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The causes of age dependent changes in the spectral response of lavas, Craters of the Moon, Idaho, U.S.A.

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Abstract. The Craters of the Moon basaltic lavas erupted between about 15 000 and 2000 years ago in short periods occurring about every 2000 years. On LANDSAT MSS imagery the appearance of pahoehoe flows with 'Blue Dragon' crusts, which has previously been used as an aid to mapping and correlation across the lava field, changes systematically with age. The overall brightness and the slope of the reflectance curve between band 4 and band 7 both increase with age. *In situ* measurements of the bidirectional reflectance factor (BRF) of natural rock surfaces in the area shows that this ageing of the remotely sensed spectral response is a combination of (1) a change in the spectral response of the rock surface due to weathering, (2) growth of lichen and moss over the rock surface, both factors causing little further change after about 8000 years, and (3) settling of windblown sand and establishment of vascular plants (grasses and shrubs), which continues with age. The relative importance of the last factor is not directly assessable from ground based radiometer measurements; however both weathering and lichen produce similar, complementary changes in BRF which can account for much of the spectral evolution seen on MSS images.

1. Introduction

The Craters of the Moon (COM) lava flows cover about 1650 km² and comprise about 30 km³ of lava, forming the largest dominantly Holocene basaltic field in the conterminous United States (figure 1). Radiocarbon and palaeomagnetic data have shown at least eight eruptive episodes between about 15 000 and about 2000 radiocarbon years ago (Lefebvre and Abrams 1976, Kuntz *et al.* 1980, 1982). More than 40 flows have erupted from vents along a 45 km length of the Great Rift and associated lava tube systems.

The higher silica lavas in the COM field formed rubbly block and aa flows whereas, except on steep slopes, the more common ferro-basalts produced pahoehoe (ropey lava) flows with a glassy crust. This often has a striking blue colour giving rise to the now generally accepted term 'Blue Dragon' crust (Russell 1902, Stearns 1924). Faye and Miller (1973) proposed that this colour is due to blue light being reflected from clusters of microscopic magnetite crystals dispersed within the glass, because of relative absorption in the 500-700 nm region caused by Fe^{2+} - Fe^{3+} and Fe^{2+} - Ti^{4+} charge transfer processes. Where present, these 'Dragon' crusts are best developed on



Figure 1. LANDSAT MSS band 5 image covering the Craters of the Moon lava field (27 August 1972). This image is about 60 km across and has been contrast stretched to enhance grey tone differences within the COM field at the expense of detail in the surrounding terrain. The darkest patches are aa flows of various ages. Pahoehoe flows become paler with age.

surfaces which are locally smooth on the millimetre scale. Surfaces which are rougher, owing to original texture or weathering effects, are redder, presumably owing to the brown colour of the glass in transmitted light (caused by Fe^{3+} to O^{2-} charge transfer and Fe^{2+} and Fe^{3+} electron transition short wavelength absorption). Some surfaces are spalled, having lost centimetre thick chunks of surface, which reveals a red-brown interior.

The climate is semi-arid with an annual rainfall which decreases from 45 cm in the north to 25 cm in the south. The surrounding Snake River Plain (SRP) lavas are largely grown over by sagebrush and various grasses, but within the COM such cover is much less. The youngest (2000 years) pahoehoe flows are almost bare, but older pahoehoe flows support communities of vascular plants occupying up to about 30 per cent of the surface area, growing in patches of trapped windblown sediment. The aa flows have little cover, because any water or sediment that encounters the surface of these flows sifts or runs down into the innumerable cracks. Only a few trees, rooting deep within cracks, are able to colonise this terrain effectively.

In an early analysis of LANDSAT MSS imagery, before extensive dating was available, Lefebvre (1975) observed that all COM aa flows have low DN but that

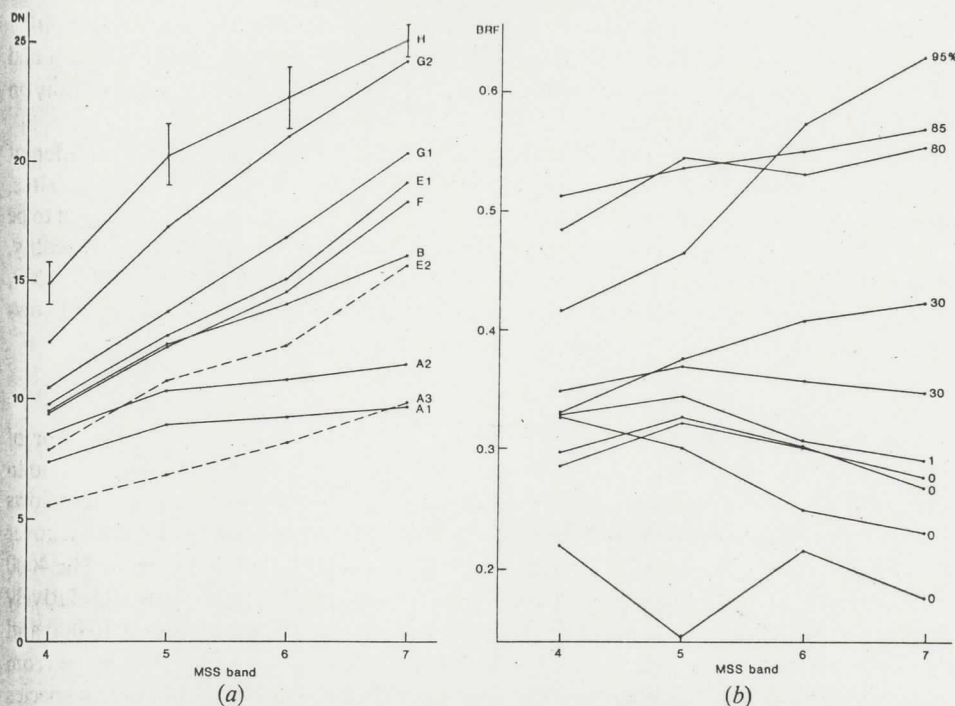


Figure 2. (a) Plot of DNs of various COM flows based on LANDSAT MSS data, showing means for whole flows excluding mixed pixels and anomalous facies. Flow ages are 2000 (A), 4000 (B), 8000 (E), 10 000 (F), 12 000 (G) and 15 000 (H) years. All are 'Blue Dragon' flows except for A3 and E2 which have a darker 'Green Dragon' crust. Standard deviation is shown for flow H, but is omitted elsewhere for clarity. Raw DN for band 7 has been doubled to put it on a 0–255 scale equivalent to the other bands, and an atmospheric path radiance correction of 15, 9 and 5 has been subtracted from the DN of bands 4, 5 and 6 respectively. (b) Bidirectional reflectance factor (BRF) for dominantly blue rock surfaces from a 2000 year old 'Blue Dragon' flow, showing the percentage cover by lichen and moss. The effect of increasing lichen on a young flow is similar to that of weathering on a lichen-free surface.

pahoehoe flows become brighter (increasing DN) with age. These trends are shown in figure 2(a). Contrast stretching and multispectral classification were used to delineate individual flows within the COM field and to determine its boundary over the paler SRP lavas, resulting in a marked improvement over the then available geologic maps. Lefebvre (1975) suggested that the observed changes in DN could be explained by the masking effects of weathering and cover by vegetation and sediment increasing with time, on original blue flow surfaces. The purpose of this study was to measure the spectral reflectance of surfaces at an outcrop scale in order to determine more closely the factors controlling their spectral ageing.

2. Rock surfaces and BRF determinations

A Milton Multiband Radiometer (Milton 1980) was used to determine the bidirectional reflectance factor (BRF) of natural surfaces *in situ* by dividing the metered radiance by that of a Kodak grey card. The sensor unit was equipped with filters emulating those of the LANDSAT MSS, enabling BRF to be determined in MSS bands 4–7. Radiance was integrated over a field-of-view of about 1 m in diameter. This

method of data collection made it inappropriate to meter in a representative way either aa flows, which consist of tilted blocks about a metre across, or sandy patches and communities of vascular plants; these surfaces become relatively homogeneous only on a scale of several tens of metres.

Field procedure was to visit several typical areas within pahoehoe flows of different age groups, and determine BRF on at least three sites at each locality, where possible. Time constraints precluded exhaustive random sampling, so the sites were chosen to be representative of the normal range of surface variation encountered at each locality. Well developed and accessible pahoehoe flows with ages of about 2000, 4000, 8000, 10 000 and 12 000 years were metered throughout the COM field. 15 000-year old flows were impractical to meter because of their degree of vegetation cover.

3. Results and discussion

As fieldwork progressed, it became evident that a hitherto unstressed factor of importance in controlling spectral response was the growth of saxicolous lichen, and to a lesser extent moss. Whereas a large majority of sites on 2000-year old pahoehoe flows have only 0 to 5 per cent lichen cover, older pahoehoe flows have up to 90 per cent cover mainly by crustose lichens with smaller amounts of foliose lichens and moss. The 4000 and 8000-year old pahoehoe flows have a cover of lichen (plus moss) spread relatively evenly across the range 5 per cent to about 90 per cent, while most sites on 10 000 and 12 000-year old pahoehoe flows have over 50 per cent cover. The lichens range from green and yellow through browns and pale grey in colour. An analysis of lichen species distribution related to lava flow age is underway and it appears that diversity increases with age.

Figure 2 (b) is a plot of BRFs metered on 2000-year old 'Blue Dragon' surfaces distinguished according to the percentage of lichen cover. There is some scatter due to general reflectivity differences between the rock surfaces, but clearly most of the spread within the data is related to the percentage of lichen cover. Lichen tends to cause an increase in BRF in all bands, in contrast with the more familiar effect of green leafy vegetation on reflectance whereby an increase in leaf area index causes a marked increase in band 7 reflectance but, even on dark substrates, a decrease in band 5 reflectance (Colwell 1974, Curran 1983). Lichen lacks the spongy mesophyll cell layers of leaves which are the cause of their high reflectance in the near-infrared (band 7). In this area, green colour within the lichen was usually confined to small patches a few centimetres across surrounded by much more prevalent pale grey and brown lichen so that red (band 5) absorption due to chlorophyll is subdued. The effect of lichen in increasing both band 5 and band 7 reflectance is simply explained as the result of superimposing a more reflective material (lichen) over a darker (lava). There is a tendency for the slope of the reflectance curve to increase with lichen cover, and the effect of adding lichen to a surface of uniform age is very similar to the general ageing effect seen on MSS data (figure 2 (a)). At sites where part of the rock surface is red the band 4/band 5 ratio is decreased but this does not correlate with any change in reflectance averaged over all four bands.

However, lichen is not the sole agent controlling the ageing of the spectral response of these lavas. An analysis of BRF data from lichen-free parts of 'Blue Dragon' surfaces shows that even on these, overall reflectance tends to increase and the band 6/band 7 ratio to decrease with age. This is probably due to chemical weathering of the actual rock surface.

Data for all sites are presented in figure 3 in the form of a 4/5 versus 6/7 band ratio

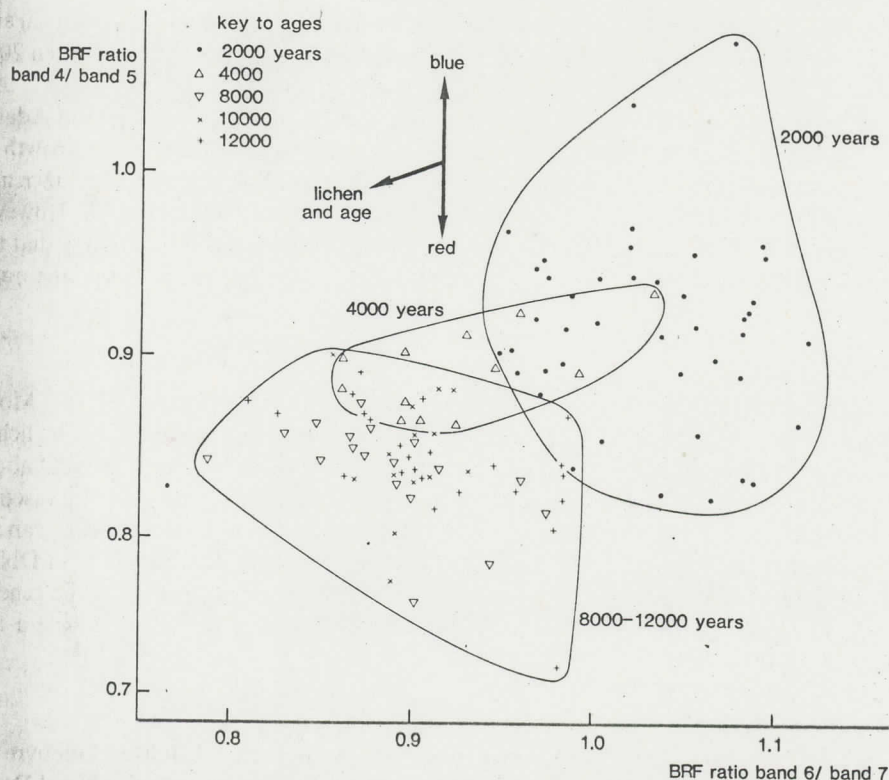


Figure 3. Bidirectional reflectance factor (BRF) ratios, band 4/band 5 plotted against band 6/band 7 for pahoehoe flows distinguished according to approximate age in years. Lichen-free sites fall towards the upper-right of the field occupied by lavas of each age group. Whereas the proportion of red-blue rock surface is responsible for most of the spread parallel to the band 4/band 5 axis, lichen cover and age both cause a decrease in band 6/band 7 and a slight decrease in band 4/band 5.

plot. The 2000-year old surfaces fall in the upper right, flows of 8000–12 000-year age plot together in the lower left and 4000-year flows tend to lie in between. The lichen-free sites occur towards the upper right of the field for each of these age groups, demonstrating an age related change in spectral response which is independent of lichen cover and accounts for the offsets between fields for each age group. Lichen cover and ageing of the rock surface are therefore complementary in shifting spectral response towards the lower left in this plot, but after about 8000 years there is little further change. Red-blue variation and lichen cover cause the data within each age group to spread parallel to the 4/5 axis.

The general form of the MSS DN curves in figure 2(a) can be attributed to a combination of lichen cover and weathering which alter the spectral response as the surface ages. However, BRF patterns tend to stabilize at about 8000 years, whereas DN continues to increase beyond this age indicating that cover by vascular plants and windblown sediment becomes the dominant process beyond this age.

4. Chemical weathering

Semi-quantitative X-ray fluorescence analyses to compare 'Blue Dragon' surfaces of COM lavas with freshly exposed (interior) surfaces of the same sample shows that

the natural weathered surfaces are enriched in S, Cl, Mn, Ti, Fe and Pb but that Cu and usually Zn, Sr and Rb are depleted. There are no significant differences between 2000 and 12 000-year old lavas. This uniformity of elemental abundance trends suggests that the changes may be due to an externally derived silica gel coating (Farr and Adams 1984) as described in the surrounding terrain by Adams *et al.* (1982). The growth of such a coating with age could explain the increase in both the general reflectance and MSS band 4 to band 7 slope observed on progressively older COM samples. However coatings can be identified only rarely on our COM samples and it is possible that the elemental changes may be related to devitrification and other processes as the outer glassy crust ages.

5. Summary and conclusions

Age related changes in the spectral response of bare Craters of the Moon pahoehoe lavas are due to weathering effects. Older flows have greater cover by lichen and moss which complements the spectral changes due to weathering. Beyond about 8000 years the greatest contribution to continued DN change is from cover by vascular plants and sediment. Within the Craters of the Moon field this process can be demonstrated to continue until about 15 000 years. Discernible differences in DN of pahoehoe flows in the surrounding Snake River Plain terrain suggests that the general age-dependent increase in reflectance continues, at a slower rate, for at least a few hundreds of thousands of years.

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