NASA volcanology field workshops on Hawai‘i: Part 2. Understanding lava flow morphology and flow field emplacement

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ABSTRACT

The Big Island of Hawai‘i presents ample opportunities for young planetary volcanologists to gain firsthand field experience in the analysis of analogs to landforms seen on Mercury, Venus, the Moon, Mars, and Io. In this contribution, we focus on a subset of the specific features that are included in the planetary volcanology field workshops described in the previous chapter in this volume. In particular, we discuss how remote-sensing data and field localities in Hawai‘i can help a planetary geologist to gain expertise in the analysis of lava flows and lava flow fields, to understand the best sensor for a specific application, to recognize the ways in which different data sets can be used synergistically for remote interpretations of lava flows, and to gain a deeper appreciation for the spatial scale of features that might be imaged in the planetary context.

INTRODUCTION

Rowland et al. (2011, Chapter 25, this volume) described the background and history of the 10 planetary volcanology field workshops that have been held on the island of Hawai‘i since 1992. These workshops have provided an opportunity for more than 130 young National Aeronautics and Space Administration (NASA)–funded graduate students, postdoctoral fellows, and junior faculty to view basaltic volcano features up close, in the company of both terrestrial and planetary volcanologists. The goal for each workshop was to give these young scientists a strong background in basaltic volcanology, and to provide the chance for them to view eruptive features up close so that the participants can then compare the appearance of these features with planetary analogs in state-of-the-art remote-sensing images.

The participants covered a wide range of disciplines during the workshop, including physical volcanology (Francis, 1993; Kilburn and Luongo, 1993; Parfitt and Wilson, 2008), planetary remote sensing (Pieters and Englert, 1993; Mouginis-Mark et al., 2000; Campbell, 2002), and volcanism on the planets (McGuire et al., 1996; Zimbelman and Gregg, 2000; Lopes and Gregg, 2004; Keszthelyi et al., 2006; Lopes and Spencer, 2007). It is also hoped that they gained some familiarity with the theoretical aspects of volcanism on the Moon (Wilson and Head, 1981), Mars (Wilson and Head, 1994), and Venus (Head and Wilson, 1986, 1992). Thus, the range of topics that they studied in the field in one short week was a mixture of geology, sensor
technology, and planetary exploration. To help the reader here, we provide a summary of the sensors used during the workshop, along with the appropriate planetary/terrestrial analog instruments, and the wavelength range and spatial resolution of the sensors (Table 1).

In this contribution, we focus on some specific planetary analog field sites developed for the workshops to aid in the interpretation of lava flows and lava flow fields. Over the course of 3 days in the field, we illustrated the level of difficulty that is involved in mapping the spatial extent and other physical attributes of a lava flow field. In the planetary context, mapping an entire lava flow is important because, together with an estimate of flow thickness, it provides a measure of the volume of lava erupted and some of the processes that control flow emplacement (Moore, 1987; Baloga et al., 2003). Use of thermal infrared data that highlight the surface glass coatings of different Mauna Loa lava flows (Kahle et al., 1988) was particularly helpful for correlating multiple flow lobes from a single eruption, and thus determining the length of each lava flow. It was also important to identify the surface roughness differences between the two principal types of lava flows, namely, relatively rough 'āʻā and relatively smooth pāhoehoe, because these differences relate to the flow rate at which the lava is erupted; 'āʻā flows are erupted at high rates (>~20 m$^3$ s$^{-1}$), and pāhoehoe are erupted relatively low rates (<~5 m$^3$ s$^{-1}$) (Rowland and Walker, 1990). An understanding of the discharge rate for planetary lava flows and total flow volume is important for interpreting the subsurface structure of a volcano (Wilson and Head, 1994; Head and Wilson, 1992), and so the workshop participants learned how to use orbital data to make inferences about the subsurface structure of a planetary volcano from the distribution of lava flow types. The utility of multiparameter (i.e., different wavelengths and different polarizations) imaging radar data for surface roughness studies was also explored, particularly in the context of studying lava flows on Venus, where the thick atmosphere precludes optical imaging of the surface.

Viewing active lava flows was an additional aid to workshop participants because they gained firsthand knowledge of the temperature distribution of the surface of an active flow, as well as the speed at which such flows can move (Lipman and Banks, 1987; Kilburn and Luongo, 1993). This knowledge could then be employed in the planetary context for modeling the emplacement of lava flows on the Moon (Schaber, 1973; Hulme and Fielder, 1977), Mars (Wadge and Lopes, 1991; Glaze et al., 2009), or Venus (Roberts et al., 1992; Lancaster et al., 1995), and it can help to interpret the duration of eruptions (Keszthelyi and Pieri, 1993; Mouginis-Mark and Yoshikawa, 1998). Knowledge of terrestrial lava flows can aid the interpretation of active effusive volcanism on Io (Williams et al., 2001). In each day in the field, use was made of the abundant remote-sensing data that have been collected for Hawai‘i over the years, including high-resolution (1 m/pixel) visible images, thermal infrared images (Kahle et al., 1988, 1995), and radar data (Gaddis et al., 1989; Campbell et al., 1993).

### TABLE 1. REMOTE-SENSING DATA SETS FOR THE EARTH AND OTHER PLANETS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Sensor full name</th>
<th>Platform</th>
<th>Planet</th>
<th>Resolution</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRSAR</td>
<td>AIRcraft Synthetic Aperture Radar</td>
<td>Aircraft</td>
<td>Earth</td>
<td>5 m</td>
<td>5.7, 25.0, and 68.0 cm</td>
</tr>
<tr>
<td>ALOS</td>
<td>Advanced Land Observation Satellite</td>
<td>Satellite</td>
<td>Earth</td>
<td>Variable</td>
<td>24 cm</td>
</tr>
<tr>
<td>Diviner</td>
<td>Diviner Lunar Radiometer</td>
<td>Satellite</td>
<td>Mars</td>
<td>~500 m</td>
<td>0.3–3.0; 7.8–100 microns</td>
</tr>
<tr>
<td>ENVIROS</td>
<td>Environmental Satellite</td>
<td>Satellite</td>
<td>Earth</td>
<td>30 m</td>
<td>5.6 cm</td>
</tr>
<tr>
<td>HiRISE</td>
<td>High Resolution Imaging Science Experiment</td>
<td>Satellite</td>
<td>Mars</td>
<td>25 cm</td>
<td>400–850 nm</td>
</tr>
<tr>
<td>HRSC</td>
<td>High Resolution Stereo Camera</td>
<td>Satellite</td>
<td>Mars</td>
<td>10 m</td>
<td>475–725 nm</td>
</tr>
<tr>
<td>IKONOS</td>
<td>IKONOS satellite</td>
<td>Satellite</td>
<td>Earth</td>
<td>1 m</td>
<td>526–929 nm</td>
</tr>
<tr>
<td>Landsat TM</td>
<td>Landsat Thematic Mapper</td>
<td>Satellite</td>
<td>Earth</td>
<td>30 m</td>
<td>450–2350 nm</td>
</tr>
<tr>
<td>LROC</td>
<td>Lunar Reconnaissance Orbiter Camera</td>
<td>Satellite</td>
<td>Moon</td>
<td>50 cm</td>
<td>450–750 nm</td>
</tr>
<tr>
<td>Mini-RF</td>
<td>Miniature Radio Frequency experiment</td>
<td>Satellite</td>
<td>Moon</td>
<td>75 m</td>
<td>3 and 12 cm</td>
</tr>
<tr>
<td>MOC</td>
<td>Mars Orbiter Camera</td>
<td>Satellite</td>
<td>Mars</td>
<td>1.5–12 m</td>
<td>500–900 nm</td>
</tr>
<tr>
<td>NIMS</td>
<td>Near Infrared Mapping Spectrometer</td>
<td>Satellite</td>
<td>Jupiter</td>
<td>Variable</td>
<td>0.7–5.2 microns</td>
</tr>
<tr>
<td>RADARSAT</td>
<td>Radar Satellite</td>
<td>Satellite</td>
<td>Earth</td>
<td>Variable</td>
<td>5.6 cm</td>
</tr>
<tr>
<td>SIR-B</td>
<td>Shuttle Imaging Radar experiment B</td>
<td>Space shuttle</td>
<td>Earth</td>
<td>20–30 m</td>
<td>23.5 cm</td>
</tr>
<tr>
<td>THEMIS IR</td>
<td>Thermal Emission Imaging System, infrared</td>
<td>Satellite</td>
<td>Mars</td>
<td>100 m</td>
<td>7.93–12.57 microns</td>
</tr>
<tr>
<td>THEMIS VIS</td>
<td>Thermal Emission Imaging System, VI$\text{S}$$\text{ible}$</td>
<td>Satellite</td>
<td>Mars</td>
<td>18 m</td>
<td>425–860 nm</td>
</tr>
<tr>
<td>TIMS</td>
<td>Thermal Infrared Multispectral Scanner</td>
<td>Aircraft</td>
<td>Earth</td>
<td>8 m</td>
<td>8–12 microns</td>
</tr>
<tr>
<td>UAVSAR</td>
<td>Uninhabited Aerial Vehicle Synthetic Aperture Radar</td>
<td>Aircraft</td>
<td>Earth</td>
<td>1.8 m</td>
<td>24 cm</td>
</tr>
<tr>
<td>Magellan radar</td>
<td>Satellite</td>
<td>Venus</td>
<td>75 m</td>
<td>12 cm</td>
<td></td>
</tr>
<tr>
<td>Cassini radar</td>
<td>Satellite</td>
<td>Saturn</td>
<td>350 m–1.7 km</td>
<td>2.18 cm</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. *Magellan* radar image from the Atla region of Venus, showing several types of volcanic vents and lava flows. Full-resolution *Magellan* data are 75 m/pixel. Note the small shields (S) that have radar-dark flows close to their summits, and radar-bright flows on the lower flanks. Also visible is a lava flow (F) with a central channel, and a collapse depression (D) that feeds into a channel that may be a lava channel. Image is centered at 9°S, 199°E. Part of Jet Propulsion Laboratory (JPL) image no. PIA00201.

Figure 2. *Apollo* handheld Hasselblad photo of lava flows in Mare Imbrium on the Moon. Direction of flow was toward the top of the image. AS15-M-1558, center coordinates 28.12°N, 28.92°W. Oblique view looking north, with a camera tilt of ~40°. Sun elevation is ~2°, and the illumination direction is from the right. The largest impact craters in this view are ~2 km in diameter.

Figure 3. Landsat 7 image mosaic of the NE rift zone of Mauna Loa. The white rectangle in the main image illustrates the area of coverage of Figure 5. North is toward top of the image. Inset at top left shows location on the island of Hawai‘i. Base mosaic was compiled by the Hawai‘i Synergy Project, University of Hawai‘i, and includes the eruption plume on 5 January 2003.
infrared data (Fig. 5) (Kahle et al., 1988; Abrams et al., 1991; Kahle et al., 1995), and many data sets serve as good planetary analogs (Table 1). High-resolution airborne radar data (Fig. 6) have been collected, and very high-resolution 0.6 m to 1.0 m/pixel mapping from commercial panchromatic images (Fig. 7) has been conducted, although these have not been used for any published investigations. Because of the coincident spectral range (8.0–12.0 μm), the Thermal Infrared Multispectral Scanner (TIMS) data (Fig. 5) could
Figure 6. L-band (24 cm wavelength) horizontally transmitted and vertically received (HV polarization) aircraft radar data collected by National Aeronautics and Space Administration’s (NASA) UAVSAR instrument, showing the same set of flows as depicted in Figure 5. Radar look-direction is from the right in this image, and the incidence angle is ~45°. North is toward top of image. Boxes delineate the IKONOS coverage presented in Figure 7.

Figure 7. Panchromatic IKONOS images for the three sub-areas (A, B, and C) illustrated in Figures 5 and 6. North is toward the top in all images. At full resolution (D), the IKONOS 1 m/pixel data are useful analogs to High-Resolution Imaging Science Experiment (HiRISE) images of Mars and Lunar Reconnaissance Orbiter camera (LROC) images of the Moon for recognizing details of lava flow lobes and structures such as channels within the flow.
be considered to be an analog to the Diviner nine-channel mapping radiometer onboard the Lunar Reconnaissance Orbiter (LRO), although Diviner has a much lower spatial resolution (~500 m/pixel; Paige et al., 2009). TIMS data are also comparable to THEMIS infrared (IR) measurements for Mars (Fergason et al., 2006), although surface dust can obscure the spectral properties of the surface in many places. As has been documented by Kahle et al. (1988), TIMS data accentuate subtle differences in the glassy surfaces of pāhoehoe flows and produce distinct (although only qualitative) differences among individual flows in principal component (PC) images (Kahle et al., 1988). Thus, data of this type can be used to map the spatial extent of pāhoehoe lava flows that have similar glassy surfaces. However, the PC image also shows that ‘a‘ā flows do not possess this glassy surface, and all ‘a‘ā flows tend to have the same color in the PC image.

An extensive array of different radar data sets has also been collected for Mauna Loa, including both orbital (Mouginis-Mark, 1995) and airborne (Kahle et al., 1995) measurements. Radar data can provide information about wavelength-scale surface roughness, as well as the dielectric properties of the material (Campbell, 2002). Because radar is a side-looking (rather than nadir-looking) instrument, it is also useful for the identification of subtle topographic features (such as faults, scars, and cones) oriented toward the sensor. Furthermore, all radars have a wavelength that can penetrate clouds, and so it is particularly useful for imaging volcanic features on the surface of Venus (Roberts et al., 1992; Lancaster et al., 1995) or Titan (Lopes et al., 2007). Radar is an active sensor (i.e., it provides its own source of illumination), and so it can also be used to image the permanently shadowed polar areas of the Moon (Spudis et al., 2010). In the case of the field workshop, we used the 5 m/pixel radar data collected by NASA’s L-band (24 cm wavelength) Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) instrument (Fig. 6), but several fine orbital data sets from the European ENVironmental SATellite (ENVISAT) Advanced Synthetic Aperture Radar (ASAR) and Canadian RADAR SATellite (RADARSAT) C-band (5.6 cm wavelength) radars, or the Japanese Advanced Land Observing Satellite (ALOS) L-band radar also exist (Table 1).

Inspection of Figure 6 illustrates the problem in using radar data for young volcanic terrains, and it illuminates the problems that may exist in the interpretation of Magellan images of Venus (Fig. 1). Despite the different ages and subtle differences in the surface roughness (Fig. 4), most of the lava flows visited on Mauna Loa appear bright in radar images, indicating that they are all similarly rough at L-band wavelengths. It is particularly difficult to map the extent of a single flow, or to distinguish among individual flow lobes that originated during the same eruption. In a few instances, the existence of a lava channel within a flow unit can be detected using the radar data because of the bright, near-specular, returns that the feature possesses within a particular image (Fig. 6). Radar shadows at the edge of some thicker (>~4 m) flows also allow some unit boundaries to be identified. The participants therefore learn that the TIMS thermal infrared data are preferable in mapping the spatial extent of pāhoehoe lava flows in this application. The problems in interpreting radar data are therefore given additional consideration during a second day in the field (see section on Lava Flow Textures).

The second objective of the hike through the Mauna Loa lava flows is to gain an appreciation for the types of features that can or cannot be identified in particular data sets. In the planetary context, these data sets include images from the High-Resolution Imaging Science Experiment (HiRISE) for Mars (25 cm/pixel) and the narrow-angle camera on the Lunar Reconnaissance Orbiter Camera (LROC) for the Moon (50 cm/pixel). Good terrestrial analogs for these data sets are IKONOS images (Fig. 7), which have a spatial resolution of 1 m/pixel. The workshop participants are given a set of full-resolution IKONOS images that allow the flow boundaries and internal structures (such as lava channels) to be compared with the appearance of these features in the field. We have found this to be particularly helpful in the interpretation of HiRISE images of flows on Mars (Fig. 8; Morris et al., 2010). The exercise also leads to a discussion of lighting geometry within a scene. This is relevant when considering satellite orbits and the local time of image acquisition because the photointerpretation of lava flow morphology and texture is much easier with data collected at low solar incidence angle (e.g., the easily identified lunar lava flows in Fig. 2) compared to images collected near local noon (Fig. 7A). Discussion of the lighting geometry can be further enhanced by considering the constraints imposed on thermal infrared data used to compute thermal inertia of the surface, as is the case with THEMIS IR data (Fergason et al., 2006). In this situation, day- and nighttime data are best collected when differences in surface temperatures are at their greatest, typically close to 2:00 p.m. and 2:00 a.m. Past workshop participants have concluded that collecting low-solar-incidence-angle data for geomorphic studies concurrently with good data for thermal inertia investigations is not possible with the same instrument on the same spacecraft.

Conclusions from this part of the workshop include: (1) Thermal infrared images are excellent for the identification of different flow lobes from the same eruption. (2) In instances where an entire area is covered by radar-bright ‘a‘ā flows, radar images are a less useful discriminator of different flow units within an extensive flow field of similar lava textures. However, radar images are good at distinguishing lava channels or the edges of thick lava flows. (3) It is remarkably challenging to locate oneself on a lava flow field using panchromatic images with 1 m/pixel spatial resolution. (4) Solar incidence angle is an important factor when interpreting planetary images.

**Lava Flow Textures**

The investigation of the radar image of Mauna Loa (Fig. 5) introduces the workshop participants to the realization that some types of radar data may not be suitable for the interpretation of topographically rough lavas such as the ‘a‘ā flows. To further explore this issue, and to provide a better insight into ways in which volcanic flows on Venus or the Moon might be studied using orbital radar data, during a second day of the workshop, we explore the value of multiwavelength, multipolarization radar data (Fig. 9). We lead the workshop participants through
Figure 8. Recent spacecraft images can have very high spatial resolution, such as the High-Resolution Imaging Science Experiment (HiRISE) instrument for Mars, and the Lunar Reconnaissance Orbiter camera for the Moon. Workshop participants compare 1 m/pixel IKONOS images with comparable images of the planets, such as this 25 cm/pixel image of a lobate flow on the southwestern rim of Tooting crater on Mars (Morris et al., 2010). Image at right shows the full-resolution view of the area outlined by the box at left. HiRISE image PSP_002646_2035. Image centered at 23°06′N, 207°34′W.

Figure 9. (A) AIRSAR C-band (5.6 cm) horizontally transmitted and horizontally received (HH polarization) image of the distal portion of the December 1974 lava flow in the Kaʻū Desert. (B) AIRSAR C-band data, horizontally transmitted and vertically received (HV polarization). Notice the greater image contrast in these cross-polarized data, which aids the identification of flow boundaries. (C) Color composite of AIRSAR images obtained of P-band (68 cm wavelength) HV data in red, L-band HV data in green, and C-band (5.6 cm) data in blue. The area shown in the visible image in Figure 10 is delineated by the white box. Direction of flow of the lava was from right to left.
the applications of radar remote sensing for the analysis of planetary radar. Campbell (2002) provided an excellent review of radar-scattering and radar-polarization nomenclature, radar reflection and transmission from plane surfaces, as well as the mathematical representations of scattering surfaces at different radar wavelengths. One of the best places in Hawai‘i to perform this analysis is in the Ka‘ū Desert southwest of Kīlauea caldera (Fig. 10). During the first few workshops, this case study was primarily relevant for the analysis of Magellan radar images of Venus but in recent years it has become useful for the analysis of Cassini radar images of Titan (Lopes et al., 2007), and of Mini-RF radar images of the Moon (Spudis et al., 2010) (Table 1).

Because of its accessibility and range of surface morphologies, the December 1974 lava flow in the Ka‘ū Desert has been the site of a number of radar-based quantitative texture studies. Gaddis et al. (1989, 1990) measured the centimeter-scale roughness of this flow (Fig. 11) in order to interpret L-band radar images collected during the 1984 Space Shuttle Imaging

Figure 10. Oblique air view of the central portion of the December 1974 lava flow. View is looking southwest, toward the distal end of the flow, which is just out of the view to the upper left. Brightness differences in the flow result from different flow textures: the pāhoehoe (P) is relatively light toned, and the ‘a‘ā (A) is relatively dark. Note parts of the Koa’e fault scarp at “S,” which is ~10 m high and is detectable in the radar image (Fig. 9) because the scarp is perpendicular to the radar look-direction.

Figure 11. Field measurements of the surface roughness of pāhoehoe (left) and ‘a‘ā (right) made along the December 1974 lava flow. These measurements have been used to understand radar backscatter from both terrestrial (Gaddis et al., 1989, 1990) and Venusian lava flows (Campbell et al., 1993; Campbell and Rogers, 1994). The vertical rods are spaced 1 cm apart and show the dramatic difference between smooth pāhoehoe surfaces and rough ‘a‘ā. Photos by L. Gaddis.
Radar-B (SIR-B) radar mission. These (and subsequent) radar data have enabled a series of comparisons between basaltic lava flows on Earth and Venus (Campbell et al., 1993; Campbell and Rogers, 1994; Carter et al., 2006), as well as more detailed analyses of centimeter- to meter-scale topography of lava flows (Campbell and Shepard, 1996; Shepard et al., 2001; Morris et al., 2008).

One motivation for such studies is to correlate lava flow type with eruption rate, specifically exploring the relationships between pāhoehoe (produced by low-effusion-rate eruptions) and ‘a’a (high effusion rates) (Rowland and Walker, 1990). Workshop participants walk more than 3 km from the vent area of the 1974 flow (Fig. 12) to the point where the flow ran up against a scarp that forms part of the Koa’e fault system (Fig. 11), during which time they see the narrow (>2 m wide) fissures, thin (<50 cm thick) proximal pāhoehoe flows, and the transition of these pāhoehoe flows into ~3–4-m-thick ‘a’ā flows.

The point where the 1974 flow encountered the Koa’e faults also provides the opportunity to discuss the way in which small fractures and faults, of the kind that are probably very numerous on the lava plains of Venus (Fig. 1), can be recognized in radar images if the viewing geometry is appropriate (i.e., perpendicular to the look-direction) and virtually invisible when the feature parallels the look-direction. At this point in the workshops, there is often a discussion of orbital radar acquisition parameters such as incidence angle and look-direction, both of which play a crucial role in the specific topographic features that can be identified in radar data (Campbell, 2002). This, in turn, engenders a discussion of orbits appropriate for imaging radar experiments; global mapping requires a near-polar orbit, but this limits the ability of radars to view north or south to detect east-west–trending structural features.

Multiwavelength and multipolarization radar data are particularly useful in distinguishing between ‘a’a and pāhoehoe lava flows (Fig. 9). Participants examine dual-polarization (i.e., both horizontally transmitted and horizontally received [HH] data, as well as horizontally transmitted and vertically received [HV] data) C-band measurements (5.6 cm wavelength), which are the closest terrestrial analog to the S band (12 cm) Magellan radar data. From Figure 9, it is apparent that in this particular case, the C-band horizontally transmitted, vertically received (i.e., cross-polarization) data (Fig. 9B) are more useful because these data reduce the high radar returns from older flows, while improving the ability to map the boundaries of the 1974 flow. Although radars with wavelengths longer than S-band have not yet been flown to other planets, we demonstrate to the workshop attendees the advantage of using longer wavelength data; a three-wavelength color composite of radar data collected from the NASA AIRSAR instrument (Fig. 9C) includes L-band (24 cm wavelength) and P-band (70 cm wavelength) data. Figure 9C shows that the surface of most flows are rough at C-band (notice the large areas of blue in the image), that there

Figure 12. Field observations of the proximal parts of the December 1974 lava flow (out of view in Fig. 9). The field party is walking between pāhoehoe flow lobes within ~100 m of the vents. Note how thin the flows are close to their vents. Mauna Loa volcano is in the background.
are several brown-colored flows (a consequence of being bright at both C- and L-band), but that only the December 1974 flow is bright at P-band (i.e., it appears as white in the image), because the surface roughness is greater than 70 cm. Inspection of radar images in the field leads to a discussion of which radar systems would be optimum for investigating the surface of a planet. We often discuss the physical sizes of the radar antennas that are needed to collect specific data sets (L-band and P-band data would require antennas that are too big to fly to the other planets on existing rockets), as well as the operational constraints (data rates, antenna power, and orbital control) that also make it challenging to fly the most appropriate imaging radars to Mars, Venus, or one of the moons of the outer planets.

Conclusions to be drawn from field studies of the 1974 flow include: (1) Multiparameter radar images provide information complementary to optical data of lava flows, but different surface textures in radar images have non-unique origins. (2) Cross-polarized radar data (HV or VH) often provide additional textural information in comparison to like-polarized data (HH or VV). (3) At longer radar wavelengths (L- or P-band), there is enhanced contrast between smooth pāhoehoe (dark) and rough ‘a’a flows (bright). (4) Structural features such as graben and fault scarps appear very bright if oriented perpendicular to the radar look-direction, and they are virtually invisible if aligned parallel to the radar look-direction. (5) Radar studies of lava flow fields on Venus (Fig. 1) must therefore consider both the wavelength and the polarization of the data sets, and recognize that shorter wavelengths may not be optimum for certain investigations.

ACTIVE LAVA FLOWS AS AN ANALOG FOR VOLCANISM ON IO

The active flow fields at Kilauea provide an excellent analog to volcanism on Jupiter’s moon Io, the only other body in the solar system where active silicate volcanism has been observed. During another day of the workshops, participants have been able to view active surface flows and/or lava ocean entry points. Direct observation provides the participants with critical insights into the thermal structure of an active flow, an understanding of the rate of advance of basaltic lavas, firsthand experience of the structure and evolution of a flow field at the time of formation, and the opportunity to inspect lava inflation features (such as tumuli, lava rises, and lava-rise pits; Walker, 1991) that may have analogs in the highest resolution planetary images (e.g., HiRISE data; Keszthelyi et al., 2008).

The heat driving Io’s extreme activity is generated by gravitational interactions between its neighbor satellites and Jupiter (Schubert et al., 1986). The prodigious heat output is manifested as massive outpourings of lava, large lava lakes, and plumes of gas and particles reaching up to 450 km above the surface (McEwen et al., 2000). Figure 13 shows a series of views of Prometheus Patera. The 75-km-high plume associated with Prometheus was observed by the Voyager and Galileo spacecraft to have migrated ~70 km to the west between the two missions (Kieffer et al., 2000). When Galileo returned high-resolution views of the surface, it could be seen that the volcanic center consisted of a lava-filled caldera (Fig. 13B), with a south-trending fissure erupting lava flowing to the west (Keszthelyi et al., 2001).

The surface of the Prometheus’ lava flows consists of a patchwork of darker and lighter flow units, with the darkest surfaces being the youngest (Fig. 13C). The flows brighten with age because as they cool, sulfur dioxide frost is deposited from the eruption plume (Lopes and Williams, 2005). The patchwork effect is produced by the successive breakout of lava from beneath cooled solid crust, in the same way that compound pāhoehoe flow fields are produced at Kilauea (Fig. 14A; Keszthelyi et al., 2001). The convoluted margins of individual breakouts at Prometheus Patera are reminiscent of pāhoehoe-like characteristics, suggesting that the Prometheus flow fields may therefore have been formed by relatively low-effusion-rate pāhoehoe eruptions (Rowland and Walker, 1990). One difference between the lavas of Kilauea and Io is that very high temperatures have been measured for Io using the near infrared mapping spectrometer (NIMS) on the Galileo spacecraft—up to 1800 K (~1526 °C; McEwen et al., 1998), compared to typical basaltic eruption temperatures of ~1150 °C on Earth (Flynn and Mouginis-Mark, 1992). This has been attributed to the possibility that lavas on Io are ultramafic (similar to ancient terrestrial komatites), or to superheating of basalt during rapid ascent in the crust (McEwen et al., 1998). Repeat imaging on successive orbits of the Galileo spacecraft showed that the rate of resurfacing at the Prometheus and Amirani volcanic centers was 0.5 and 5 km²/d, respectively (Keszthelyi et al., 2001), which is one to two orders of magnitude greater than Kilauea flows (Mattox et al., 1993).

Typically, workshop participants have been able to observe active lavas downslope from the Pu‘u ‘O‘o vent on the east rift zone of Kilauea (Mattox et al., 1993; Heliker and Mattox, 2003) (Fig. 14). Upon approaching a flow, participants recognize that the flow surface has a range of temperatures, from incandescent lava to a silver-gray crust or dark clinker, even if the flow is still moving. As has been recognized from thermal remote sensing of active flows (Flynn and Mouginis-Mark, 1992; Wright and Flynn, 2003; Wright et al., 2010), there are many different thermal components to an active flow field on Earth; lava flows in Hawaii are erupted at a temperature of ~1150 °C, but the surface may cool within tens of seconds to ~800 °C, and then completely cool over a period of days to weeks. In the planetary context, this rapid cooling is discussed as it pertains to thermal modeling of active flows and lava lakes on Io (Howell, 1997; Davies et al., 2000; Howell and Lopes, 2007), and the participants learn how the evolution of volcanic hotspots on Io may be investigated via the measurement of the spatial variations in surface temperature derived from the NIMS data.

A second key observation made by workshop participants is the relatively slow advance speed of active pāhoehoe lava flows (Fig. 14A) compared to ‘a’a flows (Fig. 14B), which can advance at many meters per minute. Of particular
Figure 13. Active flow field at Prometheus volcano, Io. (A) Global view showing the many volcanic centers on Io. (B) Closer view of Prometheus Patera and lava flows at 170 m/pixel resolution. To the upper right is a caldera, with a fissure extending to the south, from which the lavas are erupting. (C) High-resolution (12 m/pixel) images reveal that the flow field formed by successive emplacement of flow units, with darker surfaces being younger. Brightest pixels in inset boxes represent actively erupting incandescent lava. Image produced by National Aeronautics and Space Administration (NASA)/Jet Propulsion Laboratory (JPL)/University of Arizona. JPL Photojournal images PIA02308, PIA02565, PIA02568, and PIA02557.

Figure 14. Workshop participants have had many opportunities to observe active lava flows. (A) Participants of the 2010 workshop exploring an active pāhoehoe flow, and (B) a participant in 1998 viewing an ‘a‘ā flow, ~2 m high, moving toward the photographer at ~50 cm/s, across a recently emplaced pāhoehoe flow.
interest is the (small) scale of preexisting topographic depressions that can divert the advance of pāhoehoe flows (Peitersen and Crown, 2000), or of obstacles that might divert or be overrun by a moving flow (Glaze and Baloga, 2007). Stalling of a flow against a barrier provides additional insights into the dynamics of a moving lava flow, as this can promote the development of lava inflation features such as tumuli, lava pits, and rises (Walker, 1991). Over a period of about an hour, workshop participants have observed part a flow surface inflate by tens of centimeters, thereby giving them insights into the way in which the hummocky surface of a compound pāhoehoe flow field evolves over weeks or months. Although analogous inflation features have not been confidently identified on Mars, participants learn that tumuli and lava pits would be key features to search for in HiRISE images in order to identify inflated flows on Mars.

Discussions that arise at the active flows focus on the issues involved in numerical modeling of such complex processes to gain insights into planetary flow emplacement (Wilson and Head, 1994; Mouginis-Mark and Yoshioka, 1998). Often, a two-component model of surface temperature distribution (hot lava in cracks surrounded by cooler crust) is used in lava cooling models (Crisp and Baloga, 1990; Harris et al., 1998), although five components may be necessary to adequately describe the surface temperature distribution of active lava flows (Wright and Flynn, 2003). In the context of understanding the thermal variability of the lava flow surface, the participants can see (and feel) that the flow surface of a pāhoehoe flow cools rapidly in tens of seconds, but that the core of both pāhoehoe and ‘a‘ā flows may remain incandescent for many days. This realization influences their understanding of satellite remote sensing of active lava flows for the Earth (Wright and Flynn, 2003; Wright et al., 2010) as well as numerical models of lava flow emplacement on other planets. Participants are also interested to discuss the ways in which surface flows might develop lava tubes, and the ways in which the thermal infrared data that they have already seen used on Mauna Loa volcano can be used to detect active lava tubes (Realmuto et al., 1992).

These considerations often lead to discussion of the influence of different planetary environments on lava emplacement, cooling, and resulting flow morphologies, including the contrasting effects of the hot, dense, atmosphere on Venus versus the low-pressure, low-gravity environment of Mars (Head and Wilson, 1986; Wilson and Head, 1994; Snyder, 2002). The potential ability of moving lava to thermally erode its substrate to form sinuous rilles on the Moon or canali on Venus is also frequently debated (Fagents and Greeley, 2001).

Conclusions from this part of the workshop include: (1) Active lava flows have a diversity of surface temperatures, even during the time period that they are being emplaced. (2) Pāhoehoe lava flow fields grow incrementally, and several segments of the same lava flow may advance at the same time. (3) Pāhoehoe lava flows can thicken by inflation after their initial emplacement and while the flow field is still active. (4) Nothing compares to observing active geologic processes in situ.

CONCLUSIONS

We have described here only a small selection of the volcanic features that the participants visit during each of the planetary volcanology workshops. Some of these examples require several hours of strenuous hiking to study, whereas others benefit from the “drive-in-volcano” nature of Kīlauea and parts of Mauna Loa volcanoes. Although we recommend all of these sites to other investigators interested in learning about the planetary analogs that exist at Kīlauea, it is unfortunate that the summit activity that is ongoing as of this writing (July 2011) precludes access to the 1974 lava flow in the Ka‘ū Desert. Nevertheless, we recommend a visit to Hawai‘i to see the other landforms. Finally, if you have a graduate student or postdoctoral research assistant studying planetary volcanology, we hope that you will encourage them to attend a future workshop!

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