

Case History

Mapping exposed and buried lava flows using synthetic aperture and ground-penetrating radar in Craters of the Moon lava field

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ABSTRACT

The Craters of the Moon (COM) lava field has a multiple eruptive history. Burial of older flows has resulted in complex subsurface stratigraphy. For the older eruptive periods, the locations of source vents and the extension of lava flows are either speculative or unknown, because they are buried under more recent pyroclastics. In this study, we used surface and subsurface backscatter characteristics of the P- and L-band polarimetric airborne synthetic aperture radar (AIRSAR) data and ground-penetrating radar (GPR) soundings to resolve different exposed and buried lava flows. Our primary objective is to define the most effective polarization and frequency for mapping, resolving, and characterizing different lava types in the volcanic field. Polarimetric analysis of AIRSAR images from COM allows a clear recognition of the aa and pahoehoe lava types as a result of the variability in their roughness. Our results suggest that the HV cross-polarized, AIRSAR L-band is capable of producing a detailed map delineating surface lava with different surface backscattering properties. An accuracy assessment utilizing the geological map of the Inferno Cone area was performed to quantify the reliability of differentiating lava types and mapping the lava flows extension below loose pyroclastics using AIRSAR data. Results show an ability of P-band SAR to map buried structures up to 3 meters deep under loose cinder and ash deposits, resolving buried fissures, outcrops, and lava flows that were validated with ground-truth GPR surveys. The techniques used in this study provide a tool to assess volcanic hazards in remote and inaccessible places. Also it could be an aid in the study of other planets and planetary bodies in the solar system.

INTRODUCTION

Textural and geomorphologic characterization and the identification of source vents in volcanic terrains are among the primary objectives of a significant number of terrestrial and planetary investigations. On earth, volcanic terrains are one of the primary sources of natural hazards related to eruption activities. In planetary environments, they are among the most dominant type of terrain encountered on telluric planets; their characterization provides a fundamental knowledge of the planetary paleoenvironment as well as of its dynamic activity. Hence, the accurate mapping of volcanic terrain provides crucial knowledge concerning the origin and evolution of the volcanism.

Terrains with multiple eruptive periods are of particular interest because of the ambiguities associated with remotely mapping the extension of the lava flows, exploring for locations of buried source vents, and assessing variability of their textural characteristics. Different lava flows arising from different eruptive periods present an important variety in roughness (Campbell et al., 1989) and dielectric properties (Campbell, 2002) that closely relates to their textural, mineralogical, and petrophysical properties. Although such variability can be resolved in exposed lava flows using several remote-sensing methods, it is a more challenging issue for buried flows (i.e., those covered by ash, cinders, or other flows), which represent older eruptive periods and are beyond the reach of visible, infrared, and hyperspectral sensors. The burial of flows and vents in volcanic terrains results from the deposition of younger pyroclastic materials, or of flows associated with more recent eruptive events, or from aeolian processes (e.g., arid environments). Burial of older flows has resulted in a complex subsurface stratigraphy in Craters of the Moon (COM), located in the Snake River plain (Idaho). For the older eruptive periods, the locations of source vents are either speculative or unknown.

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To address these issues, we conducted a survey to validate the potential of P- and L-band polarimetric synthetic-aperture radar (SAR) and 400-MHz ground-penetrating radar (GPR) to accurately identify different types of lava flows and assess their sources. The COM lava field was selected for this study because it developed during a multiple eruptive history and has an aridity that results in low vegetation coverage and a low-loss geoelectrical context for radar-wave penetration in the subsurface (Heggy et al., 2006). Hence, we combined airborne SAR (AIRSAR) and megahertz-level GPR surveys to identify surface and subsurface textural and lithologic changes within different exposed and buried volcanic lava flows in the COM lava field. In our approach, we hypothesize that the use of these two complementary techniques will reduce the ambiguities associated with subsurface structural identification. This in turn will help to provide a better understanding of COM surface and shallow subsur-

face structural geology and the locations of source vents for older, buried lava flows.

The ability to differentiate between lava textures can serve as an aid in volcanic hazard management. Lava can be an extremely rugged terrain. In such areas, if construction or highways need to be built or repaired, the textural mapping technique can be applied to assess the topographic conditions of the area in question.

GEOLOGIC CONTEXT

The Snake River plain is a 600-km-long topographic depression, approximately 100 km wide, that extends from Oregon to the Yellowstone plateau in Wyoming (Figure 1a). To the north and southeast, it is bounded by basin-and-range block-faulted mountains, and to the southwest and northeast it is bounded by the rhyolitic and basaltic Owyhee and Yellowstone plateaus. More than 95% of the eastern Snake River plain is covered by Pleistocene and Holocene basaltic lava flows (Kuntz et al., 1992). Drilling identified rhyolitic lava flows and pyroclastic deposits underlying the younger basalt lava flows (Embree and McBroome, 1982). The sources of the rhyolitic lava flows are thought to be rhyolitic calderas that influenced the distribution and character of volcanic rift zones (Kuntz et al., 1992).

Kuntz suggests that there were nine volcanic rift zones spaced 35 km apart along the eastern Snake River plain (Kuntz et al., 1992). The general trend of these rift zones is northwest to southeast; however, variations of this trend exist (Figure 1b). Core-sample studies show that four of the nine rift zones contain flow-on-flow sequences to depths greater than 300 m (Champion and Lanphere, 2002). The thickness of basaltic lava flows decreases from north to northwest as the gradient decreases, thus allowing thicker flows closer to vents. Accumulation-rate studies show that high accumulation rates predominate near the axis of the eastern Snake River plain and near rift zones; low accumulation rates predominate in the margins of the plain and away from the rift zones (Champion and Lanphere, 2002).

Underlying calderas are important in influencing volcanic features and characteristics of rift zones in the eastern Snake River plain (Kuntz et al., 1986). These characteristics are the orientation and length of the rifts, aerial density, types of vents, and topographic features of the flows. Kuntz et al. (1986) also suggest that rift zones coincide with buried ring fractures. At the surface, the ring fracture boundaries correspond to ridges, cones, and domes. Some rift zones terminate at the caldera margins (Figure 1b). Areas with sparse vents or no vents overlie buried calderas, and the collapsed part of the caldera appears as depressions on the surface.

Volcanic rift zones in the eastern Snake River plain correspond to extensions of the basin-and-range mountains' (BRM) normal faults (Kuntz et al., 1986) (Figure 1b). The offset of the faults on the BRM decreases when approaching the plain (Kuntz et al., 1986). Volcanic and tectonic features vary if they are located on the Snake River plain or BRM. Near the plain boundary, small volcanic cones are located along the normal faults. On the plain, cinder cones and fissure eruptions developed.

The Great Rift, shown in Figure 1b, is a 2- to 8-km-wide volcanic rift zone that trends northwest-southeast for approximately 85 km in the Snake River plain (Kuntz et al., 1986). Three Pleistocene-Holocene lava fields — Craters of the Moon, Kings Bowl, and Wapi — lie along the Great Rift (Figure 2). The northern section of the rift trends northwest-southeast and contains source vents, fissure flows, shield volcanoes, and cinder cones. Craters of the Moon National Monument contains the northernmost 13 mi (7.8 km) of the Great

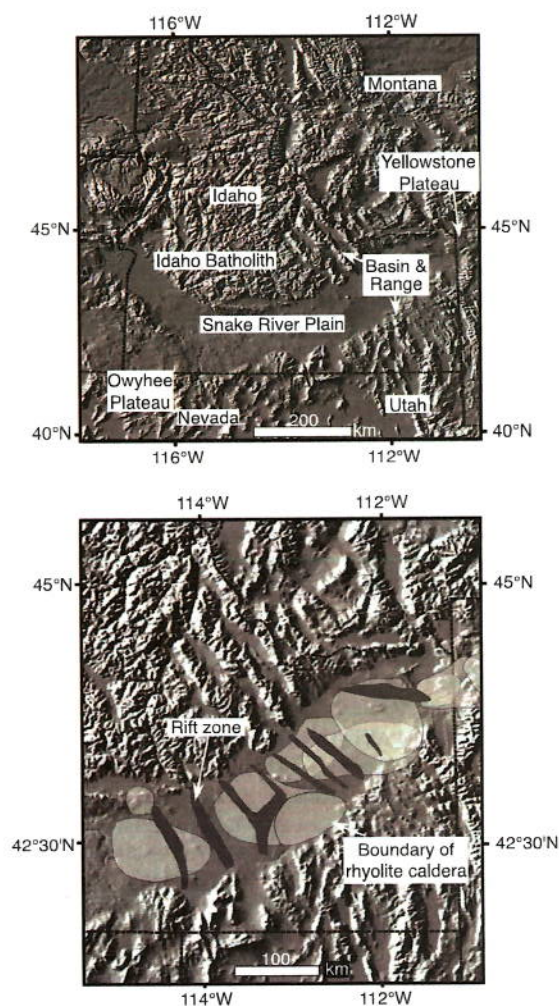


Figure 1. (a) The Snake River plain is bounded to the north and southeast by the basin-and-range block-faulted mountains and to the southwest and northeast by the rhyolitic and basaltic Owyhee and Yellowstone plateaus (after Kuntz et al., 1992). (b) Nine rift zones (dark, elongated features on the eastern Snake River plain) trend northwest-southeast. Light circular areas represent the locations of underlying, subsurface rhyolitic calderas that influence features in the rift zones. Rift zones appear as extensions of the basin-and-range normal faults (Embree and McBroome, 1982; Kuntz et al., 1992).

Rift. South of COM, the open-crack rift set is composed of two rift zones that have not revealed any volcanic activity (Kuntz et al., 1986).

The COM lava field is composed of approximately 40 lava flows, 25 volcanic vents, and at least eight eruptive fissure systems (Kuntz et al., 1986, 1992). The lava field was formed during a multiple eruptive history that has been dated by radiocarbon and paleomagnetic techniques (Kuntz et al., 1986). The oldest eruption was approximately 15,000 years ago, and the youngest began approximately 2500 years ago and ended 2000 years ago (Kuntz et al., 1986). The last eruptive episode formed three basaltic lava fields that cover most of the Great Rift. The average interval between each eruption period is 2000 years. The 2000-year eruptive period is characterized by 10 to 200 years of eruption followed by volcanic quiescence until the next eruption period.

Source vents for the different periods are known for younger basaltic flows but are unknown for the older ones. The known source vents are mainly eruptive fissures and cinder cones located along the Great Rift (Kuntz et al., 1986). The basaltic lava flows, mainly pahoehoe lavas, aa lavas, cinder, and ash, were transported from their source vent through lava tubes or fissure flows or along slopes of a cinder cone. The paths of lava flows vary through each eruptive period; burial of older flows by younger flows and pyroclastic deposits obscures the volcanic stratigraphy.

INVESTIGATION TECHNIQUES AND SURVEY SETUP

SAR and GPR have been combined in a number of terrestrial studies (e.g., Paillou et al., 2001, 2003) to reduce the ambiguities associated with subsurface identification of buried geologic structures. Although both techniques rely on the same wave-soil interaction physics, they provide different penetration ability, vertical resolution, and sensitivity to the geophysical and environmental parameters, even when considering similar sounding frequencies, as in the case

of our study (i.e., P-band AIRSAR and 400-MHz GPR). We provide a short description of each technique, its data acquisition and processing, and the survey setup. A more detailed description of SAR and GPR can be found in Campbell (2002) and Lewis and Henderson (1998), respectively.

AIRSAR

AIRSAR data are acquired by the radar program of NASA and the Jet Propulsion Laboratory (JPL). AIRSAR images (10-m spatial resolution) represent a matrix of the radar backscattered response of the surface from which a signal has reflected. Each point of this image matrix is recorded as a complex value of amplitude, polarization, and phase of the backscattered radar wave (Elachi et al., 1984). Bright features indicate that most of the radar pulses have reflected back to the antenna. Darker features indicate that fewer pulses have returned to the antenna.

Bright pixels in radar images are caused by signal backscattering, which indicates a rougher surface, a surface inclined directly toward the radar antenna, or a surface with a significant dielectric contrast (e.g., caused by higher water content; Ulaby et al., 1982). Darker pixels in the image are caused by specular reflection that can be interpreted as a flat, smooth surface from which energy is not reflected back or a surface that slopes away from the radar (Ulaby et al., 1982). The AIRSAR backscatter response can be influenced by a variety of conditions such as the target area's moisture content, the size of features where the signal scatters, signal polarization, and the operating frequency of the system.

AIRSAR P- and L-band radar waves have a constrained ability to penetrate the subsurface (Campbell, 2002). The depth of penetration is influenced by the dryness of the target area, the heterogeneity of the subsurface feature, and the wavelength of the radar system. In nondispersive volcanoclastics, typical of the basalts of COM (Heggy et al., 2006), longer wavelengths increase the depth of investigation of the radar signal. In such cases, the approximate depth of penetration is roughly the radar's nominal wavelength (Lewis and Henderson, 1998; Jensen, 2000). Radar studies conducted in the eastern Sahara describe optimal conditions for subsurface investigation (Schaber et al., 1986; Paillou et al., 2003). Resistive soils with a significant dielectric contrast and variation in interface roughness are among the optimal conditions that maximize subsurface signal return and, hence, the ability to perform shallow subsurface mapping. These conditions are met at the studied sites selected in COM.

Previous studies have investigated the radar backscatter of AIRSAR images in volcanic terrains (e.g., Dellwig, 1969; Malin et al., 1978; Campbell, 2002). Dellwig (1969) evaluates the frequency factor in radar imagery on Pissgah Crater, California. Because radar signal penetration depth increases as a function of wavelength, Dellwig (1969) studies the longer, P-band wavelength (30–100 cm) of AIRSAR images and describes a penetration through windblown silts that returned a signal from a partially buried lava. He reports penetration of 1.8 m through dry, windblown sediments in the center of the crater.

Malin et al. (1978) investigate radar images as reflectivity maps in studies of Askja Caldera, Iceland. Because of its high dielectric constant, the moist, cemented ash matrix gives a bright radar response and allows delineation of aa flows and surfaces with ash. COM contains extremely rugged block flows with a surface relief of many meters, aa flows with surface relief of submeters to a few meters, and pahoehoe flows with smooth surface relief (Wentworth and Mac-

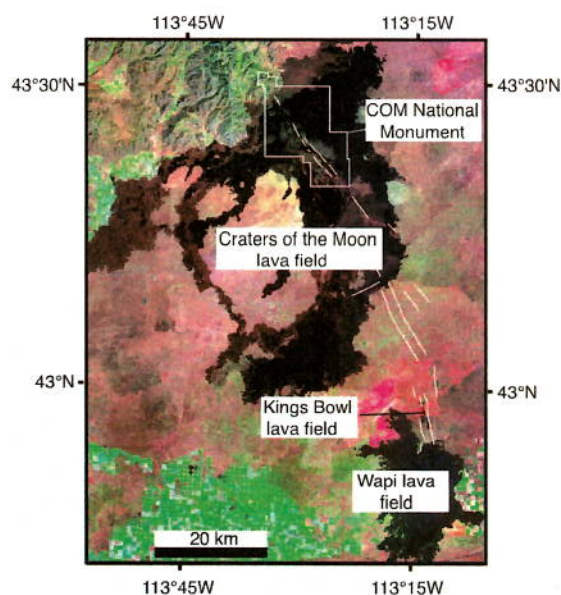


Figure 2. LANDSAT bands 7-4-3 displayed as red-green-blue (RGB) false colored image, showing the three lava fields and fissures along the Great Rift.

Donald, 1953). AIRSAR images thus delineate lava flows with respect to their textures and relief. Exposures of lava flows in cross-sectional view are limited, but the literature indicates some particular characteristics of buried features in volcanic areas (Greeley, 1982). For example, there is a change in lava viscosity as it cools and degasses away from the vent, and the older fissure vents are buried under their own flows (Greeley, 1988). Another example is the development of complex stratigraphy around lava tubes because they melt their preflowed terrain (Greeley, 1982). All of these characteristics contribute to the different backscattering signal in AIRSAR images.

Processed multifrequency, multipolarization AIRSAR data files were acquired on March 31, 2003, by NASA/JPL's radar program. The imaging bands and frequencies collected were C- (~5310 MHz), L- (~1260 MHz), and P- (~450 MHz) bands. The AIRSAR data package included a digital elevation model, a C-band vertical transmit/vertical receive (VV) polarized image, incidence angle map, correlation map, and L- and P-band polarimetry data sets. The L- and P-bands are stored in compressed Stokes' matrix form. These images were decompressed and synthesized from their original matrix format; to display them and to apply extra processing enhancement steps, we used environment for visualizing images (ENVI) for further processing.

When synthesizing AIRSAR data, we were able to select specific send and receive polarization combinations. Polarization depends on the transmit-receive antenna radar signal orientation. Copolarized images have horizontal transmit/horizontal receive (HH) and vertical transmit/vertical receive (VV) antenna orientations. The cross-polarized images have horizontal-vertical (HV) and vertical-horizontal (VH) antenna orientations. It is important to note that the radar backscattered signal and the output image change at different frequencies and polarizations. To enhance the images, a Gaussian convolution function filter was applied to the synthesized L- and P-band images.

Importing AIRSAR images into a geographic information system (GIS) environment allowed us to fuse the geologic map and optical images. Surface features observed in a LANDSAT true color image (combination band 3-2-1) were compared with suspected subsurface features observed from the AIRSAR analysis. However, resolution of the LANDSAT image (30 m/pixel) was low, and some features and flows were not detected. For this reason, 2-m/pixel-resolution U.S. Geological Survey (USGS) aerial photographs were used for comparison with AIRSAR images. The images were imported into ArcMap with the North American Datum projection UTM zone 12 North. Ground control points were found in the AIRSAR images, and they were georeferenced to the aerial photographs. The outcome consisted of multifrequency-multipolarized, georeferenced AIRSAR images fused in ArcMap with high-resolution aerial photographs.

Ground-penetrating radar

In volcanic terrain, GPR can probe the subsurface down to a few tens of meters, depending on the sounding frequency, the ground conductivity, and the subsurface heterogeneity (Grimm et al., 2006; Heggy et al., 2006). GPR operates by transmitting electromagnetic (EM) pulses to the subsurface and receiving the returned echoes as a function of the two-way traveltime (in nanoseconds). The EM waves propagate through the ground and are reflected on each encounter with each dielectric contrast. The wave propagation velocity is de-

termined by the dielectric constant of the material (Daniels, 2000), which is a function of the ground mineralogy and geophysical conditions (Annan and Davis, 1976; Jensen, 2000).

The probing depths depend mainly on the electric properties of the subsurface, the sounding frequency of the GPR, and the volume scattering (Davis and Annan, 1989). In resistive materials and porous pyroclastics (e.g., dry ash and cinders), GPR sounding can reach 20 m depth at 400 MHz (Heggy et al., 2007). In conductive material (e.g., clays, silts, and saturated soils), radar signal-range decreases to less than a few tenths of a centimeter (Davis and Annan, 1989). These changes in electrical properties are associated mainly with rock mineralogy, water content, and densities (Olhoeft, 1998). Theoretically, greater radar-wave penetration depths and, hence, deeper subsurface sounding are achieved with lower sounding frequencies (Annan and Davis, 1976; Lewis and Henderson, 1998) but with a decrease in the vertical and horizontal resolution of the probed subsurface features.

Subsurface exploration in volcanic rocks may be challenging at times because of the different amounts of iron oxides, which increase the dielectric constant and cause dielectric losses (Olhoeft, 1998; Heggy et al., 2001), and the complexity of the soil's heterogeneity and fractures, which cause scattering (Grimm et al., 2006). To interpret subsurface structure confidently from resulting backscattered echoes, permittivity measurements of samples acquired from the field are crucial to understand wave propagation and to define the amplitude of the absorption and scattering processes that constrain the maximum penetration depth (cf. Heggy et al., 2006).

In this investigation, GPR fieldwork was conducted August 2004 and 2005 during in the dry season using a pulse repetition GPR system manufactured by Geophysical Survey System Inc. (GSSI). The system was operated with two different antenna configurations covering a broad band from 100 to 400 MHz. Both antennas were coupled to the surface during data acquisition. Both a monostatic 400-MHz and a bistatic shielded 100-MHz antenna were used to acquire data in continuous mode. The system was configured to achieve maximum radar range and to allow data stacking to increase the signal-to-noise ratio. Backscattered echoes were filtered frequency to remove local coherent radio noise.

Net nominal radiated power output from the 100-MHz antennas was 800 mW, and net nominal radiated power output from the 400-MHz antennas was roughly 2 W. Remote sensing analysis of AIRSAR, LANDSAT, and aerial photographs were used to locate the anomalies to be validated with GPR fieldwork. The comparison of USGS 2-m-resolution aerial (hereafter referred to as aerial image) and AIRSAR P-band polarimetric images revealed the locations of possible buried structures and lava flows; these sites were selected for investigation with GPR surveys.

For the 2004 GPR fieldwork, a shielded, bistatic 100-MHz-frequency GPR unit was used to acquire 45 surveys with signal penetration ranging from 500 to 2000 ns. The interpretation of four of those surveys, conducted on the Inferno cinder cone, in the Boy Scout lava tube area, and along a road near Broken Top rift zone (Figure 3a), are included in this study. For the 2005 fieldwork, we mainly focused on the 400-MHz-frequency sounding to provide a comparable penetration and vertical resolution to the AIRSAR data. This survey also covered the Inferno cinder cone (Figure 3b), the road near Broken Top rift zone (Figure 3c), and Boy Scout lava tube area (Figure 3d); in addition, it included a wilderness trail that extends southeast of COM (Figure 3e). A 400-MHz survey was performed on the summit of the Inferno cinder cone to map the extension of the congealed part

of the cone below the loose cinders. Only two 100-MHz profiles were acquired from the 2005 fieldwork, one performed near the Broken Top rift zone and the second on the Inferno cone.

Spatial reference of the GPR surveys was obtained using a GeoXT handheld submeter Trimble GPS. All of the GPR profiles were processed and interpreted using the GSSI RADAN 6 data analysis tool (GSSI, 2004). Average dielectric-constant values of 5 and 8, corresponding to COM ash deposits and basalt flow, respectively (Heggy et al., 2006), were used to perform the sounding-time-ranges-to-depth conversions on the radargrams. We also applied zero-time corrections for surface-position adjustment and band-pass filtering to remove frequencies outside the 25–200-MHz range for the 100-MHz antenna and the 100–800-MHz range for the 400-MHz antenna. Hyperbolic summation migration and Kirchhoff migration methods were applied to collapse hyperbolas into their apexes.

AIRSAR OBSERVATIONS

AIRSAR images were analyzed at P- and L-frequency bands and HH, VV, and HV polarizations. The main aim of our data analysis in this section is to evaluate the effects of frequency and polarization on the ability to discriminate between aa and pahoehoe flows in the L-band and potentially to detect the extension of those flows beneath pyroclastics using the P-band. Comparison of images at these two different frequency bands and polarizations provide images with different distributions of backscattered amplitudes mainly corresponding to different radar responses from the different lava flows. The

amplitude of the backscattering is then used to investigate and map the textural and dielectric contrasts within the lava field.

Northern COM

Copolarized images are influenced by surface scattering and the lining up of features along the same antenna orientation (Campbell, 2002). Because lava flows in the northern portion of COM have irregular shapes, most features do not line up and there is no specific geometric orientation of the flows. This resulted in L-band AIRSAR HH and VV images being similar (Figure 4a and b) because the backscattered signal is totally depolarized on the rough aa lava flows but maintains its original polarization on smooth surfaces as in pahoehoe flows and smooth cinder deposits. On the other hand, there is a reliable distinction between pahoehoe and aa lava types in the cross-polarized HV image (Figure 4c).

The difference in the back response of different lava types is related to the amplitude of the backscattering in the cross-polarized images, which is influenced mainly by the different surface roughnesses and textural orientations of the flows in the lava field. Pahoehoe lava and smooth pyroclastic deposits give rise to specular reflection and, therefore, appear as dark pixel areas corresponding to a weak backscattered signal (Campbell, 2002) as the signal retains its incident polarization. Conversely, the rough aa lavas give rise to a strong surface scattering that corresponds to a strong backscattered and depolarized signal, thus resulting in bright pixels on the radar image (Campbell, 2002). This clear distinction between surface lava flows can be demonstrated by comparing a 2-m/pixel-resolution

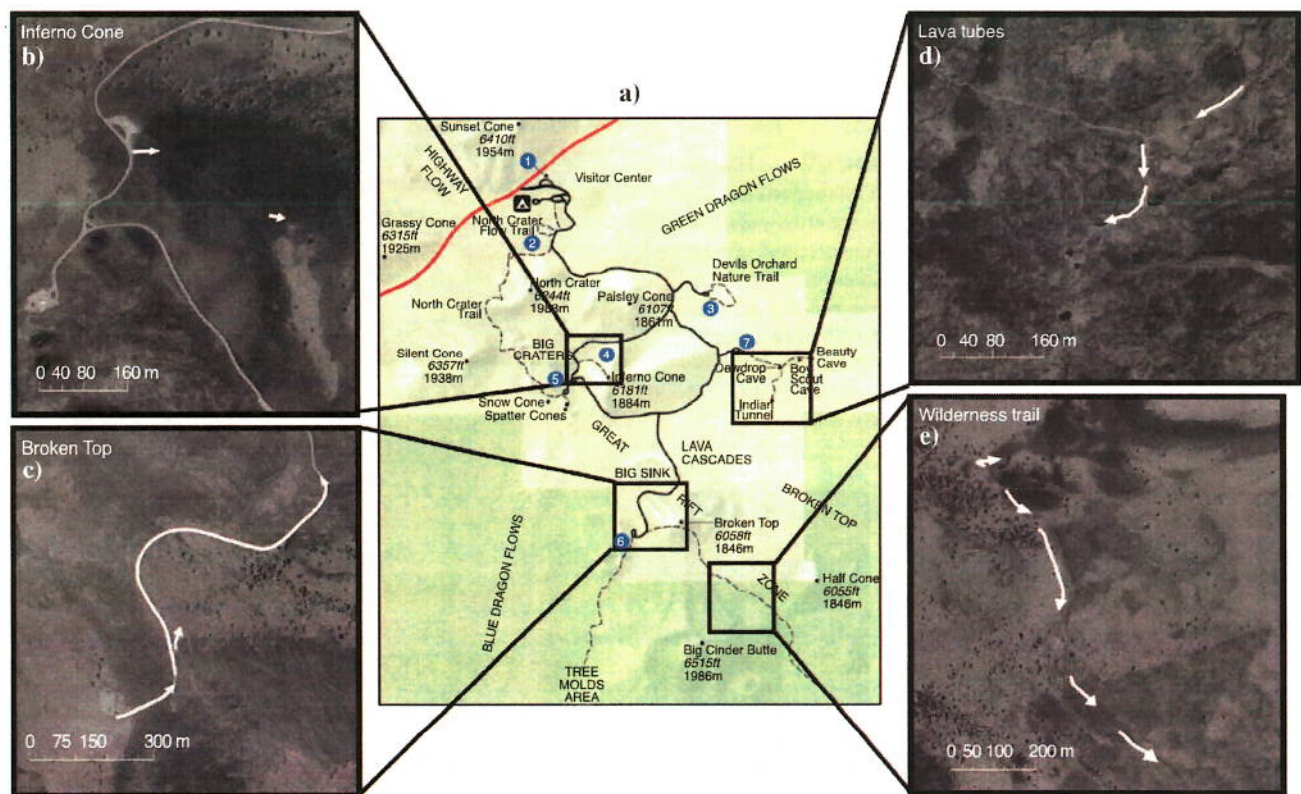


Figure 3. (a) Map of COM from the National Park Service; boxes indicate locations where GPR surveys were performed. Smaller figures are 2-m/pixel-resolution aerial photographs of (b) Inferno Cone, (c) Broken Top rift area, (d) Boy Scout Cave and Indian Tunnel area lava tubes, and (e) the wilderness trail area. Lines represent the paths over which the GPR unit was dragged, and arrows represent direction.

aerial photograph with the HV-polarized image and observing the location of contacts between lava flows, which clearly shows the correlation between the rough, dark flows in the visible image and the bright areas in the radar image.

On the frequency variation, radar responses are expected to differ among the L- and P-band images, caused by the change in the amplitude and type of scattering mechanisms (i.e., trade-off between surface and volume scattering) as well as in the wave penetration ability in soils for lower frequencies (Ulaby et al., 1982). Figure 5 compares the aerial, L-band SAR, and P-band SAR images for the Inferno Cone; the images in Figure 5b and c are both in HH polarization. In Figure 5b and c, the Inferno Cone and its tephra appear as the elongated nail-like structure in the center of the images. The cone is easily identifiable from the surrounding vegetation as a result of the difference in roughness; it consists of smooth, fine ash, whereas its surrounding area is covered partially with a moderate amount of brush, which results in increased roughness and, hence, explains the increased backscattered signal.

The L-band image near the Inferno Cone does not detect a clear surface flow that is apparent in the aerial photograph (Figure 5a). Instead, in the L-band image, the elongated surface flows appear to be a single tephra sheet covering most of the area (Figure 5b). The P-band image shows reflections of the surface flows and also an extension of the westernmost flow toward the north (Figure 5c). The flow crosses the summit of the cone and could be associated with the eruption vent. Because this elongated feature is not observed in any of the other images, it is interpreted as the radar backscatter of a buried flow, a conclusion supported by the GPR survey (discussed in the Inferno Cone section) and the lower frequency of the P-band (~ 450 MHz) compared to the higher frequency in the L-band (~ 1260 MHz); a lower frequency is associated with a greater depth of investigation, which is on the order of a few meters in the P-band in nondispersive soils (Elachi et al., 1984).

The comparison of the three polarizations (HH, VV, and HV) of the AIRSAR images from the northern part of COM suggests that the optimal polarization for identifying lava types is the cross-polarization. This cross-polarization is used to analyze the potential of both L- and P-bands in separating aa and pahoehoe flows as in Figure 6. The L-band cross-polarized image in Figure 6b matches closely the aerial image (Figure 6a) in terms of resolving the different sizes and textures of lava flows (comparison between the black and white boxes). The P-band cross-polarized image in Figure 6c shows different backscattering patterns in the white and black boxed areas.

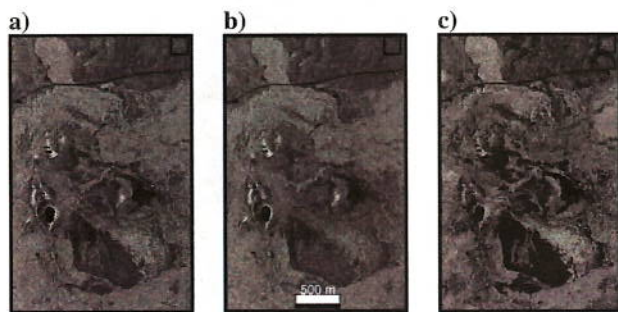


Figure 4. L-band AIRSAR images of COM at (a) HH polarization, (b) VV polarization, and (c) HV polarization. Notice there is no clear distinction between HH and VV polarized images, but HV polarization clearly defines a contact between aa and pahoehoe lava types.

A general observation is that some of the bright areas on the L-band image have become darker in the P-band image as a result of the decrease in the backscattering coefficient and vice versa. We attribute this observation, respectively, to the decrease of the P-band sensitivity to surface scattering compared to the L-band and to the penetration in the loose cinders covering the rough aa flows. Among the differences we observe between the P- and L-band images is the loss of resolution caused by the increase of wavelength in the P-band frequency. Narrow features, such as 6-m-wide roads, cannot be detected at the P-band frequency.

Southern COM

Unlike the northern part of COM, the analysis of the L-band cross-polarized HV image of southern COM (near Broken Top rift zone) in Figure 7c does not show a clear distinction between the aa and pa-

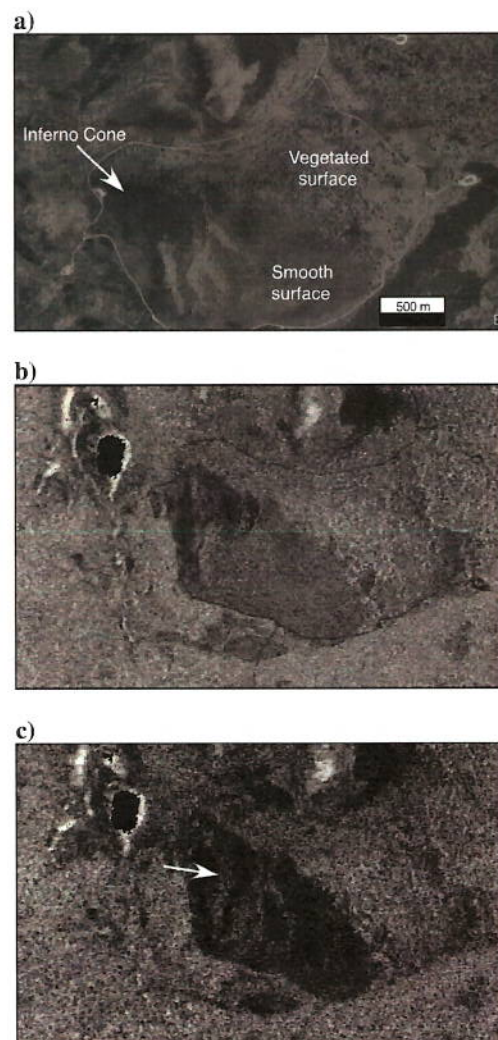


Figure 5. (a) Aerial photograph showing location of Inferno Cone (white arrow), vegetation area, and smooth cinder covering the cone. (b) L-band AIRSAR image with no clear reflections of surface flows at the summit of the cone. (c) P-band AIRSAR image; arrow indicates the extension of an elongated interpreted subsurface feature not observed on the other images.

hoehoe lava types as a result of the signal depolarization caused by the vegetation. Vegetation coverage increases toward the south of COM, which results in an increase in surface roughness and, therefore, an increase in the radar backscattering coefficient and its dependency on the polarization. Hence, smooth pyroclastics (e.g., Broken Top cinder cone) covered by vegetation appear relatively bright in the L-band VV polarization (Figure 7b). The aa flow in Figure 7b (box) is easily distinguishable from its surrounding zone. Conversely, the L-band cross-polarized HV image (Figure 7c) shows a lower degree of contrast between the aa flow and its surrounding terrains, especially in the western portion where the contact between the aa flow and vegetation-covered pyroclastics is not well defined in the radar image.

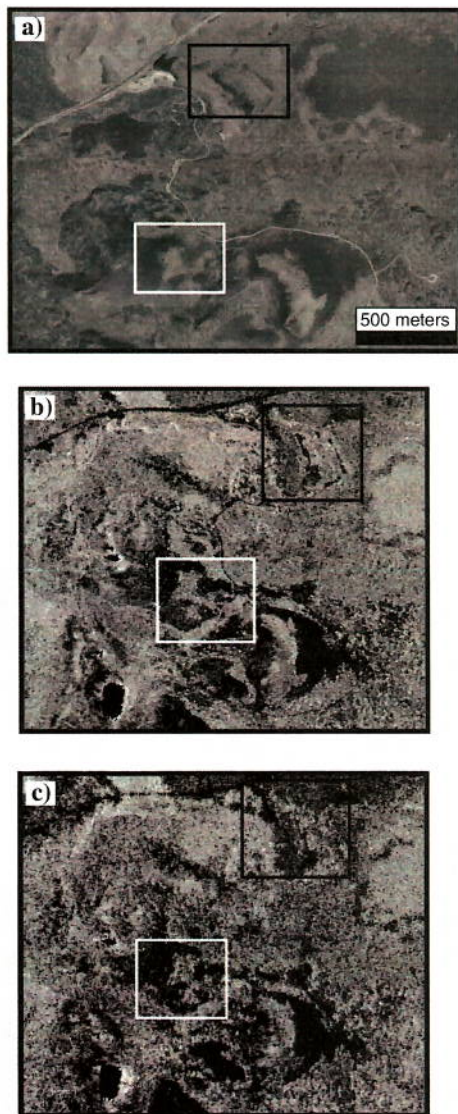


Figure 6. Images of northern COM: (a) 2-m/pixel-resolution aerial photograph; (b) L-band HV polarized AIRSAR image; and (c) P-band HV polarized AIRSAR image. Boxes indicate corresponding surface flows. Note the loss of resolution in the P-band image related to the increase of radar wavelength.

Analysis of the AIRSAR L-band HV image (Figure 7c) and the aerial images in this zone provided significant support to map cinders and ash deposits and to identify subsurface features that lie beneath them. The dark areas correlate with the occurrence of fine cinder and ash coverage. The L-band HV crosspolarization enabled us to overcome the vegetation screening of the original surface roughness (because vegetation is a vertically oriented scatterer, so the VV backscattering component is greater than the HV) and, hence, to map the smooth cinder deposits on the south of the Broken Top cinder cone.

Eastern COM

A significant number of lava tubes are located in eastern COM. This area also contains features such as collapsed structures and piles of sharp, broken basalt flows (Hughes et al., 1999). All of these structures increase surface roughness, which increases the complexity and ambiguities associated with interpreting the backscattered signal at different frequencies. Unlike the southern part of COM, this area does not have a vegetation cover or pyroclastic deposits; hence, the variation observed here can be related directly to the textural characteristics of the flows.

Because of irregular shapes on the surface and the shallow (1- to 3-m-deep) subsurface presence of the lava tubes (Hughes et al., 1999), there is no clear definition of flow types or orientation in any of the images (Figure 8). The area is mainly a pile-up and a succession of different aa and pahoehoe flows. The copolarized VV images at L- and P-bands resulted in very similar patterns with no clear delineation of potential boundaries arising from the different flow successions. In contrast, the cross-polarized images (HV) on L- and P-bands can be used to map the aa-pahoehoe flow contacts as observed (Figure 8). A rough east-west-oriented aa flow is observed in the upper part of the image. This flow, adjacent on the south with a smooth pahoehoe flow, is interbedded with some aa lava spots (~300 m) and is delineated in the north by another aa flow oriented northwest-southeast. This latter flow is not identifiable on the L- and P-bands on VV images.

Analyzing all polarizations and frequencies allowed us to map the different lava flows according to their roughness characteristics. In an attempt to integrate those observations into a comprehensive

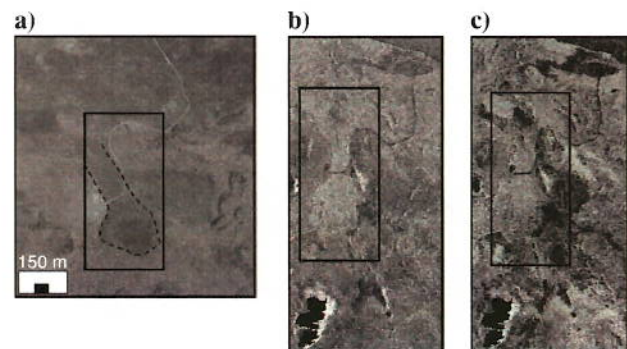


Figure 7. Broken Top rift zone: (a) aerial photograph showing a surface flow also recognizable in the AIRSAR images, (b) L-band VV polarized AIRSAR image, and (c) L-band HV polarized AIRSAR image. In other locations, HV polarized data better distinguish lava types; in this area, the VV polarized image shows a better delineation of lava flows. The area enclosed by the dashed lines in (a) appears brighter in the AIRSAR images.

map, we classified the observed flows into four groups, depending on their signal response. The classification used is darkest, dark, bright, and brightest radar signal response; the results are shown in Figure 9 for the COM study area. Smooth surfaces correspond to the darkest response and occur on specular reflections from cinder and ash deposits. The dark reflections correspond to reflections on surfaces with both pahoehoe and cinder deposits. Bright response corresponds to a combination of aa and pahoehoe lava flows (slab pahoehoe or rafted flows). The brightest response corresponds to reflections on the roughest surfaces of aa flows or highly vegetated areas. The classification of signal response describes contacts between the different flows that agree with geologic maps and fieldwork.

GPR SURVEYS

The 400-MHz GPR data confirmed the suitability of the site for shallow subsurface sounding and imaging. Survey results revealed coherent reflectors interpreted to be caused by shallow subsurface stratigraphy at different penetration depths. The data analysis suggests a strong correlation between the penetration depth and the soil geoelectric and geomagnetic characteristics, degree of heterogeneity, and porosity, as described below for each site. For locations, see Figure 10.

Inferno Cone

The surface of the Inferno Cone is mostly covered with loose cinder (Figure 11a). Cinder has an irregular shape and size, ranging from a few millimeters to less than 2 cm. Regardless of the large blocks of basalt scattered on the surface and the larger outcrop of oxidized basalts at the summit (Figure 11b), the smooth surface of the cone made the coupling of GPR antenna with the surface optimal.

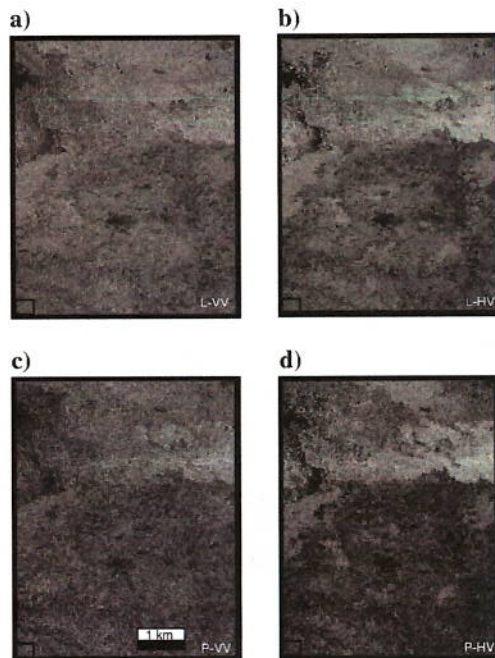


Figure 8. (a, b) L-band AIRSAR image and (c, d) P-band AIRSAR of the lava tubes area. Irregularity of the lava flows and high surface roughness does not allow for a clear definition of lava types in these images.

Figure 12 shows a 30-m-long, 400-MHz GPR profile acquired at the bottom of the Inferno Cone. The range depth of this profile is approximately 3 m (giving a dielectric constant of 5.5 for the tephra layer from Heggy et al., 2006). A low-amplitude, homogeneous radar response layer was observed about 1-m-deep at the start of the profile. This layer thins toward the margin of the survey and terminates at 27 m along the profile. A strong dielectric interface with lateral continuity underlies this homogeneous response. Three deeper interfaces interpreted as cinder layers are detected. The deeper layer, however, has a higher-amplitude response, possibly related to the change in the mineralogy. The discontinuous radar response between interfaces may be caused by the flow breakage or stacking up of loose material similar to the larger basalt blocks found on the surface.

To probe the deeper subsurface, a 140-m-long, 100-MHz profile was acquired a few meters parallel to the 400-MHz profile described above. This longer profile extends from the top to the bottom of the cone. As expected, the resolution of the lower-frequency GPR does not detect the cinder layers in detail (Figure 13a). These interfaces follow a similar trend of thinning toward the top of the cone for the uppermost 30 m. A deeper, stronger dielectric interface abruptly ends the trend of the layers above it. This stronger interface buries two larger, higher-amplitude interfaces interpreted as older, even deeper flows, possibly from a different source vent. Figure 13b shows an 80-m-long, 100-MHz profile acquired at the bottom of the Inferno Cone; it is a continuation of Figure 13a. Shallow cinder layers appear thicker, and the stronger amplitude interface described above occurs at greater depth.

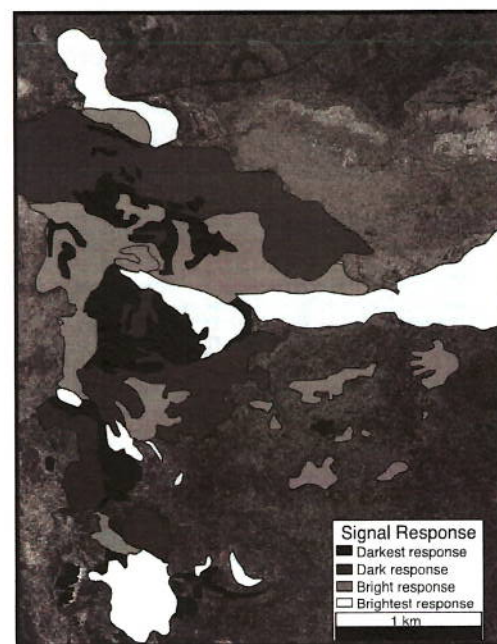


Figure 9. Map of lava types on the AIRSAR image according to their different signal responses and surface roughnesses.

A 400-MHz GPR profile carried out at the summit of the cone illustrates the extent and burial of the oxidized basalt outcrop (Figure 14). A strong interface near the surface at the outcrop gently dips toward the beginning of the profile until a depth of approximately 1.5 m (Figure 14). Parallel GPR profiles of this area show the lateral extent of this buried flow that forms the congealed part of the cone.

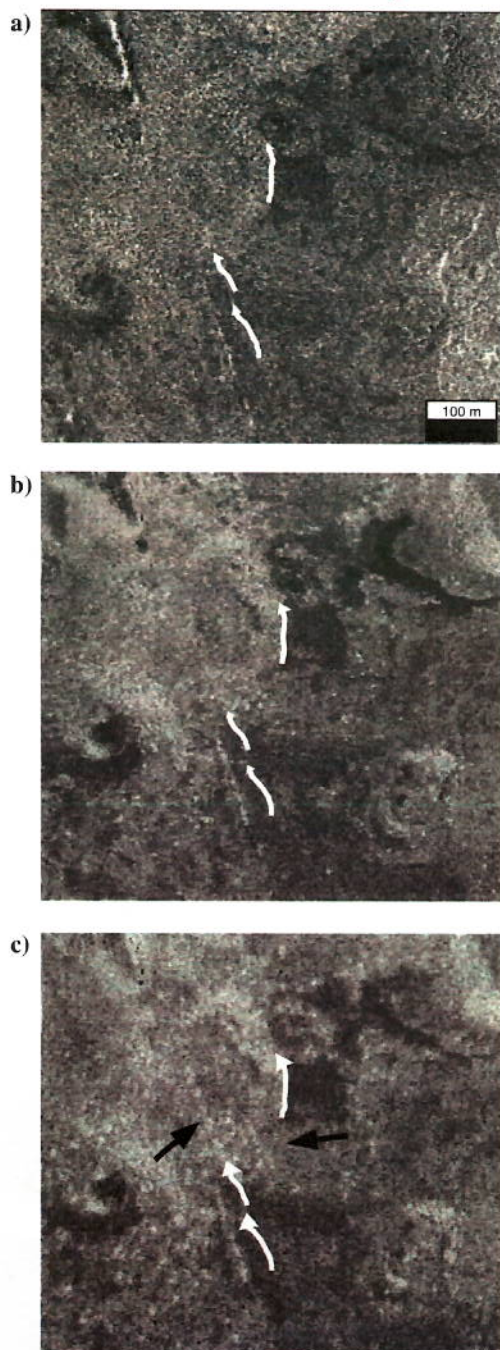


Figure 10. AIRSAR images showing the location of three GPR surveys (white lines) performed on the wilderness trail. (a) C-VV image; (b) L-HV image; and (c) P-HV image. Black arrows in the P-HV image (c) indicate two subsurface features not observed in the C-VV image (a).

The buried flow shown in Figure 14 is observed at the first 2 m, indicating termination of the buried flow beyond 2 m in the east direction. The location of this buried flow fits the one identified on the AIRSAR P-band image (Figure 5c), which in turn suggests the validity of the subsurface origin of the linear extension of the buried flow observed in the AIRSAR data. At this location, however, another buried flow is detected (indicated by the white arrow in Figure 14). It has the same flow direction as the previous one but does not reach the surface. These discrete, smaller flows may result from shorter eruptions.

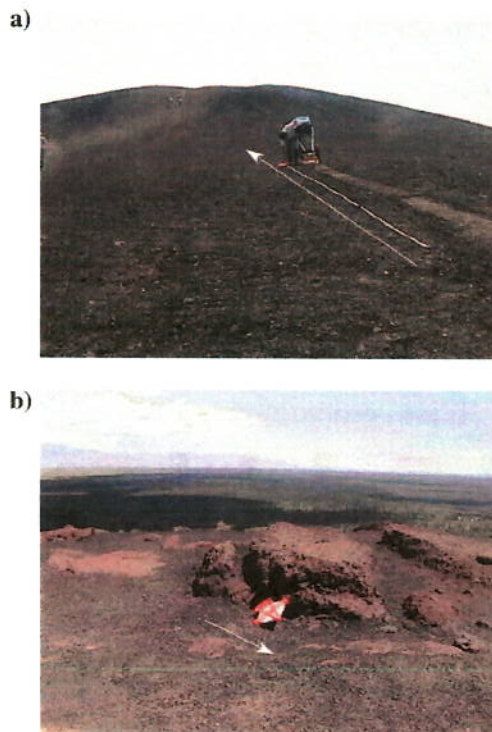


Figure 11. Photographs of Inferno Cone area, showing the path of the GPR surveys (white lines) at (a) the bottom and (b) the summit of the cone. Most of the surface of the cone is covered with loose cinder except on the summit where oxidized basalt crops out.

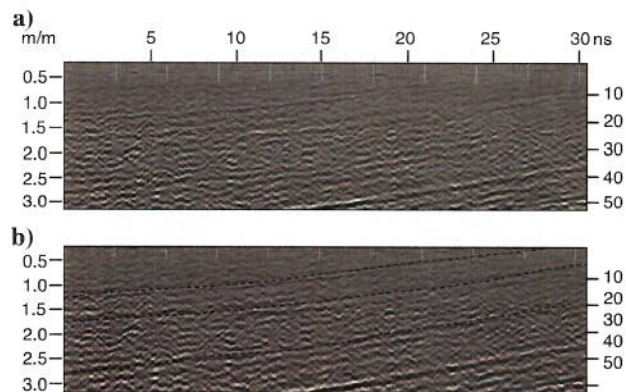


Figure 12. (a) Uninterpreted and (b) interpreted 400-MHz GPR profiles surveyed at the bottom of Inferno Cone. Dashed lines indicate strong-amplitude dielectric interfaces.

Lava tubes

The lava tube area in COM is composed of three lava caves: Beauty Cave, Boy Scout Cave, and Indian Tunnel. The caves are accessible to observe basaltic stalactites, the piled-up basalt from lava flow breakage, and collapse of the caves or ice on the floor of the caves. A walking trail connects all of the caves at the surface and also provides a smooth surface to perform the GPR survey with optimal ground-antenna coupling. Structures similar to those found inside the caves (collapsed and piled-up sharp, broken basalt) occur on the surface.

Figure 15 shows a 400-MHz GPR survey performed on the lava tube trail. The GPR profile does not show clear interfaces that can be

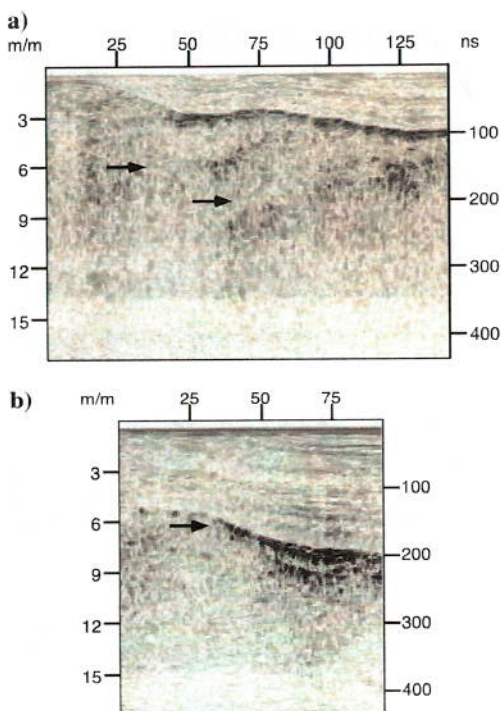


Figure 13. (a) A 140-m-long, 100-MHz GPR profile from the top (left) to the bottom (right) of Inferno Cone. Profile shows a strong amplitude interface (3 m deep) that thins toward the top of the cone and buries two deeper, higher-amplitude response interfaces (black arrows). (b) An 80-m-long, 100-MHz GPR profile at the bottom of Inferno Cone. Shallow lava flows are thicker than at the top of the cone, and the stronger interface is buried at approximately 6 m (black arrow).

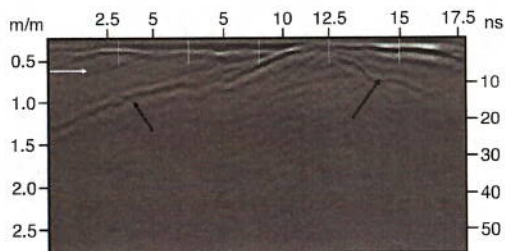


Figure 14. A 400-MHz GPR profile located at the summit of Inferno Cone. Notice the shallow subsurface flow (white arrow) and a stronger, deeper amplitude interface (black arrows) that crops out at approximately 12 m along the profile.

followed laterally, probably related to the loose, broken, and collapsed lava flows similar to the flows observed on the surface. The survey shows a change between a homogeneous, lower amplitude signal response and a deeper, stronger amplitude signal response. This variation of radar response is interrupted laterally by short (0.5-m-long), vertical higher-amplitude interfaces that appear in most of the signal range. These vertical interfaces are from loose rocks caused by the collapse of the flows near a cave entrance. This 56-m-long survey starts at the entrance of Boy Scout Cave. It has a strong amplitude signal response, 2–3 m deep, which corresponds to the floor of the cave.

Broken Top rift zone

A smooth road and a walking trail intersect the Broken Top rift zone; these were used as access routes to carry out the GPR survey (Figure 16a) because all other routes would have been constrained significantly by the terrain roughness. To the south of the walking trail, there is a surface contact between aa and pahoehoe lava types (Figure 16b). The 400-MHz GPR survey performed on this trail detected a strong interface (2 m deep) that dips toward the center of the profile. A surface aa/pahoehoe contact is observed at 43 m along the profile. Shallower flow-on-flow sequences are detected, which start at this location and terminate at the end of the profile. These shallower flows bury the stronger interfaces detected at the left of the profile.

A short GPR survey was performed on the western side of the Broken Top rift zone to investigate the aa/pahoehoe surface contact (Figure 16c and d). A strong-amplitude interface was detected at the start of the survey at 1.5 m depth (Figure 17). This high-amplitude, laterally continuous interface terminates at approximately 43 m along the profile and has a weaker signal response at the location that corresponds to the surface aa/pahoehoe contact. Starting at this location and extending toward the right of the profile, there are no clear interfaces. Signal response is chaotic because of the reflections of the aa lava deposits found here.

A 900-m, 100-MHz GPR profile with deeper signal penetration depth (than the previous 100-MHz profile) was performed on a sinuous road located near the contact between the Blue Dragon flow and the Broken Top cinder cone (Figure 16c and d). The southern section of the profile detects three flat, strong interfaces at depths of 5, 15, and 30 m (Figure 18a). Lateral continuity of these interfaces is inter-

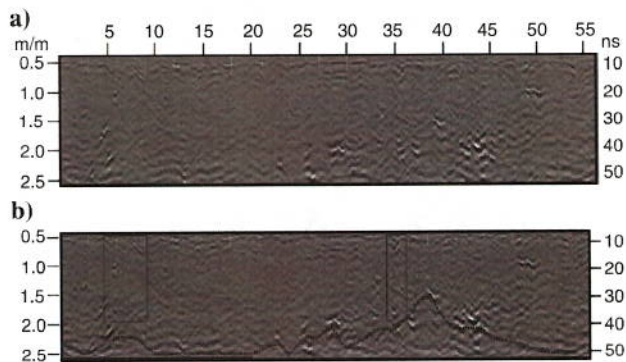


Figure 15. (a) Uninterpreted and (b) interpreted 55-m-long, 400-MHz GPR profile of Boy Scout Cave. Dashed line indicates the floor of caves; notice that lateral discontinuities of responses (boxes) are an indication of loose, broken lava flows typical of collapsing lava tubes, including the cave's entrance, leftmost box in view (b).

rupted by a 50-m section with no clear definition of interfaces. This section corresponds to faulting at the rift zone. On the northern section of the profile, three interfaces dip toward the rift area (Figure 18b). These interfaces bound homogeneous layers that thin toward the rift area. In this area, there is no clear definition of interfaces. This is possibly the result of the highly faulted area surrounding the rift and also may be related to the higher roughness of the aa lava flows.

Wilderness trail

A 4-km wilderness trail starts at Broken Top cinder cone and extends to the southeast of COM. The isolated trail allowed us to perform longer GPR surveys than on other sites of COM. There are no manmade roads on this trail, and GPR surveys were performed on the loose, smooth cinder (Figure 16e and f). In some locations, there are small basalt outcrops and buried blocks of basalt. A GPR survey was performed parallel to the small outcrops. The profile shows 2-m-long interfaces interpreted as a discrete, buried, faulted, single lava flow (Figure 19a). This flow terminates at around 3.5 m depth at a deeper interface. The faulting of the lava flows may be caused by flow breakage during lava cooling.

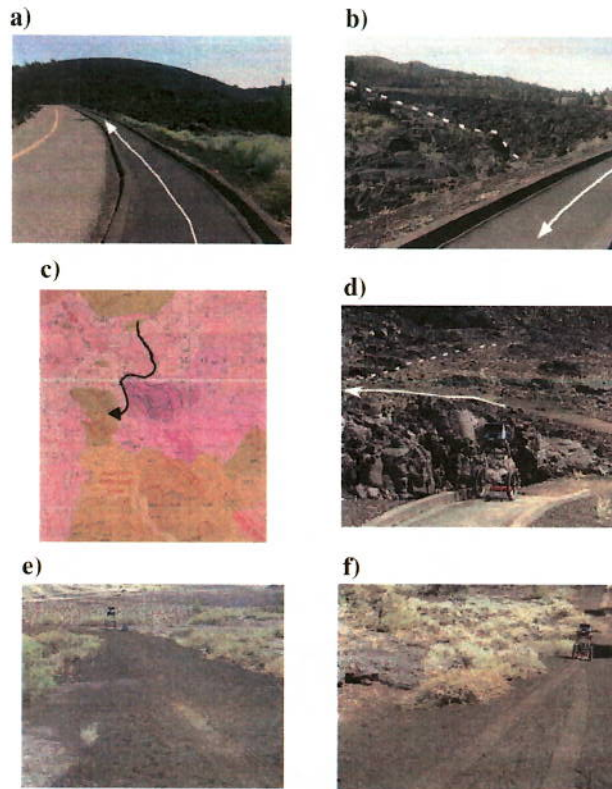


Figure 16. (a) Photograph of the road where the GPR survey was performed; arrow represents the location and direction of the survey. (b) Photograph showing surface contact (dashed line) between aa and pahoehoe lava types. (c) GPR survey path (arrow) drawn on COM geologic map, showing location of contact between lava flows and rift zone. (d) Photograph showing the location of the GPR path (white arrow); dashed line represents the pahoehoe/aa surface contact. (e, f) Photographs along GPR survey sites on the wilderness trail. GPR surveying was along the smooth path covered with loose cinder. Notice the increase of vegetation and scattered outcrops of basalt.

A 400-MHz GPR profile illustrates different interfaces following the same general flat trend with a small mound, located 10 m from the starting point of the survey (Figure 19b). A steeper flow on the left side of the section combined with data from the geologic map may indicate that flow direction is from right to left. A strong, high-amplitude interface underlies all of the flows at approximately 3.5 m depth. This continuous interface is interrupted for 1 m at about 27 m along the profile. The discontinuity probably indicates breakage of the basalt flow.

Another 400-MHz GPR profile clearly illustrates flow breakage (Figure 19c). This profile has a deep, high-amplitude interface at a shallower depth than the previous GPR profile. The discontinuity of the flow indicates that after the flow solidified, it became brittle and overlying flows created extra pressure, thus breaking the deeper flows.

The last three north-south-trending, 400-MHz GPR profiles show a high-amplitude interface at a depth of approximately 2 m, similar to the strong interface detected in the shorter profiles of the wilderness trail. Deeper, weaker interfaces were detected, but they lacked the clarity of the shallower interface, which is probably related to signal attenuation.

DISCUSSION AND VALIDATION

Three factors define the amplitude of the radar backscattering in the AIRSAR data: surface slope, roughness, and dielectric properties of the surface and shallow subsurface (Elachi et al., 1984). The qualitative analyses (i.e., amplitude and polarization of the backscattered signal) of the AIRSAR images allow detailed mapping of the aa and pahoehoe lava types. The flow map in Figure 9 was created on the basis of the reflective properties of the surface and shallow subsurface. It delineates and classifies flows according to their surface roughness. Malin et al. (1978) delineate aa flows on volcanic terrain in Iceland and distinguish contacts of ash deposits.

Other radar imaging studies have observed responses similar to those in COM; for example, Campbell (2002) classifies radar signal responses of Kilauea and the Ka'u desert. Similar to COM, the very bright radar responses are caused by variation in surface roughness. The darker responses are attributed mainly to specular reflection from relatively smooth surfaces such as pahoehoe flows and loose cinder. The brighter responses are attributed mainly to rough terrains such as aa lava flows and, in some local areas, to vegetation coverage, as in the western part of the Inferno Cone.

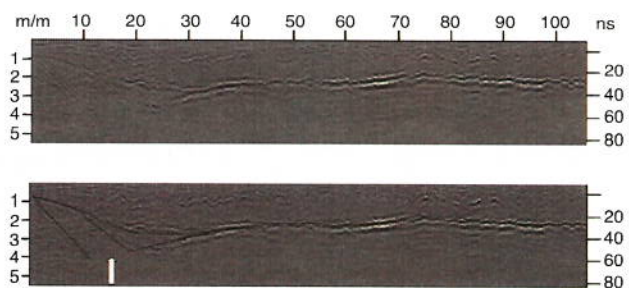


Figure 17. A 400-MHz GPR profile showing a strong, laterally continuous interface at 2–3 m depth (dashed line). At 1 m deep, signal response of interface is laterally discontinued, possibly related to flow breakage. Structure to the left of the profile corresponds to fissure flows. Arrow indicates area where radar signal is lost, related to the overlying loose basalt.

Using different frequencies and polarization in the SAR mapping of volcanic terrains provides scientific benefits:

- 1) Radar reflectivity at different frequencies and polarization yields the ability to map the textural variation in the volcanic terrains.
- 2) Use of the P-band yields the potential to detect buried features under pyroclastic deposits.
- 3) Crosspolarization of the P-band provides the capability to categorize surface lava roughness in moderately vegetated terrains.

An accuracy assessment was performed to quantify the reliability of mapping lava flows and lava types using AIRSAR data. The geologic map of the Inferno Cone quadrangle (Kuntz et al., 1986) was used as reference data. The number of pixels for each geologic unit (ash, pahoehoe, slab pahoehoe, and cinder) was considered as the accurate reference data. These values were compared to the number of pixels obtained from interpreted lava flows on the georeferenced AIRSAR image (both at the same spatial resolution).

The accuracy varied, depending on the surface of the radar response. Mapping of slab pahoehoe was 98% accurate; however, values of 68% accuracy were obtained near areas around the Broken Top rift zone, caused by errors induced by vegetation roughness. Mapping of the Devil's Orchard aa lava flow obtained values of 87.7% accuracy. Mapping this flow was straightforward, owing to the bright signal response, large surface area, and lack of vegetation coverage. Mapping of cinder and ash deposits was the least accurate. Values of 46%–62% accuracy show the low correlation between interpreted deposits and the reference data. Ash and cinder deposits work as specular reflectors of the radar signal and emit a darker response that may be confused with the radar's shadow zone corresponding to the cinder cones (usually associated with ash and cinder deposits).

As for the GPR data, the interpretation of the profiles provided an adequate correlation with the AIRSAR data. Reflections are generated by lithologic changes such as voids, tubes, changes in electrical properties, and changes in bulk density at interfaces. GPR surveys



Figure 18. (a) Uninterpreted (top) and interpreted (bottom) 100-MHz GPR profile along the southern section of the road of Broken Top rift zone. Profile shows three strong amplitude interfaces (dashed lines) at depths of 5, 15, and 30 m and also a discontinuity of these interfaces for about 50 m length corresponding to faults in the area. (b) Uninterpreted (top) and interpreted (bottom) 100-MHz GPR profile along the northern section of the road of Broken Top rift zone. Three strong interfaces dip toward the rift area, where there is no clear definition of interfaces.

detect (1) cinder layering and subsurface lava flow of a cinder cone, (2) floor and ceiling signal response of lava tubes, (3) buried flows and chaotic radar response perpendicular to a rift zone and source vent, and (4) buried fractured features with no surface exposure in the wilderness trail. GPR surveying in COM was successful because volcanic deposits are thin (<100 m), compositionally homogeneous, and electrically resistive (Russel and Stasiuk, 1997). The GPR survey at the Inferno cinder cone detected cinder layering underlain by a strong-amplitude interface interpreted as a lava flow buried 25 m deep. Similar GPR results have been acquired by Grant and Shutz (2004), showing aeolian reworking of layered cinder overlying a basalt flow in Sunset Crater, Arizona.

Interpretation of surveys performed on lava tubes is more complex, because of the characteristics of lava tubes. Roughness and irregularity of the surface causes scattering and dispersion of the radar wave and reflects as noise in GPR data (Miyamoto, 2003). Even though there are three known lava tubes in the area, they can be identified only when part of the tube collapses and is exposed to the surface; therefore, the possibility of an unknown tube system cannot be discarded (Mattox and Heliker, 1993).

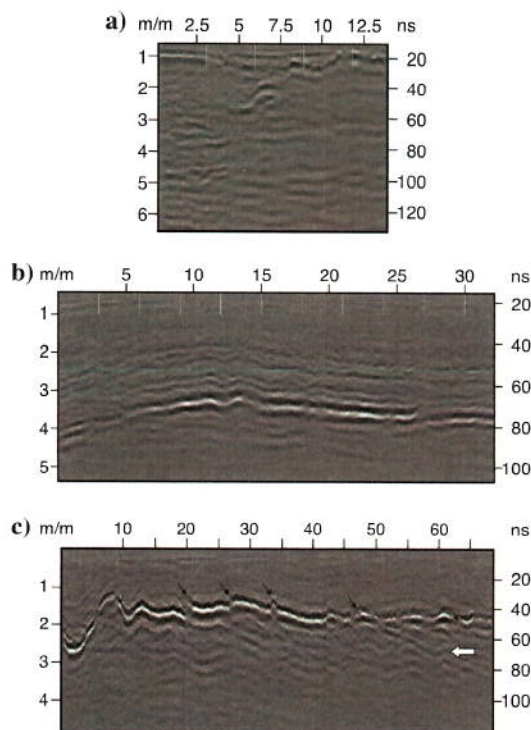


Figure 19. GPR profiles from the wilderness trail area. (a) This 400-MHz GPR profile shows strong amplitude interfaces. The shallower interface is discontinuous, and deeper interfaces are interpreted as buried flows. Basalt outcrops at the surface. (b) A 33-m-long, 400-MHz GPR profile on the wilderness trail; a high-amplitude flow at 3.5 m indicates flow is from right to left. Discontinuity of the interface at approximately 27 m along the profile represents breakage of the flow related to cooling. (c) This 400-MHz GPR profile shows a high-amplitude interface (~2 m deep) of similar depth as in other surveys on the wilderness trail. Arrows indicate discontinuity of the interface from flow breakage. Deeper radar response at the right of the profile (white arrow) shows an interface dipping toward that direction.

GPR profiles of the rift zone show three clear interfaces that dip toward the source vent. The homogeneous radar response between these interfaces is consistent with the structureless character of the lava flows. The faulting on the western flank of the Broken Top cinder cone produces a chaotic GPR signal response that is difficult to interpret; lateral continuity of strong amplitude interfaces is lost in this faulted area. A typical cross section of the basalt flow in the eastern Snake River plain shows that layering of cinder, ash deposits, thin sheets of lava, and open, horizontal fractures are found near source vents (Smith, 2004).

The Broken Top rift zone is located near a source vent, so the layers described above contribute to the chaotic GPR signal responses found in the northern section of the GPR profile. Even though there is no surface exposure, the GPR surveys detected subsurface features and fracturing of lava flows in the wilderness trail. Fracturing and lava breakage develop from stresses during cooling: As lava flows crystallize and cool, they may develop these fractures and columnar joints (Smith, 2004). A hyperbolic reflection was detected at the fracture of the interpreted flow. These hyperbolic reflections are caused by EM energy reflected from sharp edges or embedded discontinuities of similar size to the resolution of the GPR antenna. The buried interpreted lava flow (1 m deep) was detected in all of the GPR surveys performed in the area, which indicates the great extent of this flow.

Three main factors allowed a comparison between AIRSAR and GPR data. The first factor was whether AIRSAR data revealed features that could be interpreted as subsurface structures. The second factor was whether GPR surveys crossed the interpreted subsurface feature. The third factor was whether the GPR survey was long enough to detect the interpreted structure in the AIRSAR images at a resolution of 10 m/pixel.

After considering the factors described above, two linear features were detected in the subsurface fissures interpreted from the P-band AIRSAR images (Figure 10). Comparison to surface fissures and fissure flows in the area support this interpretation. A GPR survey was performed that crosses the southern section of the western feature. The GPR profile (Figure 19) detected three interfaces at the location of the linear feature. The deeper interface has a low-amplitude response caused by signal attenuation from overlying dense basalt flows. The lengths of the shallower interfaces indicate they correspond to the interpreted subsurface structure.

CONCLUSIONS

Both the SAR and GPR surveys show a constrained ability to distinguish between aa and pahoehoe flows and to map buried flows in the volcanic context of COM volcanic field. The surface and subsurface mapping capabilities of AIRSAR were examined and validated using fieldwork, visual observations, and GPR surveys. The use of multiple polarization and multiple frequencies has resulted in construction of a detailed map, delineating changes in lava types. The most effective polarization and frequency for mapping lava types is the HV-polarized L-band image. Additionally, the AIRSAR P-band data was successful in determining subsurface features such as fissure flows and change in subsurface lava types. Presence of these features was confirmed with 400-MHz GPR surveys on the identified anomalies.

The ability of the SAR L- and P-bands to map buried flows and to assess their textural characteristics (i.e., aa or pahoehoe types) is the major output of our analysis. Such an approach is of significant im-

portance when attempting to map the different eruptive periods in active volcanic terrains where old flows are covered by more recent pyroclastics deposits. The mapping of old flows allows a better understanding of the intensity of the different eruptive periods and provides information for making statistical models of lava flows, parameters that are of primary importance in risk assessment in those terrains.

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