X-644-72-99
PREPRINT

NASA TM X- 65877

APOLLO 14:
SOME GEOCHEMICAL ASPECTS

APRIL 1972

GSFC —— GODDARD SPACE FLIGHT CENTER ——
GREENBELT, MARYLAND

Apollo 14: Some Geochemical Aspects

by

John A. Philpotts, C. C. Schnetzler, David F. Nava,
*Michael L. Bottino, *Paul D. Fullagar, Herman H. Thomas,
Shuford Schuhmann, and Charles W. Kouns

Planetology Branch
Goddard Space Flight Center
Greenbelt, Maryland 20771

*Presently at University of North Carolina, Chapel Hill, North Carolina

Abstract

Chemical analyses have been obtained for five samples of Apollo 14 regolith fines, three 14230 core samples, soil clod 14049, breccias 14305 and 14319, 14310 basalt, and some separated phases. The chemical uniformity of these Apollo 14 samples indicates thorough mixing and/or uniform source rocks. Basalt 14310 can be matched well in composition by a four to one mixture of soil and plagioclase. Eu^{2+}/Eu^{3+} ratios calculated for 14310 pigeonite and plagioclase are similar to those for Apollo 12 and 15 mare-type basalt phases; this indicates similar redox conditions. Our Apollo 14 samples are chemically similar to Apollo 12 and 15 KREEP as distinct from Apollo 11, 12 and 15 and Luna 16 mare-type basalts. A relationship, relating the two types of basalt and in which mare-basalts would represent fused cumulates, is suggested.

INTRODUCTION

Apollo 14 was the first mission to visit an uplands (i.e., non-mare) region of the moon. The Fra Mauro Formation, which underlies the landing site, is thought to represent throwout produced during an impact that formed the Imbrium basin (LSPET, 1971). Thus the Apollo 14 returned lunar samples were expected to represent material sampled at some depth within the moon and to be older than most mare-basalts, at least those at the surface. Subsequent dating of these samples (Turner et al., 1971; Papanastassiou and Wasserburg, 1971; Compston et al., 1971) bore out this expected age relationship. Preliminary chemical studies of the Apollo 14 samples, almost all of which are fragmental, revealed affinities to the dark component of 12013 breccia and the exotic component in the Apollo 12 soils rather than

to the Apollo 11 and 12 mare-basalts (LSPET, 1971). The purpose of the present paper is to report chemical data we have obtained to date on Apollo 14 samples and to discuss briefly some of the implications. Data obtained in this laboratory for two Apollo 14 soils have been discussed previously (Schnetzler and Nava, 1971).

Samples

Soils: 14003, 32 < 1 mm (90% of total mass), Contingency Fines

                14148, 29 < 1 mm (93% of total mass), Surface of Trench Fines, Station G.

                14149, 45 < 1 mm (72% of total mass), Bottom of Trench Fines, Station G.

                14156, 29 < 1 mm (91% of total mass), Middle of Trench Fines, Station G.

                14421, 24 < 10 mm, Reserve from unsieved bulk fines.

Core: 14230, 105 Fines 12 cm below top of drive-tube liner, Station G.

                14230, 114 Fines 18 cm below top of liner, Station G.

                14230, 123 Fines 22 cm below top of liner, Station G.

Soil Clod: 14049, 32 Extremely friable breccia (coherent soil), 80 m east of Station B. This sample was separated into 4 sieve fractions: > 100, < 100, < 200, and < 325 mesh.

Breccias: 14305, 121 fine sawdust, 40 m west of the Comprehensive Sample site.

                14319, 8 Station H. Sample received as chip and subsequently separated on the basis of colour and mineralogy. Fraction C represents dark breccia clasts and fraction E, light coloured breccia.

Crystalline: 14310,131 basalt, Station G. Sample received as chips. 430 mg were

taken for a whole-rock sample. Mineral separates of the

remainder yielded 370 mg of pyroxene and 200 mg of

plagioclase.

Phase separations were carried out utilizing heavy-liquid, electromagnetic

and hand-picking techniques. Any sieving of samples was through nylon mesh. Any

grinding of samples was on boron carbide.

Analytical Procedures and Results

Determination of most major ($>$ 1%) and minor elements (0.01 - 1%) in

cosmochemical materials by atomic absorption spectrophotometry (AAS) using

samples as small as 0.05 g has been demonstrated (Nava, 1970; Maxwell et al., 1970;

Nava et al., 1971; and Schnetzler and Nava, 1971) to yield analytical results having

precisions and accuracies equal to, or better, than those obtained with classical

chemical methods, owing to the main atomic absorption features of high analytical

sensitivity and relative freedom from chemical interferences. Due to the limited

quantities available, a combined semi-micro analytical scheme of atomic absorption

and colorimetric spectrophotometry was devised to provide accurate bulk chemical

analysis for all of the major (Si, Ti, Al, Mg, Ca, Fe) and most of the minor (Na,

K, Mn, P, Cr) constituents of these Apollo 14 samples.

Prior to undertaking the elemental analyses, each Apollo 14 sample was

optically examined to check for obvious contaminants from grinding, sawing, and/or

packaging (plastic or aluminum vial particles). All samples appeared to be

acceptable and aliquants of approximately 50 mg (duplicates when available, as listed

in Table 1) were weighed on a precision microbalance and prepared without further grinding (either as received from MSC or as yielded by the mineral and grain size fraction separations in our laboratory) by the teflon decomposition, HF - H_3BO_3 matrix procedure described by Bernas (1968). All samples were quantitatively diluted to a volume of 100 ml, which included 0.5 ml aqua regia, 3 ml HF, and 2.8 g H_3BO_3. The AAS analysis method (Bernas, 1968) was modified, however, in the following ways in order to maximize accuracy. Close bracketing sets of synthetically prepared (from Matthey Specpure and Spex Industries spectrographic grade metals and reagent compounds and J.T. Baker acids) composite analytical standards, containing the equivalent fluoborate acid matrix concentration, were used for calibration of the double beam atomic absorption and colorimetric spectro-photometers. All of the AAS determinations were made on the original sample solution volume, without further dilution, by means of appropriate selection of burner heads and rotations. Samples were analyzed in small-numbered sets, each with their own set of composite analytical standards, in order to minimize instrumental variables such as drift. The solution matrix of fluoborate, in addition to providing a common interference suppressant matrix for AAS determination of Si, Al and Ca (acetylene-nitrous oxide flame) and of Fe (total), Mg, Na, K, Mn, and Cr (acetylene - air flame), served as a complexing agent to eliminate iron interference in colorimetric determinations of Ti by H_2O_2. Another aliquot of the AAS solution was taken for colorimetric P via molybdivanado - phosphoric acid complex. Due to limited sample availability and anticipated low concentrations in these lunar materials, H_2O^- and H_2O^+ were not determined.

Sample analysis sets consisted of: a) 14003, 14148, 14149, 14156, 14421, and 14310 whole rock; b) 14305, 14049 sized fractions, 14230 cores, and 14319 light and dark fractions; c) 14310 feldspar; and d) 14310 pyroxene. Reagent blanks were monitored during all analyses. Accuracy of this combined semi-micro analytical scheme was monitored by simultaneous analyses of U.S. Geological Survey reference silicates W-1, BCR-1, and AGV-1, and can be assessed from the results listed in Table 1, along with recent recommended literature values for comparison. Relative total precision (decomposition, volumetric, plus instrumental) of this method for the Apollo 14 duplicates and USGS reference replicates was ± 1%, or better, for most elements.

Sample 14305, a breccia sawdust, which by optical observation appeared to be clean, was analyzed for copper by AAS (and found to be <0.01%) because some sawdust samples were known to include segments from a copper-wire saw (Rose, personal communication, 1972).

The trace-element results given in Table 2 were obtained by mass-spectro-metric stable-isotope dilution. Chemical procedures utilized for the soil samples were those used previously in our Apollo 11 and 12 work (Philpotts and Schnetzler, 1970; Schnetzler and Philpotts, 1971). 14310 and its separates underwent the slightly modified chemistry utilized in the analysis of Luna 16 soils, and 14305 that were used for the Luna 16 rock chips (Philpotts et al., 1972). Blanks prepared along with the Apollo 14 samples have not yet been analyzed. However, blank values obtained using each of the chemical techniques indicate generally negligible corrections; the largest corrections (using the previously determined blank values) were for

Zr ($\sim$ 2%), Lu ($\sim$ 1.4%), and K ($\sim$ 1%) values for the plagioclase separated from 14310. All the values reported in Table 2 are for single determinations. Precision and accuracy of previous analyses (Philpotts et al., 1972) of standard rock monitors indicate that all the Apollo 14 data are probably good to within less than ± 3% relative.

Homogeneity of Apollo 14 Samples

It is apparent from the data in Tables 1 and 2 and those for 14163 and 14259 (Schnetzler and Nava, 1971), that the Apollo 14 soil samples analyzed in this laboratory are quite homogeneous in chemical composition. For these surficial fines, trench and core samples, and the soil clod, the largest ranges in element concentrations, expressed in terms of the percent deviations from the mean of the extreme values, were: Na 12; P 11; K 9; Ti, Mn, Cr 8; Zr 7; Al, Li 6; Mg, Rb 5 and Fe 4. Ranges for other elements were smaller and close to the expected precisions of the analytical techniques. The apparent ranges for Mn and Cr may be analytical, in part, because of the low concentrations. The variations of Na and K are thought to be largely real. Na and K tend to vary sympathetically. The fact that Zr also appears to be positively correlated with Na and K (as does Li) suggests that selective volatility is not the cause of these variations. Ti shows some positive correlation with Na and K but there appear to be other factors (ilmenite?) influencing its concentration. P variations appear to be relatively random and may reflect somewhat heterogeneous distribution of phosphates. Al is low in the soil clod samples 14049, two of which have relatively high Mg and Fe; this might reflect a somewhat lower plagioclase/mafics ratio for these samples. The sympathetic variations in alkalis and Zr most probably reflect somewhat heterogeneous distribution of a phase rich in these elements, possibly

6

resembling the mesostasis material of lunar basalts. Our data do not indicate any definite general variations in soil composition correlated either with grain size or with collection depth. Na and K (and correlated elements) are lowest in 14259 (Schnetzler and Nava, 1971), and highest in 14149 and 14049 (100-200 mesh fraction). 14259 is the finest grained and 14149 the coarsest grained of the soil samples (LSPET, 1971) and this suggests a possible correlation of alkalis with grain size. However, 14421 a coarser grained sample from the same site as 14259 is also low in K. The data indicate a possible geographic variation in alkalis, inasmuch as 14259 was collected farthest away from Cone Crater, and except for 14049, 14149 was the closest. However, with the limited number of samples, and lacking material from the ridge Fra Mauro Formation and Cone Crater throwout, firm conclusions are not possible at this time.

Although there is some heterogeneity as discussed above, the most interesting conclusion resulting from inter-comparison of Apollo 14 soil samples is that they are, in fact, remarkably homogeneous. This uniformity is brought out in Figure 1 for the trace elements; concentrations have been normalized to the chondritic values given in the last column of Table 2. The situation is in marked contrast to that holding for the Apollo 12 soils (eg. Schnetzler and Philpotts, 1971). The homogeneity of Apollo 14 soils indicates thorough mixing of the regolith at this site, and/or relatively homogeneous source rocks with chemical composition very similar to that of the soils.

14305 breccia sawdust is similar in many respects in chemical composition to the soils (Table 1). However, Al_2O_3 is distinctly lower and MgO distinctly higher

in the breccia. Also most of the trace elements are enriched in the breccia although their relative concentrations are not much affected (Table 2; Fig. 1). These differences relative to the soil could be accounted for in terms of a deficiency of feldspar and the presence of an accessory phase(s) rich in trace elements. For breccia 14319 we have at present only the major element analyses of light and dark portions reported in Table 1. In terms of Al_2O_3 and MgO, 14319 is intermediate between 14305 breccia and the soils. The high P_2O_5, Na_2O and K_2O of the 14319 materials indicate that other trace elements might also be relatively enriched. The light and dark portions of 14319 show some chemical differences, particularly for SiO_2 and TiO_2; it appears likely, however, that the bulk concentrations of these oxides in 14319 might be close to those for 14305 breccia. The variations in composition within and between these breccias tempt the speculation that the average chemical composition of the Fra Mauro breccias might be very similar to the soil composition (except for solar wind components, etc.).

14310 Basalt

14310 is the only Apollo 14 basalt that we have studied. It is apparent from Tables 1 and 2 and Figure 1 that 14310 is similar in chemical composition to the Apollo 14 soils. However, the composition of 14310 is not within our soil range. Whereas the major element data for the breccias indicate an excess of mafic phases relative to the soil, the 14310 data indicate an excess of plagioclase. Caution is warranted, of course, in comparing 4 b.y. old rocks (Turner et al., 1971; Papanastassiou and Wasserburg, 1971; Compston et al., 1971) with soil samples that were evolving up to the time of their collection. Nevertheless, the fact that the

14310 and breccia compositions bracket those of the soils suggests that any addition of foreign components to the soils may not have greatly affected the concentrations of the elements we have determined. The 14310 composition is matched remarkably well by a mixture of soil and feldspar; the data appear to preclude addition or subtraction of significant amounts of other components. These points are well illustrated in Figure 2 in which the compositions of the soil average, 14310 separated plagioclase (Tables 1 and 2), and a 4:1 soil-feldspar mixture are plotted, all data being normalized to the composition of 14310 whole-rock. As can be seen, the concentrations in the mixture are within ± 10% of those in 14310 for almost all of the 25 elements. The major discrepancy is for Eu which is 25% higher in the mixture than in 14310. The agreement among the soil Eu values indicates that this discrepancy is not due to error in the average soil value. It is possible, however, that the soils contain, as a foreign component, plagioclase (anorthosite?) with a very large positive Eu anomaly. If this is the explanation of the discrepancy then the amount of feldspar needed in a mixture with uncontaminated soil to match the 14310 composition would be greater than the indicated 20%. Analytical error is possible in the determination of the 14310 whole-rock and plagioclase Eu concentrations but we see no reason at the present time to doubt these values. Helmke and Haskin (1972) report a 14310 whole-rock Eu concentration of 2.08 ppm and Hubbard et al. (1972) one of 2.15 ppm, in good agreement with our value of 2.09 ppm. The Eu discrepancy would be reduced if feldspar with less Eu than 14310 plagioclase were used in the mixture. A lower feldspar Eu concentration could be explained by one or both of two possibilities. Feldspar from a more rapidly cooled chemical equivalent of 14310 would be expected to have a smaller

Eu anomaly because of kinetics, inherent contamination, etc. However, if this were

the explanation Sr would be expected to show a discrepancy similar to that for Eu,

and it does not. The second possibility entails having in the mixture a feldspar with

lower Eu/Sr than 14310 plagioclase. Eu/Sr in lunar basalts and constituent feldspars

tends to increase with increasing overall trace element concentration which presumably

reflects extent of differentiation. The lowest Eu/Sr yet reported for a lunar plagio-

clase is for 15415 anorthosite (Hubbard et al., 1971); use of this material in the 20%

plagioclase-soil mixture would result in a Eu excess of only 7%.

The second largest discrepancy in modeling 14310 in terms of a soil-feldspar

mixture is for Zr. This discrepancy is probably not due to analytical error; the soil

data are internally consistent, and 14310 whole-rock has a reasonably Zr/Hf ratio.

It could well be due to the presence in the 14310 sample analyzed of an excess of an

accessory phase rich in Zr. A deficiency in 14310 of ilmenite etc. could similarly

explain the Ti discrepancy.

Although there are some discrepancies, the overall compositional match of

14310 whole-rock and the 4:1 soil-plagioclase mixture is good. It seems entirely

possible that the soils come close to representing the average composition of Apollo

14 rocks, at least for the elements we have studied, and that 14310 deviates from this

typical composition in containing an excess of plagioclase. If 14310 represents a fused

soil or breccia as has been suggested on the basis of its "meteoritic" component

(Morgan et al., 1972) then the feldspar excess indicates local heterogeneity in

surficial fragmental material at that time. If 14310 represents an igneous rock then

both the excess feldspar and the "meteoritic" component may have been added by

assimilation and/or by mechanical incorporation of xenolithic material in accord with the suggestion of Ridley et al. (1972).

Analytical data for feldspar (An_{84}) and pyroxene (pigeonite) separated from 14310 are given in Tables 1 and 2. The phases were separated utilizing heavy liquid, electromagnetic, and hand-picking techniques; microscopic examination indicated that the feldspar separate was about 99% pure whereas the pyroxene separate contained about 10% contaminants. Except for Li, Sr and Eu, which are largely accounted for, the whole-rock, plagioclase, and pyroxene data indicate that about half of the whole-rock trace-element content is concentrated in accessory phases; this is in accord with previous observations (Philpotts and Schnetzler, 1970; Schnetzler and Philpotts, 1971; Schnetzler et al., 1972).

The Eu^{2+}/Eu^{3+} values reported for 14310 feldspar and pyroxene in Table 2 were calculated according to the method of Philpotts (1970). Eu^{2+}/Eu^{3+} ratios calculated using the whole-rock data are within 20% of these mineral-mineral values. The plagioclase ratio is very similar to those calculated for plagioclases from two Apollo 11 basalts (Philpotts, 1970) and lower than those for 12035, 12040 (Schnetzler and Philpotts, 1971), and 15555 (Schnetzler et al., 1972) plagioclases. The pyroxene Eu^{2+}/Eu^{3+} ratio is higher than any previously determined for this mineral in lunar samples. The difference between the 14310 pyroxene and feldspar ratios is smaller than any previously determined for lunar samples with the exception of that for 12021 which shows a similar spread. The spread in pyroxene-feldspar ratios tends to be smaller in finer grained rocks and may be due to kinetics, inherent contamination of phases, or other factors. Taking this effect into account and assuming (a) equilibrium

in all cases, (b) the validity of the calculation, and (c) that Eu^{2+}/Eu^{3+} reflects redox conditions, then it appears that 14310 crystallized under conditions slightly more reducing than those holding for the Apollo 11 basalts and perhaps similar to those holding for 12035, 12040 and 15555. These relationships appear to be in accord with petrographic observations (Ridley et al., 1972).

Petrogenesis

The Apollo 14 materials appear to be identical in composition to the exotic fragments in the Apollo 12 regolith that were termed KREEP (Hubbard and Gast, 1971). KREEP-type material also appears to be abundant in the Apollo 15 soils judging from their chemistry (LSPET, 1972; Schnetzler et al., 1972; our unpublished data). In contrast, the compositions of the soils from Apollo 11 (Philpotts and Schnetzler, 1970) and Luna 16 (Philpotts et al., 1972) indicate very little KREEP component. These bulk chemistry conclusions are in accord with the studies by Reid et al. (1972) of regolith glasses. The abundance of KREEP at the Apollo 12, 14 and 15 sites and its paucity at the Apollo 11 and Luna 16 sites, suggest that this material may be related to the Imbrium basin or its throwout. The Apollo 15 γ-ray experiment is of interest in this respect in that it indicated high Th, U, and K concentrations (as in KREEP) in Mare Imbrium and Oceanus Procellarum and a smooth decrease in concentration away from these regions (Metzger et al., 1972). It appears, therefore, that Apollo 14 type material may have a restricted geographical distribution.

Apollo 14 material shares with the mare basalts certain lunar characteristics such as low volatile content. However, relative to the mare basalts, Apollo 14 material has higher concentrations of large-ion lithophile trace elements and Al, higher Mg/Fe, and lower Fe. Some of the difficulties encountered in attempting to relate these two types of material have been touched upon by Hubbard and Gast (1971). It appears most unlikely that they are directly related to each other in terms of various degrees of partial fusion or fractional crystallization of the same source material. If they were so related it is difficult to explain the equivalent concentrations of Mg considering the distinctly different Al, Fe, and trace-element concentrations, for example. It appears that different source materials are required. There appears to be general agreement among experimental petrologists that Apollo 14 material probably resulted from partial fusion of an olivine-plagioclase-pyroxene assemblage (Biggar et al.,1972a; Ford et al., 1972; Kushiro, 1972; Ringwood et al., 1972; Walker et al., 1972). The mare-basalts are of less certain origin (Biggar et al., 1972b).

It has been suggested that the different source materials of the Fra Mauro and the mare basalts reflect primary accretion layering of the moon, with the more refractory source of the (older) Fra Mauro basalts being at shallower depths than the source of the mare basalts (Hubbard and Gast, 1971; Gast and McConnell, 1972; Ringwood et al., 1972). One possible problem with this hypothesis is that it requires material being added during the later stages of accretion to be more refractory than the earlier materials, whereas if any heterogeneity in accretion is expected at all, it might generally be expected in the reverse direction. Further, ratios of volatile to involatile elements for both the high alumina and the mare basalts do not appear to support this hypothesis.

13

K and Ba may be the best pair to consider in that they show good geochemical coherence in igneous processes (hence K/Ba for a basalt is expected to be quite similar to K/Ba of its source rock) but have quite different volatilities. K/Ba ratios of 8.4 and 4.5 for trace element enriched and depleted Apollo 11 mare-type basalts, respectively (Philpotts and Schnetzler, 1970), bracket the ratios for all other bulk lunar samples that we have analyzed. The Apollo 14 samples have K/Ba ratios from 4.9 to 6.4 (Table 2); 12013 samples have ratios from 4.6 to 6.6 (Schnetzler et al., 1970). Ratios for Apollo 11 enriched-type, normal Apollo 12 (Schnetzler and Philpotts, 1971), and Apollo 15555 (Schnetzler et al., 1972) mare-type basalts are higher than those for the KREEP-type materials. But ratios for Apollo 11 depleted-type, Apollo 12038, and Luna 16 (Philpotts et al., 1972) mare-type basalts are at or below the lower values of the KREEP-type material. Thus no good case can be made for K/Ba being distinctly different in the source materials of the two basalt types. On the contrary, the evidence tends to indicate that K/Ba may have been identical, initially, in both source materials. This appears to be difficult to reconcile with a simple model of volatility dependent, heterogeneous accretion. Any simple volatility related process sufficient to effect sizable increases in the concentrations of refractory elements such as Al might be expected to effect very extensive depletion of volatile elements such as K. It is possible, of course, that all of the accreting material was depleted in volatile elements to the extent that they were at essentially equilibrium values prohibiting further loss. However, before giving exhaustive consideration to such possibilities, homogeneous accretions models merit appraisal.

O'Hara and colleagues (Biggar et al., 1972a; Ford et al., 1972) have suggested that Apollo 14 type aluminous liquids might be produced by partial melting in

systems rich in alkalis and/or water, and that these volatiles have subsequently been lost. The mare-type basalts might then be produced by partial melting of the volatile and feldspar depleted residue. However, as far as alkali loss is concerned there is first the problem of the mechanism whereby significant loss could be effected and secondly the fact that the K/Ba (etc.) data and the Rb-Sr data show no evidence that any significant alkali loss has taken place. Similarly, the available data on aluminous lunar rocks show no evidence (such as hydrous phases, deuteric alteration, etc.) of significant concentrations of water in their evolution. At the present time these ideas, therefore, appear to be interesting but unsupported speculations.

An apparently more attractive homogeneous accretion model is one in which Apollo 14 and other aluminous lunar materials represent primary aluminous liquid and plagioclase rich cumulates in various proportions formed in an igneous event taking place during the first few hundred million years of lunar evolution, whereas mare-type basalts result from later fusion of mafic-rich cumulates formed during the initial event(s). This model seems to fit adequately the chemical and geochronologic constraints. Detailed thermal calculations for this model have not yet been made but it appears that modifications of Hays' (1972) third model would suffice.

References

BERNAS B. (1968) A new method for decomposition and comprehensive analysis of silicates by atomic absorption spectrometry. Anal. Chem. 40, 1682-1686.

BIGGAR G. M., FORD C. E., HUMPHRIES D. J., WILSON G. and O'HARA M. J. (1972a) Melting relations of more primitive mare-type basalts 14053 and M (Reid 1970); and of breccia 14321 and soil 14162 (average lunar crust?) (abstract). In Lunar Science - III (editor C. Watkins), 74-76, Lunar Science Institute Contr. No. 88.

BIGGAR G. M., O'HARA M. J., HUMPHRIES D. J. and PECKET A. (1972b) Experimental crystallization of Apollo 11 and 12 lavas - a re-examination (abstract). In Lunar Science - III (editor C. Watkins), pp. 77-79, Lunar Science Institute Contr. No. 88.

COMPSTON W., VERNON M. J., BERRY H. and RADOWSKI R. (1971) The age of the Fra Mauro formation: a radiometric older limit. Earth Plan. Sci. Lett. 12, 55-58.

FLANAGAN F. J. (1969) U.S. Geological Survey Standards - II, First compilation of data for the new U.S.G.S. rocks. Geochim. Cosmochim. Acta 33, 81-120.

FLEISCHER M. (1969) U.S. Geological Survey Standards - I. Additional data on rocks G-1 and W-1, 1965-1967. Geochim. Cosmochim. Acta 33, 65-79.

FORD C. E., HUMPHRIES D. J., WILSON G., DIXON D., BIGGAR G. M. and O'HARA M. J. (1972) Experimental petrology of high alumina basalt, 14310, and related compositions (abstract). In Lunar Science - III (editor C. Watkins), 274-276, Lunar Science Institute Contr. No. 88.

GAST P. W. and McCONNELL R. K. Jr. (1972) Evidence for initial chemical layer-
  ing of the moon (abstract). In <u>Lunar Science</u> - III (editor C. Watkins), 289-
  290, Lunar Science Institute Contr. No. 88.

HAYS J. F. (1972) Radioactive heat sources in the lunar interior. <u>Phys. Earth</u>
  <u>Planet. Interiors</u> <u>5</u>, 77-84.

HELMKE P. A. and HASKIN L. A. (1972) Rare earths and other trace elements in
  Apollo 14 lunar samples (abstract). In <u>Lunar Science</u> - III (editor C. Watkins),
  366-368, Lunar Science Institute Contr. No. 88.

HUBBARD N. J. and GAST P. W. (1971) Chemical composition and origin of non-
  mare lunar basalts. <u>Proc. Second Lunar Sci. Conf., Geochim. Cosmochim.</u>
  <u>Acta</u> Suppl. 2, Vol. 2, 999-1020, MIT Press.

HUBBARD N. J., GAST P. W., MEYER C., NYQUIST L. E. and SHIH C. (1972)
  Chemical composition of lunar anorthosites and their parent liquids.
  <u>Earth Plan. Sci. Lett.</u> (in press).

HUBBARD N. J., GAST P. W., RHODES M. and WIESMANN H. (1972) Chemical
  composition of Apollo 14 materials and evidence for alkali volatilization
  (abstract). In <u>Lunar Science</u> - III (editor C. Watkins), 407-409, Lunar
  Science Institute Contr. No. 88.

KUSHIRO I. (1972) Petrology of lunar high-alumina basalt (abstract). In <u>Lunar</u>
  <u>Science</u> - III (editor C. Watkins), 466-468, Lunar Science Institute Contr.
  No. 88.

LSPET (Lunar Sample Preliminary Examination Team) (1971) Preliminary examina-
  tion of lunar samples from Apollo 14, <u>Science</u> <u>173</u>, 681-693.

References

LSPET (Lunar Sample Preliminary Examination Team) (1972) The Apollo 15 lunar samples: a preliminary description. Science 175, 363-375.

MAXWELL J. A., PECK L. C. and WIIK H. B. (1970) Chemical composition of Apollo 11 lunar samples 10017, 10020, 10072 and 10084. Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 1, Vol. 2, 1369-1374, Pergamon.

METZGER A. E., TROMBKA J. I., PETERSON L. E., REEDY R. C. and ARNOLD J. R. (1972) A first look at the lunar orbital gamma ray data (abstract). In Lunar Science - III (editor C. Watkins), 540-541, Lunar Science Institute Contr. No. 88.

MORGAN J. W., KRÄHENBÜHL U., GANAPATHY R. and ANDERS E. (1972) Volatile and siderophile elements in Apollo 14 and 15 rocks (abstract). In Lunar Science - III (editor C. Watkins), 555-557, Lunar Science Institute Contr. No. 88.

MORGAN J. W., LAUL J. C., KRÄHENBÜHL U., GANAPATHY R. and ANDERS E. (1972) Major impacts on the moon: chemical characterization of projectiles (abstract). In Lunar Science - III (editor C. Watkins), 552-554, Lunar Science Institute Contr. No. 88.

NAVA D. F. (1970) Atomic absorption and classical chemical analyses of the Lost City meteorite (abstract). E.O.S. Transactions of the American Geophysical Union, Vol. 51, p 580.

NAVA D. F., WALTER L. S. and DOAN A. S. Jr. (1971) Chemistry and mineralogy of the Lost City meteorite. J. Geophys. Res. 76, 4067-4071.

PAPANASTASSIOU D. A. and WASSERBURG G. J. (1971) Rb-Sr ages of igneous rocks from the Apollo 14 mission and the age of the Fra Mauro formation. Earth Plan. Sci. Lett. 12, 36-48.

PHILPOTTS J. A. (1970) Redox estimation from a calculation of Eu^{2+} and Eu^{3+} concentrations in natural phases. Earth Plan. Sci. Lett. 9, 257-268.

PHILPOTTS J. A. and SCHNETZLER C. C. (1970) Apollo 11 lunar samples: K, Rb, Sr, Ba and rare-earth concentrations in some rocks and separated phases. Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 1, Vol. 2, pp. 1471-1486. Pergamon.

PHILPOTTS J. A., SCHNETZLER C. C., BOTTINO M. L., SCHUHMANN, S. and THOMAS H. H. (1972) Luna 16: Some Li, K, Rb, Sr, Ba, rare-earth, Zr, and Hf concentrations. Earth Plan. Sci. Lett. 13, 429-435.

REID A. M., RIDLEY W. I., WARNER J., HARMON R. S. and BRETT R. (1972) Chemistry of highland and mare basalts as inferred from glasses in the lunar soils (abstract). In Lunar Science - III (editor C. Watkins), 640-642, Lunar Science Institute Contr. No. 88.

RIDLEY W. I., WILLIAMS R. J., BRETT R. and TAKEDA H. (1972) Petrology of lunar basalt 14310 (abstract). In Lunar Science - III (editor C. Watkins), 648-650, Lunar Science Institute Contr. No. 88.

RINGWOOD A. E., GREEN D. H. and WARE N. G. (1972) Experimental petrology and petrogenesis of Apollo 14 basalts (abstract). In Lunar Science - III (editor C. Watkins), 654-656, Lunar Science Institute Contr. No. 88.

ROSE H. J. (1972) Private Communication.

References

SCHNETZLER C. C. and NAVA D. F. (1971) Chemical composition of Apollo 14 soils 14163 and 14259. Earth Plan. Sci. Lett. 11, 345-350.

SCHNETZLER C. C., PHILPOTTS J. A. and BOTTINO M. L. (1970) Li, K, Rb, Sr, Ba and rare-earth concentrations, and Rb-Sr age of lunar rock 12013. Earth Plan. Sci. Lett. 9, 185-192.

SCHNETZLER C. C. and PHILPOTTS J. A. (1971) Alkali, alkaline earth, and rare-earth element concentrations in some Apollo 12 soils, rocks, and separated phases. Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 2, Vol. 2, 1101-1122. MIT Press.

SCHNETZLER C. C., PHILPOTTS J. A., NAVA D. F., SCHUHMANN, S. and THOMAS H. H. (1972) Geochemistry of Apollo 15 basalt 15555 and soil 15531. Science 175, 426-428.

TURNER G., HUNEKE J. C., PODOSEK F. A. and WASSERBURG G. J. (1971) ^{40}Ar-^{39}Ar ages and cosmic ray exposure ages of Apollo 14 samples. Earth Plan. Sci. Lett. 12, 19-35.

WALKER D., LONGHI J. and HAYS J. F. (1972) Experimental petrology and origin of Fra Mauro rocks and soil. (abstract). In Lunar Science - III (editor C. Watkins), 770-772, Lunar Science Institute Contr. No. 88.

Table 1: Major Element Composition (in wt. %) of Apollo 14 Samples and Standard Rock Monitors

(Analyst: D. F. Nava)

Constituent	Soils					Core 14230		
	14421,24	14003,32	14148,29	14156,29	14149,45	,105	,114	,123
SiO_2	48.4	48.2	48.5	48.1	48.0	48.2	48.4	48.0
TiO_2	1.70	1.75	1.71	1.71	1.61	1.66	1.73	1.62
Al_2O_3	17.52	17.69	17.38	17.15	17.45	17.27	17.03	17.60
MgO	9.41	9.52	9.66	9.55	9.54	9.43	9.54	9.45
CaO	10.49	10.32	10.40	10.16	10.54	10.78	10.94	10.80
Na_2O	0.68	0.69	0.71	0.72	0.75	0.70	0.70	0.70
K_2O	0.52	0.55	0.53	0.53	0.58	0.56	0.56	0.56
FeO	10.54	10.53	10.55	10.55	9.95	10.17	10.21	10.09
MnO	0.14	0.13	0.13	0.14	0.13	0.12	0.13	0.13
P_2O_5	0.48	0.49	0.50	0.49	0.48	0.48	0.48	0.49
Cr_2O_3	0.19	0.18	0.19	0.19	0.19	0.19	0.19	0.19
H_2O-	-	-	-	-	-	-	-	-
Sum of Constituents Determined:	100.07	100.05	100.26	99.29	99.22	99.56	99.91	99.63
Sample Weights, mg:	49.8 50.1	50.1 49.9	49.8	50.0	49.9	50.1	49.9	50.0

Table 1: Major Element Composition (in wt. %) of Apollo 14 Samples and Standard Rock Monitors

(Analyst: D. F. Nava)

| Constituent | Soil Clod 14049,32 | | | Breccias | | | Basalt 14310,131 | | |
	< 325 mesh	< 200 mesh	< 100 mesh	14305,121	14319,8 -L, dark	14319,8 -E, light	Whole-Rock	Feldspar	Pyroxene
SiO_2	48.4	48.4	48.3	48.2	47.7	49.3	48.3	46.6	50.6
TiO_2	1.77	1.75	1.75	1.71	1.63	1.82	1.25	0.10	.1.28
Al_2O_3	16.74	15.65	16.20	15.16	16.40	15.76	20.74	32.84	8.84
MgO	9.32	10.23	10.00	11.12	10.71	10.12	8.00	0.63	17.57
CaO	10.96	10.64	10.63	10.13	10.33	9.67	11.61	17.57	7.11
Na_2O	0.73	0.71	0.74	0.87	0.86	0.84	0.76	0.93	0.34
K_2O	0.58	0.55	0.60	0.73	0.69	1.05	0.52	0.31	0.27
FeO	10.37	10.86	10.83	10.88	10.03	9.76	7.78	0.84	13.68
MnO	0.14	0.14	0.14	0.13	0.12	0.12	0.11	<0.01	0.20
P_2O_5	0.50	0.40	0.44	0.64	0.83	0.60	0.38	0.06	0.25
Cr_2O_3	0.20	0.21	0.20	0.19	0.16	0.16	0.17	0.01	0.35
H_2O^-	-	-	-	-	-	-	-	-	-
Sum of Constituents Determined:	99.71	99.54	99.83	99.76	99.46	99.20	99.62	99.90	100.49
Sample Weights, mg:	50.0 49.8	50.1	49.9	50.0 50.1	50.0 50.1	49.8 50.1	50.1 50.2	50.0	50.0

Table 1: Major Element Composition (in wt. %) of Apollo 14 Samples and Standard Rock Monitors

(Analyst: D. F. Nava)

Standard Rock Monitors

Constituent	BCR-1 Split 22 *	BCR-1 Position 22 ‡	BCR-1 Position 22 ⊕	W-1 *	W-1 ‡	W-1 ⊕	AGV-1 Split 70 ‡	AGV-1 Position 12 ⊕
SiO_2	54.6	54.6	54.58	52.7	52.7	52.64	59.4	58.99
TiO_2	2.19	2.20	2.23	1.06	1.11	1.07	1.06	1.08
Al_2O_3	13.65	13.61	13.66	15.04	15.01	14.85	17.32	17.01
MgO	3.45	3.44	3.28	6.81	6.73	-6.62	1.69	1.49
CaO	7.11	7.11	6.95	10.86	10.81	10.96	4.87	4.98
Na_2O	3.33	3.25	3.31	2.09	2.16	2.15	4.35	4.33
K_2O	1.72	1.70	1.68	0.71	0.72	0.64	2.85	2.89
FeO	11.84	11.85	12.22	9.94	9.89	9.98	5.98	6.11
MnO	0.18	0.18	0.18	0.17	0.17	0.17	0.09	0.10
P_2O_5	0.35	0.35	0.36	0.14	0.13	0.14	0.47	0.49
Cr_2O_3	< 0.003	< 0.003	~ 0.002	0.018	0.015	0.016	< 0.003	~ 0.002
H_2O^-	0.86	0.86	0.83	0.17	0.17	0.13	0.99	1.03
Sum of Constituents Determined:	99.28	99.15	99.18	99.71	99.61	99.33	99.07	98.49
Sample Weights, mg:	50.2 50.2 49.9	50.0 50.2		49.8 50.1 50.0	50.0 50.1		49.7 49.7	

23

Table 1: Major Element Composition (in wt. %) of Apollo 14

Samples and Standard Rock Monitors (Analyst: D. F. Nava)

Footnotes

*Analyzed with 14230, 14049, 14305, 14319, and 14310 separates.

ǂAnalysed with 14421, 14003, 14148, 14156, 14149, and 14310

whole-rock.

⊕Literature values - BCR-1 and AGV-1, Table 4 of Flanagan

(1969); W-1, Table 1, column 3b of

Fleischer (1969). Total iron expressed

as FeO.

Table 2: Trace Element Concentrations (in ppm by wt.) in Apollo 14 Samples

	Soils				
	14421	14003	14148	14156	14149
Li	31.7	32.1	30.3	30.5	34.0
K	3980	4260	4190	4190	4730
Rb	13.9	14.6	14.8	14.7	14.5
Sr	180.5	176.5	177.4	179.2	177.5
Ba	806	823	824	813	827
Ce	170	170	171	169	169
Nd	105	107	107	107	108
Sm	29.7	30.2	30.6	29.9	30.1
Eu	2.68	2.63	2.55	2.57	2.56
Gd	-	35.5	34.4	34.9	34.7
Dy	38.8	38.9	38.9	38.9	39.3
Er	23.0	22.9	23.2	23.1	23.4
Yb	21.7	21.6	21.6	21.8	22.0
Lu	3.27	-	3.31	3.27	3.34
Zr	858	877	992	913	907
Hf	20.9	20.7	20.6	-	20.8
K/Rb	286	291	283	285	326
K/Ba	4.94	5.18	5.08	5.15	5.71
Rb/Sr	0.0770	0.0828	0.0839	0.0820	0.0817
Ce/Yb	7.85	7.87	7.92	7.75	7.68
Sm/Eu	11.1	11.5	12.0	11.6	13.4
Sr/Eu	67.4	67.1	69.6	69.7	69.3
Zr/Hf	41.1	42.4	48.2	-	43.6
Eu^{2+}/Eu^{3+}	-	-	-	-	-
Sample Weight	0.100g	0.10076g	0.11739g	0.10318g	0.09049g

Table 2: Trace Element Concentrations (in ppm by wt.) in Apollo 14 Samples

| | Breccia 14305 | Basalt 14310 | | | Normalizing Values |
	Sawdust	Whole-Rock	Feldspar	Pyroxene	
Li	38.4	27.5	24.0	28.9	1.8
K	5940	3920	2230	2040	1000
Rb	19.0	12.7	4.39	6.78	3
Sr	165.9	180.9	281.6	72.6	11
Ba	924	649	373	343	3.66
Ce	193	143	35.0	89.6	0.787
Nd	121	87.9	20.0	59.3	0.580
Sm	34.4	24.6	5.06	17.5	0.185
Eu	2.56	2.09	2.87	0.971	0.071
Gd	40.1	–	–	22.4	0.256
Dy	46.7	31.7	5.79	26.8	0.303
Er	28.3	19.3	3.29	16.7	0.182
Yb	23.3	18.1	2.97	17.0	0.188
Lu	3.82	2.66	0.440	–	0.034
Zr	1060	893	155	709	7
Hf	28.6	21.0	–	16.3	0.2
K/Rb	313	308	508	300	333
K/Ba	6.42	6.04	5.98	5.94	273
Rb/Sr	0.1142	0.0704	0.0156	0.0934	0.273
Ce/Yb	8.28	7.90	11.8	5.27	4.19
Sm/Eu	13.4	11.8	1.76	18.0	2.61
Sr/Eu	65.2	86.6	98.1	74.8	155
Zr/Hf	37.0	42.5	–	43.5	35.0
Eu^{2+}/Eu^{3+}	–	5	41	2.9	
Sample Weight	0.09353g	0.11283g	0.11709g	0.15835g	

Figure Captions

Figure 1.   Chondrite normalized trace element concentrations for 14305 breccia sawdust, 14310 whole-rock basalt, and seven Apollo 14 soil samples.

Figure 2.   14310 whole-rock normalized elemental concentrations for average Apollo 14 regolith fines (x), 14310 plagioclase (⊙), and a 4:1 soil:feldspar mixture (●).
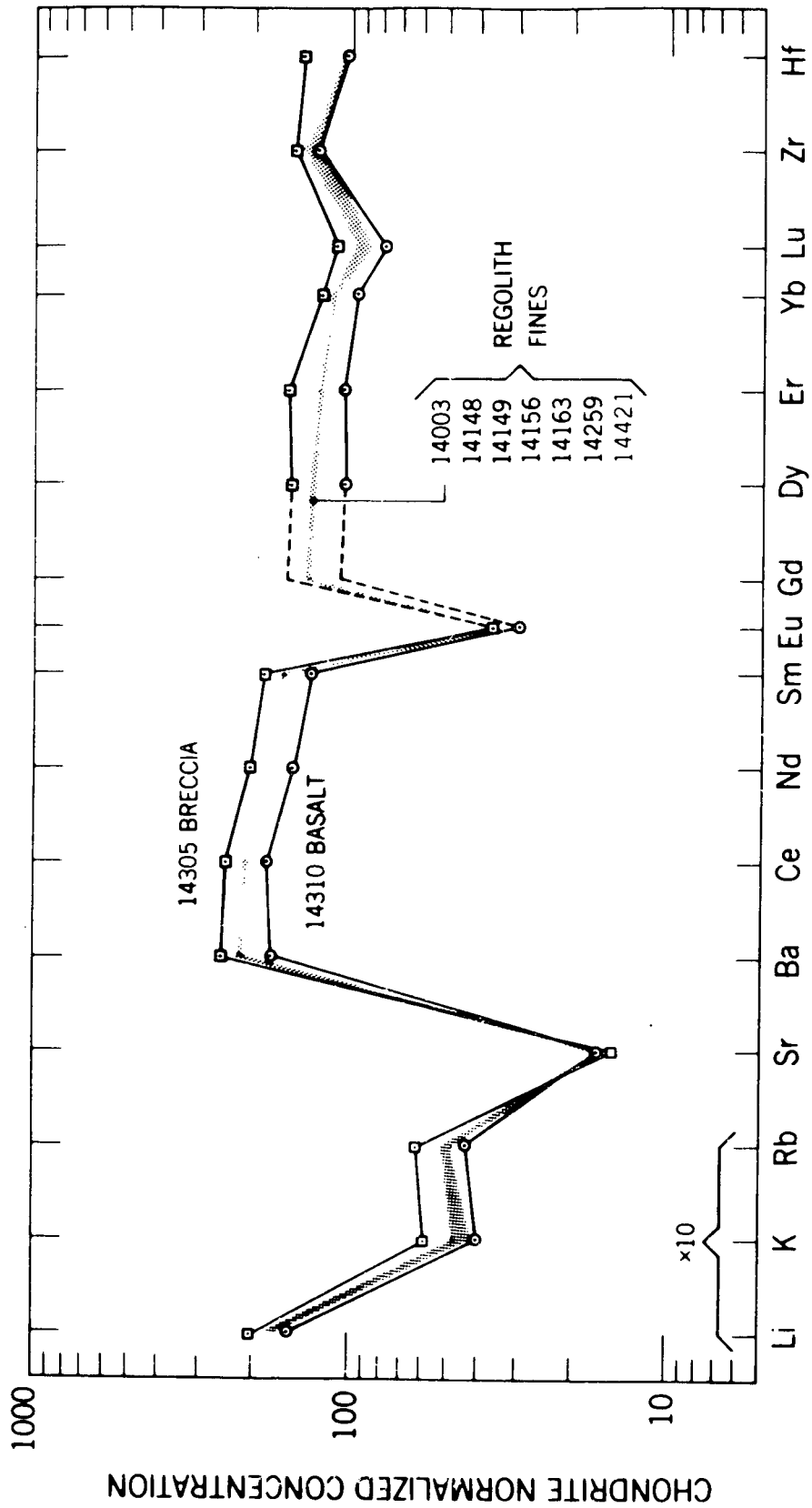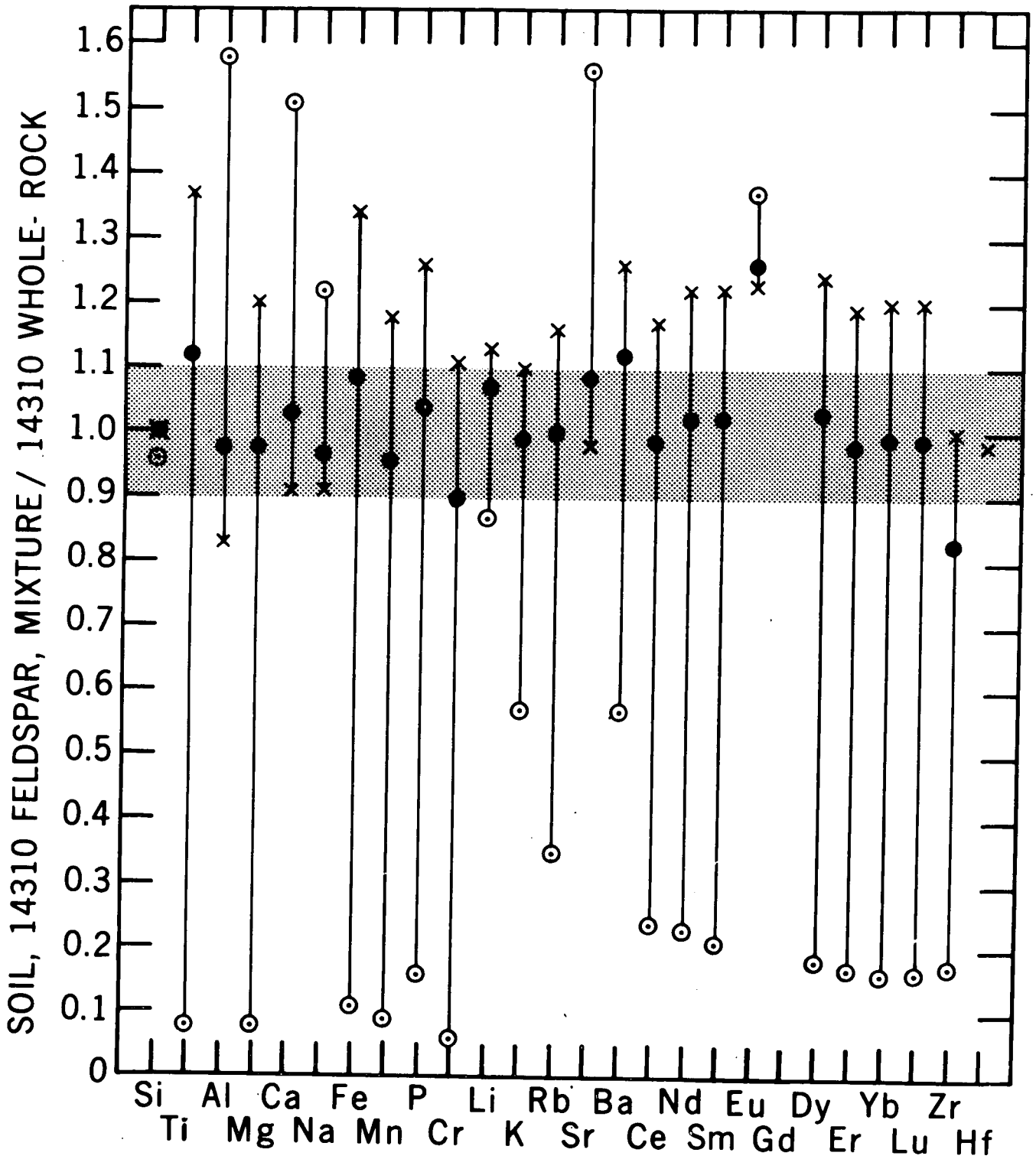
Fig. 1.

Fig. 2