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Are early magnesium-rich basalts widespread on the moon?

Constance G. Andre*, Robert W. Wolfe**, and Isidore Adler*

*University of Maryland, College Park, Maryland 20742
**Smithsonian Institution, Washington, D. C. 20560

Abstract—Orbital X-ray data indicates that high-magnesium material systematically occurs along mare/terra boundaries in all the lunar nearside basins for which there is orbital X-ray coverage. These peripheral units appear to represent the earliest stages of volcanism within each of the basins, although they were not necessarily emplaced at the same time in lunar history. High-magnesium subsurface layers excavated by post-mare impact craters in central Mare Crisium and Mare Fecunditatis suggest that the peripheral units are the only visible edges of a basin-wide basalt layer, largely buried by younger less-magnesian flows. This evidence suggests that early magnesium-rich mare basalts are widespread on the moon and that their volumes may be greatly underestimated. Abundant early mare deposits of this type would place severe constraints on models of mare basalt petrogenesis.

Apollo and Luna mare landing sites within the Apollo 15 and 16 X-ray coverage are all located in or very near these magnesium-rich mare borders. Therefore, soil samples from these sites fail to represent the predominance of less-magnesian basalts elsewhere in these maria. Thus, returned *surface* soils may typify early basalts that are most abundant in *subsurface* layers—an interesting paradox.

INTRODUCTION

This paper focuses on the application of orbital X-ray fluorescence data from the Apollo 15 and 16 lunar missions as a means of tracing the distribution of magnesium-rich mare basalts on the lunar surface.

Although mare basalts cover less than 20% of the lunar surface, knowledge of the variety and relative abundance of basalt types comprising flow layers in the basins is needed to place constraints on petrogenetic models of lunar evolution. Surface units that represent the final stages of mare volcanism are not necessarily typical of the composition of previous underlying flows. Therefore, it is important to discover the subsurface distribution of different basalt types.

It is generally assumed that chemical information from sample and orbital data is limited exclusively to the surface veneer. This is not strictly true; in fact, there is reason to believe that a third stratigraphic dimension can be inferred from both sample and remote sensing data. For instance, orbital X-ray data indicate that impact craters have excavated buried layers of magnesium-rich basalts from beneath less-magnesian surface layers in Mare Crisium (Andre *et al.*, 1978). Remnants of early subsurface mare basalt layers may also be visible near basin borders. Subsidence of the central part of a basin (due to the initial mare basalt load) would leave these borders at higher elevations, protected from inundation by later flows (Head, 1976). Therefore, orbital X-ray data, limited to surface measurements may be used to characterize the composition of subsurface units if they have been uncovered by large meteorite impacts or if the fringes of these layers have been preserved as surface units along mare benches.

We have chosen to use the Mg/Si ratio rather than the Mg/Al ratio because silicon remains fairly constant for lunar soils, whereas the Mg/Al ratio is subject to sharp increases in aluminum in terra soils surrounding the maria. This effect on the ratio can obscure the increases in the X-ray signal due to magnesium content in peripheral areas of the maria. Al/Si ratios from these border units are equally difficult to interpret.

Another question that may be answered using orbital X-ray data is whether soil samples from Apollo and Luna landing sites are representative of surface soils in the maria from which they were collected. A direct comparison of the range, frequency distribution and areal distribution of orbital Mg/Si values to those of soils from the Apollo and Luna landing sites will show the returned samples in a broader chemical context.

Data reduction procedures applied to the orbital X-ray fluorescence experiment and corrections for interorbit solar effects are described briefly in Andre *et al.* (1977) and Bielefeld *et al.* (1977).

APOLLO AND LUNA SOIL SAMPLES IN PERSPECTIVE

A comparison of orbital magnesium values to those for Apollo and Luna soil samples is shown in Fig. 1. The upper half of the figure includes the range and relative frequency of orbital Mg/Si data and the lower half, the magnesium ranges for soils from the various landing sites. The soil sample ranges extend both above and below the magnesium limits measured from orbit. This result is expected because the extreme magnesium values found by analyzing returned soil samples are averaged over the tens of kilometers encompassed by the field of view of the orbiting X-ray spectrometer. A breakdown of the total distribution into separate histograms for mare and non-mare areas (Bielefeld, 1979) reveals two modes. In this paper, we are specifically interested in the mare basalt curve (dots), but it is interesting to note that the range of Mg/Si values for mare and non-mare regions is comparable. One possible explanation for this will become apparent as we investigate some interesting discrepancies between "ground truth" at specific sites and the broader picture provided by the orbital X-ray data.

The orbital X-ray data indicate a scarcity of mare basalts on the lunar surface with MgO values greater than 10 weight percent. The mare soil sample ranges, on the other hand, are skewed toward much higher magnesium values, especially Apollo 12, 15, and 17 samples which extend well beyond 10 percent. The geographic distribution of this more magnesian material, where orbital X-ray data is available, will be shown in Figs. 2–6.

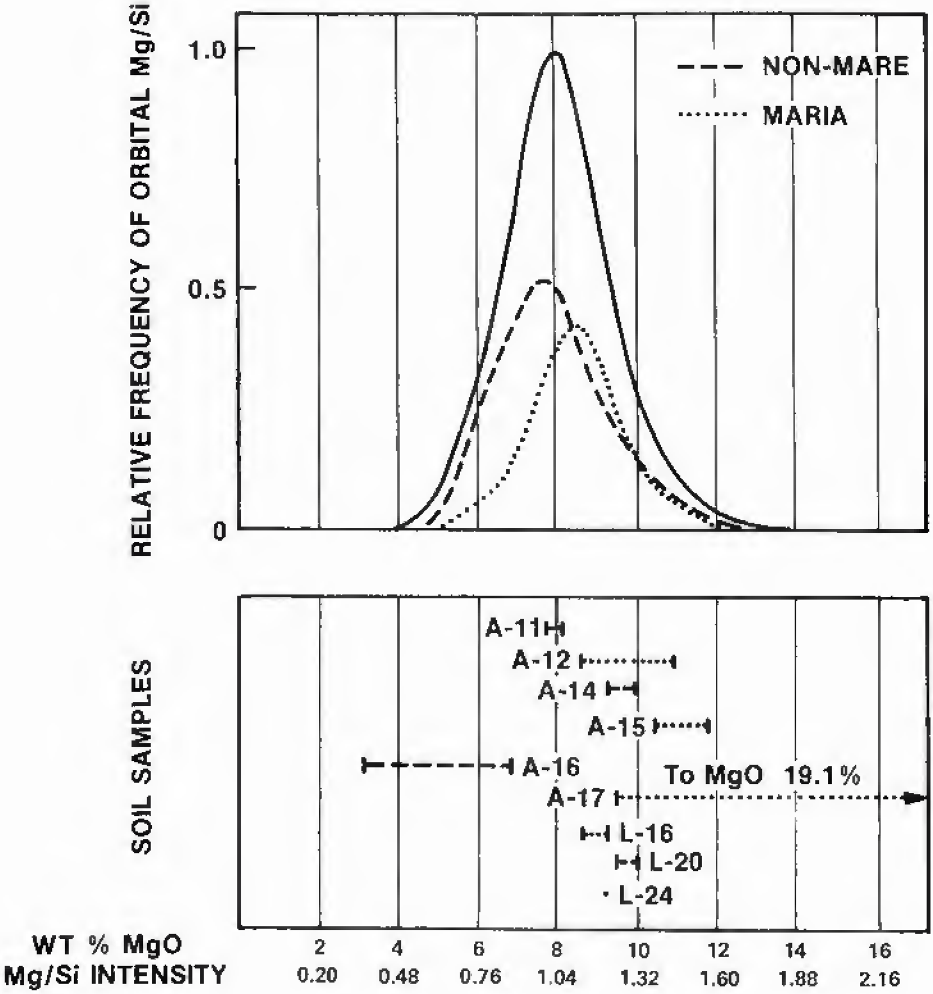

Fig. 1. The frequency distribution of Mg/Si intensity (and corresponding MgO) values from Apollo 15 and 16 orbital X-ray data as well as the histograms of its mare and non-mare components (top) are compared to the ranges of MgO values for returned samples from the Apollo and Luna missions (bottom).

GEOGRAPHIC DISTRIBUTION OF MAGNESIUM-RICH BASALTS IN MARE CRISIUM

The Mg/Si ratios from three Apollo 15 low altitude orbits provide new information on magnesium concentrations within several maria. These early elliptical orbits approached the lunar nearside much closer than the later circular orbits. The spatial resolution for acceptable data during the closest approach (15 km) is improved by a factor of 7 over data from orbits that maintained an average altitude of 100 km above the moon. Figures 2 and 3 show the continuous paths of the

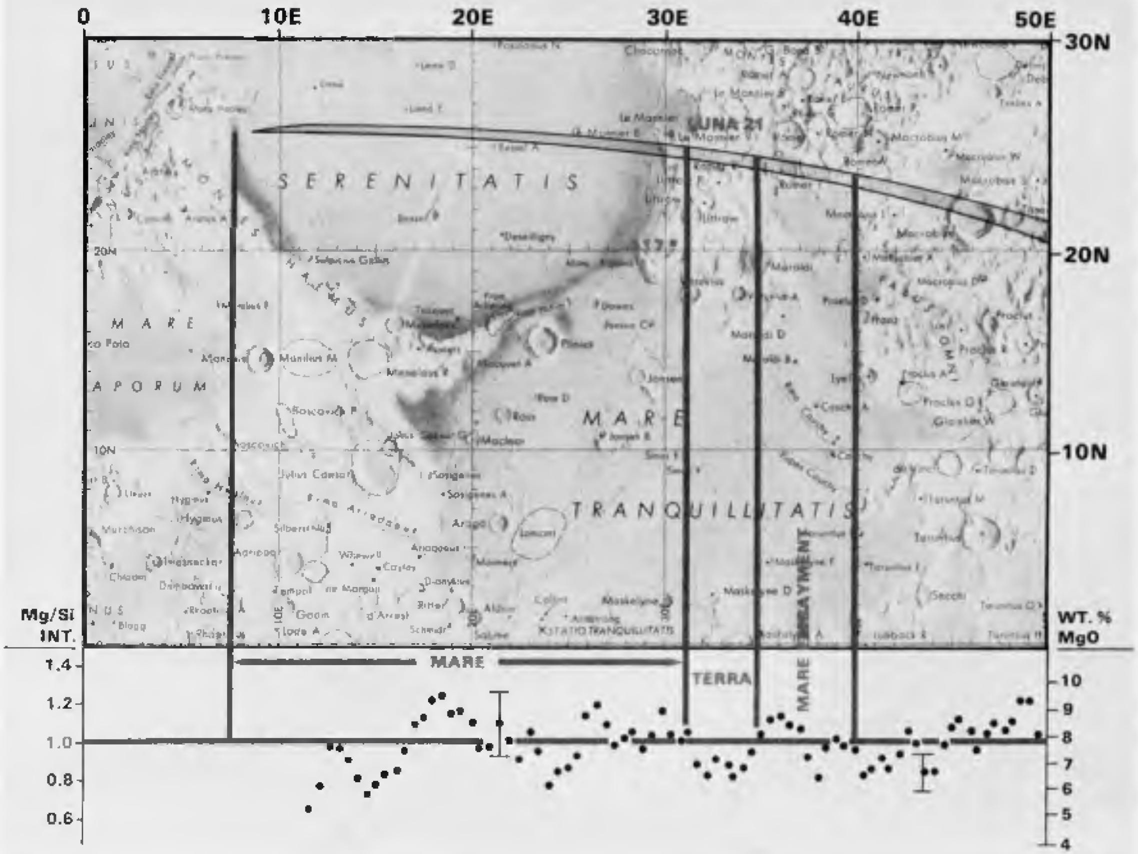

Fig. 2. The combined areal coverage of three Apollo 15 low-altitude orbits is outlined on the map. The Mg/Si ratios and corresponding MgO values calculated by Adler *et al.* (1972) are shown below (See text.).

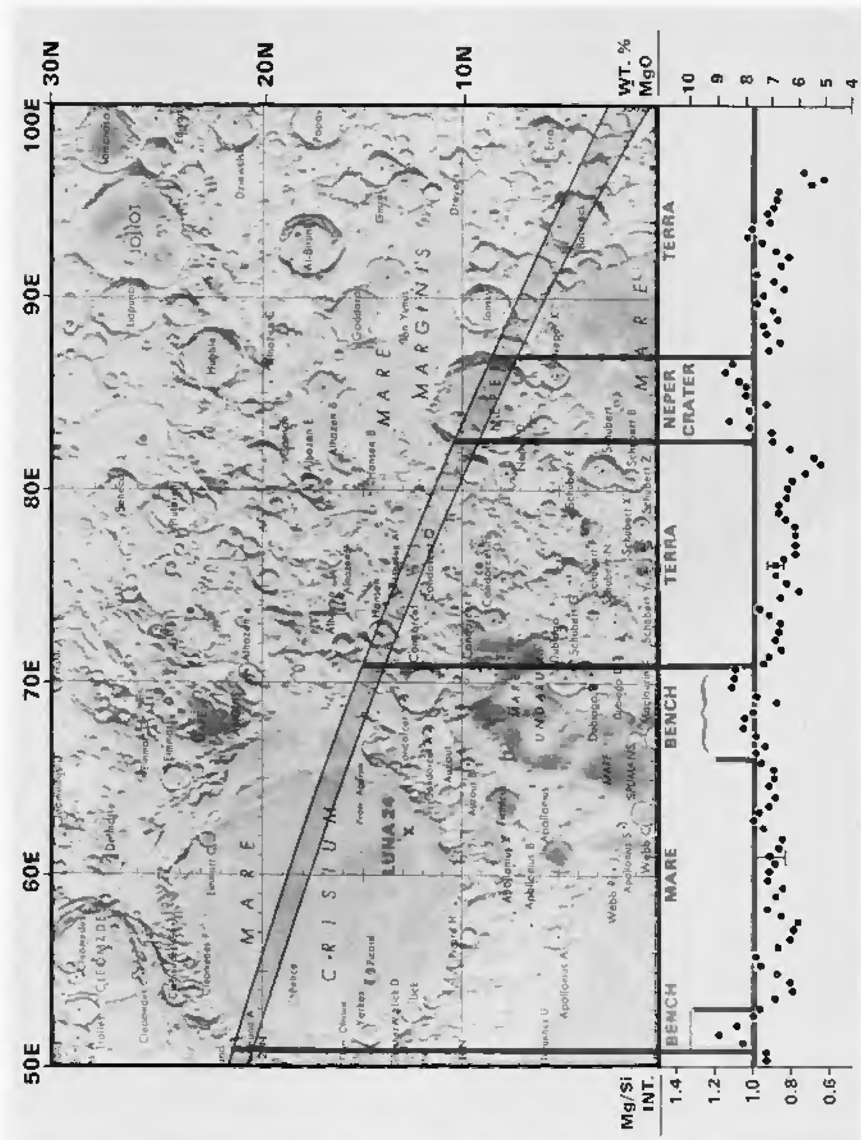

Fig. 3. This map and orbital X-ray Mg/Si profile is a continuation of Fig. 2 from 50 E to 100 E. Notice the higher concentration of magnesium in basalts along the benches in Mare Crisium and within the crater, Neper.

three low altitude orbits as a swath that represents the diameter of their combined effective fields of view (the area from which about 85% of the signal intensity is received). This area observed by the detector decreased from a diameter of 26 km at 100 E to 8 km at 10 E.

The Mg/Si profiles at the bottom of these figures show solar-corrected data from the three orbits, averaged at the same longitudes, and then smoothed along the orbital path by a 3-point weighed sliding average. This procedure substantially improves the signal-to-noise ratio because the distance between data points is smaller than the diameter of the field of view.

These low altitude orbits, traversing Mare Crisium from east to west (Fig. 3) show the highest Mg/Si ratios associated with the topographically higher mare benches on both the east and west sides of the mare basin. The actual MgO values for these structures may be higher than those measured from orbit because the features are not large and they border the mare/terra contact which produces a mixed signal. These two border units are the oldest mare material in the Crisium basin according to relative age data by Boyce and Johnson (1978).

Two later circular orbits include data from the crater, Picard, and the southeast bench area of Mare Crisium. In addition to the high-magnesium bench units in Fig. 3, these orbits indicate that the magnesium content of the soil also rises sharply at the southeast bench structure (Fig. 4). In fact, this material is as magnesium-rich as that found at Picard in central Crisium. The high concentration of magnesium centered on the post-mare impact at Picard and at Peirce (not shown here) is interpreted as ejecta from a subsurface layer of magnesium-rich basalt (Andre *et al.*, 1978). The three border areas of high-magnesium material found in this mare and the evidence of a high-magnesium subsurface layer excavated at Picard and Peirce indicate that there may be a basin-wide layer that remained as a surface unit only on the mare benches bordering the terra. Furthermore, this unit may represent the earliest initial outpouring of mare basalts in the Crisium basin. Interestingly, topographic bench units in eastern and southeastern Mare Crisium as well as the unit centered at Picard, all defined by X-ray data as high-magnesium, coincide with the early high-titanium (3.5 to 5.5 weight percent) basalt units identified using spectral reflectance data (Head *et al.*, 1978). Magnesium values from orbital X-ray data at low altitudes (Fig. 3) indicate that this early basalt is also exposed along the northwest bench of Mare Crisium. (This border area has not yet been subdivided using spectral reflectance data.)

These indications of early volcanism along mare/terra boundaries in Mare Crisium led to a survey of other maria to look for similar variations in Mg/Si ratios.

GEOGRAPHIC DISTRIBUTION OF HIGH-MAGNESIUM MARE MATERIAL

The early magnesium-rich border units in Mare Crisium that appear to be extensions of basin-wide basalt layers, largely concealed by later flows, are found in other maria. The distribution of these high-magnesium materials within the Apollo

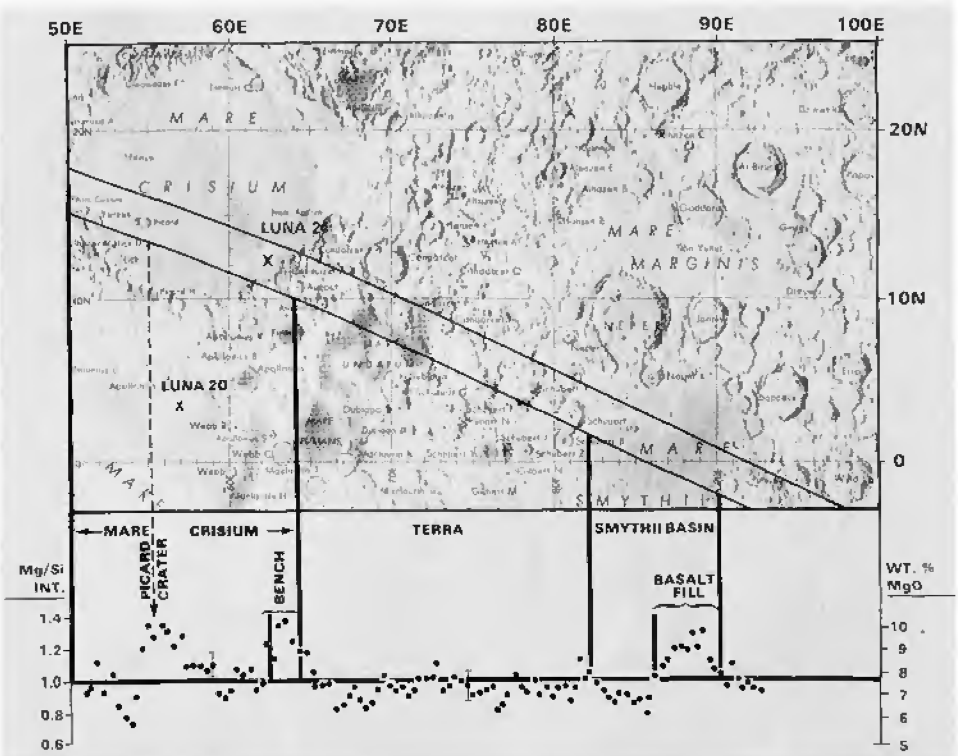

Fig. 4. The combined areas "observed" by the detectors during two orbits at higher altitudes than those in Figs. 2 and 3 are shown on the map. Corresponding magnesium variations resulting from a 5-point weighted sliding average of the original data points are shown below. Ejecta around the impact crater, Picard, the southeast bench of Crisium and mare basalts in the northeast quadrant of the Smythii basin have similar high-magnesium values.

orbital X-ray coverage produces some interesting geologic patterns. The locations of the highest Mg/Si values for each mare observed during individual orbits by the X-ray detectors are shown in Fig. 5. With very few exceptions, these Mg/Si values also exceed those for terra regions. The results show an overwhelming proportion of high-magnesium values clustering along mare margins.

This distribution explains some apparent inconsistencies in comparisons of the orbital data with sample analyses shown in Fig. 1. For example, soil samples for the Apollo 15 and 17 landing sites range well beyond 10 weight percent MgO, whereas orbital X-ray data indicate very limited amounts of such material on nearside mare surfaces. The cluster of high-magnesium values from orbital X-ray data at these landing sites (Fig. 5) means that returned samples were from relatively uncommon locations of magnesium-rich mare basalts along mare borders. This may be true of Apollo 12 samples as well. In other words, these samples and Luna 24 samples, were all collected in or near high-magnesium mare annulus

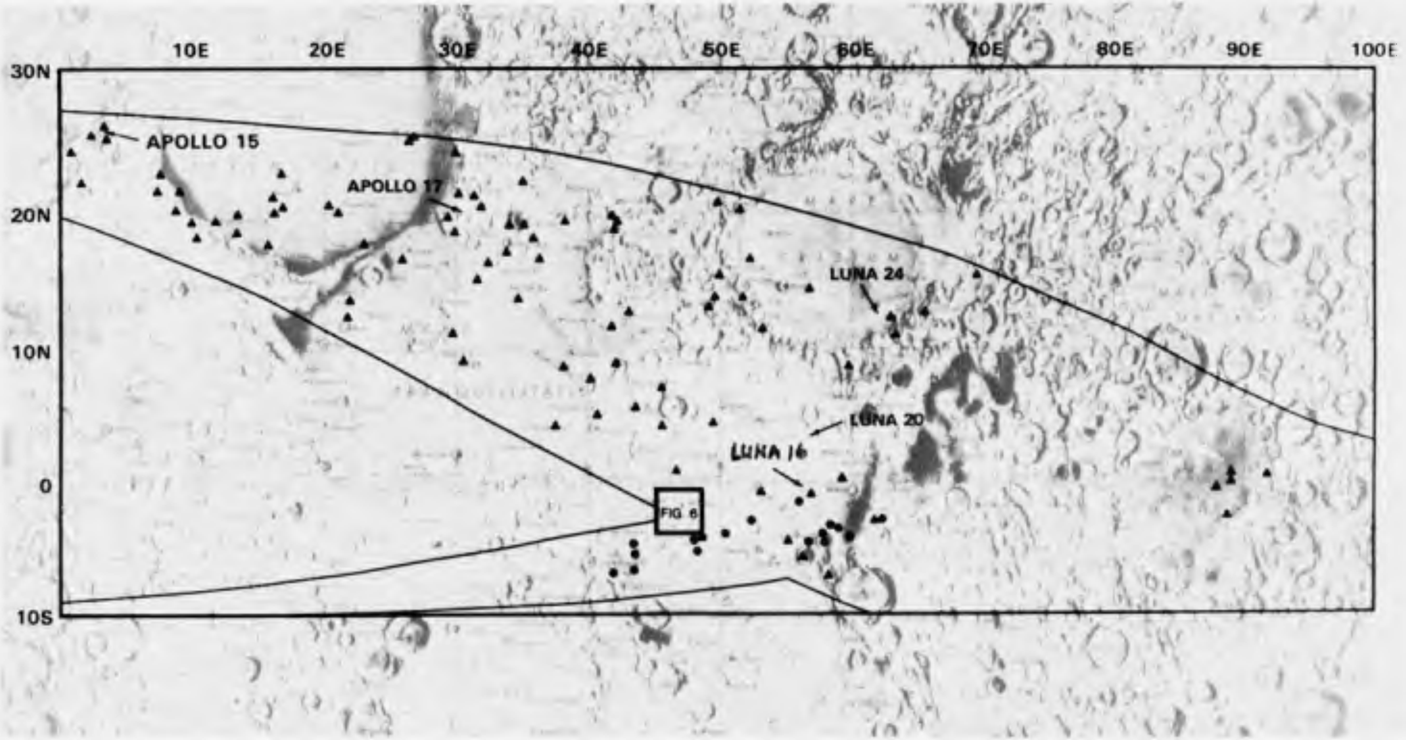

Fig. 5. High-magnesium basalt distribution map. The triangles and circles represent the one highest Mg/Si value in each mare from individual Apollo 15 or Apollo 16 orbits respectively. Notice the concentration of high values along mare margins, especially in the areas where soils were sampled during the Apollo 15, 17 and Luna 24 missions.

units according to the X-ray data. Thus, the lunar sample collection fails to indicate the predominance of mare soils with MgO values ≤8.5 weight percent which are evident from the orbital X-ray frequency distribution shown in Fig. 1. Ironically, these returned "surface" samples probably represent mare basalts that are now primarily "subsurface" units.

Another question is raised by comparing the mare and terra histograms. The areal distribution in Fig. 5 indicates that on the basis of the Mg/Si values shown, the geographic breakdown into mare and non-mare designations would not be a simple matter. The frequency distribution of orbital X-ray data (Fig. 1) indicates that mare and non-mare materials have the same upper MgO limit and frequency profile above 10 weight percent MgO. Considering returned sample analyses from both mare and terra areas, and the modal peaks, this is unlikely. It is apparent from Fig. 5 that nearly all the high Mg/Si values originate along mare boundaries and usually extend slightly "inland" to include bordering terra areas. To photogeologists, there often appear to be ambiguous contacts between mare and terra material when the mare unit is old and extremely degraded or when terra terrain appears to be mantled with mare material. Therefore, many high Mg/Si mare values may in fact be recorded as "non-mare" material in the orbital X-ray histogram (Fig. 1).

There may be another explanation for the similar mare and non-mare frequency distributions above 10 weight percent MgO. High Mg/Si units at Taurus-Littrow and Sulpicius Gallus correlate with "dark mantle" units and have high Mg/Al values as well (Schonfeld and Bielefeld, 1978). Soils from the Apollo 17 site at Taurus-Littrow were found to contain orange and black glass spherules that give the soil its "dark mantle" characteristics and magnesium-rich composition (up to 19 weight percent MgO). This soil component is generally believed to be the product of lava fountains (Heiken *et al.*, 1974; Meyer *et al.*, 1975) at basin edges where highland topography is also mantled. Showering of lava over wide areas may, therefore, also explain the high Mg/Si values found in terra soils bounding the maria (Figs. 1 and 5). High Mg/Si mare values along these same boundaries suggests that lava fountains may be commonly associated with the emplacement of early magnesium-rich basalts. Pyroclastic activity has been correlated with early mare volcanism at the Apollo 17 site where there is a strong similarity between the glass component in the soils and the subfloor basalts (Head, 1974).

There is a striking correspondence between the magnesium-rich mare borders seen on Fig. 5 and blue mare basalts seen on a color-difference photograph (6100 Å minus 3700 Å) by Whitaker (1972). There is also a strong correlation between high-magnesium basalts along mare margins and the oldest units to be emplaced into each basin (Boyce and Johnson, 1978). These oldest units were not necessarily emplaced at the same time in lunar history. For example, the oldest mare basalts visible on the surface of Mare Serenitatis are about 3.7 b.y., whereas those bordering Mare Smythii are only 3.2 b.y. The earliest basalts yet detected in Mare Procellarum are also blue, appear only along a mare border in the northwest section of the mare, and are largely buried by later flows (Whitford-Stark and Head, 1978). Unfortunately, no orbital X-ray data exists for this region.

One elongated unit trending NNW in Mare Serenitatis (Figs. 2 and 5) is a rare example of high-magnesium soils isolated from mare borders. It parallels rays which extend north and south of the crater Bessel. Evidence of layering within this Mare is visible in the walls of Bessel (Young, 1977). Whether high-magnesium ejecta from Bessel could have produced a unit of this extent is uncertain.

HIGH-MAGNESIUM MATERIAL IN INTERMARE AREAS

High-magnesium materials are not restricted to the interiors of basins. They are also found in craters and irregular depressions in intermare areas. For example, the floor of the crater, Neper, north of Mare Smythii, was inundated by mare basalts with Mg/Si values noticeably higher than central Mare Crisium (Fig. 3). Direct comparisons of Mg/Si values for Mare Smythii to those for Mare Crisium are shown in Fig. 4. The localized mare fill in the northwest quadrant of the Smythii basin has magnesium concentrations comparable to the 10 weight percent MgO values for the Picard area and bench structure in Mare Crisium. The highest Mg/Si values in the flooded part of the Smythii basin are contained within the older of two units identified (Boyce and Johnson, 1978).

Increases in magnesium relative to adjacent terrain also occur in "plains" units in the craters Babcock and Macrobius (Figs. 2 and 3). The units are described as having the characteristics expected of early, degraded mare lava flows and may even predate the onset of mare volcanism (Scott and Pohn, 1972; Wilhelms and El-Baz, 1977). Other variations in the measured Mg/Si ratios near Macrobius are due to mare basalt fill of topographic lows in this predominantly terra region.

EVIDENCE FOR BURIED MAGNESIUM-RICH BASALTS IN CENTRAL MARE FECUNDITATIS

Border units in Mare Fecunditatis located along the northeastern, eastern and western mare boundaries are characterized by high Mg/Si ratios (Fig. 5). These units may be visible remnants of extensive flows that are now largely buried. In north central Fecunditatis, the post-mare impact crater, Messier A, appears to have excavated magnesium-rich material from beneath surface flows (Fig. 6). Supporting evidence for this interpretation are the dark rays which surround the crater on all sides except where rays extend west of the crater (Cameron *et al.*, 1974). Mg/Si intensities increase from <0.94 ($<7\%$ MgO) to >1.18 ($>9\%$ MgO). This crater exhibits abrupt increases in magnesium concentration relative to the surrounding surface of Mare Fecunditatis. The calculated MgO, considering that the feature diameter is less than the area observed by the X-ray detector, is at least 10 weight percent. The high-magnesium material has been excavated from depths less than 1.7 km (crater depth) below the mare surface in this deepest portion of the basin, according to De Hon (1975), where early volcanic flows would tend to collect. This suggests that the crater sampled early flows that are related to those observed along the higher margins of the mare that were not covered by later less-magnesian flows.

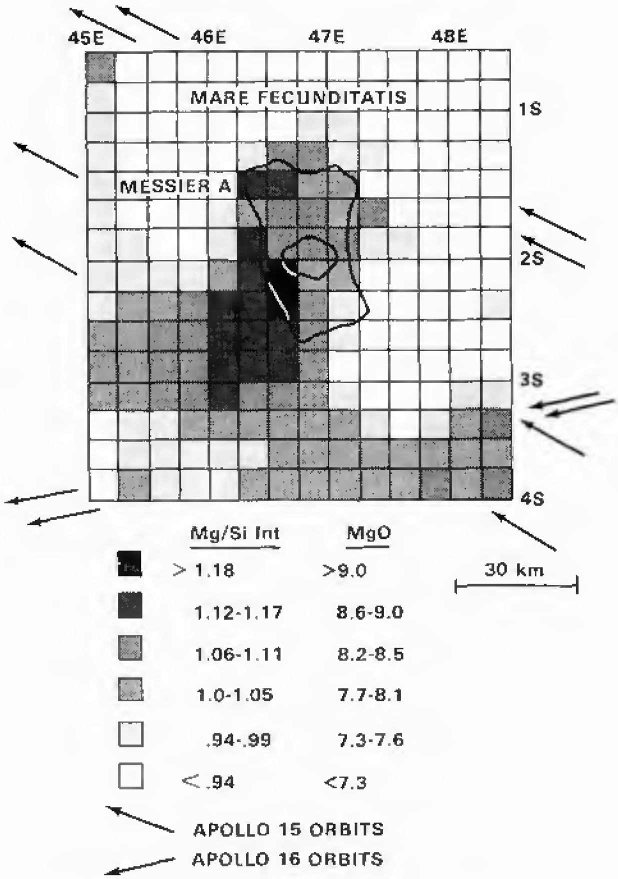

Fig. 6. High Mg/Si intensities related to Messier A, an impact crater in north central Mare Fecunditatis, suggests that earlier Mg-rich basalts have been dredged up from below less-magnesian surface flows. This area is shown by the outline on Fig. 5.

If we may infer from the evidence of early high-magnesium subsurface basalts in Mare Crisium and Mare Fecunditatis that high-magnesium borders are part of basin-wide layers (largely buried), then the geographic distribution of this material (Fig. 5) may have far-reaching implications for volumetric estimates of high-magnesium mare basalts and for models of mare basalt petrogenesis.

DISCUSSION

Orbital X-ray data indicate that, in general, high-magnesium mare basalts encircle the inner mare units in six nearside basins: Imbrium, Serenitatis, Tranquillitatis, Fecunditatis, Crisium and Smythii. In two of these maria, large post-mare craters have excavated material from a depth that is higher in magnesium than surface basalts.

We propose that early stages of volcanism in these basins erupted high-magnesium lavas. Continued volcanism caused the inner portions of the basins to subside and the early flows were buried by less-magnesian basalts. However, the early, high-magnesium basalts near the basin margins remained perched at relatively higher elevations and were not covered. This interpretation is consistent with data from the Apollo Lunar Sounder Experiment (e.g., Maxwell and Phillips, 1978) and with most accepted models for the structural evolution of mare basins (e.g., Solomon and Head, 1979).

If one were to estimate the volume of high-magnesium basalts based on their limited surface exposures, this estimate would be much too low in light of our study. These basalts evidently comprise a substantial portion of mare material and represent early extensive volcanism in each of several basins, although their emplacement was not contemporaneous.

If these interpretations are correct, magnesium-rich basalts are widespread on the moon and they may have profound significance for models of mare basalt petrogenesis.

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