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Evidence for early volcanism in Mare Smythii

James Conca

Department of Geological Sciences, Brown University, Providence, Rhode Island 02908 and
The Lunar and Planetary Institute, Houston, Texas 77058

Norman Hubbard

NASA Johnson Space Center, Houston, Texas 77058

Abstract—The major geologic units in and around the Smythii basin are clearly reflected in the Al_2O_3 and MgO values obtained using improved orbital X-ray fluorescence data from Apollo 15. One of these units is a high albedo plains-forming unit that has Al_2O_3 and MgO concentrations different from those of similar plains-forming units located in the terra west of Smythii and south of Crisium, and also different from those of adjacent terra and mare materials. The chemical composition of the plains-forming unit suggests a volcanic origin and indicates an Al_2O_3 and MgO–rich basaltic composition similar to that of some lunar norites. The inferred Al_2O_3 and MgO–rich nature of this presumed early volcanic material is supported by the fact that even the later, low albedo, lightly cratered mare fill in Mare Smythii has a high MgO value, and its Al_2O_3 concentration is higher than that of similar basaltic material in other maria.

INTRODUCTION

The origin of plains-forming units in the terra areas of the moon has long been debated (Hartman and Wood, 1971; Oberbeck *et al.* 1974; Boyce *et al.* 1974). They may be either ejecta deposits that fill depressions or they may be early volcanic deposits that have been much more heavily cratered than the later, lower albedo mare units. It seems reasonable to presume that an individual plains-forming unit may have had either origin. In either case, the higher cratering flux that they have experienced has led to a much greater contamination of these deposits by adjacent terra material than has been the case for maria, where terra contamination is minor ($\lesssim$5%, Hubbard, 1979), and thus the original chemical composition of the plains-forming unit is somewhat masked. Given the situation where there is no chemical contrast between the light plains unit and the surrounding terra, the chemical data support the impact origin. On the other hand, when a plains-forming unit is surrounded by anorthositic terra material and itself has a ''basaltic'' chemical composition, this chemical contrast suggests that the volcanic origin is more probable. This chemical evidence presumes nothing about the current physical state of the ''basaltic'' material; it may now be so heavily cratered that all morphological features suggestive of volcanism have been lost. The latter situation is found for the plains-forming unit in Smythii. The Smythii basin also contains large amounts of obvious mare material that complicates interpretation of remote sensing chemical data. We will present geochemical evidence relevant to the origin of the plains-forming unit in the Smythii basin (henceforth, referred to as the Smythii plains unit). The evidence is obtained from the improved orbital X-ray data obtained by Apollo 15 and recently reduced at the Johnson Space Center (Hubbard *et al.*, 1974; Hubbard, 1979). These data have been calibrated via lunar samples to give Al_2O_3 concentrations (Hubbard, 1979), thus allowing a more thorough geochemical analysis by combining lunar sample and orbital data.

DATA

Figure 1 is a sketch map of Mare Smythii and some relevant areas to the west. Table 1 shows the Al_2O_3 and MgO concentrations for several photogeological units noted in Fig. 1. These averages were obtained by first plotting the location

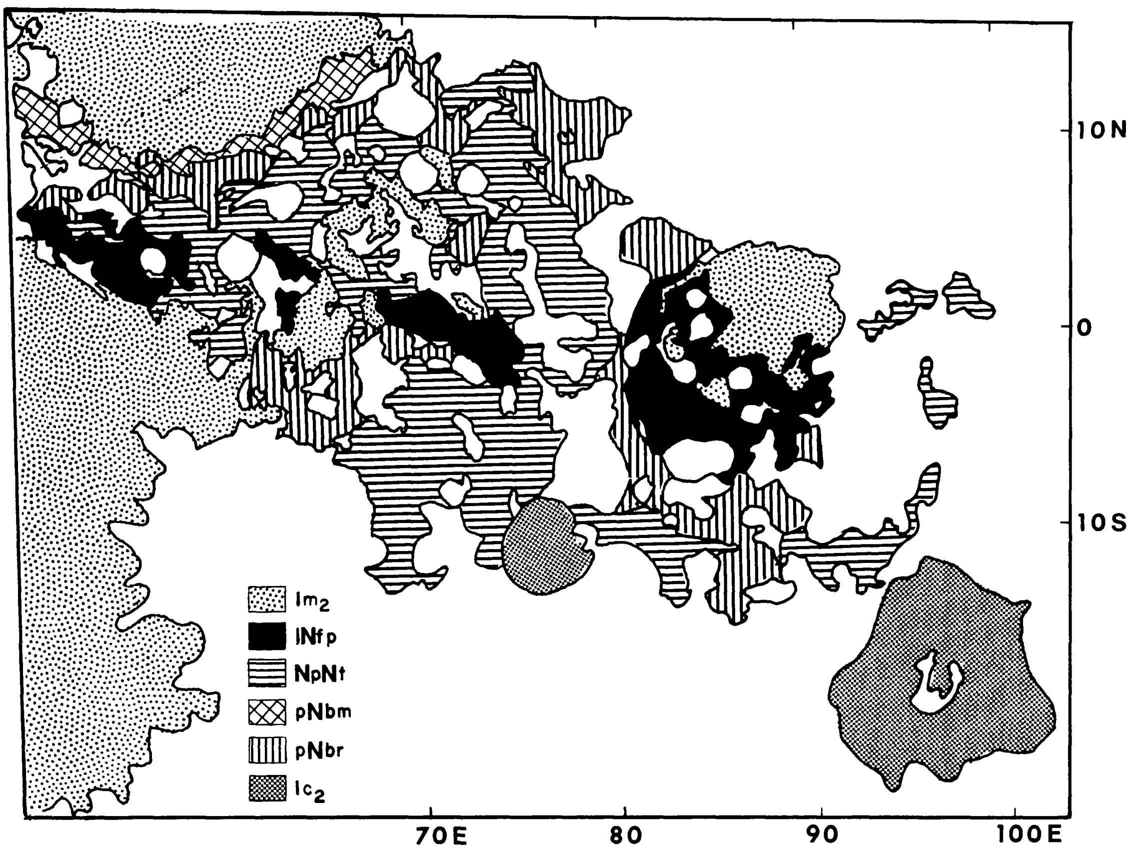

Fig. 1. A sketch map, based on Wilhelms and El Baz (1976), showing the geologic setting of Mare Smythii and environs. Mare Smythii is centered at ~85°E and ~2°S. The three extensive areas of the plains forming unit, INfp, are shown; one within Smythii (called Smythii plains unit in text), one west of Smythii and south of Crisium. Other units are Im_2, younger mare material, NpNt, partly mantled terra, pNbm, basin massiffs, pNbr, rugged basin terrain, Ic_2, relatively fresh craters.

Table 1. MgO and Al_2O_3 concentrations for Mare Smythii and environs. Orbital data only, in wt. %.

Unit	Location	N†	Al_2O_3*	MgO*	Notes
Im_2	Within Smythii	45	16.9	11.9	Mare
INfp	Within Smythii	44	22.8	10.2	Smythii plains unit
	West of Smythii	14	25.5	7.3	Terra
	South of Crisium	29	26.0	7.8	Terra
NpNt	Northwest of Smythii		29.0	8.3	Terra
	Southwest of Smythii		26.4	7.3	Terra
	East of Smythii		30.4	4.0	Terra
Ic_2	West of Smythii		26.0	5.6	Terra
	Southeast of Smythii		29.6	4.0	Terra
Terra West	72.0°E to 80.0°E 5.0°N to 10.0°N	80	26.6	8.2	Terra
Terra East	93.0°E to 100.0°E 0.0° to 10.0°S	92	28.7	5.7	Terra

* All Al_2O_3 values for terra are from the middle line in Fig. 3, as is the Smythii plains unit. The lower line was used for the mare value.

† Number of 8-second data points that were averaged.

of the 8-second X-ray data points on a geological map (Wilhelms and El-Baz, 1976). The means and standard deviations for Al/Si and Mg/Si intensity ratios were then calculated for photogeologically homogeneous units. The data used have been smoothed by a five point sliding average that was weighted to mimic the response function of the x-ray detector, and then unwanted solar effects were removed (Hubbard *et al.*, 1974; Hubbard and Keith, 1977, 1979). These Al/Si and Mg/Si intensity ratios were then converted to Al_2O_3 and MgO values using the calibration curves shown in Figs. 2 and 3: see Hubbard (1979) for more information about this calibration. There is an ambiguity in the Al/Si to Al_2O_3 calibration curve that has not yet been resolved, and thus three different lines are shown. The lower one is considered to be more accurate for mare materials and the intermediate one to be more correct for terra materials. The third and upper line illustrates the maximum conversion for terra. In the figures and discussion that follow we show the effect of using different lines and note the consequences.

Figure 4 shows the orbital X-ray data for Al_2O_3 and MgO together with selected lunar sample data. The cluster of filled circles labeled Common Apollo Mare Basalts are average data for the various types of mare basalts collected by Apollo in hand specimen sized fragments. For a description of aluminous mare basalts see Ridley (1975). The filled squares in the maria cluster are whole maria averages obtained using the lower line in Fig. 3. The two points for the mare unit in Smythii show the effect of using the lower line (filled square) or the middle line (open square). The other three Smythii data points, terra east, terra west and plains unit show the effect of using the middle line (open squares) and the extreme terra line (open square with X). The data field labeled very high Al_2O_3 basaltic composition was taken from Hubbard and Rhodes (1977) and the anorthositic data are from Hubbard *et al.* (1974). Data for sample 78235 are from Dymek *et al.*

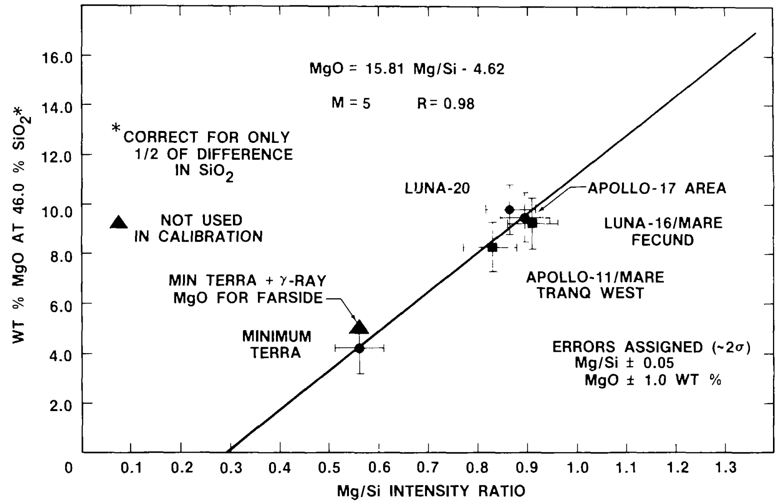

Fig. 2. An empirical calibration of the orbital x-ray fluorescence data for Mg/Si intensity ratios to MgO concentrations. The construction of this calibration curve is described in Hubbard (1979).

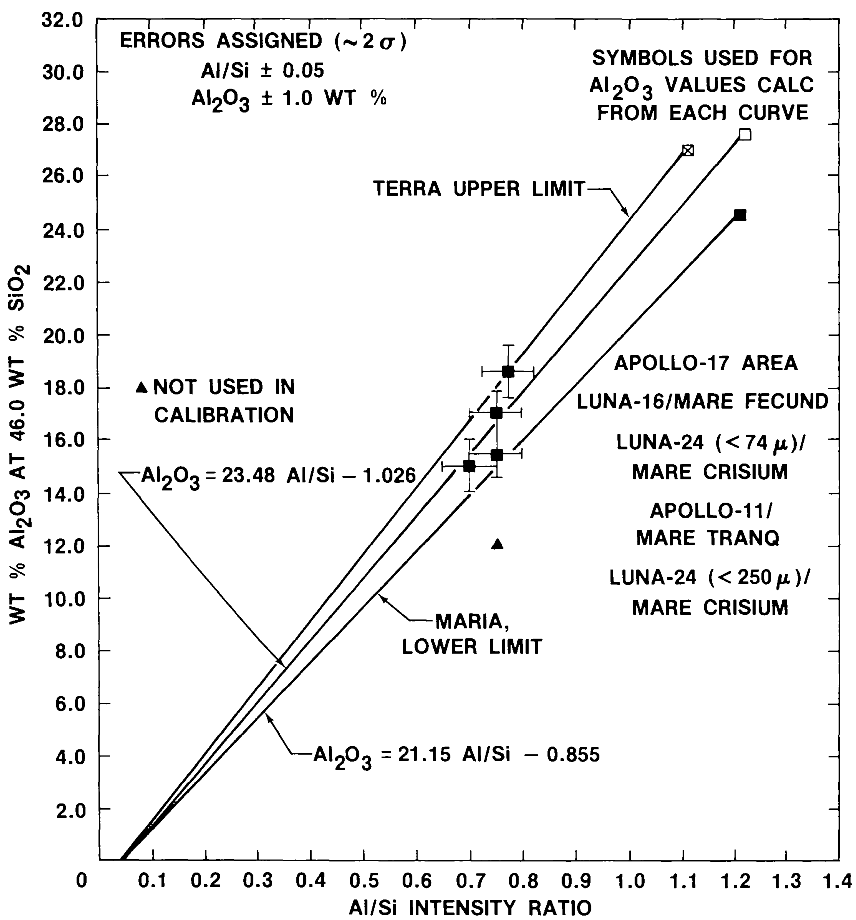

Fig. 3. An empirical calibration of the orbital X-ray fluorescence data for Al/Si intensity ratios to Al_2O_3 concentrations. The results are somewhat ambiguous and three different lines are shown. These three lines are briefly discussed in the text and more fully in Hubbard (1979).

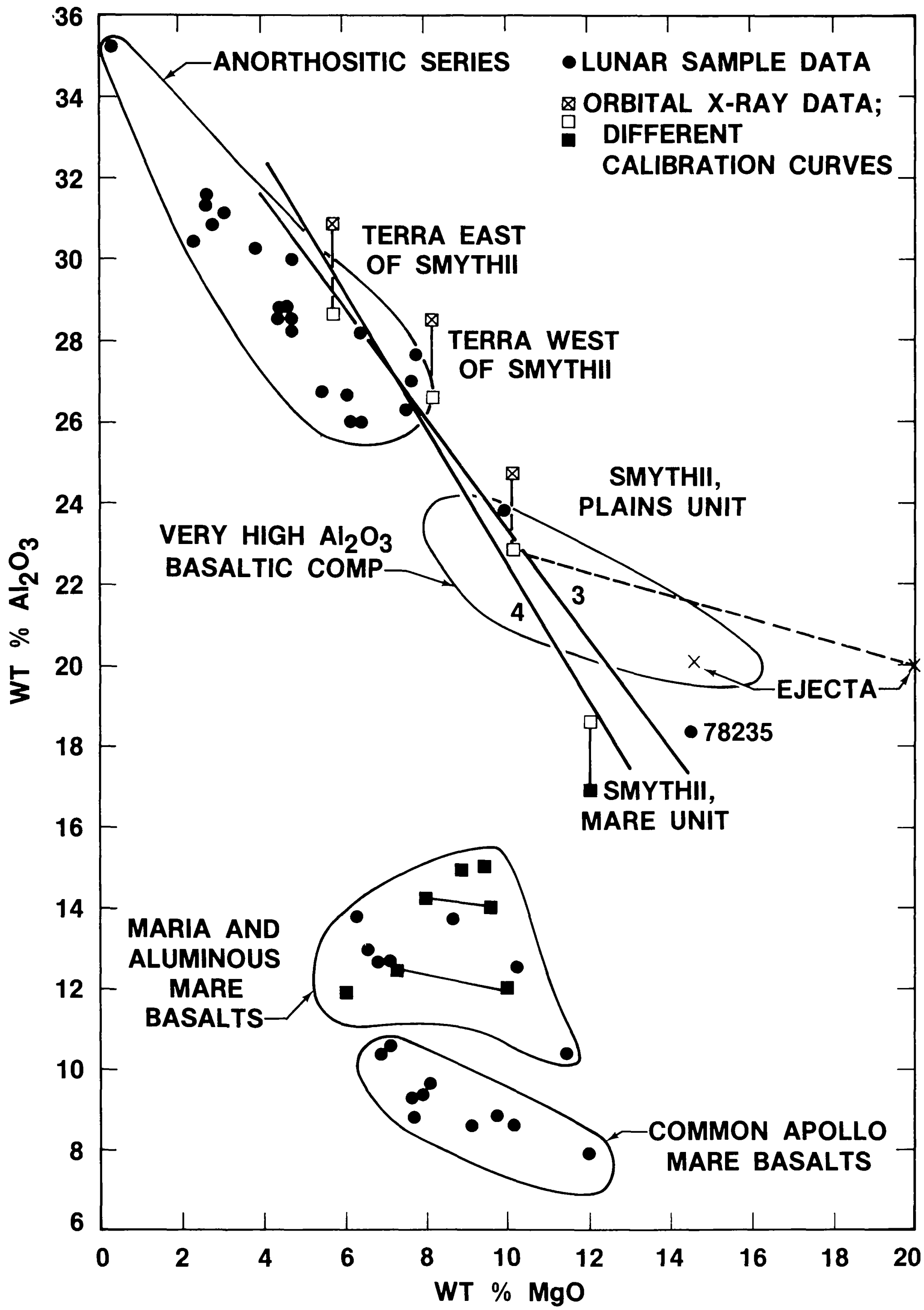

Fig. 4. Comparison of orbital and lunar sample data for Al_2O_3 vs. MgO. Lunar sample data are shown for four types of lunar materials, the anorthositic series (Hubbard *et al.*, 1974), the very high Al_2O_3 basaltic composition (Hubbard and Rhodes, 1977), aluminous mare basalts (Ridley, 1975) and common Apollo mare basalts. The orbital X-ray fluorescence data are for several lunar maria and the terra areas east and west of Mare Smythii. The orbital X-ray data are coded with symbols to show which line in Fig. 3 was used to derive them.

(1975). Clearly, all materials in Mare Smythii are very high in Al_2O_3 relative to those in other maria. The Al_2O_3 and MgO measured by orbital X-ray for the terra materials both east and west of Mare Smythii are very similar to those of the anorthositic series.

DISCUSSION

The Smythii basin is situated at the eastern limb of the moon and is one of the older lunar basins, certainly formed prior to the Crisium Basin (Stuart-Alexander and Howard, 1970). According to the geologic map of Wilhelms and El-Baz (1976), Smythii's interior is partially flooded with mare material (unit Im_2) in the northeast and in many smaller patches on the basin floor. The remaining portions of the basin are filled with a plains-forming unit (INfp) that is morphologically similar to other plains-forming units located west of the Smythii basin and south of Mare Crisium and described as having closely spaced irregular furrows and pits (kilometers in size) that are superposed on Nectarian craters and overlain by Imbrian features (Wilhelms and El-Baz, 1976). This unit in Smythii is heavily cratered by small impacts and has a smooth appearance which suggests that it has been draped over the large (20–80 Km) Nectarian and perhaps pre-Nectarian craters that have given a wide range of elevations to the surface of this unit (Wolfe and El-Baz, 1976). The presence of large post-basin craters (20–80 Km) assures that the upper part of this unit contains a substantial component of material that was once at depths of a few to perhaps several kilometers and may partly be from below this unit. Apollo photographic coverage of Smythii shows that this unit has a very mottled albedo and an average albedo that is intermediate between those of the mare and terra (Stewart *et al.,* 1975) and nearly as high as that of the highlands adjacent to Smythii (Wolfe and El-Baz, 1976). This high albedo rules out the presence of substantial amounts of mare material ($\lesssim$25%), either as pyroclastics or lava flows. It seems realistic to conclude from the albedo and crater data that the material in this Smythii plains unit has multiple compositions and origins and that very little of it is mare material.

Stewart *et al.* (1975) divided the Smythii plains unit into a hummocky unit (IpIh in their nomenclature), which they considered to be non-volcanic, and an Imbrian plains forming unit (Ip), which they considered to be an early volcanic unit. Our data are exclusively for their hummocky unit because the northern unit does not have large areas that are well resolved from the mare unit by the Apollo 15 orbital X-ray experiment. We use X-ray data only from Apollo 15 and convert the Al/Si and Mg/Si intensity ratios to Al_2O_3 and MgO concentrations. For information on the accuracy with which our orbital Al^2O^3 and MgO data can be compared with lunar sample data the reader is referred to Hubbard (1979). The surface of the area covered by our data appears to be covered by ejecta from post-basin craters such as Kiess, Widmannstatten, Helmet, Warner, etc., that impacted into this unit. Although these impacts have extensively erased the original morphology of this unit, they have not erased the distinctive chemical signature of this plains unit. Because we have used both Mg/Si and Al/Si data and converted to Al_2O_3 and MgO concentrations we are able to analyze this signature for its unique contribution to understanding the origin of the Smythii plains unit by comparing the orbital data with the lunar sample data.

As shown in Table 1, whenever this photogeologic unit (INfp) occurs outside Smythii it is similar in Al_2O_3 and MgO concentrations to surrounding terra units, such as NpNt and Ic[2]. Thus an impact origin is supported by the chemical data for these areas. However, unfit INfp within the Smythii basin has average Al_2O_3 and MgO concentrations that are different from those of the mare and surrounding terra materials. The observation that this particular occurrence of the INfp unit has a chemical composition that is restricted to the Smythii basin indicates that the unit is intimately related to Smythii. Andre *et al.* (1977) did not study the plains unit in the south and therefore their results cannot be directly compared with ours. They considered the bulk of the northwestern plains forming unit to be either the original basin floor material or an ejecta blanket from Crisium. As discussed below, the chemical data suggest a different explanation for the southern unit.

Because the Smythii plains unit (INfp) is restricted to the Smythii basin one must examine its chemical composition in terms of local materials and processes. Given the limitations of the orbital X-ray data we are limited to: 1.) presenting data showing that the chemical composition of this unit is of local origin and that it is not a mixture of material from the local mare unit with local terra material, and 2.) to deducing the major features of its average composition. The orbital x-ray data that have been averaged to obtain the Al_2O_3 and MgO values for the plains unit were carefully chosen to eliminate patches of low albedo mare material. First, we will examine the hypothesis that the Smythii plains unit is a mixture of local materials, specifically mare plus terra. On Fig. 4, we have plotted two lines that show the effects of mixing. The line labeled #4 illustrates the situation if all Al/Si data are converted to Al_2O_3 concentrations using the middle line in Fig. 3. Clearly, such a mixture may explain the data. However, it is known that the post mare cratering flux cannot move the required large amounts (~50% of the surface regolith) of mare material over the remainder of the basin (Rhodes 1977, Hörz 1978, Hubbard 1979) and thus this explanation is not viable if impact gardening is the mechanism responsible. The high albedo of the Smythii plains unit is also counter to this explanation, or to any other that requires the addition of massive amounts of mare material, such as the addition of pyroclastic materials of mare composition. Further, visible low albedo mantling deposits in Smythii, which are presumed to be pyroclastic deposits (Wolfe and El-Baz, 1976), are much more limited in extent and have been avoided in our calculation of the average MgO value for the Smythii plains unit. One could postulate a high albedo pyroclastic deposit that mantled the plains unit, giving it the observed Al_2O_3 and MgO concentrations. However, no evidence has been found in the lunar samples that such pyroclastic deposits exist on the moon. Finally, if one calculates the Al_2O_3 value for the mare fill using the lower conversion in Fig. 3 then the line joining the terra and plains unit (line #3) in Fig. 4 misses the mare point by over three sigma, substantially weakening any argument for mixing of mare and terra materials to produce the plains composition. Hubbard (1979) shows that the lower conversion line is more appropriate for maria than is the middle line.

Although the arguments against mixing of mare and terra (Rhodes 1977, Hörz 1978, Hubbard 1979) are quite strong, the mixing of terra material into the surface regolith being developed on an earlier volcanic fill is much more likely because the premare cratering flux was much greater. Further, some of the larger post-plains craters may have excavated material from below the Smythii plains unit: such material may have an anorthositic composition. Thus, the Al_2O_3 and MgO values measured from orbit for the Smythii plains material may have been substantially altered toward the local terra values. Clearly, the subtraction of any anorthositic terra material will move the composition of the Smythii plains unit further toward a basaltic composition, such as that represented by sample 78235 (Dymek *et al.*, 1975).

There is a crater in Mare Smythii at 83.4°E and 3.5°S that provides some qualitative information about the chemical composition of the Smythii plains unit (crater #2 in Fig. 6). Orbit 34 crosses this small crater (4.6 km diameter, which is smaller than the field of view for the detector) and shows no change in Al/Si intensity ratio whereas the Mg/Si ratio increases about ~20%. In Fig. 5, we have plotted both the unsmoothed and smoothed Mg/Si data to demonstrate that the increase in Mg/Si is real. It can be seen from the raw data that the ~ 20% increase in the smoothed Mg/Si ratios is caused by two adjacent data points that are about 40% above the local average and located at the crater. We then modeled this crater and its ejecta blanket by a 12.5 km diameter spot that has a Mg/Si ratio much higher than the surrounding value of ~1.0. The observed data are ade-

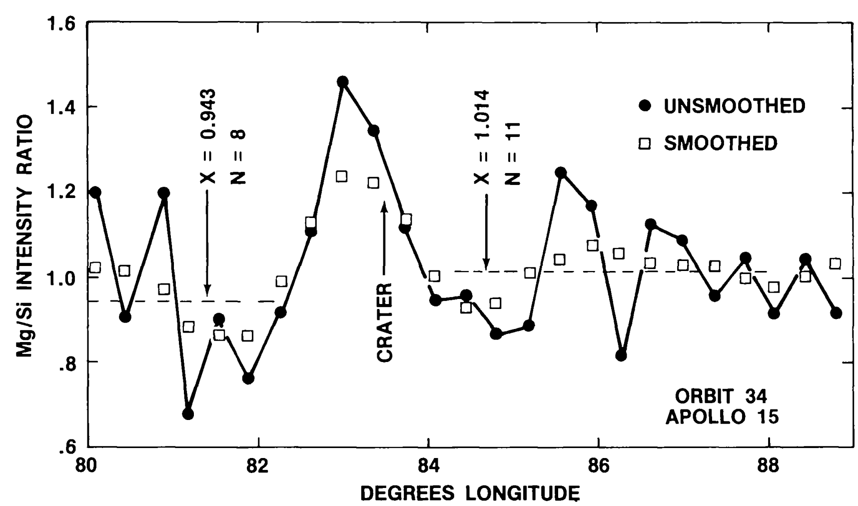

Fig. 5. The Mg/Si data are shown for an orbit that crosses a 4.6 km diameter crater at 83.4°4E and 3.5°S, which has excavated about 900 meters into the Smythii plains unit. This crater and its ejecta blanket have been modeled by a 12.5 km diameter spot, which is the smallest that can be treated in this analysis.

quately reproduced when the Mg/Si ratio of the spot is 1.6 to 1.8. A spot twice this diameter and with this ratio produces a Mg/Si peak that is too broad. Conversion of these Mg/Si ratios to % MgO gives 20 to 24% MgO. The Al/Si ratio does not change over this small feature so that we can conclude only that the Al_2O_3 concentration of the ejected material is not sharply different ($\lesssim$20%) from that of the surroundings. If we assume that this material has 20% MgO and 18–22% Al_2O_3, it will then plot on the extreme right-hand edge of Fig. 4 at an Al_2O_3 value slightly lower than that for the plains unit. (The Al_2O_3 is lowered somewhat on the assumption that a large increase in MgO will be accompanied by at least a modest decrease in Al_2O_3). If this data point (20% MgO) is taken literally, it indicates that very little of the surface regolith on the Smythii plains unit is admixed terra material because the tie line between the plains point and this point diverges sharply from the mixing line. A 10% or perhaps even 20% admixture of terra will not be distinguishable because the two sigma errors in the orbital data are equal to about ±1.5 wt. % Al_2O_3 for these Al_2O_3 values. However, the Al/Si data do not allow an Al_2O_3 value anywhere nearly low enough to put the ejecta from this crater onto the extension of the mixing line from terra through Smythii plains, which requires an Al_2O_3 value of about 10% if the MgO is 20%. The lower limit for the Mg/Si (1.2) and MgO (14.4%) places the point inside the field for the very high Al_2O_3 basaltic series above the sample 78235. Even if the MgO value were as low as 14.4%, the Al_2O_3 value would have to be about 17.0%, which should also be visible in the data. However, the tie line between the data for plains and ejecta (MgO 14.4–20.0%) is approximately parallel with the data fields for the very high Al_2O_3 basaltic composition and the common Apollo mare basalts, which are typical for basaltic suites (Hubbard and Rhodes, 1977, Hubbard *et al.*, 1974). Following this line of interpretation, we suggest that the small crater excavated an olivine rich layer that exists at depths of a few to several hundred meters. This in turn suggests questions that cannot be presently answered. For example, was a troctolitic cumulate excavated or a very MgO rich lava? If it is a cumulate, does that imply that the early filling of Smythii produced a thick pool of lava rather than a stack of thin flows? Dymek *et al.* (1975) suggest that 78235 and apparently related samples may have crystallized in a local igneous event, although they prefer to explain this sample as a product of early lunar differentiation. One can also ask if a large post-plains impact penetrated through the Smythii plains unit and excavated a troctolitic layer that was produced during the early lunar differentiation that resulted in the anorthositic lunar crust.

Further discussion of the geologic history of volcanism in Smythii is better done using a geological cross section. Figure 6 illustrates an interpretation of the data in a cross section through the basin. The lowest unit consists of fallback and ejecta materials from the formation of the basin and the early bombardment. This is covered by an early volcanic unit whose composition is high in both Al_2O_3 and MgO. The upper surface of this volcanic unit has been reworked by impacts to produce the present surface morphology and surficial chemical composition of the Smythii plains unit. The low albedo lightly cratered fill that is concentrated in the northeast was produced by "normal" mare volcanism and partially covers

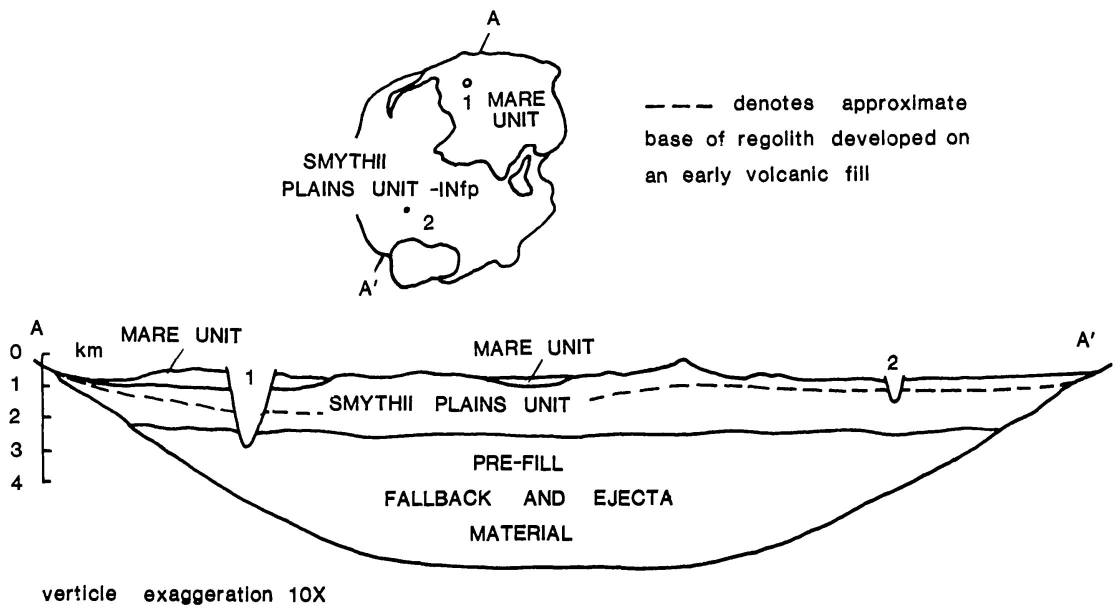

Fig. 6. This cross section through the Smythii basin illustrates possible stratigraphic relationships of the major units and of two craters that have exposed materials from underlying units. Crater #1 is Peak Crater and crater #2 is the unnamed crater at 83.4°E and 3.5°S. The width of this cross section is about 350 km. The lower boundary shown for the basin itself is purely conjectural and does not affect the discussion.

the earlier volcanic unit. The transient cavity of Peek crater (87.0°E, 3.0°N) has excavated to a depth of ~2.6 km and exposed material of lower MgO and higher Al_2O_3 than that of the surrounding mare material. Thus, the lower Mg/Si and higher Al/Si ratios for Peek ejecta indicates that this ejecta contains large amounts of the anorthositic prefill material, which in turn indicates that the higher MgO early volcanic unit contributes very little to this ejecta because it is either absent or very thin below Peek crater.

CONCLUSIONS

1. All of the materials in and around Mare Smythii have high Al_2O_3 concentrations, ranging from about 17.0 wt. % for late mare fill to about 30.0 wt. % for some of the terra areas east of the basin.
2. The pre-mare fill in Smythii (Smythii plains unit) has a composition that is confined to the basin and not seen in the orbital data for surrounding terra regions. In this respect, the light plains units in Smythii is different from some other occurrences of light plains units.
3. The average composition of the Smythii plains unit is deduced to be that of an Al_2O_3 and MgO rich basaltic composition. The deduced basaltic composition in turn implies an igneous origin for this material. It is suggested that this material was produced by early volcanism in the Smythii basin.

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