts, the majority of which have been observed by earth-based telescopes. These two endmembers may balance each other out, however, resulting in an average hotspot lifetime of about 40 years. Measurements of the heat output of several volcanoes by the Galileo PPR instrument has shown that Loki has approximately the same thermal output as it did during Voyager, but that both Amaterasu and Daedalus have significantly less thermal output than they did during Voyager (Spencer et al., 2000b). This is consistent with waning activity at these two locations.

Since the majority of resurfacing by lava flows takes place in just the few percent of the surface covered by active flows and calderas, the 40 year lifetime for active hotspots has important implications for global resurfacing. Carr (1986) suggested that global resurfacing was accomplished, on average, by small local volcanic centers forming and disappearing, and eventually covering over all of Io’s surface. If active hotspots really do have such a brief, 40-year lifetime, this suggests that Carr’s model could be correct, and that much of Io’s volcanic activity is fleeting. At any one point in time, there are around 50 or so active features on Io’s surface, but as one is extinguished, another forms, on average about 1 per year. Thus, even though at any one time, resurfacing by lava flows is only taking place on a small part of Io’s surface, this activity, when averaged over geologic time, is sufficient to resurface most of the planet.

2.5.7: Fading of plume deposits
Comparisons of images taken by Voyager 1, Voyager 2, and Galileo have revealed the ephemeral nature of the color and albedo signature of many plume deposits on Io's surface, and the longevity of others. For example, plume deposits formed at the features Surt and Aten over the 4 months between the two Voyager flybys in 1979, as the result of inferred eruptions in that time interval. However, when the same regions were viewed by Galileo in 1996, the plume deposits have mostly disappeared and the surface has reverted to its pre-eruption appearance (McEwen et al., 1998a). However, the bright red plume deposit surrounding Pele is still present, and has changed remarkably little in shape and size since the Voyager 2 flyby. The Pele plume is also active at about the same level of activity as it was during Voyager. This suggests that some, perhaps most, plume deposits are thin surface coatings which must be constantly replenished or they will fade away. In the case of Masubi, we have observed that a new dark ring-shaped plume deposit took at most 8 months to be completely removed from the surface, which reverted back to its previous appearance. A new bright deposit formed at Ra Patera between 1994 and 1995, as observed in HST images (Spencer et al., 1997a). This surface change was greater than any apparent changes in the 1994 HST – Voyager comparisons, suggesting either that such changes are rare, or that they fade over a time period of less than 15 years. The new bright deposit lasted for at least a year until next observed in June 1996. More recent observations have shown that the Ra deposit has faded at low phase angle, but is still unusually bright at high phase angle. This could imply that the deposit contains fine-grained SO2 (Simonelli et al., 1997).
The appearance of plume deposits could be changed over time in a variety of ways. If the red deposits are due to metastable $S_3$ or $S_4$, these chains could be recombined over time into more stable compounds like $S_8$ that blend into the background coloration of yellows on Io's surface. In regions like the Pillan plume deposit, much of the material on the western end has been covered over due to interactions with Pele's bright red plume deposit. To the north of Pillan, however, a bright pre-existing feature can be seen to return in the I24 and E26 images of the area. As discussed previously, the return of this bright feature could be due to its topography: it could be a local cold trap for the recondensation or renewed sapping of bright $SO_2$ frost. If the area has substantial topographic variations, the dark pyroclastic deposit from Pillan could be removed by downslope movements which revealed the underlying bright material.

The dark diffuse Pillan deposit could be as thin as a few microns to be optically thick and obscure the preexisting surface features. An interesting comparison can be made to the nearby dark Babbar Patera deposit, which appeared similar in albedo, size, and morphology to the Pillan deposit when Pillan had just formed. However, Babbar has had a constant, non-fading dark albedo throughout the Voyager and Galileo observations, while Pillan has changed over 2 years. One possibility, if the composition and thickness of the Babbar deposit is the same as the Pillan deposit, is that Babbar is just not located within the fallout zone of Pele or other vents, and thus has remained uncovered while the Pillan deposit was quickly obscured by Pele. Another possibility is that there have been other Pillan-style eruptions associated with other new dark flows, such as those which formed between Voyager and Galileo at Prometheus and Zamama.
The new dark flows at Prometheus and Zamama could be as much as 17 years old, so if the flows were originally surrounded by a dark deposit similar to the one at Pillan, the dark deposits would have had plenty of time to fade or be covered over, leaving only the dark flows.

HST recently detected S$_3$ in the Pele plume (Spencer et al., 2000a), with a column density of 1.5 ± 0.5 x $10^{16}$ cm$^{-2}$. Since S$_2$ is unstable to photolysis by UV radiation, it is likely that the S$_2$ is rapidly converted into S$_3$ and S$_4$, which are the compounds thought to produce the bright red coloration of the Pele plume deposit. The timescale for such conversion at Jupiter's distance from the sun is only about 190 minutes. The Pele plume also contains between 2.5 and 15 times as much SO$_2$ as it does S$_2$. However, no bright SO$_2$ frost is visible in the red Pele plume deposit, indicating that the SO$_2$ is likely mixed with red S$_3$ and S$_4$, and the color of the deposit is dominated by the red species (Spencer et al., 2000a).

An estimate of the lifetime of a red plume deposit would require 1) the observation of the emplacement of a new red deposit; 2) the observation of cessation of the plume activity responsible for the deposit; and 3) the observation of the removal of the deposit over time, with no intervening activity. An attempt was made by Lopes-Gautier et al. (1999) to estimate the lifetime of red material observed near Tohil Patera, but this region was likely contaminated by the continuing deposit of red material from nearby Culann Patera. We have observed the fading of one lobe of the red Culann deposit (section 2.3.6), but do not have any observations of the emplacement of this deposit, so cannot get a full lifetime of the material from this. The fact that we do observe fading of
the red material over less than a year implies that this unit is relatively unstable, and is transformed to \( S_8 \) over timescales of a few years or less if not continually replenished.

2.6. Summary

Comparisons of images of Io taken by Voyager 1 and 2, and by Galileo SSI and NIMS on orbits from G1 through E26, have explained some of the puzzling observations from the Voyager era, and revealed many new puzzles. The changes described in the preceding pages document our brief glimpse of Io in 1979, which was followed by Galileo 17 years later with 4 years of repeated surface monitoring from 1996-1999 and culminated in high-resolution imaging of a small portion of Io’s surface in 1999 and 2000.

We have used our observations to estimate the resurfacing rates on Io from plume deposits and lava flows. Plume deposits dominate the surface albedo changes seen at many active locations, but are very thin and contribute little to the global resurfacing rate. Lava flows cover less of the surface of Io, but are thicker and denser than plume deposits. Measurements from our ratio images have suggested an upper limit on Io’s resurfacing rate of between 0.4 and 14 cm/year. A lower limit of about 0.02 cm/year on the resurfacing rate of Io can be calculated from the lack of impact craters.

Thus, analyses of ratio images of Io’s surface yield a resurfacing rate of about 1 to 10 cm/year. Again, this is an upper estimate, and is based on the assumption that all the new dark regions that also appear dark in the ratio images are due to the emplacement of new dark lava flows. This new estimate of Io's resurfacing rate is crude, but is
nevertheless useful, because it provides an upper bound to the resurfacing rate by changes in lava flows, rather than the lower limits proposed in many other studies from plume resurfacing and other methods. The maximum resurfacing rate possible due to komatiitic lava flows, given the observed heat flux of Io, is 0.69 cm/year, and the average lava flow thicknesses in this case is about 50 cm.

Thus, we estimate from this work that Io's resurfacing rate is likely between 0.1 and 0.7 cm/year for a purely komatiitic case. This estimate could increase to 1.3 cm/year for basaltic flows. Thus, we suggest that if the bulk of Io's lava flows, which produce the bulk of Io's resurfacing, are komatiitic in nature, that the net resurfacing rate is around 0.7 cm/year, and the average flow thickness is around 1 meter. If the lava flows are more equally distributed between basaltic and komatiitic flows, this resurfacing rate could be slightly larger, and the average flow thickness thicker, than in the purely komatiitic case discussed above. Thus, the net resurfacing rate is likely between 0.1 and 1 cm/year, with a lower limit of 0.02 cm/year from the lack of observed craters.

Detailed analysis of the active volcanic centers Kanehekili, Masubi, Pillan, and Prometheus, and less-detailed studies of Lei-Zi, Culann, and Zamama has begun to reveal the nature of volcanic activity on Io. We have confirmed the "typical" structure of an active center on Io, as described in McEwen et al. (2000). The silicate lava reaches the surface at a lava vent, often located near a fissure or caldera. This lava is the source of tube-fed flows, which can extend for up to several hundred kilometers from the lava vent. The lava vent is also the source of a plume, most likely rich in $S_2$,.
which results in a diffuse, red, \( S_3 \) or \( S_4 \)-rich plume deposit. This red plume deposit can fade on timescales of a year, and thus marks the source vent of an active eruption. The main, \( SO_2 \)-rich plume, however, issues from near the end of the distal flows, where Io's thermal gradient is suppressed by hot lava injected beneath the surface of an inflated flow overlying the volatile-rich \( SO_2 \) snowfields that cover much of Io's surface. A small, high-temperature hot spot is located at the lava vent, and a larger, lower-temperature hotspot is located at the plume vent. There may also be intermediate hotspots associated with breakouts of lava from the main inflated flow complex. The type example of this sort of eruption is seen at Prometheus, but this analysis has revealed similar structures at Kanehekili, Zamama, and perhaps Culann.

Masubi, located at a latitude of 45 degrees south, may be an intermediate case between the equatorial, Prometheus-style continuous eruptions and the polar short-period outbursts observed mostly in ground-based IR observations, but also caught by SSI at Tvashtar (McEwen et al., 2000). The thermal signatures of these eruptions are consistent with intense temperatures at very small areas for short periods of time, consistent with the observations of a fire-fountain at Tvashtar by SSI. Perhaps the thermal gradient in the polar regions cannot sustain the equatorial-style eruptions, or perhaps there is not a sufficient reservoir of volatiles to drive a Prometheus-style stable plume. Masubi, located at an intermediate latitude, has shown evidence of three separate eruptive periods, one during Voyager and two during Galileo, during which a dark circular plume deposit was emplaced. The plume observed on orbit C22 at Masubi was a typical umbrella-shaped plume, similar to those seen at lower latitudes. One
possibility is that Masubi erupts in a manner similar to Prometheus, but there is either not a sufficient volume of hot lava or a sufficient volume of volatiles to drive a continued eruption. Instead, either the lava or the volatiles are exhausted, and the system turns off until the reservoirs are replenished a few years later. We do not have observations at a high enough resolution of Masubi to determine whether two hotspots are present, or whether there is red material associated with a silicate vent.

Pillan is a puzzle. Immediately following the eruption on orbit C10, Pillan appeared to be a new type of volcano, perhaps most similar to Babbar Patera and other dark diffuse deposits on Io. However, two years after the eruption, the dark deposit has almost completely faded away, leaving a dark central flow complex with a bright red linear feature similar to the lava tube at Culann. It is difficult to distinguish red material that is intrinsic to Pillan from that which is fallout from Pele’s bright red plume. The dark flows are reminiscent of Prometheus or Zamama. Perhaps, over time, as the Pillan lava flows mature and develop their own type of activity, Pillan will develop into a stable plume system like Prometheus, or perhaps it will continue to fade and the activity will die out completely. Recall that both Zamama and Prometheus formed new dark flows in the 17 years between Voyager and Galileo. The resemblance between the new Pillan flows and the flows at Zamama and Prometheus, coupled with the fact that any potential dark diffuse deposit which was associated with the formation of the Zamama or Prometheus flows would have had ample time to fade away completely over that 17 year period, suggests that perhaps after 20 or so years, Pillan will have developed a stable plume system similar to that at Prometheus and Zamama. The other possibility is
that Pillan represents an entirely different type of eruption on Io that defies classification.
Appendix A: Systematic processing and change detection technique

A.1: Image calibration and cosmetic clean-up

This procedure documents the steps taken to calibrate a Voyager/Galileo image pair of either Europa or Io in the United States Geological Survey software package Integrated Software for Imagers and Spectrometers (ISIS) (Torson and Becker, 1997). A sample file with program commands is available in Appendix D. Raw Galileo images were distributed to team members by MIPL (multi-mission image processing lab), part of JPL in Pasadena. These images are in VICAR format. Thus the first image processing step is to run vicar2isis, an ISIS program which converts images from VICAR format into ISIS format. Voyager images, and Galileo images from the early orbits, are available on CDROMs in the PDS image format. These can be converted into ISIS by using cd2isis.

Once this conversion is complete, naiflab (or spicelab for Voyager images) is run, which puts geometric information ("spice") into the header of the image file. ISIS files, or "cubes", have two main parts: first is an image header, which contains information specific to the particular image (target body, filter, exposure time, etc), as well as an image processing history with a record of each processing step run on that image, and the parameters used. The second part of an ISIS cube is the actual image data: this can be a single plane, for a single-band image, or can consist of multiple planes for a multispectral image cube taken in a number of filters. An image can also have "backplanes", which can be added to a cube by the user and contain information
such at the latitude or longitude of each point, the emission angle, the phase angle, the resolution, or other useful parameters.

When naiflab or spicelab is run, ISIS looks at the time the image was taken, and then compares this time with the spacecraft spice kernel database which contains spacecraft position and camera vectors as a function of time. This information is used to compute the spacecraft position, target body position, camera angles, distance from target body, and other geometric parameters. This information is placed into the image header. The spice kernels are updated periodically throughout the mission: at first, only predicted spacecraft position files are available. After an encounter, updated spice files with reconstructed spacecraft positions are available. This spice information from naiflab or spicelab allows first-order latitude-longitude information for each pixel of the image to be calculated. The accuracy of the pointing information varies from orbit to orbit, and within individual orbits. For some images, the initial pointing is quite good, but for others the pointing can be far off and the images must be tied to other images which have already been geometrically controlled. This will be discussed later on.

Next, the images are radiometrically calibrated with ssical or voycal. These ISIS programs perform a radiometric correction, converting the data values into units of actual radiometric flux by taking into account the image gain state and using a known dark-current calibration file. The image is then scaled into units of I/F. Ssical also removes blemishes and other known bad data points from the images. See Klaasen et al. (1999) for a detailed description of the steps used to calibrate Galileo images. The reseau marks were then cropped out from the Voyager image using findrx and remrx.
*Findrx* puts the locations of the reseaux into the image header, and *remrx* nulls out those areas, replacing them with empty space. Next, the Voyager Europa images were ratioed with a noise template to improve image clarity (Eliason and McEwen, 1990).

The Galileo data is returned from the spacecraft in a compressed format, using a number of different compression algorithms, from lossless to lossy, with different degrees of compression. In some highly-compressed images, compression artifacts are obvious, and it is advantageous to remove them before further processing is done. A VICAR program, *ictfix*, is available to mitigate these compression artifacts, and is usually run on the raw VICAR image files. This program uses information from the image headers to determining the compression algorithm and parameters used, and finds boundaries between compressed data blocks (usually 8x8 pixels). The program then attempts to interpolate over these boundaries using data from the centers of these compressed blocks. *Ictfix* has proved useful on highly-compressed images, but for images of medium compression, it has not proved as valuable. Therefore, *ictfix* is not part of the standard processing procedure, and is used only when necessary, on highly-compressed images.

The Galileo data also sometimes suffers from bad pixels and lines. This is often due to the loss of part of an 8x8 compressed block in transit -- when this happens, the whole block is often lost. *Ssical* removes some of these artifacts, but not all. Two programs can be used in order to remove any remaining artifacts before additional processing is done. First, images often have bad lines of data along the edges. The ISIS program *trim* can be used to remove these. *Trim* nulls out one or more lines of data
along the top, bottom, left, or right of an image cube. Partial lines of data or bad pixels in the center of a cube can be removed with an interactive function called \texttt{tvdoctor}, which is part of the ISIS image display program \texttt{qview}. \texttt{Tvdoctor} allows the user to interactively click on bad pixels and have them nulled out in the image cube. These bad pixels can either be left as "holes" in the image, or filled in with a low-pass filter (\texttt{boxfilter}, \texttt{filt=lpfz}).

Once bad data and compression artifacts are removed from the image, blemishes can remain in the form of radiation noise due to cosmic ray hits and other radiation picked up by the CCD. The amount of noise is dependent on the exposure time, filter, gain state, and most importantly the distance from Jupiter and location with respect to the plasma sheet. In most images, radiation noise is in the form of bright pixels scattered throughout the image. These can be removed by means of a series of iterations with the ISIS program \texttt{boxfilter}, in a routine designed by Alfred McEwen. In this routine, the value of each pixel is first compared to the value of a 3x3 and then a 5x5 box surrounding it, using \texttt{boxfilter} with \texttt{filt=stdz}. If the pixel's value is more than a certain number of standard deviations above the values of the surrounding pixels, the pixel is assumed to be noise, and is set to a null value. Once all noise has been nulled out, these null values are next replaced with the average value of the surrounding pixels, using \texttt{boxfilter} with \texttt{filt=lpfz}. In a final step, since filtering as part of the noise removal process tends to smear out the edges of an image, the final image is masked by the original image to restore the original image boundaries. This is accomplished by using the ISIS program \texttt{mask}. In all these steps, the user sets the tolerances, box sizes, and
accepted number of standard deviations for a pixel to be considered noise -- these values are determined from inspection of the data, and are dependent on exposure time, filter, and other image parameters. This noise removal algorithm is quite successful, but does require monitoring by the user to make sure that the procedure does not remove valid data in its quest for noise.

Some images also have a noise gradient from top to bottom, due to the increased residence time on the chip before the bottom of the image is read out. This is especially noticeable in the SSI Im8 mode, which is a full-frame image with a slower readout. Since the top of the image is read out before the bottom, the bottom lines of the image spend much longer on the radiation-sensitive camera CCD chip, and thus accumulate more radiation hits in that time. This phenomenon is especially noticeable in large mosaics of Io, though it has also been seen in Europa image (the Galileo color image of Europa in Part 1, Plate 1 has visible seams due to this phenomenon). The noise gradient can be removed with some work by modeling the brightness increase from top to bottom, and subtracting out that slope from the data values. The process is helped by comparing the bottom of one image to the overlapping top of another image, to establish the correct brightness levels in that area.

Galileo data are relayed from the spacecraft in two separate passes through the tape recorder. Thus, we often have a chance to replay data which was missing or garbled in the first attempt to play it back. This results in different versions of a single image. Other versions are sometimes generated by MIPL re-decoding the data in an attempt to find missing bits. Sometimes, 10 or more versions of a single image will
exist! Later versions usually, but not always, contain more data than previous ones, but it is sometimes necessary to merge previous versions together to generate the most complete image possible. This is done by using the ISIS program `mosaic`, in a mode where it just places image data from one image over null pixel values in another image, using the coordinates of each pixel in the frame for placement information (option=rect). Most of these problems will be removed when the images are merged into final versions for distribution on CDROMs to the scientific community, but in some cases, especially where cut-out windows were replayed over features of interest with different compression parameters, such merging is not possible. It will be up to the end user of such products to decide how best to merge them.

A.2: Geometric control and reprojection

As discussed above, the ISIS program `naiflab` places preliminary pointing information (camera angles) in the header of the image cube, allowing latitudes and longitudes to be estimated. This initial pointing information varies in accuracy from image to image, however, and for the production of image products and mosaics, it is best to use a consistent pointing scheme. A difficulty at Europa is that the two Voyager spacecraft imaged only about 20% of Europa at resolutions of 1-2 km/pixel; the rest of the satellite was poorly imaged at resolutions of 15-20 km/pixel. Thus, Europa lacks a good geometric control grid, and the positions of features are not well constrained. Errors in the Voyager-era basemap range up to a few degrees in latitude and longitude.
A limb fit correction was performed to full-disk images such as many of the low-resolution views of Io from Voyager and Galileo, to provide a first-order improvement on the raw spacecraft geometric pointing information. In some cases, where absolute pointing information was required, the raw images were tied to a geometrically-controlled basemap to provide the absolute latitudes and longitudes of the features of interest in the image. The production of a geometrically-controlled basemap which merges Galileo and Voyager images of Europa will be discussed in section 3.2. For the change detection techniques, however, the relative offset between the features in the Voyager and Galileo images (or the two Galileo images) was more important, and they were just tied to each other.

To tie images to each other, match points between the two images were found manually using the \texttt{wmatch} package written for Interactive Data Language (IDL), a commercial software package from Research Systems, Inc. (see http://www.rsinc.com for more information). \texttt{Wmatch} allows the user to select a number of points in the two images which are at the same place on the surface of the planet. These matches are made purely in relative line-sample space. For absolute pointing updates, images can be tied to a basemap using the IDL routine \texttt{tvtie}, which assigns each point in the input image an absolute latitude and longitude from the controlled image. After either \texttt{tvtie} or \texttt{wmatch}, an ISIS routine called \texttt{jigsaw} was then run to iteratively update the camera pointing angles, based on minimizing the error in a linearized least-squares solution. \texttt{Jigsaw} can hold one or more images constant while moving the rest of the images around for the best fit. When tying together multiple images at different resolutions,
such as for putting high-resolution images into a lower-resolution context image, *jigsaw* can be run multiple times. In this situation, the best technique is to run *jigsaw* once to tie one central high-resolution image or images at the ends of a high-resolution image strip to the low-resolution context image, and then run *jigsaw* again on just the high-resolution images to improve their alignment, while holding the images previously tied to the context image. This results in the best match between the high-resolution images and the context image, and between the individual high-resolution images.

Next, the images were reprojected. For most applications, reprojecting into either an orthographic or sinusoidal projection is best. The ISIS program *planorth* takes an image in its raw viewing geometry and constructs a transformation file to change it into an orthographic projection, and *plansinu* does the same for a sinusoidal projection. An orthographic projection is the simplest viewing geometry, similar to a point perspective, and when given the sub-spacecraft latitude and longitude to use as the center of the projection, it simulates the view of the surface that would be seen if the spacecraft had been directly overhead. Images in an orthographic projection are easy to view and interpret, and it minimizes image distortion, since each view is optimized for the viewing geometry of that particular image. The sinusoidal projection has the advantage that it preserves all data – images can then be reprojected from a sinusoidal projection into any other projection with the production of minimal artifacts. Sinusoidal projections are therefore useful for the construction of global-scale mosaics, while orthographic projections are best for more localized mosaics. For the construction of
localized orthographic mosaics, the average sub-spacecraft latitude and longitude, as well as resolution, are used to reproject all images in the mosaic.

Reprojection has two steps. The first is to run either planorth or plansinu, depending on which output projection is desired. The input parameters include the center latitude and longitude of the projection, and the image resolution. These values can be found in the image header. Planorth and plansinu both create transformation files, called "tfile.dat" by default, that contain the transformation information. Once the transformation data file is created, the next step is to run the program geom. This program takes the transformation file and actually applies it to the image, performing a "rubber-sheet" geometric transformation from one projection to another. This set of operations also adds the "map projection" block to the image headers.

In most cases, this projection was centered around the subspacecraft point to preserve the three-dimensional spacecraft view of the surface. In the comparison case, the images were reprojected to a common orthographic map projection, centered around an average of the subspacecraft points for the two images to produce an intermediate viewing geometry which has a minimum distortion for the image pair. In this step, for the comparison case, the resolution of the Galileo image was also set to match the resolution of the Voyager image, resulting in identical pixel scales. Once the comparison images were reprojected, the area of overlap of the two images was cut out using the mask procedure in ISIS. The resulting comparison images show the Voyager and Galileo violet-filter views of one subarea of the surface of Europa, reprojected to the same viewing geometry. Figures 1.6a and 1.6b show the result of processing the
raw images in Figure 1.5 using the steps above, including reprojecting and masking. At this stage, for the comparison case, a subpixel coregistration procedure was run on the images, using the ISIS procedure \textit{subpreg}. This performs a "rubber-sheet" subpixel registration of the two images, in which control points are automatically found and run through a least-squares fit to a polynomial equation to create a transformation file which is then used to reproject the second image so that it is closer in registration to the first. This procedure effectively "stretches" the images to align them better. After this step, the images were once again masked to remove smear which accumulates at the edges of the images, due to the subpixel registration.

At this point, the images were photometrically corrected, using a Lunar-Lambert function with $L=0.5$ for Europa (McEwen, 1991) and with $L=0.8$ for Io. This was done using \textit{photompr} and \textit{photom} in ISIS. The photometric correction serves to brighten the terminator regions of the images but is solely dependent on lighting and viewing geometry and does not take into account differences in terrain types. This results in some problems for both Europa and Io. Since Io has a very complicated photometric function (Simonelli \textit{et al.}, 1997; see also section 2.1), the photometric correction is least successful there.

\textbf{A.3: Iterative Coregistration}

Once the photometric correction was completed, the images were ready for the iterative coregistration procedure. This was done using the ISIS routine \textit{coreg}, which performs a subpixel registration of the first input image to the second input image, using
a polynomial equation. The two images were coregistered back and forth to one another: the first image was registered to the second image, and then the second image was registered to the first, and so on. This series of coregistrations was performed until the correlation coefficient reached a maximum, which in the case of the Europa images usually took between 10 and 30 iterations. A similar number of iterations was needed for the Io images, with the number of iterations dependent on how well-matched the two images were in viewing and illumination geometry. This series of steps serves not only to align the two images as closely as possible but also effectively resamples the Galileo image so that its apparent resolution more closely matches the lower resolution of the Voyager image. While the pixel scales of the two images were set to match each other in the reprojection step, the inherently higher resolution and increased sharpness of the Galileo image in Figure 1.6b were still noticeable when compared to the Voyager image in Figure 1.6a. The resampling due to the coregistration degrades this sharpness, and when the correlation coefficient is maximized, not only do the images match closely in geometry, but the apparent resolutions are also quite close. Figures 1.6c and 1.6d show a post-coregistration comparison pair of images, with a much less sharp Galileo image than in Figure 1.6b.

After the coregistration was completed and the correlation coefficient was maximized, the images were again masked to remove false data which had smeared out their edges. A final subpixel registration sequence was run, where each image was registered to the other, and finally a ratio image was generated by dividing the Galileo image by the Voyager image. Areas where the Galileo image is darker will be dark in
the ratio, and areas which have brightened since Voyager will be bright. A sample ratio image is shown in Figure 1.6e. This final product is then examined closely to search for surface changes.

A.4: Creating mosaics

After reprojection and photometric correction, images taken as part of a mosaic sequence can be merged together into a final image product. This can be accomplished a number of ways. If the images are all from a consistent observation, such as a 6-frame mosaic taken through a single filter on a single orbit, the ISIS program mosaic can be used. The first time mosaic is run, it initializes the output mosaic file. Parameters such as latitude and longitude range, number of bands, number of images, etc. are all set in this first run of mosaic. Rather than using the rectangular method described earlier for piecing together different image versions, this run of mosaic uses option=map, which results in the program using the latitude and longitude of points in each image to determine where it goes in the output mosaic. This stage is where the accuracy of the geometric control from the wmatch/jigsaw step can be checked.

Once the output mosaic is initialized, mosaic is run once for each other image to be placed in the mosaic. The default is to place each new image on top of what is already in the mosaic, so typically the lowest-resolution image is first, and the highest-resolution image is last. Thus, the latitude and longitude range specified in the initialization step must include all images to be placed in the output mosaic. The final
mosaic file can then be viewed with the program *qview*, and inspected for alignment along seams.

The program *mosaic* is fine for sets of images which make up a single, uniform observation. However, to create images which merge data from many different observations and which can include both Voyager and Galileo data, a more sophisticated method is necessary. To adjust brightness and contrast levels between different images, the programs *fit* and *poly* are useful. *Fit* computes a polynomial function, of user-specified degree, to correlate the overlapping areas of two input images. The output function from *fit* can then be applied to the second image using the program *poly*. Usually, using either a first or second-order polynomial works quite well.

*Fit and poly* account for overall differences in brightness level between images. There are often still problems along image boundaries even after they have been run, however, and in this case the program *noseam* is useful. *Noseam* replaces *mosaic*, and takes as its input a list of images, along with the mosaicking parameters such as latitude and longitude range. *Noseam* performs a boxfilter seam removal process, which involves running each input image through a high pass filter, and mosaicking them together to produce a high pass filtered mosaic. The base mosaic is then run through a low pass filter, and the high pass filter mosaic is added to this to result in a seamless (or at least better) output mosaic. The sizes of the boxfilters can be adjusted by the user depending on the scale of the variations along image seams. For the Europa images, filter sizes of 201x201 and 301x301 have been successful.
The program *equalizer* can also be used to correct brightness differences between images. First, the program *photopt* is run, which finds various statistics about each of the cubes to be used with *equalizer*. *Photopt* records the mean pixel value of each image, the mean of each cube in overlap regions with other cubes, the slope of a best fit line between brightness values of two cubes, and the number of points used in calculating these statistics. Once this information has been stored in the headers of the images, *equalizer* constructs a pdf which can then be used to correct the brightness differences. Within *equalizer*, one or more images can be held at constant brightness, and the fit can be set to multiplicative, additive, or both. Once the images have been run through the pdf created by *equalizer*, they can be mosaicked together with *mosaic* or *noseam*. *Equalizer* has proved especially useful in dealing with images taken at different phase angles and through different filters.

The above discussion has focused on the processing of single-band images. ISIS, however, was developed in part to deal with images taken through multiple filters, or even with semi-continuous imaging spectrometer data. Working with color images is quite simple: each filter is processed separately, and tied to each of the other filters in that observation in the *wmatch / jigsaw* step described above. After reprojection and photometric correction, the images are then stacked together in the band direction with the ISIS program *cubeit*, and can then be mosaicked together into a multi-band image cube.
Appendix B: Production of geometrically controlled Europa basemap

While initially the new Galileo Europa images were tied to the old Voyager basemap, it soon became clear that the inconsistencies in the Voyager basemap required the construction of a new Galileo-based control grid. Creation of a more accurate Galileo-based coordinate system for surface features began with a limb fit to a global G2 image using the IDL program \textit{tvtie}. The resulting camera angles were used to derive positions of features in that image, and all the Galileo images were tied to this updated image. This could then be used to build up a new basemap for Europa. Tie points from each new set of images were sent to Mert Davies and Tim Colvin at RAND Inc., who run them through a computer program which uses all the Europa images we have so far, along with tie points, and determines the best-fit feature coordinates and thus camera matrices. The new pointing information is then returned to the labels of the Europa images, and the iterative process continues. This is an ongoing process; however, now that near-global coverage of Europa has been obtained on Galileo orbits E14 and I25, a final solution should be possible in the near future. Mapping experts at USGS Flagstaff are currently using the tie points, coupled with the new geometric control solution from RAND, to construct a final controlled basemap of Europa.

Establishment of a consistent geometric control began with a limb fit to a global G2 image as described above. Then, each subsequent image was tied to its overlap region with images which were already controlled. This allowed the construction of an interim controlled basemap for use in planning of Galileo Europa observations while the final control was still pending. The accuracy of the positions in the interim map,
however, decreases with distance from the limb-fit image. Other global images were
gained on orbits E14, E19, and 125, and these should increase the accuracy of the
feature locations.

Images are tied together by using the program *wmatch*, which is part of the ISIS
extensions written to IDL. *Wmatch* allows the user to display two images side-by-side,
and select pairs of points in the two images which correspond to the same location or
feature. These "match points" are then saved in the image headers. Once sufficient
match points have been located in all the images in question, the ISIS program *jigsaw* is
run. *Jigsaw* takes a list of files as its input, and also requires a list of images to be held
constant. These images are the controlled images, ones whose positions have already
been established through ties to other images. The camera angles of the non-held
images are then adjusted by *jigsaw* to find the best fit solution which allows all the
indicated match points to be aligned. *Wmatch* and *jigsaw* used in conjunction as
described above allow the user not only to tie individual images in with the global
control grid, but also to tie together individual frames into a mosaic. Once these steps
have been run, therefore, the images have been tied to each other as well as into the
global pointing system.
Appendix C: Combined low-resolution, high-resolution synthetic color

A limited number of color images of Europa and Io were acquired during the Galileo mission due to severe constraints on tape recorder space and downlink. Most of the color observations of Europa which were returned to Earth are at global scales of a few kilometers or more per pixel. Most of the high-resolution images of Europa were taken through the clear filter, and thus do not distinguish between different color units on Europa's surface. A similar situation is also in place for Io, where there are multiple global-scale color observations taken for surface monitoring, but only a few high-resolution images from orbits 124 and 125, most taken with the clear filter. It is instructive, therefore, to investigate methods of producing synthetic color data by combining the low-resolution color views of the surface with the high-resolution clear-filter images. The production of a multi-stage merged synthetic color view of one region of Europa will be discussed in detail, and a briefer discussion of a different technique for creating merged products for Io will follow.

C.1: Merged Europa color products

First, the relationships between color, albedo, and topography must be examined. Topography on Europa is in general quite subdued; rises of a few hundred meters are typical, with the maximum topographic relief approaching perhaps a kilometer. Interestingly, the surface appears quite different when viewed at either very low or very high phase angle. Figure C.1 is an image of a portion of the surface taken at low phase angle, and Figure C.2 is that same region at high phase (as well as higher
resolution). It is clear that Figure C.1 is basically an albedo map of the surface -- no topographic relief is visible. In Figure C.2, however, the same features were much closer to the terminator, and topography is clearly visible. It is important to note that Figure C.1 contains albedo, but no topography, while Figure C.2 contains a wealth of topographic information, but very little albedo information. Clearly, these two datasets must be combined to produce the best data products to enhance scientific understanding of the region.

Color information is also available for this area, but at a much lower resolution than either the topography or the albedo. Covering this part of the planet, there are three sets of Galileo observations: a three-filter global color observation, containing violet, green, and 1-micron images at about 7 km/pixel; a medium-resolution low-phase-angle set of observations, taken at 1.2 km/pixel, and a high-resolution, high-phase-angle set of images, taken at 180 m/pixel. These three datasets can be combined to produce a synthesized view of Conamara Chaos region of Europa's surface, located just below the "X" in the medium-resolution and high-resolution images.
Figure C.1. Observation of Europa from orbit E4, taken at low phase angle. The resolution of this image is 1.2 km/pixel.
Figure C.2. Observation of the same region of Europa from orbit E6, taken at a higher phase angle. The resolution of this image is 180 m/pixel.
Figure C.3. Color observation of the trailing hemisphere of Europa from orbit G2, at 7 km/pixel. Images taken through the 1 micron, green, and violet filters were combined and stretched to produce this enhanced-color image.
Figure C.4. Combination of the color information from Figure C.3 with the higher-resolution image from Figure C.1, by Paul Geissler. The relationships between color units and surface features are more evident, but comparisons with the higher-resolution Figure C.2 are still difficult.
Figure C.3 shows the color observations covering this area of the surface. The color data is intriguing, but the resolution is far too low to compare directly to the high-resolution E6 image shown in Figure C.2. A first attempt to improve this is shown in Figure C.4. This image, made by Paul Geissler, contains the E4 image of Figure C.1 with the G2 color data from Figure C.3 superimposed on it. In this image, the relationships between color and surface features can be seen a bit better, but this image still can't be compared well with the high-resolution Figure C.2.

One way to improve the effective resolution of the color image is to use the G2 color and the E4 albedo to map color variations to albedo variations, creating a synthetic set of E4 color images at 1.2 km/pixel. These images can then be superimposed on the high-resolution E6 images (at 180 m/pixel), to produce a synthetic E6 color image. The first step was to reproject the G2/E4 overlap region to the same viewing geometry as the E6 images. This was accomplished by using nuproj, with an orthographic projection. The appropriate areas of the three G2 color images were first reprojected to the E6 viewing geometry with a resolution of 1.8 km/pixel. Ratio was then used to make G2 color ratio images (gr/1μm and gr/vt). Then the E4 mosaic was reprojected to the E6 viewing geometry at 180 m/pixel, and magcube was used to make a version of this mosaic at a resolution of 1.8 km/pixel (lscale=0.1, sscale=0.1).

Next, the program fit was used to find a second-order polynomial fit between each of the G2 color ratio images and the E4 image. Poly was used to apply this fit to the E4 image, thus making two synthetic E4 color ratio images. The fit was first applied to the subsampled E4 image, and then to the full-E6-resolution version when the
result was satisfactory. Next, the region of each synthetic E4 color ratio which overlapped with the E6 high-resolution mosaic was cut out. This resulted in two synthetic E4 color ratio images, at the same resolution and covering the same area as the E6 image. Using the E6 image as a model green image, the E6 image was ratioed with the two color ratios (E6 "green" / (E4 gr/vt ratio) = E6 "violet") to produce synthetic E6 violet and 1 μm images. These could then be stacked together with cubeit to make a synthetic E6 color image (again, using the original E6 mosaic as green).

The result of this process is visible in Figure C.5, which has been stretched to bring out color contrasts while retaining each of the distinct units. Three distinct color units on the surface are clearly visible in Figure C.5. The rays of ejecta from the crater Pwyll, visible in Figure C.1, are bright white. The material in the region of disrupted terrain below the "X", as well as along the lineaments and surrounding the upwelling domes, is reddish, and the background icy plains show up as bluish. Figures C.6 and C.7 show a zoomed-in image of the region of disrupted terrain below the "X". In Figure C.6, slight albedo variations are visible indicating the location of the ray from Pwyll and other spectral variations, but Figure C.7 clearly shows the different units. This image shows that the bright rays from Pwyll are superimposed on the entire region, and thus that the Pwyll impact that formed these rays must have happened after the region of disrupted terrain was formed.
Figure C.5. Combination of the color / albedo information from Figure C.4 with the high-resolution topography of Figure C.2. The image has been stretched to bring out the three distinct color units. The ejecta from the crater Pwyll are bright white, the material located along the ridges and in Conamara chaos (the region of disrupted terrain below the "X") is reddish, and the background ridged plains appear bluish.
Figure C.6. Even higher-resolution view of the region of chaotic terrain beneath the "X" in Figure C.5. Albedo variations are visible, indicating the location of the ray from the crater Pwyll which cuts through this image.
Figure C.7. Color information from Figure C.5 combined with the topographic information of C.6. Different color units are visible on the surface, but the mapping of color to albedo breaks down at this resolution.
C.2: Merged Io color products

A similar technique has been also used to map new high-resolution Io images onto lower-resolution global color images. Figure 2.25 shows the appearance of the Pillan caldera and lava flows on orbit E14 in a near-terminator, clear-filter image. The large mountain to the north of the Pillan caldera is clearly visible. The second image shows the appearance of Pillan on orbit E26, in the highest-resolution color view we have of the area. The E26 image shows the dark lava flows, the red of the Pele plume deposit, and the curious white area to the north of Pillan which was covered by dark material in the C10 post-eruption image, but returned to its pre-eruption white appearance when next seen on orbit C21. Clearly, it would be interesting to know whether the white deposit falls on the mountain or elsewhere.

To combine these two datasets, first the two images were tied together with \textit{wmatch} and \textit{jigsaw}, and registered to subpixel alignment with \textit{coreg}. Then they were reprojected to a common viewing geometry and pixel scale, and the region of interest was cut out of both images. The technique described in the previous section for combining Europa color and albedo images does not work well in this situation because in this case we do not have an intermediate albedo image to map the color data to. Instead, we used a different technique. First, we performed a high-pass filter on the E14 clear-filter image with a box size of 11x11 pixels (\textit{boxfilter}, \textit{filt=hpf}). This extracts the high-frequency topographic information, while removing the lower-frequency albedo information. This filtered version of the E14 was then added to each of three bands of the E26 color image. Adding the boxfiltered E14 to each band results in small changes
around the central mean of each filter, but does not change the overall color. The addition of high-frequency topographic data is visible in the third image in Figure 2.25, where the mountain suddenly appears in the color image. This image reveals that the white patch is in fact a plateau to the north of the main mountain, which could be covered with bright white SO$_2$ frost due to sapping from either of the bounding scarps. Also visible is a bright red linear feature, which appears to be a fissure. This red feature lines up exactly with one of the faults in the mountain. This could imply that the faulting which allowed the release of lava in the Pillan flows and caldera is also related to the forces that formed the mountain. Thus, the combination of color images with topographic images has resulted in a new understanding of the merged datasets, both in the case of Io and Europa.
Appendix D: Sample PDF file for processing images in ISIS

procedure

body

!!Voyager image:

cd2isis from=mask/vtl.imq to=mask/vtl.cub
spicelab tblfrom=~/Data/voyager/europaspice.rnd .
to=mask/vtl.cub
findrx from=mask/vtl.cub
trim from=mask/vtl.cub to=mask/vtl.trm top=5 bot=5 left=5+
right=5
remrx from=mask/vtl.trm to=mask/vtl.rem sdim=5 ldim=7 +
action=null
voycal from=mask/vtl.rem to=mask/vtl.cal
ratio from=mask/vtl.cal +
from2=~/Data/voyager/v2noise.template +
to=mask/vtl.calr

!!Galileo image:

vicar2isis from=s0440984939.1 to=s0440984939_1.cub
naiflab s0440984939_1.cub
ssical from=s0440984939_1.cub to=s0440984939_1.cal

vicar2isis from=s0440984939.6 to=s0440984939_6.cub
naiflab s0440984939_6.cub
ssical from=s0440984939_6.cub to=s0440984939_6.cal

mosaic from=s0440984939_1.cal to=s0440984939_16.cal +
bandchk=no option=rect slm=1 ssm=1 iniT:=yes nlm=800 +
nsm=800 nbm=1

mosaic from=s0440984939_6.cub to=s0440984939_16.cub +
bandchk=no option=rect slm=1 ssm=1 iniT:=no

trim from=s0440984939_16.cal to=s0440984939_16.tcal +
left=2 right=2 top=2 bottom=2

!!copy both files to _2 label
!!wmatch in idlisis....

jigsaw150 from=(s0440984939_16_2.tcal, vtl_2.calr) +
   hold=s0440984939_16_2.tcal option=2

planorth from=s0440984939_16_2.tcal clat=0 clon=166 +
   km=1.92 lat=(-26.91, 71.36) lon=(132.78, 228.70)
geom from=s0440984939_16_2.tcal to=s0440984939_16_2.vorth
ush /bin/rm tfile.dat

planorth from=vtl_2.calr clat=0 clon=166 km=1.92 +
   lat=(-26.91, 71.36) lon=(132.78, 228.70)
geom from=vtl_2.calr to=vtl_2.vorth
ush /bin/rm tfile.dat

mask from=vtl_2.vorth from2=s0440984939_16_2.vorth band=1+
   to=vtl_2.mask
mask from=s0440984939_16_2.vorth from2=vtl_2.mask +
   to=s0440984939_16_2.mask band=1

subpreg from=(vtl_2.mask, s0440984939_16_2.mask) +
   to=vtl_2.preg nlbox=30 nsbox=30 sl=450 ss=345

mask from=vtl_2.preg from2=s0440984939_16_2.mask band=1 +
   to=vtl_2.pmask
mask from=s0440984939_16_2.mask from2=vtl_2.pmask +
   to=s0440984939_16_2.pmask band=1

ratio from=s0440984939_16_2.pmask from2=vtl_2.pmask +
   to=vg_vtl_2.prat otype=2 orange=(0,10)

!!!photometric corrections...

photompr from=s0440984939_16_2.pmask func=lunlam L=0.5
photom from=s0440984939_16_2.pmask +
   to=s0440984939_16_2.phomask otype=2 orange=(0,2)
ush /bin/rm sun.dat

photompr from=vtl_2.pmask func=lunlam L=0.5
photom from=vtl_2.pmask to=vtl_2.phomask otype=2 +
   orange=(0,2)
ush /bin/rm sun.dat
ratio from=s0440984939_16_2.phomask from2=vtl_2.phomask otype=2 orange=(0,10)

!!sequential coreg's....

coreg from=s0440984939_16_2.phomask from2=vtl_2.phomask2 otype=2 orange=(0,1) +
ltol=30 stol=30 band=1

coreg from=vtl_2.phomask from2=s0440984939_16_2.phomask2 otype=2 orange=(0,1) +
stol=30 band=1

coreg from=s0440984939_16_2.phomask2 from2=vtl_2.phomask2+
to=s0440984939_16_2.phomask3 otype=2 orange=(0,1) +
ltol=30 stol=30 band=1

coreg from=vtl_2.phomask2 from2=s0440984939_16_2.phomask3+
to=vtl_2.phomask3 otype=2 orange=(0,1) ltol=30 +
stol=30 band=1

coreg from=s0440984939_16_2.phomask3 from2=vtl_2.phomask3+
to=s0440984939_16_2.phomask4 otype=2 orange=(0,1) +
ltol=30 stol=30 band=1

coreg from=vtl_2.phomask3 from2=s0440984939_16_2.phomask4+
to=vtl_2.phomask4 otype=2 orange=(0,1) ltol=30 +
stol=30 band=1

coreg from=s0440984939_16_2.phomask4 from2=vtl_2.phomask4+
to=s0440984939_16_2.phomask5 otype=2 orange=(0,1) +
ltol=30 stol=30 band=1

coreg from=vtl_2.phomask4 from2=s0440984939_16_2.phomask5+
to=vtl_2.phomask5 otype=2 orange=(0,1) ltol=30 +
stol=30 band=1

coreg from=s0440984939_16_2.phomask5 from2=vtl_2.phomask5+
to=s0440984939_16_2.phomask6 otype=2 orange=(0,1) +
ltol=30 stol=30 band=1
coreg from=vtl_2.phomaskS from2=s0440984939_16_2.phomask6+ 
to=vtl_2.phomask6 otype=2 orange=(0,1) ltol=30 + 
stol=30 band=1

coreg from=s0440984939_16_2.phomask6 from2=vtl_2.phomask6+ 
to=s0440984939_16_2.phomask7 otype=2 orange=(0,1) + 
ltol=30 stol=30 band=1

coreg from=vtl_2.phomask6 from2=s0440984939_16_2.phomask7+ 
to=vtl_2.phomask7 otype=2 orange=(0,1) ltol=30 + 
stol=30 band=1

coreg from=s0440984939_16_2.phomask7 from2=vtl_2.phomask7+ 
to=s0440984939_16_2.phomask8 otype=2 orange=(0,1)+ 
ltol=30 stol=30 band=1

coreg from=vtl_2.phomask7 from2=s0440984939_16_2.phomask8+ 
to=vtl_2.phomask8 otype=2 orange=(0,1) ltol=30 + 
stol=30 band=1

ratio from=s0440984939_16_2.phomask8 from2=vtl_2.phomask8+ 
to=vg_vtl_2.phomask8 otype=2 orange=(0,10)

coreg from=s0440984939_16_2.phomask8 from2=vtl_2.phomask8+ 
to=s0440984939_16_2.phomask9 otype=2 orange=(0,1)+ 
ltol=30 stol=30 band=1

coreg from=vtl_2.phomask8 from2=s0440984939_16_2.phomask9+ 
to=vtl_2.phomask9 otype=2 orange=(0,1) ltol=30 + 
stol=30 band=1

coreg from=s0440984939_16_2.phomask9 from2=vtl_2.phomask9+ 
to=s0440984939_16_2.phomask10 otype=2 orange=(0,1)+ 
ltol=30 stol=30 band=1

coreg from=vtl_2.phomask9 + 
from2=s0440984939_16_2.phomask10 to=vtl_2.phomask10+ 
otype=2 orange=(0,1) ltol=30 stol=30 band=1

coreg from=s0440984939_16_2.phomask10 + 
from2=vtl_2.phomask10 to=s0440984939_16_2.phomask11 + 
otype=2 orange=(0,1) ltol=30 stol=30 band=1
coreg from=vtl_2.phomask10 +
  from2=s0440984939_16_2.phomask11 to=vtl_2.phomask11+
  otype=2 orange=(0,1) ltol=30 stol=30 band=1

mask from=s0440984939_16_2.phomask11 +
  from2=s0440984939_16_2.phomask band=1 +
  to=s0440984939_16_2.phomask11.mask

mask from=vtl_2.phomask11 from2=vtl_2.phomask band=1 +
  to=vtl_2.phomask11.mask

ush /bin/rm tfile.dat
ush /bin/rm cfile.dat

subpreg from=(vtl_2.phomask11.mask, +
  s0440984939_16_2.phomask11.mask) +
  to=vtl_2.phopreg11.mask deg=2 nlbox=30 nsbox=30 +
  minr=0.8
ush /bin/rm tfile.dat

subpreg from=(s0440984939_16_2.phomask11.mask, +
  vtl_2.phopreg11.mask) +
  to=s0440984939_16_2.phopreg11.mask deg=2 nlbox=30 +
  nsbox=30 minr=0.8
ush /bin/rm tfile.dat

ratio from=s0440984939_16_2.phopreg11.mask +
  from2=vtl_2.phopreg11.mask +
  to=vg_vtl_2.phorat11.mask otype=2 orange=(0,10)

cubeit from=(s0440984939_16_2.phopreg11.mask, +
  vtl_2.phopreg11.mask) to=vg_vtl_2.cub.mask

drop proc
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