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The subaerial weathering of Hawaiian basaltic lava flows is manifested by distinctive chemical and mechanical changes, beginning during initial cooling and continuing over a period of hundreds or thousands of years. These changes can be used to estimate relative ages of individual basaltic flows. We have used remote sensing techniques and multispectral thermal infrared (IR) images to do this quantitatively. This approach exploits differences among thermal infrared emittance spectra to identify chemical constituents in the scenes and only secondarily uses the temperature information also contained in the multispectral images. It is especially effective for young flows (<1.5 ka) (1 ka = 1000 radiocarbon years before “present” (A.D. 1950) e.g., “1.5 ka” is approximately A.D. 450) that are just beginning to weather but for which the weathering products are not yet readily apparent to the field observer.

On the windward side of the island of Hawaii and in other humid areas, vegetation growth is so rapid that lava surfaces are obscured from aerial view in a very few years. In contrast, lava flows in arid regions on the island are nearly unvegetated and may remain barren for more than 100,000 years. During this interval the change most obvious to the eye is the oxidation of iron, so that the surface, originally black or dark brown, becomes reddish or tan [Lockwood and Lipman, 1987]. Other less obvious changes also occur, including the accretion of silica-rich veneers or coatings (≈80 wt % SiO₂) derived largely from windblown soil [Curtiss et al., 1985] or tephra [Farr and Adams, 1984] and the devitrification of the thin (≈50 μm) glassy crusts or chill coats so common on fresh pahoehoe. The coats may also spall to reveal a more vesicular crystalline substrate.

Although not as striking to the eye as the reddening due to the oxidation of iron, the effect of silica rinds and glassy chill coats on the thermal IR emittance spectra of the lavas is quite strong, as predicted by Farr and Adams [1984]. We have measured these effects using NASA’s airborne Thermal Infrared Multispectral Scanner (TIMS), as well as in the laboratory and with field spectrometers. We find that TIMS data, displayed as images, can be used as a basis for quantitative relative-age assessment and mapping of lavas. In this article we present false-color three-channel airborne IR images of lava flows on the north slope of Mauna Loa and of recent Mauna Ulu flows across the Holei Pali south of Kilauea, on the island of Hawaii (Figure 1). We note characteristic spectral differences of the lavas of various ages and compare our results to previous geologic maps made by field investigators.

Field Study Areas

The study areas shown in Figure 1 are at elevations of ~2000–2300 m (Mauna Loa) and 0–600 m (Holei Pali) above mean sea level; yet the average annual precipitation is similar. Annual rainfall [Armstrong, 1973] grades from 50 cm on the northwestern side of the Mauna Loa area to 125 cm (northeastern corner); and from 100 cm on the southwestern side of the Holei Pali area to 250 cm (northern corner). Farr and Adams [1984] observed the accretion of silica coatings where there was annual rainfall in the range 64–115 cm, the situation in much of our two study areas. Lichen growth is rapid where yearly rainfall exceeds 125 cm; therefore fresh rock surfaces are quickly obscured. Desert varnish is thought to accrete where rainfall is less than 25 cm/yr [Elvidge, 1979]. On the island of Hawaii, such arid regions are found only on the northern Kona Coast. Thus the basalt in much of our study areas is not susceptible to rapid obscuration by lichen or other vegetation, and the exposed rock is not covered by desert varnish. Petrographically, the basalts of Mauna Loa and Kilauea are similar [Wright, 1971]. Phenocrysts consist of plagioclase, pyroxene, and/or olivine. Groundmass phases include
glass, magnetite, and ilmenite, in addition to plagioclase and pyroxene.

The oldest Mauna Loa flows are exposed along fault scarps or deep river channels and exceed 40,000 years in age. However, Mauna Loa's surface is being covered by lava flows at a rate of about 40% of its area each 1000 years [Lockwood and Lipman, 1987], so that exposures of pre-Holocene flows are rare. Within the 95 km² Mauna Loa study area, about two dozen individual lava flows are present. These include five flows of historic age (1935, 1899, 1880, 1855, and 1843) and prehistoric flows ranging in age from ~200 to >8000 years. The prehistoric flows were separated into five age groups for comparison with the TIMS image: group I (0.2–0.5 ka), group II (0.5–1.5 ka), group III (1.5–4 ka), group IV (4–8 ka), and group V (>8 ka). These ages are based on radiocarbon dates for charcoal recovered from beneath the flows. Some of these dates are given by Rubin et al. [1987]; others are from J. P. Lockwood (unpublished data, 1988).

Vegetation cover in the Mauna Loa study area has been measured in field transects by J. B. Adams (personal communication, 1988). Historic flows in this area are largely unvegetated. Flows of groups I and II typically have only a few percent cover of grasses and small shrubs, whereas those of group III have 5–15% cover. Flows of group IV are extensively weathered and heavily vegetated, especially in the eastern part of the study area (the result of greater precipitation there). Group V flows are deeply weathered and largely covered by ash erupted from Mauna Kea; they are also heavily vegetated.

Surface flows of Kilauea are nearly all <1000 years old. Prehistoric flows (before A.D. 1790) in the Kilauea study area (Figure 1) are heavily forested in the high-precipitation areas above Holei Pali but have 5–25% vegetative cover in the dry coastal areas. By 1985, the 1969–1974 Mauna Ulu flows supported new shrubs above 500 m altitude; however, below the palsi they had relatively little vegetation.

**Spectral Basis for Distinguishing Between Basalt and Weathering Products**

Laboratory thermal IR reflectance spectra for freshly broken, unaltered basalt (Figure 2a) exhibit a major broad peak from 8.5 to 12 μm and centered near 10 μm, in the general vicinity of the Si-O vibrational (reststrahlen) bands [Hunt, 1980]. These spectra resemble those of basalt fused and quenched in the laboratory to make glass (Figure 2b), rather than spectra of the phenocryst phases (plagioclase, pyroxene, and olivine) which have more and narrower peaks (Figures 2c, 2d, and 2e). Peak shape in thermal infrared reflectance spectra is more diagnostic than amplitude, which varies with sample particle size, surface roughness, and other characteristics. G. R. Rossman (personal communication, 1988) attributed the broad bands of Figures 2a and 2b to disordered glass. We note that the peak in Figure 2a is at a shorter wavelength (=9.5 μm) than the peak in Figure 2b (≈10.0 μm). Two possible explanations for the difference in peak position are (1) shorter Si-O bond lengths in the natural basalt glass, which cooled more slowly than the sample fused in the laboratory and hence has more order, and (2) spectral bands from the phenocrysts (particularly plagioclase) overlapping the glass band at wavelengths at ≈9–10 μm.

Farr and Adams [1984] concluded that the accreted coatings found on the weathered basalt contained amorphous silica, perhaps increasingly crystallized with age. Such a coat even a few microns thick would be largely opaque to thermal radiation. Thus the spectrum of an affected lava might resemble opal (Figure 2f) rather than the basalt substrate, perhaps even for samples that to the eye appeared not to be coated. A spectrum of obsidian is also shown for comparison (Figure 2g). The spectrum of this natural glass resembles that of opal more than that of the fused basalt.

As noted above, rock surfaces in areas significantly drier than Mauna Loa or Holei Pali will tend to be coated with a desert varnish consisting largely of illite clay together with the manganese and iron oxides that impart its distinctive dark colors [Potter and Rossman, 1977]. The thermal IR spectrum of such varnish (Figure 2h) is dominated by the spectrum of the clay [Salisbury et al., 1987], which is distinct from both the basalt and the silica coating. In wetter areas, rock surfaces tend to break down through hydration, oxidation, and decationization reactions to form clay and oxide minerals [Sherman, 1952; Hay and Jones, 1972] represented in Figures 2i and 2j by hematite and palagonite.

Spectrally, the clay, iron oxide, and silica weathering products are all distinct from the basalt substrate. Thus multispectral thermal IR images are in principle capable of distinguishing weathered from fresh basalt and of distinguishing among different weathering products.

**Thermal Infrared Images**

**Data Acquisition and Processing**

TIMS, on board a NASA C-130 aircraft, was flown over the island of Hawaii during April and November 1985. TIMS acquires radiance data in digital image format. There are six spectral channels of data between 8 and 12 μm (spectral bands for channels 1–6 are 8.2–8.6, 8.6–9.0, 9.0–9.4, 9.6–10.2, 10.3–11.1, 11.3–11.7 μm, respectively [Palluconi and Meeks, 1985]). The sensitivity (NEΔT) is ~0.1°C. Images are acquired using a mirror that scans an arc of ±38° about nadir.
Fig. 2. Laboratory thermal IR reflectance spectra for basalt and some of its constituents and weathering products: (a) fresh interior of basalt, (b) fused basalt, (c) plagioclase, (d) diopside, (e) olivine, (f) opal, (g) obsidian, (h) desert varnish, (i) hematite, (j) palagonite.

and perpendicular to the line of flight, with an angular resolution of 2.5 mrad. The C-130 operates at altitudes up to 7.7 km above sea level; thus TIMS acquires data with a nadir ground resolution (pixel size) of 25 m or less.

Sixty-four flight lines were obtained, including coverage of most of Mauna Loa and Kilauea. Ground resolution varied within an image depending on elevation, aircraft altitude, and scan angle, but typical values were 5–15 m. Typical image widths were 3–7 km. Images from two of these lines (Figure 1) are discussed in this article. The images were both acquired shortly before local noon, when ground temperature was high, for maximum signal/noise and before the daily buildup of clouds.

The radiance from a surface is a function of both its temperature and spectral emittance. The emittance is the parameter related to the composition of the surface. The spectral emittance variation in most natural terrestrial surfaces is subtle, and temperature dominates TIMS images. In order to display the emittance information, we processed the calibrated TIMS data using our “decorrelation stretch” method, described in detail by Gillespie et al. [1986]. This method is based on principal component analysis. It exaggerates emittance differences, while deemphasizing the temperature information, which dominates the acquired data but is of secondary importance in this study.

After decorrelation stretching, the data from three of the six channels were displayed in “false-color” by assigning the primary colors blue, green, and red to channels 1, 3, and 5, respectively. In this false-color scheme, relative spectral emittance information is displayed as the chromaticness (color, hue, and saturation), whereas temperature information is displayed as the intensity or lightness (hot = light; cold = dark). The chief effect of the decorrelation stretch is to exaggerate color saturation; it has little effect on the intensity and the relative hues in the image, although hues may be changed if the average color is not “gray” [Gillespie et al., 1986]. These TIMS data are not “gray,” and the color shift is such that blackbody radiation is rendered as blue-green. Nevertheless, the colors in the enhanced image are related to the spectral character of the surface in a simple and predictable manner. Because the decorrelation stretch depends upon the frequency distribution of radiance values with the particular image being stretched, colors of the same materials generally vary slightly from image to image.

TIMS Images

Plate 1 shows a decorrelation-stretched image of basalt flows on the north flank of Mauna Loa. (Plate 1 can be found in the separate color section in this issue.) (The road running diagonally across the image is the Hilo-Kona jeep trail.) Plate 2 shows a similar image of the Mauna Ulu flows erupted from the southeastern rift of Kilauea. (Plate 2 can be found in the separate color section in this issue.) Despite the chemical and petrologic similarity of the unweathered basalts, Plates 1 and 2 have a wide range of different thermal IR “colors,” both within and among the numerous individual lava flows.

Field checking of these and other Hawaiian TIMS images and comparison with geologic maps [Holcomb, 1987, J. P. Lockwood, manuscript in preparation, 1988] reveal systematic relationships between the TIMS colors and the type of basalt and its degree of weathering and hence age. Pahoehoe and aa flows are consistently separable in the images where
Fig. 3. Index map for Mauna Loa TIMS image (Plate I) showing flow outlines and ages (dates for historical flows; radiocarbon age groups for prehistoric flows $I = 0.2$-$0.5$ ka; $II = 0.5$-$1.5$ ka; $III = 1.5$-$4$ ka; $IV = 4$-$8$ ka; $V = >8$ ka); "a" is aa; "p" is pahoehoe. Sample locations are shown: Stars indicate where data were taken from the image for Figure 7; circles mark location for samples of Figure 5; open squares are for Figure 6. Numbers in boxes give the vegetation cover measured in the field for selected flows (J. B. Adams, personal communication, 1988).

there is little or no vegetation. Single basalt flows of either type may show some image color differences even immediately after eruption; however, the greatest color differences appear to be related to age (Figure 3).

Freshly broken and unweathered basaltic cinders and crushed basalt exposed in quarries consistently appear cyan or light blue-green in the false-color pictures. In contrast, young aa flows appear dark blue-green, and this color shifts to dark brown or orange with increasing age. The oldest flows are heavily vegetated and appear dark green. In the false-color pictures these are not always easy to distinguish from young, largely unvegetated aa. However, they may be separated by temperature. In Plate I, lightly vegetated aa flows ranged in surface temperature from 35° to 43°C; heavily vegetated flows were ~29°C.

In our experience, both with the images shown in Plates 1 and 2 and with TIMS images of other areas, very young pahoehoe generally appears blue in the false-color images. However, locally, it may be magenta or pink. Pahoehoe flows of the 1969-1974 Mauna Ulu eruptions show this intraflow variation in a striking fashion (Plate 2). We have seen these variations in image color even in year-old flows that have not had time to weather. They thus appear to represent a range in the initial state or condition of the surface of the lava. We have not observed colors intermediate between blue and magenta (e.g., purple) in young flows, except where the extreme colors may be mixing at a subpixel scale (e.g., along contacts).

There is a pronounced and systematic color change with increasing age of pahoehoe. The TIMS color shifts from dominantly blue to purple and magenta (compare, for instance, the 1935 and 1880 flows in Plate 1). This range of colors mimics the range for the different initial states but includes intermediate purple. Increasingly older flows show colors not observed for young flows: red (1843, Plate 1) and orange (0.2-$1.5$ ka), mixed orange and green (1.5-$4$ ka), and ultimately light green (4-$8$ ka). The oldest lavas ($>8$ ka) are forested and appear dark green. Heavily vegetated aa and pahoehoe are probably indistinguishable from each other.

Unvegetated pahoehoe was warmer than aa. Surface temperatures for pahoehoe in Plate I ranged from 43° to 54°C.

We have compared Plate 1 (Mauna Loa) with a field-derived geologic map of the same area. The contacts of some flows are more accurately portrayed in the images. In a few cases, geologic relations that were difficult to map in the field can easily be seen in the images. One example of this is the boundary between the 1843 (red) and 1935 (blue) pahoehoe flows, which is difficult to distinguish in the field but is very different in the TIMS image. On the other hand, many of the prehistoric aa flows (brown) are difficult to separate in Plate 1 but were separable based on their "true" color and stratigraphic relationships in the field.

We have also compared Plate 2 to the geologic map of the Kilauea area of Holcomb [1987], who separated the 1969-1974 Mauna Ulu flows by age of eruption. In these very young flows there has been little weathering, and the TIMS data do not readily discriminate the age boundaries.

Parenthetically of interest in Plate 2 is a clear demonstration of how the temperature and spectral effects are separated in the thermal IR images. The Mauna Ulu lava flows drop over steep cliffs (Holei Pali, in the center of the image, is from 240 to 500 m high). The palis are sun-facing and hence warmer than their surroundings (~10° warmer for Plate 2). These sunlit slopes are the light bands that run
across the image: lighter than the adjacent cooler flows above and below the palis but not strongly changed in color.

Data were sampled from the TIMS image as shown in Figure 3. We have displayed the systematic false-color changes described above on ternary “chromaticity” diagrams (Plate 3) for Mauna Loa basalts. (Plate 3 can be found in the separate color section in this issue.) Chromaticity diagrams are a conventional means for pictorially describing quantitative color relationships [Wyszecki and Stiles, 1982]. Here we are not concerned with “true” perceived color but with false color in the image domain [see Gillespie et al., 1986]. In Plate 3 the three variable, respectively, each normalized to the sum of the three radiance values. We have additionally superimposed the approximate decorrelation-stretched colors used in Plate 1 over the diagram, so that the radiance chromaticity coordinates and the display colors may be easily related.

Plate 3 displays the image colors associated with flow type, initial states of the flow surface, and different weathered surfaces for the northern flank of Mauna Loa. Variations in color due to differences in surface composition and texture are represented by broad distributions of chromaticity coordinates. Flows with homogeneous and similar surfaces have similar colors and are represented by tight distributions or clusters. Data for flows may be organized by degree of weathering or by age. The flows represented in Plate 3 are all from one fairly small area; therefore organization by weathering and organization by age are approximately equivalent. This would not be true if the flows were from different environments.

The Progression of “chromaticity” coordinates across the ternary diagram as a function of weathering defines a trajectory that describes the change in image color with flow age. Presumably, image color for a given flow would follow this trajectory if it were observed over a span of time. The trajectory is a valuable concept because it can be used to estimate age from image color, provided that (1) there is a monotonic relationship between image color and age, (2) the relationship is calibrated by a sufficient number of dated flows, and (3) the scatter of chromaticity coordinates normal to the trajectory (but in the plane of the ternary diagram) is not so great that the different segments sidetapel.

Aa and pahoehoe flows have such different surface characteristics that we expect them to exhibit different initial states and weathering trajectories in the chromaticity diagrams. The distribution of chromaticity coordinates for Mauna Loa aa flows (Plate 3a) is tightly clustered. Nevertheless, if the data are viewed as a function of age, some structure is evident. The youngest aa flows in Plate 1 (e.g., 1935) plot at the upper left of the curved trajectory (unsaturated green). Older historic flows plot increasingly closer to red. This trend culminates with the youngest prehistoric flows (0.2–0.5 ka), which are reddish brown in Plate 1. For older prehistoric flows the trajectory reverses direction, proceeding toward yellow-green (closer to the g−r edge of Plate 3a). In Plate 1 this color is a dark brownish-green because of the low temperature of the aa flows. Apparent differences in Plate 1 among the dark image colors of aa on this leg of the trajectory are minor.

The distribution of chromaticity coordinates for Mauna Loa pahoehoe flows (Plate 3b) is less tightly clustered than for aa. If the data are organized by age, a well-defined trajectory is evident, but it is more complex than the one for aa. This complexity is due to the historic flows. The youngest flows (1935) are largely blue but also magenta in Plate 1. These data are dispersed along a line subparallel to the b−r side of the ternary diagram. This blue-magenta line represents very nearly the range of initial states of pahoehoe surfaces, from a spectral standpoint. The 1935 flow is only slightly weathered, and the colors have evolved but little from the actual line of initial states.

For historic and recent prehistoric flows, dual evolutionary trends are observed: the dispersion in the blue-magenta direction decreases with age, and the colors are increasingly red. The trend toward red is oblique to the blue-magenta line. Pahoehoe initially near blue may evolve toward purple; pahoehoe initially near magenta will plot closer to red. The dispersion of colors for a single flow becomes smaller with age, until they cluster about a single point. For the Mauna Loa study area this convergence occurred for the 1843 flow.

For prehistoric flows the trajectory turns toward r. In the Mauna Loa study area the end of this leg was represented by a prehistoric flow of age 0.2–0.5 ka. For older flows the trajectory turns sharply toward g, and unvegetated prehistoric flows plot near orange or brown and finally light green. Along this leg the colors for single flows again disperse but this time along the trajectory instead of oblique to it. Also along this leg, the aa and pahoehoe trajectories come into coincidence. (Aa of this age range is darker in Plate 1 than equivalent pahoehoe because the temperature is typically 10°C lower.)

**Field Observations**

We studied each of the basalt flows of Plate 1 in the field in order to establish a correspondence between TIMS image color and visual estimates of weathering for the lavas.

Pahoehoe and aa are physically distinct lava textural types derived from solidification under different rheological and flowage conditions [Peterson and Tilling, 1980]. Individual Hawaiian lava flows generally include areas of both pahoehoe and aa texture, as well as textures gradational between the two types. Pahoehoe and aa have identical chemical and mineralogical compositions within individual lava flows and differ in their genesis only by their physical conditions of emplacement. Pahoehoe is formed by direct freezing in place from flowing liquid; aa reaches its final resting place as a complex aggregate of individual blocks which have formed by the fracturing of solidifying lava during flowage. Lava may transform from pahoehoe to aa during flow; the opposite has not been observed. Many Hawaiian basaltic lavas are initially erupted as pahoehoe but commonly transform to aa downstream from eruptive vents.

**Aa.** The aa that we examined is quite rough and similar in appearance from flow to flow, although locally smooth surfaces were found, especially along channel walls. Incipient scrotal coats, visible under magnification, appeared on aa more than a few decades old in the Mauna Loa area (e.g., the 1843 flows). The youngest prehistoric aa flows (0.2–0.5 ka) were lighter in color than the black fresh aa. The principal effect of weathering appeared to be the growth of a thin reddish or tan rind or coat. Under the rind was a sharp transition to fresh-looking black basalt. Farr and Adams [1984] report that this coat consists of alternating clear and red layers of silica and hydrous or amorphous iron oxides. In
older aa the rind was thicker, and the sharp boundary was not evident. Instead, exposed lava was pervasively weathered. The natural colors of these surfaces were reds and ochers. Presumably much of the basalt has been replaced by hydrous iron oxides (limonite or palagonite) and claylike minerals [Macdonald, 1971; Lipman, 1980].

Pahoehoe. The pahoehoe that we examined was everywhere characterized by a layer of surface glass, commonly up to ~1 cm in thickness. At least locally, this layer was topped by a smooth, thin (~50 μm) glassy chill coat. The surface glass graded downward into more crystalline basalt. Locally, the glassy chill coat was well developed and continuous, with a vitreous luster. Near fissures and old fumaroles the glass was commonly devitrified and had a waxy luster. In yet other areas the chill coat and the layer itself were discontinuous or spalled soon after eruption to reveal the substrate. We have seen these variations in the condition of the glassy crust even in pahoehoe that had just cooled. They thus represent a range in the initial state of the surface. On older flows the glassy crust commonly appeared dull. To the unaided eye, the dulled chill coat undergoing the first weathering stages of weathering can be easily confused with the waxy chill coat of the youngest flows.

The 1843 pahoehoe had lost some of its luster, but the surface was similar in appearance to that of the 1935 flow. In fact, the contact between the 1935 and 1843 flows is not easy to recognize in the field and is not resolvable on either black-and-white or color aerial photographs. These and older pahoehoe flows also supported the same translucent accretionary coats seen on aa flows. Likewise the oldest prehistoric flows exhibited the pervasive ocher weathering rinds discussed above.

A pahoehoe with an age of 1.6 ka was pervasively weathered. Several different flows within this age unit could be distinguished in the field by their textures and amounts of iron oxide (i.e., different colors in visible light). These separate flows corresponded to the orange and green units seen on the TIMS image. No desert varnish was observed on any of the flows in the Mauna Loa study area.

**SEM Observations**

In order to analyze surface roughness and coatings at a microscopic scale comparable to the ~10 μm wavelength of the IR radiation measured by TIMS, we made images of typical aa and pahoehoe of different ages (Figure 4) on a Canscan scanning electron microscope (SEM) equipped with a Tracor Northern Energy Dispersive Spectrometer (EDS) system. This system is equipped with internal software standards which enable one to do semiquantitative elemental analyses for elements heavier than neon. However, similar microorganisms found on exposed surfaces show high quantities of silica, leading us to conclude that they are coated with the silica rinds. This provides additional evidence for the accretional nature of the coatings. The upper, exposed surface in Figure 4f shows a thick (~20 μm) coating composed of silica, with minor aluminum and a trace of iron. The coating here appears to be eroding rather than accreting. In the macroscale this sample has the typical tan appearance of the older weathered Hawaiian pahoehoe of age >1000 years.

All of the SEM images shown here were of the samples collected from the area shown in Plate I of the north flank of Mauna Loa at an elevation of approximately 2200 m. The silica coatings do not appear to be as common at higher elevations on the same flows. From our analysis of ~100 SEM images we conclude that the coatings are in a nonsteady state, undergoing both accretion and erosion (the latter by etching and spalling) much of the time. The exact nature of the coating at any location is a function of age, local climate, surface texture, and other environmental factors. Its nature, accretion, and erosion are the subjects of continuing study.

**Spectral Measurements**

**Procedure**

In order to understand the spectral information stored in the six-channel TIMS images and to relate the chromaticity'
Fig. 4. SEM micrographs of lavas collected from the north flank of Mauna Loa. Scale bars are shown in each picture. (a) 1935 aa. (b) 1935 pahoehoe. (c) 1843 aa. (d) Closer view of the center of Figure 4c. (e) 1843 pahoehoe. (f) Broken surface of prehistoric pahoehoe (group IV).
trajectories to chemical changes in the basalt caused by weathering, we collected samples from freshly broken and natural weathered surfaces for each flow in Plate 1. We then measured laboratory thermal IR reflectance spectra of the samples and calculated from these the emittances expected for the six TIMS spectral bands. These data were compared to emittance data calculated from the TIMS images for the same sites. Locations for samples discussed below are shown in Figure 3. Biconical thermal IR reflectance spectra covering the region 8–12 µm for natural weathered surfaces from each sample were measured at the Jet Propulsion Laboratory (JPL), using an analog Fourier transform IR (FTIR) spectrometer [Carroll and Doyle, 1981]. The field of view is −45°; thus the data are intermediate between strictly bidirectional and hemispherical reflectance. Reflectance spectra are the complements of emittance spectra according to Kirchhoff’s law [Siegel and Howell, 1972]. Complemented reflectance data have long been used as proxies for emittance data [e.g., Lyon, 1965] which are more difficult to measure (see Hunt [1980] for a justification of this practice).

In order to verify the applicability of the reflectance spectra to our TIMS emittance measurements, emittance spectra were measured in the field, using JPL’s Portable Feld Emission Spectrometer (PFES) [Hoover and Kahle, 1986]. The PFES has a much larger field of view than the FTIR: −450 cm² versus 1 mm². We measured spectra for several different spots at each sample locality in order to estimate surface heterogeneity. This step is necessary if the PFES spectra are to be related to the TIMS emittance data, taken in 10 x 10 m pixels. However, data acquisition with the PFES was limited by bad weather; cloud-free skies are required.

Emittances were calculated from TIMS radiance measurements after calibration for instrument sensitivity [Palluconi and Meeks, 1985] and correction for absorption and emittance by the atmosphere between the ground and the NASA C-130 aircraft. Atmospheric corrections are especially important for removing the differential effects due to the large scan angle (±38°) of TIMS. The atmosphere was characterized by radiosonde data and modeled using LOWTRAN6 [Kneizys et al., 1983], following the method of R. E. Walker and A. Gabell (unpublished manuscript, 1988). The atmosphere absorbed 5–15% of the thermal radiation emitted by the surface; it also emitted roughly half the amount it absorbed.

In order to eliminate completely atmospheric effects from the TIMS images, R. E. Walker and A. Gabell (unpublished manuscript, 1988) found it necessary to model variations in atmospheric ozone and local variations in water content over the imaged area. The radiosonde data were from Hilo, a much wetter part of the island than the test site, so it was necessary to adjust these data to match local conditions. Walker and Gabell estimated these small effects from the nominally corrected TIMS radiance over totally vegetated areas in the image, arguing that the spectral emittances there should be constant (PFES and FTIR spectra show that vegetation emits thermal radiation as a graybody). Applying local corrections to the image that caused vegetation to become a graybody was assumed to remove the atmospheric effects remaining after the nominal correction. The atmospheric profile yielding the “best” vegetation graybody spectra was thus deemed the most appropriate to correct the TIMS data. The size of the differential effects estimated this way was less than 1% of that estimated by LOWTRAN6.

Emittances were calculated from the radiance data using the method of Kahle et al. [1980]. This procedure assumes the value of the emittance for one reference channel. This is necessary because there are seven unknowns (six emittance values and the temperature) but only six radiance measurements. For the reference channel a model temperature is calculated from the measured radiance using Planck’s law. From the model temperature, blackbody radiance values may be calculated for the other five TIMS channels. The ratios of the measured to calculated radiances are taken to be the emittances for these channels. Calculating emittances this way gives correct values only if the value assumed for the reference channel is correct. Lyon [1965] used an 11-µm reference channel because he was primarily concerned with granitic rocks; for these quartzose and felsic rocks most of the spectral structure in the TIMS window is in the 8–10 µm region. We have followed this convention in this study, using TIMS channel 6 (11.3–11.7 µm) as the reference and setting the emissivity in channel 6 to 0.95. The effect of a small error (a few percent) in the assumed emissivity value is the introduction of a slope error of a few percent in the calculated emittance spectrum.

**Laboratory Reflectance Spectra**

Laboratory reflectance spectra for Mauna Loa aa and pahoehoe flows are shown in Figure 5. Each of the flows was sampled at several locations indicated in Figure 3 by circles. We note three main features in spectra of exposed basalt, which are common to all of the Mauna Loa basalts that we studied. The three features are feature A, a band centered between 8.1 and 8.3 µm (TIMS channel 1); feature B, a stronger band centered near 9.2 µm (channel 3); and feature C, a broad band extending from 10 to 12 µm (channels 3-6) and centered near 11.5 µm (channel 5). Their amplitudes are recorded by TIMS channels 1, 3, and 5, respectively, the channels used in the color pictures of Plate 1. Each of the six TIMS channels was affected by one or more of these features; thus the choice of channel 6 as the reference channel for emittance calculations was somewhat arbitrary.

Each of the three spectral features is found in the spectra of both aa and pahoehoe; however, spectral features of aa are generally very subdued compared to those in pahoehoe, especially for the younger lavas. In the Mauna Loa study area the three features are generally not all well developed in the same spectrum, and the amplitudes of features that do occur together are not correlated. Features B and C are commonly observed together in the same spectra. Typically, these are spectra for the historic flows (200 years old or less). In older flows, A and B are present but not C. As the rocks age further, A and B become more subdued until, in the oldest rocks, all spectral features are essentially absent.

The young pahoehoe flows having the most prominent 11-µm bands (C) are the ones with well-developed chill coats. For flows with discontinuous and/or detritved crusts, C is much weaker, although B is strong. Feature A appears after ∼100 years in the Mauna Loa area and becomes more pronounced for young prehistoric lavas. (In contrast, spectra of the Mauna Ulu flows contain A, even though the lavas are only ∼15 years old.) In spectra with a pronounced A, the central wavelength of B appears to be a little less than in other spectra: 9.1 instead of 9.2 µm. For the purposes of the
immediate discussion this shift is overlooked. It is much less than the spectral resolution of TIMS. Feature A is pronounced for flows with accreted silica rinds.

Feature C is poorly developed in aa flows, which lack the chill coats common on young pahoehoe. Feature B is also weaker than in pahoehoe spectra, although it is stronger than C. Just like for pahoehoe, A is pronounced for aa flows with a well-developed silica-rich coat. Spectra for thickly coated and pervasively weathered aa and pahoehoe are similar.

It is significant that none of the three spectral features (A, B, and C) observed in the spectra of the exposed surfaces of basalt correspond to the spectral features of the interior of the same lava (Figure 2a). As noted earlier, the spectrum of freshly broken pahoehoe may consist of two broad overlapping features: one attributed to reststrahlen bands of silicate crystals in the basalt, especially plagioclase, and the second attributed to the interstitial glass. A possible reason for the differences between the spectra of interior basalt and spectra of exposed surfaces is discussed below.

**PFES Spectra**

Field emittance spectra for the 1935 and 1843 Mauna Loa pahoehoe flows are shown in Figure 6. The sites are indicated by squares in Figure 3. Note the complementary relationship to the reflectance spectra of Figure 5. Despite the larger field of view of the PFES compared to the FTIR spectrometer, the same spectral features are seen, and the spectra resemble each other closely. This correspondence encourages us to use our larger data set of laboratory reflectance spectra to aid in the interpretation of the TIMS data.
TIMS Emittance

Emittance "spectra" calculated from the six-channel TIMS data are shown in Figure 7. The spectra describe large \(-10 \times 10\) pixel areas within the flows, not just the restricted sites measured by the laboratory and field spectrometers. Emittances for reference channel 6 are all set to the same value: \(e_6 = 0.95\). The correspondence between these and the full-resolution spectra is evident: the same three features can be seen, and their relative strengths follow the patterns described for the laboratory reflectance spectra above. Feature B is pronounced in most of the spectra in Figures 7a and 7b despite the limited spectral resolution. Feature C is only seen in the top spectrum of Figure 7b (1935 pahoehoe) by the depression of the emittance of channel 5. Feature A, also best seen in Figure 7b, is revealed by the depression of the values in channel 1, relative to channels 4, 5, and 6 for flows of 1843 and older compared to the 1935 flow.

DISCUSSION

The orderly progression of false colors with age of the basalt flows (Plate 1 and Figure 3) strongly suggests that the changes are caused by weathering products. This suggestion is strengthened by field study of the lavas, SEM micrographs, and thermal IR spectra. Below we discuss the link between the observed weathering trajectories and the various initial components and weathering products.

We associate spectral feature A, the narrow peak between 8.1 and 8.3 \(\mu\)m, with amorphous silica in the accreted rind. The main peak is at the same wavelength (8.2 \(\mu\)m) as a reststrahlen band for opal. Opal has a second and larger peak at 9.1 \(\mu\)m, which nearly coincides with B. This may be fortuitous because B is observed in the absence of A and, in any case, has its maximum at 9.2, not 9.1 \(\mu\)m. However, the near coincidence may explain why A apparently is found only with B.

We are uncertain of the cause of B. It is not a reststrahlen band of any of the silicate phenocrysts found in these basalts (olivine, pyroxene, and plagioclase), nor is it attributable to Fe or Ti oxides (magnetite or ilmenite). Yet its narrow shape is incompatible with amorphous glass, the other main constituent of most Hawaiian basalt. We have fused and quenched powdered samples of basalt to make glass pellets and measured their reflectance spectra (Figure 2b). In these spectra, B was missing. However, sharp features similar to B have been observed for commercial sodium glasses [Simon and McMahon, 1953] and for obsidian (Figure 2g). Many of the commercial glasses were heated for long periods to promote devitrification. We suspect that B may be caused by loci of ordered silica within the unstructured glass. In natural lavas these may result from hydrothermal reactions during cooling and also during subsequent hydration at ambient temperatures. Perhaps quenching of our laboratory basalt glasses inhibited this process.

Spectral feature C is attributed to glass in the chill coat. Its breadth is suggestive of the wide range of Si-O bond lengths in glass, and similar features are seen in spectra of other volcanic and manufactured glasses. Feature C is most strongly developed in pahoehoe with vitreous chill coats. As shown in Figure 2, the broad feature characteristic of freshly broken pahoehoe (and the similar feature for our quenched glasses) is at a significantly lower wavelength (10.8 \(\mu\)m) than C (11.5 \(\mu\)m). The shift in the peak from groundmass glass to chill coat may reflect a different cooling history of the skin and interior of the lava and is the subject of further research.

The ordered behavior of the trajectories is best explained as a consequence of systematic changes to flow surfaces caused by weathering. We suggest the following scenarios. For aa, young rough flows are associated with dark blue-green TIMS colors and very weak spectral features, including subdued B and even some C. Because aa and pahoehoe of the same flow have essentially identical compositions, we attribute the subdued spectrum of the aa to multiple scattering in the rough surface (cavity or blackbody radiation). The dark colors in the radiance images are due to low temperatures in the shadowed portions of the rough surface, not yet warmed by the sun at the time (\(-1100\) LT) of data acquisition.

The shift to brown image color with increasing age of aa is directly caused by the silica-rich rinds, which resemble opal spectrally and contain both A and B. We attribute the increased color saturation of these flows to filling of small cavities with the thermally opaque silica, thereby reducing the amount of blackbody radiation. There is no very old unvegetated aa in the study area. The color of the oldest aa flows in Plate 1 is controlled by the admixture of vegetation, which consistently appears dark green in the false-color images. This effect is not represented on the trajectory of Plate 36.

The colors for young pahoehoe are controlled by the original state of the glassy chill coat and its degree of devitrification and spalling. Fresh-appearing vitreous chill coats are associated with pronounced B and C peaks; "waxy" or missing chill coats have comparable B peaks but diminished or missing C peaks. We speculate that in these cases the chill coat may devitrify during or shortly after formation, perhaps because of chemical alteration accompanying degassing of the lava during cooling. We have also observed that the chill coats may spall, again affecting and reducing the strength of the C peak. In fact, both spectral features B and C are usually present in the spectra of young...
vesicularity. The issue of within-flow variance is quite complicated and is the subject of continuing study.

Our results show the utility of remote sensing in the relative dating of similar basalts in a restricted environment. The existence of weathering trajectories implies that it may prove possible to estimate flow age from remotely sensed data, provided that progression along the trajectory has already been calibrated for a given region. However, this technique is far from proven. The trajectories that we have described are complicated and reflect a delicate balance of

Fig. 7. Emittance values calculated from atmospherically corrected TIMS data, for the same flows as Figure 5. Letters A, B, and C refer to spectral features discussed in the text. (a) Aa. (b) Pahoehoe.

pahoehoe; but the relative strength of each determines the color: a strong C will be blue, a weak C will be magenta.

The shift to orange accompanying the development of A reflects the accretion of the silica-rich rinds. As shown by the SEM images, the silica coatings, like the chill coats, crack, spall, and are etched. Obviously, competing processes of accretion and destruction control the development of A. Thus the trajectory for basalt in general need not be as simple as the one we have studied.

The final stage in the chromatic evolution of pahoehoe in our study areas is the shift from orange to light green. This shift is caused by the flattening or loss of contrast in the spectrum (Figure 5b). These old pahoehoe flows are pervasively weathered and are coated with thick (~1-10 mm) rinds of palagonite (which is spectrally flat, Figure 2j), which appear to obscure the spectral features of the underlying unweathered basalt.

We are proposing that the chromatic trajectories can be used for the relative dating of basalt flows. For this to be true, it is necessary that the chromatic variance within flows of the same age is less than the variance among flows of different ages. This is in general true for the basalts we have studied, as can be seen by inspection of Plates 1 and 2. Yet we have already noted the blue-magenta dichotomy in the young flows. Additionally, we have noted mixed orange and green areas in flows of age group III apparently related to differential rates of weathering dependent upon original
weathering rates and processes. It is unlikely that rates for the various processes identified in this study will be the same, or will even differ proportionately, for different environments. For example, an intriguing question is why the silica coatings accreted faster on flows from Mauna Ulu than from Mauna Loa. Curtiss et al. [1985], noting a similar disparity for flows from the Ka`u desert and from Mauna Kea, attributed rapid accretion in the Ka`u desert to the higher eolian dust flux there. Perhaps the Mauna Ulu flows had an enhanced source of silica from fine windblown tephra. It may also be that other processes operate in other volcanic regions. Nevertheless the relative dating of basalt flows in a range of arid and semiarid environments is an intriguing prospect. We find it interesting that young basalt, desert varnish, silica rinds, and iron oxides are all spectrally distinct in the thermal IR. Thus it is theoretically possible to identify different styles of weathering by remote sensing. It may also be possible to map the extent of development of desert varnish using TIMS. This is a task that is difficult to accomplish with conventional aerial photographs because the varnish and basalt are both dark.

In this article we have focused upon thermal IR images. Obviously, the more conventional and readily available visible/near-IR (VNIR) images from sensor systems such as the Landsat MSS and TM [Short, 1982] also contain information on weathered basalts. We expect these data to complement TIMS images. For instance, VNIR data are more sensitive to iron oxides than TIMS data (because the strong Fe-O charge transfer affects ultraviolet and blue wavelengths) but less sensitive to the presence of silica and glass (because the reststrahlen bands are found in the thermal IR wavelengths). The full story will be revealed only by studying both types of data together, an important consideration in planning the next generation of spaceborne sensors.

**SUMMARY AND CONCLUSIONS**

Sparsely vegetated aa and pahoehoe flows weathering under semiarid conditions on Hawaii are progressively altered in ways that may be monitored remotely, using multispectral thermal IR images such as acquired by NASA's Thermal Infrared Multispectral Scanner (TIMS). Important influences on the thermal spectra appear to be cavity radiation, physical and chemical degradation of glassy crusts, accretion of silica-rich coats, replacement of basalt by iron oxides, and vegetation. At least for the north slope of Mauna Loa, these effects occur in characteristic sequences and at different rates, so that false-color pictures show distinctively colored flows at different stages of their development. The observed color changes may be analyzed quantitatively: plotting emittance data as a function of age on (for instance) “chromaticity” diagrams reveals distinctive trajectories.

It is premature to claim that these trajectories will apply to all semiarid and arid regions of the world, but the possibility exists that similar ones will be found. These could prove useful in reconnaissance geologic mapping in volcanic fields. After local age calibration, it may prove possible to estimate age of flows remotely.

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Plate I [Kahle et al.]. TIMS image of part of the north flank of Mauna Loa. Age and vegetation cover information are given in Figure 3.
Plate 2 (Kahle et al.). TIMS image of part of Mauna Ulu flows on the Holol Pali, Kilauea.
Plate 3 [Kahle et al.]. Ternary diagrams showing "chromatic" differences in TIMS channels 1, 3, and 5 for Mauna Loa lava flows of different ages; $b$, $g$, and $r$ are radiances in TIMS channels 1, 3, and 5, respectively. Contours depict the probability of encountering each color in Plate 1. The contour intervals are uniform but arbitrary; the maximum probability occurs within the smallest closed contour, near the $g$-$r$ line. Data points are means for 20-100 picture elements for each sample location of Figure 3. Arrows enclosing the data points show trends in display color with increasing flow age; these trajectories through the chromaticity plane reveal systematic changes in the exposed surfaces of the lavas. Background colors relate in a general way to colors in Plate 1. However, lightness differences are not represented: (a) aa; (b) pahoehoe.