Proc. Lunar Sci. Conf. 8th (1977), p. 933–944.
Printed in the United States of America

Mare Crisium: Compositional inferences from low altitude X-ray fluorescence data

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Abstract—Analysis of Apollo 15 low altitude X-ray fluorescence data over Mare Crisium indicates that despite the relative homogeneity of Crisium mare material, small regions of dark mare material in the eastern part of the basin have a lower Al/Si intensity ratio than average Crisium mare. Dark mare material is characterized by irregular ridges, incomplete crater rims, and a rougher surface than higher albedo Crisium mare. The morphologic similarity to areas of probable pyroclastic origin in Mare Serenitatis, and variations in earth-based radar reflectivity support an origin by pyroclastic volcanism.

Using Apollo 17 bulk soil analyses, a factor for converting measured Al/Si intensity ratios to concentration ratios has been calculated for Apollo 15 X-ray data. Although the factor was derived from and can be applied to high altitude data, use of the conversion for low altitude data indicate that average Crisium mare aluminum concentration is higher than that of Apollo 17 basalts. The small dark mare units in eastern Crisium have aluminum concentrations up to 5% lower than average Crisium mare, and may be compositionally similar to Apollo 17 basaltic regolith.

INTRODUCTION

THE APOLLO 15 AND 16 X-RAY fluorescence (XRF) spectrometers have yielded data that are useful in interpreting the lunar surface chemistry of both large regions (Adler *et al.*, 1973; Podwysocki *et al.*, 1974) and small surface features (Andre *et al.*, 1975a; 1976). Because of the effects of smoothing, the X-ray data as portrayed in the Frontispiece of this volume do not allow recognition of small variations in the chemistry of surficial units. Consequently, correlations with small geologic units may best be done using 8 or 16 sec ratio data within the constraints imposed by statistical fluctuations (Andre *et al.*, 1975a,b).

The interpretation of Al/Si intensity ratios in terms of concentration ratios is dependent on extrapolating the limited number of Apollo and Luna groundtruth concentration ratios to areas larger than the landing sites. Therefore, this is highly dependent on the mixing of different chemical compositions within large areas of the regolith. Since regolith samples from the Apollo 17 site show a compositional variation from station to station, these data were used to derive an empirical relationship between Al/Si intensity and concentration which can be associated with broader areas viewed by the Apollo X-ray spectrometers.

Apollo 15 XRF data from low altitude orbits provide the improved spatial resolution necessary for recognition of relatively small lunar geologic units. The total resolution cell (area from which 100% of the signal is returned) of the low altitude orbits is 20 × 32 km for a nominal spacecraft altitude of 20 km, which is a factor of 16 smaller in area than the high altitude (110 km) X-ray data. Although the low altitude data are available from only four orbits of Apollo 15, the 8 sec intensity data used here have errors of about 0.08–0.1 in Al/Si intensity ratio (about 12%). The repeated orbital coverage of the same units (within 0.5° of latitude) increases the reliability of the data. In addition, the overall characteristics of the low altitude data (Fig. 1 in Maxwell *et al.*, 1977) agree with the high altitude data (Fig. 17-8 in Adler *et al.*, 1972) in that average Al/Si values for Mare Crisium are higher than those of central Mare Serenitatis.

Detailed procedures of XRF data reduction have been described elsewhere (Adler *et al.*, 1973; Trombka *et al.*, 1974). In summary, there are three detectors for the elements Al, Si, and Mg, which are sensitive to the fluorescent X-ray flux produced by solar radiation incident on the top few microns of the lunar surface. The measured radiation is therefore dependent on both the angle between the sun and detectors (phase angle), the intensity of solar radiation and the spectral distribution at any given time. For these reasons, use of the ratios Al/Si and Mg/Si have been favored in order to remove effects of sun-angle variation. Use of ratio data also minimizes systematic error due to matrix effects and particle size. However, even using ratios, effects of intensity variation still remain in both orbit-to-orbit and mission-to-mission values which are largely due to the change in the solar spectral distribution (Bielefeld, 1977). The groundtruth normalization factor used for the Apollo 15 low altitude data was generated from Apollo 15 high altitude data.

The purpose of the present paper is to: (1) investigate the correlation of low altitude XRF data with small, dark mare patches in eastern Mare Crisium; (2) compare the overall character of Crisium mare material with other maria sampled by the Apollo 15 XRF spectrometer; and (3) present preliminary results of an empirical method for converting Al/Si measured intensity ratios to regolith concentration ratios.

GEOLOGIC SETTING

Light mare units

With the exception of a few small (generally less than 500 km^2) low albedo mare patches in eastern Crisium (Fig. 1) most of Crisium mare materials have been mapped as a relatively homogeneous unit of Imbrian-age basalt (Casella and Binder, 1972; Olson and Wilhelms, 1974; Wilhelms, 1973). Based on crater morphology (Offield and Pohn, 1970), the mare in Crisium is about the same age or slightly younger than that of southern Imbrium. Consequently, the mare may be of Imbrian age or slightly younger (Casella and Binder, 1972). Dating based on the morphology of superposed craters suggests a similar age to that of the central mare of Serenitatis, which approximates the Imbrian-Eratosthenian boundary (Maxwell and El-Baz, 1977). However, the multitude of rays as seen on high sun-angle photographs (Fig. 1) and recent crater counting results indicate an older central mare region in Crisium perhaps as old as that of

Fig. 1. Apollo 8 photograph 2491 showing albedo variations of mare within the Crisium Basin. (A) Extensive dark mare of northeastern Crisium. (B) Small, dark patches of mare sampled by Apollo 15 low altitude X-ray fluorescence.

Tranquillitatis (Boyce and Johnson, 1977). Age dating of the Lunar 24 samples will undoubtedly help resolve this problem.

Both polarized and depolarized 70 cm earth-based radar (Thompson, 1974) indicate that Crisium has a relatively homogeneous surface in terms of surface blockiness and dielectric constant. Mare material of Crisium is as low in radar reflectivity as northern Mare Tranquillitatis. It does not exhibit the variation in strength seen in central Mare Serenitatis or Oceanus Procellarum (also noted on spectral data; Johnson *et al.*, 1977). The dark mare areas of eastern and northeastern Crisium have a slightly higher reflection in both the polarized and depolarized modes. Since the Crisium mare is near the limb region, direct comparison with the central nearside maria is limited by the fact that the echo strength is dominated by a diffuse component (Thompson, 1974).

Because of the glancing incidence, the 3.8 cm polarized earth-based radar reflectance from Mare Crisium should be more of a measure of surface blockiness (at a scale of 1–50 cm) than of changes in chemistry and dielectric constant (Zisk *et al.*, 1974). These data show relatively low returned power surrounding the craters Picard and Pierce, and even lower values associated with dark mare material in the eastern part of the basin (Fig. 1).

Recent spectral measurements of the Crisium Basin have indicated the presence of a variety of mare basalt types that differ in TiO_2 content by only 1–5% (Pieters *et al.*, 1976). Based on these data, the crater Picard may have ejected high TiO_2 basalt. As shown in Fig. 2 of Pieters *et al.* (1976), the low albedo mare is represented by a somewhat high TiO_2 basalt, although the .40/.56 μm image suggests that the TiO_2 content is not as high as that ejected from Picard. Consequently, there are several possible inner mare units that may represent late-stage flooding by thin basalt units.

Within the band covered by the low altitude XRF data, however, there are no

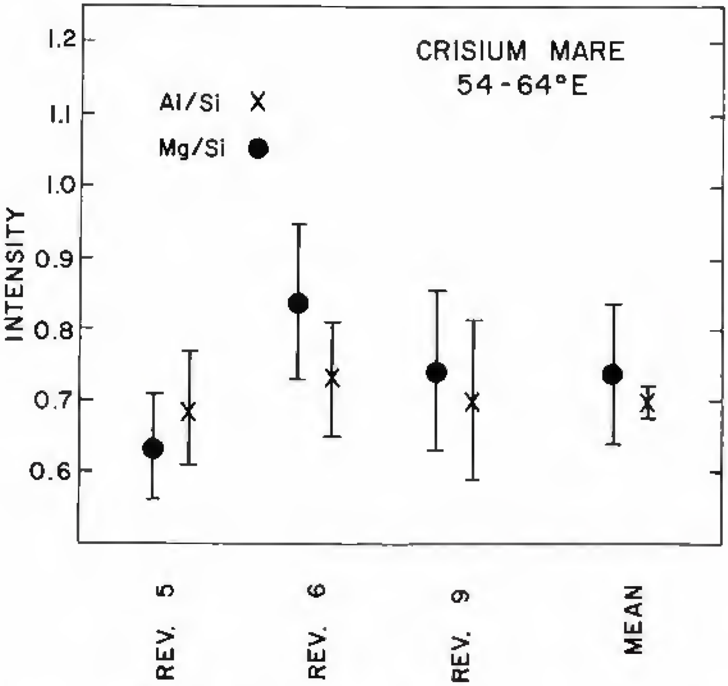

Fig. 2. Average Al/Si and Mg/Si intensity ratios from 16 sec data (and 1 σ error bars) for the central mare region of Mare Crisium. Average Al/Si values contain less scatter than Mg/Si, and suggest a relatively homogeneous mare unit. Orbital separation is about 10 km from rev. 5 to 6.

large-scale changes in Al/Si intensity ratios across Mare Crisium. Instead, the mare is relatively homogeneous with respect to Al/Si and Mg/Si ratios (Fig. 2).

Dark mare units

Small, dark mare patches in eastern Crisium are distinctive because of their low albedo and rough topography. They have been mapped as younger mare material on the basis of albedo (Casella and Binder, 1972), and may have been associated with the later stages of mare filling. Indistinct, gradational contacts of

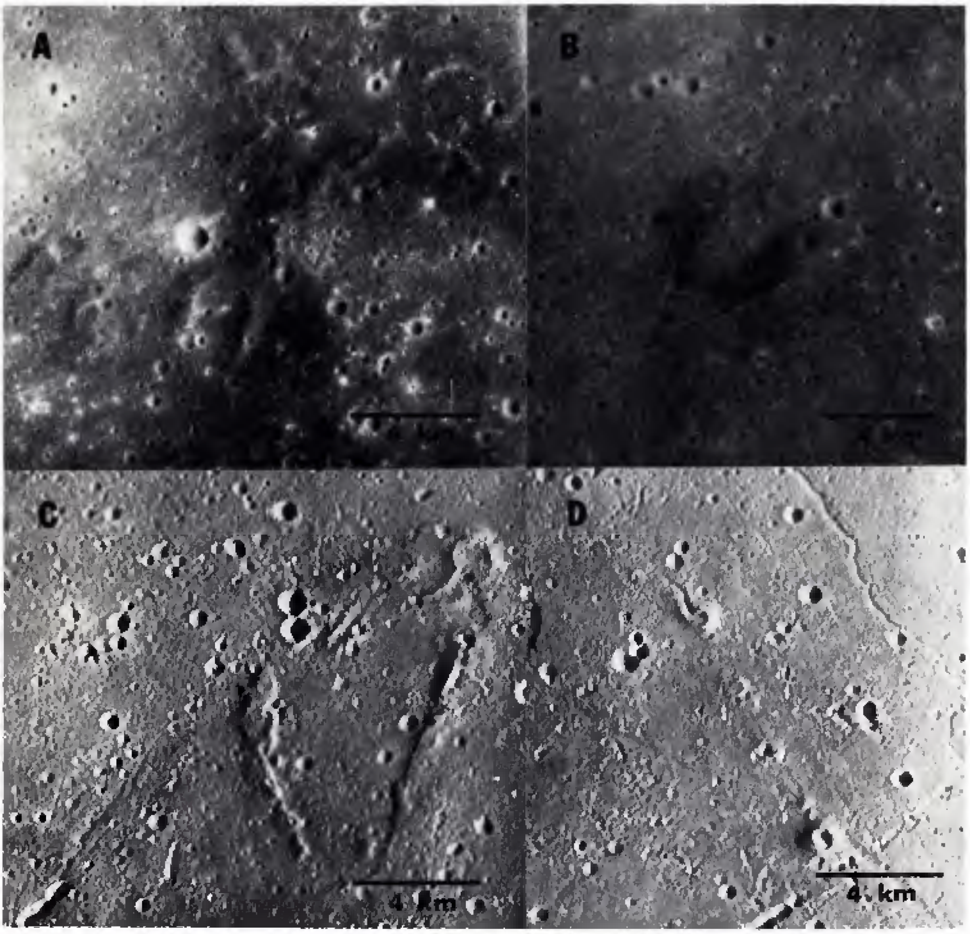

Fig. 3. (A) Dark mare material in eastern Crisium. Note irregular ridges and incomplete (partially flooded) craters (Apollo 17 pan Fr. 2226). (B) Dark dome in mare northwest of region shown in (A) (Apollo 17 pan Fr. 2232). (C) "Abetti", in southeastern Mare Serenitatis; note similarity of ridges with those in Crisium (Apollo 17 pan Fr. 2322). (D) Probable pyroclastic domes (Isis and Osiris) formed on southeastern part of dark annulus in Mare Serenitatis (Apollo 17 pan Fr. 2322).

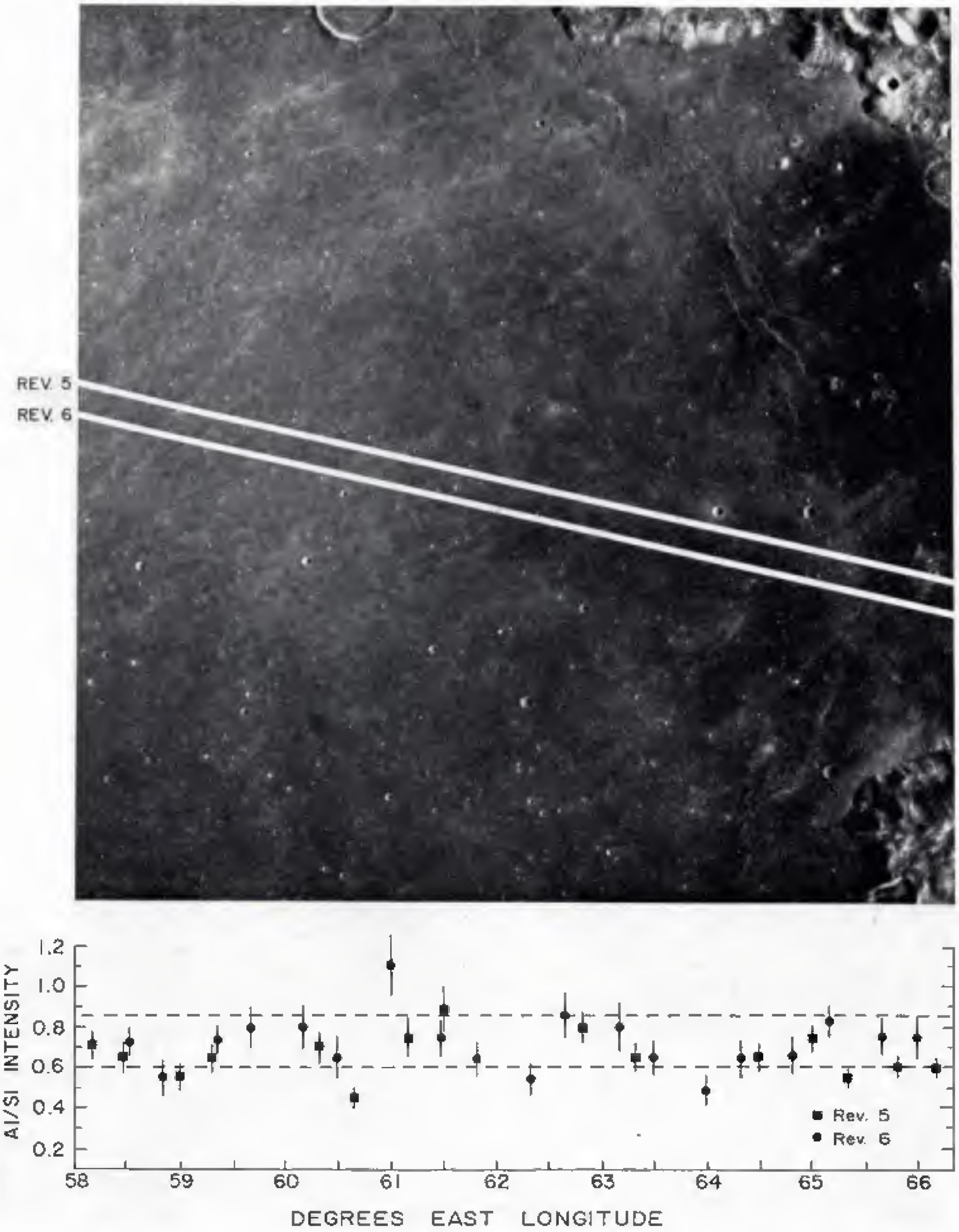

Fig. 4. Groundtracks of Apollo 15 revs. 5 and 6 low altitude 8 sec XRF data. Coverage of revs. 4 and 9, although more sporadic, indicates similar correlation of low Al/Si intensity with dark mare patches centered at 62.25° and 64°. (Low ratios at 59° are not matched by data from rev. 9.) One standard deviation errors are shown for individual data points. Dashed lines are upper- and lowermost bounds of 1 standard deviation from average Crisium mare on revs 5 and 6 (8 sec data).

the dark mare with the surrounding light mare (Fig. 3A), and lack of sufficient area for reliable crater-age statistics do not allow more specific dating. Morphologically, the dark mare is characterized by incomplete, irregular crater rims (1–2 km across) and scalloped, elongate ridges (about 500 m wide) that do not have the same trends as lineaments surrounding the Crisium Basin. Two similar irregular craters and domes to the northwest of this region are not surrounded by dark mare (Fig. 3B). If these structures are related to the areas associated with dark mare deposits, then they indicate that deposition of dark mare and probable volcanic constructs preceded the latest episode of mare flooding. Therefore, the dark mare may represent a shallow, buried layer in eastern Crisium.

The morphology of Abetti, an irregular *V*-shaped pair of ridges in southeastern Serenitatis (Fig. 3C), is strikingly similar to the ridges in eastern Crisium. Both may be protrusions of underlying material. Domes in dark mare material of southeastern Serenitatis (Fig. 3D) have been interpreted as sites of pyroclastic vents (Scott, 1973), and are located less than 100 km southwest of the Apollo 17 site. The morphologic similarity of domes and ridges in Crisium and Serenitatis, and the blanketing nature of the dark mare material of Crisium both suggest an origin by pyroclastic volcanism. In addition, earth-based radar data are consistent with such an origin. The higher reflectivity of the 70 cm data can be interpreted in terms of a higher radar reflection coefficient (possibly arising from an increase of Fe and Ti, thus raising the dielectric constant). The spectral data seen in Fig. 2 of Pieters *et al.* (1976) also suggest a slightly higher TiO_2 content.

Two orbits of Apollo 15 low altitude XRF data indicate a lower Al/Si intensity ratio over dark mare material than observed for average Crisium mare material (Fig. 4). High Al/Si values are associated with the numerous rays and secondary crater fields here and elsewhere in Crisium. Some of these rays and crater chains may have originated from the farside crater Giordano Bruno (Butler and Morrison, 1977). However, occurrence of the same Al/Si trends on neighboring orbits and the anomalously low values that fall below the standard deviation for average Crisium mare material all suggest that the chemical trends seen from orbit are a function of the lunar material rather than instrumental scatter.

X-RAY FLUORESCENCE DATA

Conversion of intensity to concentration

Conversion of measured X-ray intensity ratios to elemental concentration ratios has been done on a semi-theoretical, semi-empirical basis (Adler *et al.*, 1972). Calculations based on selected lunar samples have resulted in elemental concentrations that agree well with the elemental abundances of returned Luna and Apollo samples (Adler *et al.*, 1972). The present method for conversion is totally empirical and is dependent on the following assumptions:

(1) A constant solar radiation, although variations in solar X-ray distribution will increase scatter in the calculated conversion factor. Also, the effect of phase angle is assumed to be removed through the use of ratio data.

(2) Measured soil sample compositions from individual sampling sites are representative of entire geologic units.
(3) The different surface units have similar physical characteristics (e.g., amounts of glasses and agglutinates; grain-size) such that the measured intensity is solely a function of chemistry.

Given these assumptions, the conversion factor (K) can be calculated based on the relative amount of each geologic unit in the total area seen by the spectrometer, and a measured (from sample data) or assumed concentration ratio for that unit, such that:

$$A_iC_i + A_jC_j + \cdots A_kC_k = K_iI_i, \tag{1}$$

in which A_i and C_i are the percent area and concentration ratio respectively of the unit "i". Therefore, the method is highly dependent on whether the compositions of regolith samples distinguish among various geologic units.

Published bulk compositions of 70 soil samples from the Apollo 17 site were used to provide the groundtruth concentration ratios for the Apollo 15 XRF data. Although the XRF data of the Taurus-Littrow area were from high altitude, the correspondence of the low and high altitude data substantiates use of the derived conversion factor. Justification for assumption 2 is provided by the fact that bulk compositions distinguish the different units sampled on Apollo 17 (Fig. 5). Three different compositions can be recognized from the soil data, dark mantle, massif, and sculptured hills materials. The Al/Si concentration ratio

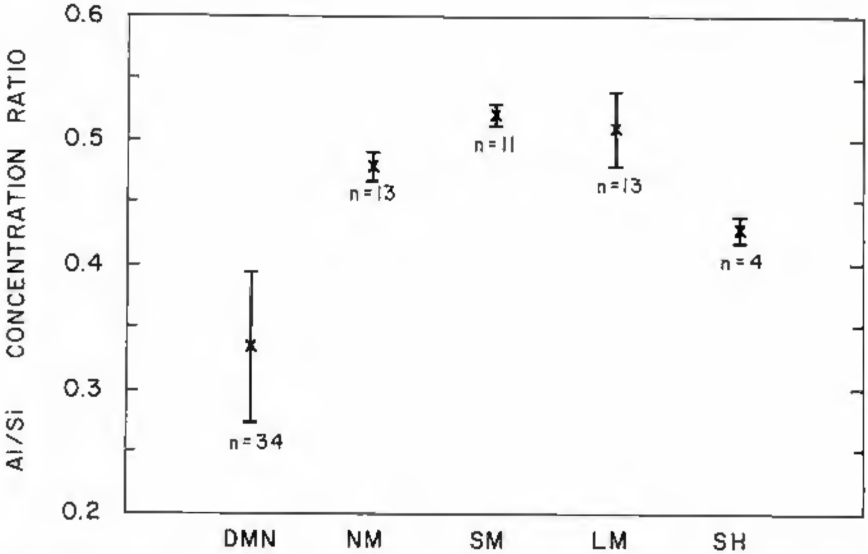

Fig. 5. Groundtruth Al/Si concentration ratios derived from 70 bulk soil analyses at the Apollo 17 site (DMN = dark mantle; NM = North Massif; SM = South Massif; LM = light mantle; SH = sculptured hills; "n" is number of samples).

from the light mantle exhibits the range in ratios found between the North and South Massifs.

The proportion of each geologic unit in each resolution element of the spectrometer (using 8 sec data) was measured and then weighted by the corresponding Apollo 17 groundtruth concentration ratio. For those units which were not sampled, compositions were assumed: dark mare was approximated by Apollo 11 soil; plains by Apollo 16 soil (although this value may be slightly high); and light mare by a value slightly higher than dark mare or dark mantle (Fig. 6). Results of these calculations were then used to calculate the conversion constant for Apollo 15 XRF data. Within an orbit, K varies by about ±20% of the intensity ratio value (Fig. 6).

Chemical inferences for Mare Crisium

Using the average constant derived for the Apollo 15 data (0.58; Fig. 6), the average Al/Si elemental concentration ratio from the low altitude data of Crisium mare is $0.41 \pm .02$. This is distinctly higher than Apollo 17 dark mantle samples (Al/Si conc. = 0.34), but not significantly different from the assumed concentration ratio for Serenitatis light mare (0.40). For a basalt of 40 wt.% SiO_2, this average Crisium mare value indicates about 14.5 wt.% Al_2O_3. However, Apollo 15 high altitude data indicate that Crisium mare material has higher aluminum than Serenitatis or Imbrium mare (Adler *et al.*, 1972). Average values from the high altitude data calculated (assuming 40 wt.% SiO_2) suggest that Crisium Al_2O_3 is about 4% higher than Serenitatis mare material.

The anomalously high aluminum values from the high altitude data (when compared with sampled basalts from other maria) may result from: the addition of a significant amount of highland material (rays) to the mare, or an actual composition of very high aluminum basalts. Although preliminary results of Luna 24 sample analysis indicate a high Al basalt similar to Luna 16 samples (Barsukov *et al.*, 1977), photogeologic evidence suggests that at least some of the Al/Si variation may be the result of rays of highland material.

The low altitude data over the dark mare material, normalized to a 40 wt.% SiO_2 basalt, yield values that are as much as 5 wt.% Al_2O_3 lower than average Crisium mare. The concentration ratio can also be predicted by reversing the method shown for converting measured intensity to concentration. By measuring the percentage of light and dark mare, the composition of which has been measured by the spectrometer, and assuming a light mare composition similar to that of Luna 16 (Barsukov *et al.*, 1977), the predicted concentration ratio for the dark mare material is 0.32. This is similar to the sampled concentration ratios of Apollo 17 dark mantle basalts.

Low albedo, domical structures in southeastern Mare Serenitatis, which have been attributed to pyroclastic activity (Scott, 1973) show a similar Al/Si relationship, although the data is from high altitude measurements. As shown by trend-surface analysis (Podwysocki *et al.*, 1974), and individual orbital data, the Al/Si intensity ratio is lower near the domes than in the mare to the east.

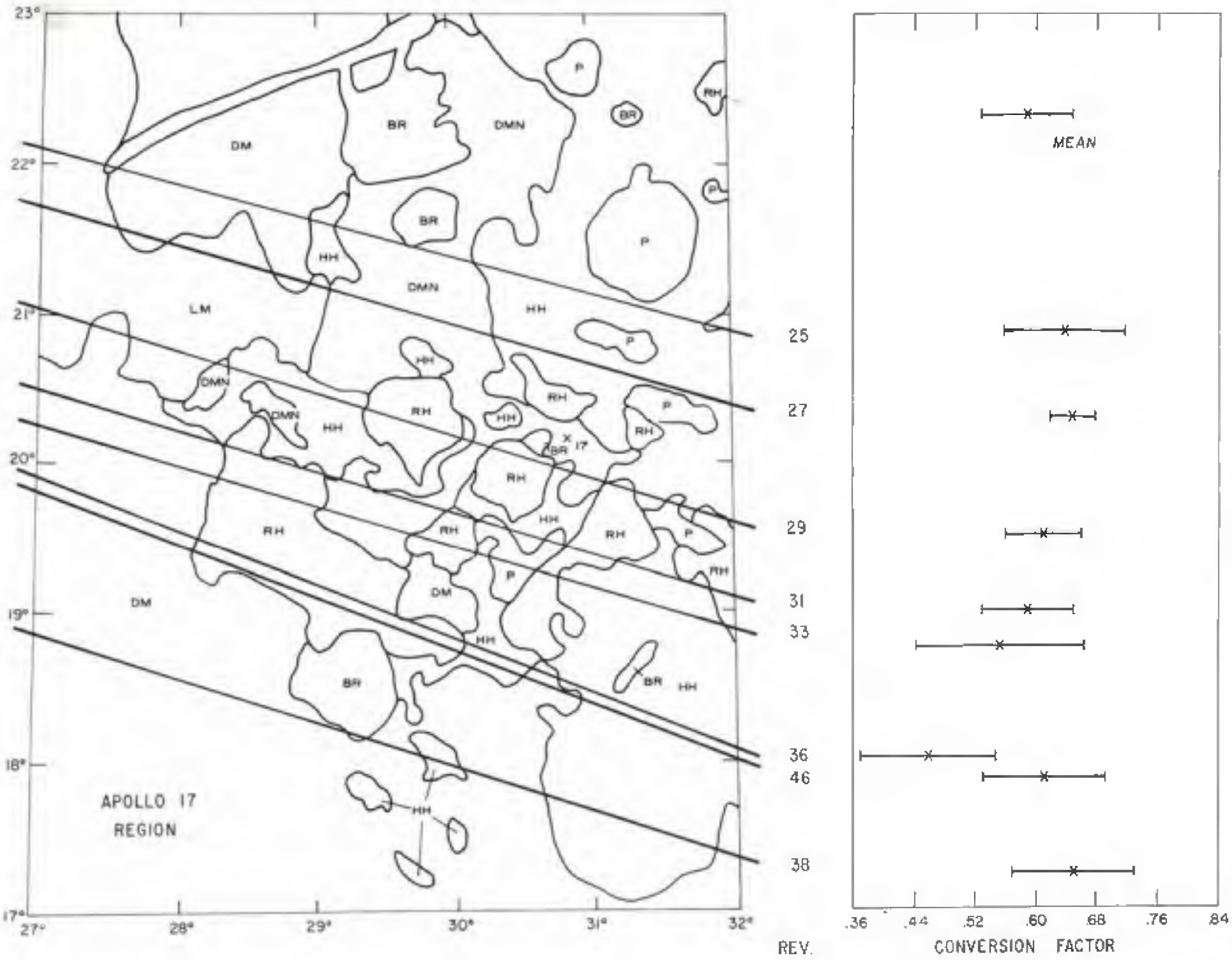

Fig. 6. "Surficial unit map" of the Apollo 17 region showing Apollo 15 orbits used to derive intensity-concentration conversion factor. Units on map are: LM, light mare; DM, dark mare; DMN, dark mantle; P, plains; HH, hummocky highlands (sculptured hills); RH, rough highlands (massifs); and BR, bright rays. Graph at right shows within-orbit and orbit-to-orbit variation of calculated conversion factor

CONCLUSIONS

The conversion of measured intensity to concentration has been determined by using bulk analyses of soils sampled at the Apollo 17 site. Despite the variance within the sampling sites, the Al/Si element concentration ratios of samples at the individual stations distinguish three of the six major geologic units. This method has produced conversion constants that are comparable to previous studies (Adler *et al.*, 1972), and results in concentration ratios that are within the total range of concentrations for returned lunar samples.

Based on analysis of low altitude XRF data, it is possible to estimate chemical characteristics for relatively small areas of the lunar surface. The low altitude data is especially suited to detailed correlation with surface features; however, only a limited amount of coverage is available. Results from our studies of Mare Crisium indicate that: (1) average low altitude Al/Si concentration ratios for Crisium mare material are similar to the high altitude data, and suggest higher concentration of Al_2O_3 in the central mare than in the darker eastern region (assuming constant SiO_2); and (2) morphologic, spectral and radar information are all compatible with a pyroclastic origin for dark mare and associated domes in eastern Mare Crisium. In this area, the low altitude XRF data indicate an Al/Si concentration ratio that is lower than that of average Crisium mare, and which may be the result of a high Ti mare basalt composition.

Acknowledgements—We thank C. Andre, R. Schmadebeck, and J. Trombka for providing the low altitude X-ray data and discussing many aspects of its interpretation. We are also indebted to I. Adler, A. Metzger, and R. Wolfe for their reviews of the manuscript. Enlargements of Apollo photographs were provided by NSSDC. This research was supported by NASA grant NSG-7188.

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