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THE APPLICATION OF TREND SURFACE ANALYSIS TO A PORTION OF THE APOLLO 15 X-RAY FLUORESCENCE DATA

M. H. Podwysocki, J. R. Weidner, C. G. Andre, A. L. Bickel, R. S. Lum
Department of Geology, University of Maryland
College Park, Maryland 20742

I. Adler
Department of Chemistry, University of Maryland
College Park, Maryland 20742

J. I. Trombka
Spectroscopy Branch (Code 682)
NASA - Goddard Space Flight Center
Greenbelt, Maryland 20771

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Greenbelt, Maryland

ABSTRACT

X-ray fluorescence data for 8 and 16 second time integrals gathered by Apollo 15 in circum-lunar orbit were analyzed to determine the capability for chemical mapping of relatively small lunar features in a portion of Tranquillitatis and Serenitatis basins. Spatial mapping using trend surface analysis demonstrated that a useable signal could be extracted from Al/Si intensity ratios calculated for 8 second time spans. Reliability of the Al/Si ratio was enhanced when 16 second data were compiled using a sliding average technique. Residual anomalies from the trend surface mapping were identified and correlated with relatively small lunar surface features.

Preliminary interpretations associated some Al/Si residual anomalies with changes in albedo of mare materials. Al/Si values significantly higher than the surrounding mare appear to be associated with several wrinkle ridge areas within Mare Serenitatis. Al/Si intensity ratios measured over several impact structures suggest sampling of several stratigraphic horizons within both the maria and highlands.

Without correction for changes in the shape of the solar spectrum, higher time integrations with a corresponding loss of special resolution will be required for trend surface analysis of Mg/Si intensity ratios. Corrections for changes in the solar spectrum, if possible, would allow use of shorter time span data.

THE APPLICATION OF TREND SURFACE ANALYSIS TO A PORTION OF THE APOLLO 15 X-RAY FLUORESCENCE DATA

INTRODUCTION

Chemical analyses using X-Ray fluorescence measurements from lunar orbit have been made for regional mapping of the lunar surface (Adler, et. al., 1972 a,b,). They reported that (1) from mare to highland and the Al/Si concentration ratio can increase by more than a factor of two (2) Al/Si and Mg/Si values vary inversely on a regional basis (3) an increase in Al/Si concentration ratio was detected from west to east on the lunar near side and (4) Al/Si and Mg/Si concentration ratios correlated closely with laboratory analyses for samples returned from the Descartes area. This report will discuss some useful techniques for the detailed chemical mapping of the lunar surface from the X-ray fluorescence data using Al/Si and Mg/Si intensity ratios and preliminary geologic interpretations of some relatively small lunar physiographic features. A detailed presentation of the statistical methods and data treatment used will be presented elsewhere (Podwysocki et. al., 1974).

A portion of the Serenitatis and Tranquillitatis basins (15-50° E, 0-25° N) and their adjacent highlands overflown by the Apollo 15 mission was chosen because (1) this area exhibits small features which might be detected against a relatively homogeneous mare background, (2) sufficient contrast would be available between the maria and the highlands to conclusively determine the statistical reliability of the intensity ratio data using short time integrals and (3) this portion of the moon was covered by relatively closely spaced orbits which would allow repetitive coverage of given areas to determine the precision of the calculated ratios.

DATA SELECTION

Both 8 and 16 second time integral data were compiled. The 8 second data represent the shortest interval available. In each instance the data were selectively culled to eliminate deficiencies due to low spacecraft altitude, incorrect attitude, high error factors associated with the calculated ratios, low levels of counting statistics and periods of high solar activity.

In the case of the 16 second data, a sliding average technique was used to compile the intensity ratios. Integral counts of two adjacent 8 second data points within an orbit were summed and their respective ratios calculated. The next data station consisted of the last of the two previous points and the next point along the flightpath. Several advantages were realized using this method: (1) Previous work by Adler et. al., (1972 a,b) summed data over a given time span of 24 or 64 seconds without considering the actual number of 8 second data points which fell within that period. Experience has shown that the error factors associated with time integrals decrease with the addition of each additional 8 seconds of data. Hence, integration of a different number of data points within a given time interval tended to introduce an additional source of variability in the data. By consistently integrating only two 8 second data points, this source of variation was eliminated. (2) The sliding average generated data points having a higher degree of precision than the original 8 second data points. (3) Given the 60 km instrument resolution limit, there is relatively little degradation of resolution since the centerpoint of the instrument field of view shifted only 12 km between data stations.

Spatial modeling using trend surface analysis (Krumbein and Graybill, 1965, Ch. 13; O'Leary et. al., 1966) was applied because simple contours of the data tend to parallel orbit paths. A trend surface is a least squares "best" fit of an "n" degree polynomial equation to data points in three dimensions where two dimensions represent the map coordinates of a sample location and the parameter under investigation is plotted in the third dimension. The method is useful where a high degree of variability is present in the data, allowing extraction of generalized regional models. Relatively small areas can be identified by deviations (residuals) from the model. The ratios were normalized where necessary using a $\log_2$ transformation so that additional parametric tests could be applied to the statistics generated by the trend surface analysis. Analysis of variance (Krumbein and Graybill, 1965, Ch. 13) was applied to these output statistics to determine the highest order surface which represented an acceptable level of improvement over its lower order neighbor based on the .001 level of rejection.

Eight second data were analyzed and some results based on the 2nd order solution were reported by Adler et. al. (1973). Information levels were generally low, with a low signal to noise ratio. Subsequent analyses of 16 second data indicated greater spatial structuring and very similar low order surfaces. The following will be a discussion of the more useful information contained in the 16 second data and a comparison with the 8 second data to show improvements in the levels of information.

The first point to be considered is whether or not systematic variations do in fact exist in the data. This was tested by comparing the trend surfaces of the original data to trend surfaces of totally randomized data. The elemental ratios were randomly reassigned to the lunar coordinates. This procedure removes all systematic variation from the data. Tables 1 and 2 indicate the percent variation explained for the 8 and 16 second Al/Si data for each order surface from 1 through 6. The percent variation explained by the randomized data is very small compared to the original data, indicating that the original data contains systematic variations.

A second point to be considered is the intra-orbit and inter-orbit variation. As mentioned earlier, simple contours of the Al/Si and Mg/Si intensity ratios tended to parallel orbit paths. Adler et. al. (1972a) indicated that the majority of the inter-orbit variation is due to the energy shifts in the solar spectrum. A measure of the inter-orbit variability is provided by trend surfaces generated from data randomized along orbits. Both the 8 and 16 second data indicate that about 5 to 20% of the variation explained is due to inter-orbit variation. Intra-orbit variability is indicated by the difference between the variation explained by trend surfaces of the original data and surfaces generated from orbitally randomized data. This difference is 7-9% for the 8 second data and 23-34% for the 16 second data.

The 16 second data is more structured as indicated by the nearly twofold increase in the percent variation explained by a given order surface when compared with its 8 second equivalent. In addition, the percent variation explained in the orbitally randomized 16 second data is a smaller proportion of the total variation explained by the original data. Another qualitative indicator of the greater stabilization of the 16 second data was the configuration of the individual trend surfaces. The contours of third and higher order surfaces for the 8 second data tended to parallel orbit paths. This tendency did not occur in the 16 second data until the sixth order surface was reached.

Application of the same techniques to the Mg/Si data, summarized in Tables 3 and 4, shows that the overwhelming part of the variation present is accounted for by inter-orbit variations. This does not however preclude the use of the Mg/Si intensity ratios to differentiate changes which might occur along an individual orbit or carefully selected pairs of orbits. This analysis strongly suggests that correction factors should be implemented to eliminate this variation from the data by studying the response of the system to changes in the solar spectrum. However, a differential does appear between the 8 and 16 second data which implies that some useful signal for spatial analysis may be extracted from the Mg/Si ratio data by simply using longer time integrals for the sliding average.

Table 1

Results of Trend Surface Analysis Using Al/Si Intensity Ratios
(8 Second Data - 691 Points)

Surface Order	Variation Explained (in %)		
	Original	Totally Randomized	Randomized Along Orbits
1	12.8	0.5	5.4
2	23.9	0.5	14.0
3	24.6	0.7	15.9
4	26.6	1.5	17.6
5	27.9	2.2	19.2
6	30.1	3.8	20.8

Table 2

Results of Trend Surface Analysis Using Al/Si Intensity Ratios
(16 Second Data - 1388 Points)

Surface Order	Variation Explained (in %)		
	Original	Totally Randomized	Randomized Along Orbits
1	31.6	0.1	8.5
2	44.5	0.2	11.6
3	46.4	0.8	12.9
4	49.2	1.0	14.9
5	50.4	1.4	16.4
6	52.3	1.6	17.8

Table 3

Results of Trend Surface Analysis Using Mg/Si Intensity Ratios
(8 Second Data - 691 Points)

Surface Order	Variation Explained (in %)		
	Original	Totally Randomized	Randomized Along Orbits
1	0.3	0.0	0.3
2	2.7	0.2	2.5
3	4.7	0.4	4.7
4	7.7	0.6	7.2
5	10.2	0.7	9.8
6	14.8	2.7	13.2

Table 4

Results of Trend Surface Analysis Using Mg/Si Intensity Ratios
(16 Second Data - 1388 Points)

Surface Order	Variation Explained (in %)		
	Original	Totally Randomized	Randomized Along Orbits
1	5.9	0.1	5.3
2	6.9	0.2	5.9
3	11.2	0.4	9.0
4	14.9	0.6	11.9
5	18.0	1.1	13.2
6	20.2	1.7	15.1

INTERPRETATION

The fourth order trend surface of 16 second Al/Si ratio data is shown in Figure 1. The fourth order surface was chosen for mapping purposes as the highest order surface in a series which continuously showed the accepted level of improvement. Ratios are highest in the highlands to the northeast and become progressively lower toward the mare. Low ratios are associated with the maria proper, with the lowest values occurring in Mare Serenitatis in the northwest portion of the mapped area. A relatively high Al/Si ratio is indicated by the Haemus Mountains in the western part of the map. The general model conforms well to previous generalized conclusions of Adler et. al. (1972a) who showed that highlands have higher Al/Si intensity ratios than maria. This model closely conforms to the second order trend surface using Al/Si data cited in Adler et. al. (1973) with the exception of high ratio values in the vicinity of the Haemus Mountains.

Figure 2 illustrates some selected chemical anomalies based on the residuals from the fourth order surface for the Al/Si ratio data. Mg/Si values were also calculated for these anomalies, however, the values are not associated with residuals based on the Mg/Si trend surface analysis and should be interpreted with caution because of the previously mentioned limitations. Only areas which showed residuals (i.e. either all positive or all negative) across several orbits were outlined. In two cases the data culling criterion based on levels of solar activity was compromised to fill in relatively large unmapped areas. In both these cases, nearly the whole orbit exhibited residuals which were either all positive or negative. These orbits were ignored when outlining the residuals.

Areas 10 and 11 and area 3, representing Taurus-Littrow and Haemus highlands respectively, show quite similar Al/Si ratios. Morris and Wilhelms (1967) and Carr (1966) map the Haemus highlands as Imbrian age Frau Mauro Formation, whereas the Taurus-Littrow highlands have been mapped as pre-Imbrian in age. Adler et. al. (1974) have shown that soft X-rays measured during the mission have a maximum penetration depth of about 10 microns, thus only surface materials are mapped. Hence, it is possible that Imbrian ejecta is being mapped in the Taurus-Littrow highlands even though it may form only a thin blanket. The crater Proclus covered in area 21 has considerably different Al/Si and Mg/Si ratios as compared to area 20, ejecta material derived from Proclus (Scott and Pohn, 1972; Wilhelms, 1972). These disparate results for materials of the same provenance suggest stratigraphic variations within Proclus and the highlands.

The crater Plinius, area 5, is a distinct positive anomaly in contrast to the adjacent maria materials, areas 4 and 6. The crater occupies an area of

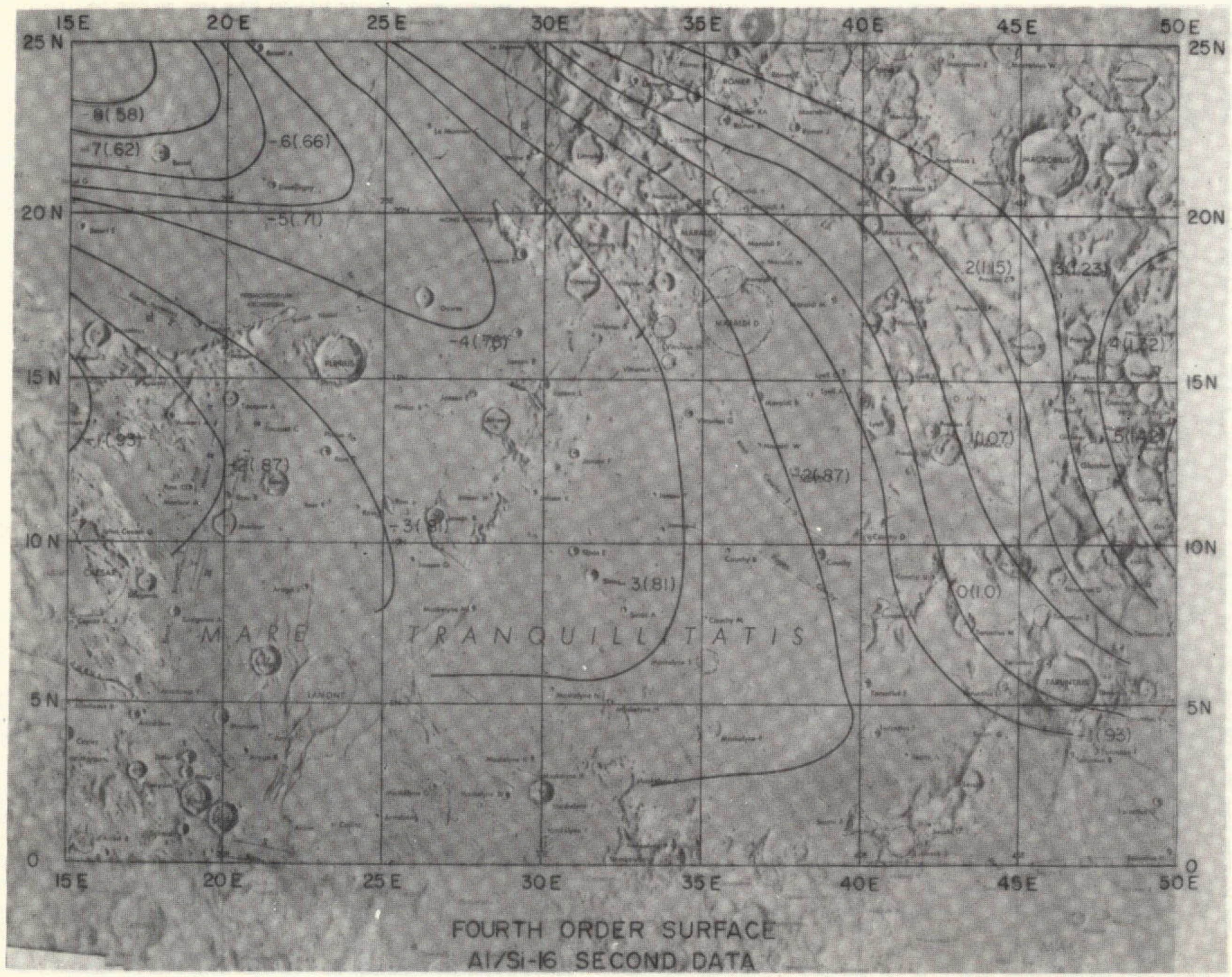

Figure 1. Fourth Order Trend Surface Map for Al/Si Intensity Ratios Using 16 Second Data. Contour Values Enclosed in Parentheses are Original Intensity Ratio Values, While the Others Represent Their Normalized Log_2 Equivalents.

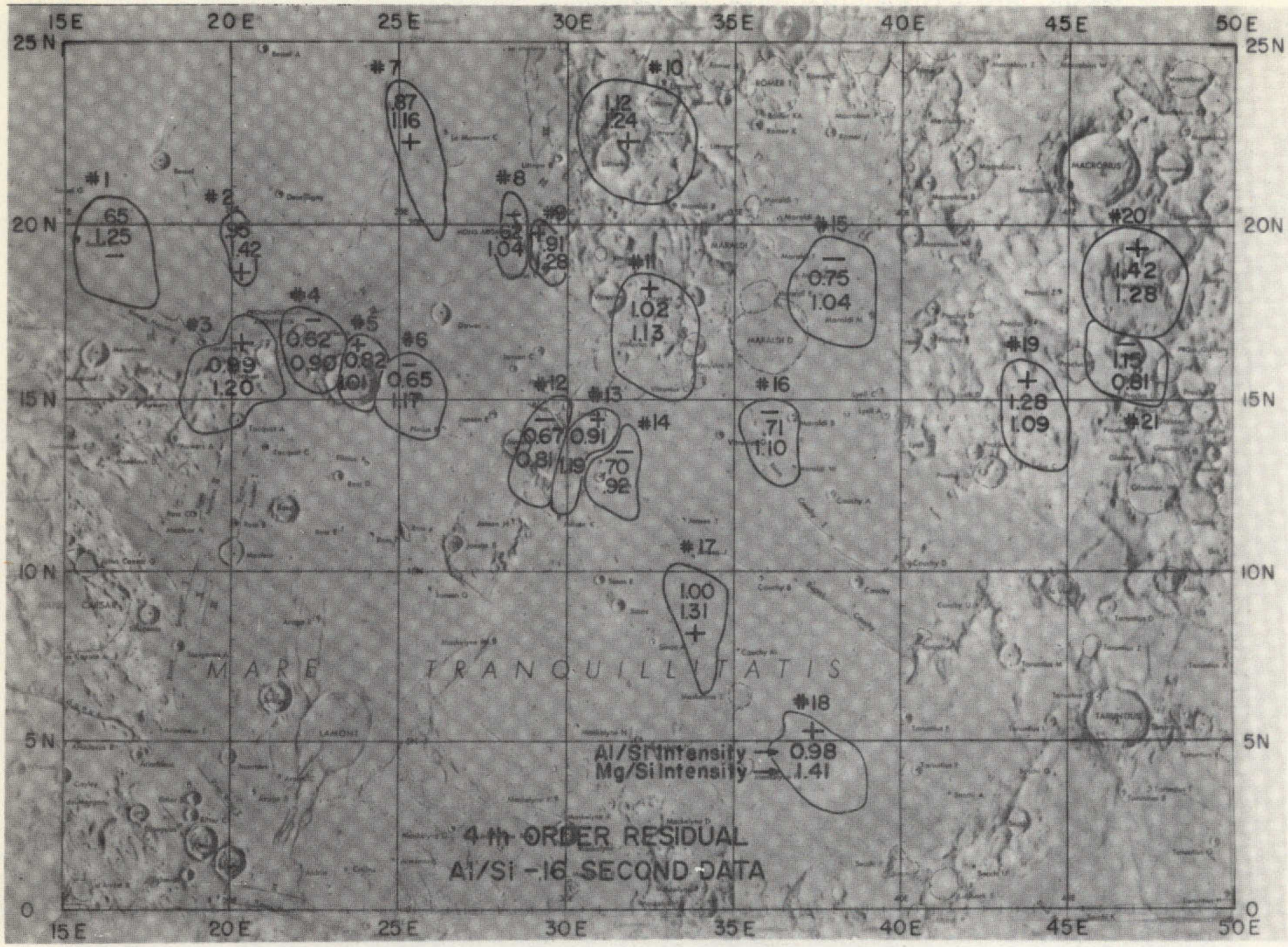

Figure 2. Residuals from the Fourth Order Trend Surface for Al/Si Intensity Ratios. Departures or Deviations are Based on Normalized Data. A "+" Denotes a Positive Residual; a "-" Indicates a Negative Residual. Calculated Intensity Ratios are given in Original Units for ease of interpretation.

relatively thin mare materials at the transition between Maria Tranquillitatis and Serenitatis. Crater excavation due to impact has most likely excavated and exposed highland material from the subsurface. Topographic data indicate that the crater has excavated approximately 1200 meters below the mare floor. This sets a maximum limit for the mare thickness, which De Hon (1974) estimates as 500-600 meters in this area.

Two additional positive mare anomalies are areas 7 and 2. Area 7 corresponds to a wrinkle ridge and high albedo mare material as mapped by Carr (1966). Examination of Apollo 15 metric photography indicates some features which could be interpreted as volcanic terrain or extrusive igneous features. Both Young et. al. (1973) and Hodges (1973) report possible extrusive igneous features in the same general vicinity. Mare Serenitatis materials of low albedo are typified by ratios such as those in the negative residual of area 1. This suggests that at least two types of substantially different mare basalts are present within Mare Serenitatis. Lowman (1972) suggests that wrinkle ridge areas may contain the final differentiation products of a large basaltic body and should contain higher alumina concentrations. Area 2, associated with a rectilinear junction of four mare ridges forming a parallelogram, also displays a similar positive anomaly.

Positive residuals in areas 17 and 18 appear to be associated with zones of the highest albedo mare materials within Mare Tranquillitatis as mapped by Wilhelms (1972). The positive residual in area 13 is interesting, for it is not associated with the Jansen craters as might be expected, but is located to their east. Perhaps this anomaly is due to the concentration of ray materials as mapped by Morris and Wilhelms (1967).

CONCLUSIONS

Although still in its preliminary stage, it has been shown that relatively small lunar features can be distinguished as anomalies by using trend surface analysis on data generated by the X-ray fluorescence experiment flown on the Apollo missions. Some correlations between albedo differences and elemental ratios can be found within mare areas. A lower useful limit of 16 seconds has been established for time integrals of Al/Si intensity ratios. It is not yet possible to determine the minimum time integration necessary for the best spatial mapping of the Mg/Si data. Removal of inter-orbit variations of the ratio data caused by changes in the solar spectrum will greatly enhance the precision and the interpretive capability of the data.

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