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Chemical, mineralogical and textural systematics  
of non-mare melt rocks: Implications  
for lunar impact and volcanic processes

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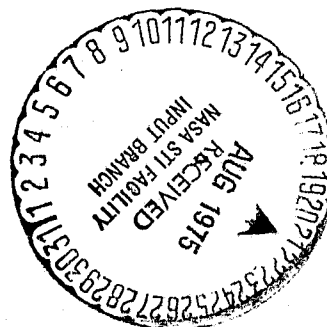
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### ABSTRACT

Based on a synthesis of chemical data for over 200 samples, the non-mare rocks with fine grained melt textures can be classified into 7 major groups: anorthositic basalts, troctolitic basalts, VHA basalts, Apollo 14-type KREEP basalts, Apollo 15-type KREEP basalts, Apollo 17-type KREEP basalts, and aluminous mare basalts. Review of chemical, mineralogical, textural and experimental evidence leads to the following preferred hypotheses for the origins of these rocks. The anorthositic, troctolitic, VHA and Apollo 14-type KREEP basalts, which characteristically contain xenolithic ANT-suite debris, have high siderophile element abundances and contain metal of non-lunar Ni-Co content, are very probably impact total melts of varying mixtures of ANT-suite rocks and a KREEP component (eg. Apollo 15-type KREEP basalt). The aluminous mare basalts are possibly partial melts from depths of  $\sim 200$  km, and, if so, imply that the lunar mantle is heterogeneous in Al and LIL elements. Isotopic data require a two-stage origin for the Apollo 15 - and Apollo 17 - type KREEP basalts. It is possible that they were ultimately either partial melts or residual liquids derived from depths of  $\sim 100$  km and erupted at  $\sim 4.3 - 4.1$  b.y., but they must then have been totally remelted (without mixing) by large scale impacts at  $\sim 4.0 - 3.9$  b.y.

## INTRODUCTION

The Apollo and Luna missions to the moon have provided a wealth of information on the constitution of the surface regions of the planet, and it is now appropriate to systematize this information and critically re-examine its petrogenetic implications. For some time it has been recognized that the textural diversification in lunar rocks due to impact processes is very great, and this has led to an emphasis on chemical composition as the major petrogenetic index. This certainly remains valid, but with the large suite of samples now available, it has become possible to also consider in systematic fashion the substantial amount of genetic information available in the textures of the samples. Clearly, the genetic constraints imposed by combining chemical, textural, mineralogical and experimental data must be stronger than those imposed by any of these alone.

This paper focusses attention on a texturally very distinctive group of lunar rocks - the non-mare melt rocks. These rocks show evidence of existing at the lunar surface as liquids or as liquids with varying amounts of suspended crystalline material. It is important, however, to distinguish those liquids which are products of impact melting

from those which are volcanic in origin and which may therefore have a direct bearing on the constitution of the lunar interior.

The purposes of this paper are twofold: to propose a classification for non-mare melt rocks, and to review the evidence from a number of different sources bearing on their origins. In doing this an attempt has been made to reference the most important relevant papers for each concept discussed, but it has been impossible to include all pertinent references.

#### CLASSIFICATION AND NOMENCLATURE

The term "melt rock" is used here in a purely descriptive sense for a fine grained rock whose dominant texture (apart from any xenolithic clasts) is either intersertal, subophitic, vitrophyric, variolitic or poikilitic. Grainsizes of intersertal to variolitic melt rocks are generally less than 100 microns; in poikilitic melt rocks, the dimensions of chadacrysts and the interchadacryst distances are also generally less than 100 microns, although some individual oikocrysts are larger than this. The intersertal, subophitic, vitrophyric and variolitic textures are universally accepted as indicative of crystallization from a melt. The poikilitic texture is more controversial, but

the arguments advanced by Simonds et al. (1973) and Grieve (1975) for crystallization from a melt (at a varying cooling rate) are considered compelling, and are in accord with the author's own observations. The term "igneous" is avoided here since it carries the connotation of a deep origin, encompasses rocks formed by crystal accumulation processes, and is not readily applied to impact melts.

The classification proposed in this paper is based on three criteria:

(1) overall texture (ie. intersertal, poikilitic, or other melt texture), irrespective of any xenolithic material

(2) variation of bulk abundances of large ion lithophile (LIL) elements (especially trivalent rare earth elements and  $K_2O$ ) with  $Al_2O_3$  content

(3) bulk 100 Mg/Mg+Fe molecular ratio, henceforth referred to as the "Mg value" ( $Mg = MgO \div 40.32$ ,  $Fe = FeO \div 71.85$ ). Other features such as the presence or absence of xenolithic clasts, abundances of siderophile elements, abundances of Cr and Sc, and the chemistry of metal phases, are examined below for their systematics and genetic implications, but are not part of the classification.

Chemical data have been gathered from numerous published and unpublished sources for only those rocks whose melt textures could be established beyond doubt. The textures of most of the samples, many of which are rake samples

and lithic fragments from fines, were confirmed by personal examination of thin sections. For other samples, published photographs and/or petrographic descriptions provided adequate documentation of the textures. Data for  $\text{Al}_2\text{O}_3$ , Mg value,  $\text{K}_2\text{O}$ , Sm, Hf, Ba, Th, U, Rb, Sr, Eu, Cr and Sc for 97 melt rock samples are compiled in Table 1, together with references to data sources and comments on sample type and textural verification.<sup>1</sup> These samples are listed and classified in the Appendix. A further 109 samples for which only major element data are available and for which  $\text{K}_2\text{O}$  data are included in Fig. 2, are also listed with data sources in the Appendix.

The plot shown in Fig. 1 of  $\text{Al}_2\text{O}_3$  versus Sm (as a typical trivalent rare earth element) confirms the existence of seven quite distinct major groups of non-mare melt rocks with intersertal, subophitic, vitrophyric or variolitic texture. Data for poikilitic melt rocks have been plotted separately. Furthermore, each group has a limited and distinctive range of Mg values. A similar pattern is evident from the  $\text{Al}_2\text{O}_3$  versus  $\text{K}_2\text{O}$  plot of Fig. 2. Elements of such

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<sup>1</sup>Copies of Table 1 and references can be obtained from the author on request, or by ordering NAPS document from ASIS National Auxiliary Publication Service, c/o Microfiche Publications, 305 East 46th St., New York, New York 10017, remitting \$1.50 for microfiche or \$5.00 for photocopies.

a classification have been employed by others (eg. the Hubbard and Phinney groups), but they did not apply both textural and chemical criteria to such a large number of samples.

The nomenclature adopted for the non-poikilitic melt rocks represents a compromise between chemical and textural features. It is also an attempt to rationalize existing nomenclature without adding to an already confusing situation. The term "basalt" has already been widely applied to many of these rocks in a strictly textural sense, and for each major non-poikilitic melt rock group the textural term "basalt" has been combined with a prefix which has chemical significance. Most of these names have been used before, although there are numerous synonyms. In particular, the troctolitic basalts have been commonly called "troctolites" or "spinel troctolites", but these names are considered better reserved for coarse grained rocks (in line with their terrestrial definition). The Apollo 17-type KREEP basalts are the "quartz-normative pigeonite basalts" of Stoesser et al (1974a,b). The name "VHA basalt" is retained because of widespread usage, but is narrower than originally used by Hubbard et al. (1973a) because of the textural restriction.

The distribution of the major types of non-mare melt rocks at lunar landing sites is summarized in Table 2.



## CHEMICAL SYSTEMATICS

### Analytical and sampling considerations

Almost all the trace element data used in this synthesis is by isotope dilution mass spectrometry or neutron activation analysis, with some by X-ray fluorescence spectrometry (Ba, Sr, Rb, Th, Cr,  $K_2O$ ) and gamma-ray spectrometry ( $K_2O$ , Th, U). Major elements ( $Al_2O_3$ , MgO, FeO) are by X-ray fluorescence spectrometry, neutron activation analysis, atomic absorption spectrophotometry, colorimetry ( $Al_2O_3$ ) or defocussed-beam electron microprobe analysis. Defocussed-beam microprobe analyses have also yielded much of the available  $K_2O$  data (especially for lithic fragments from fines); despite its lower precision and accuracy, such data yields variation patterns highly consistent with those based on data from other methods. Any scatter in the microprobe data appears to be no larger than that expected from sampling biases. The good agreement among multiple (up to 21) independent determinations for given samples (which are averaged in Table 1) indicate that sampling biases (as well as inter-laboratory analytical biases) for these fine grained melt rocks are minimal (see also Haskin et al., 1973, pp.1278-1280).

### Large ion lithophile elements

The variations of Ba, Hf, Th, U and Rb abundances with

$\text{Al}_2\text{O}_3$  content (Fig. 3) are similar to those for Sm and  $\text{K}_2\text{O}$ . As expected, each of these elements classify a given sample in the same group, although  $\text{K}_2\text{O}$ , Rb and to some extent U behave differently to the other elements and are not as useful as discriminants. It is possible that further trace element analyses will show the anorthositic, troctolitic and VHA basalts (all characteristic of the Apollo 16 site) to be gradationally related, despite their clearly separate identities from the presently available data. Considering the fairly random sampling of analyzed materials, the observed clustering of data into these and the other groups is an unexpected feature which requires explanation. Within each of the melt rock groups there are varying degrees of incoherence among the individual LIL element abundances (see Table 1), which may be due partly to analytical uncertainties and partly to sampling problems.

The systematic variations in Mg value and  $\text{Al}_2\text{O}_3$  are accompanied by systematic variations in the other major elements. The aluminous mare basalts are further distinguished by their relatively high  $\text{TiO}_2$  contents (1.5 - 7.7%). Two samples, 14068 (with Mg value of 75.8) and SAO 488-1 (Apollo 15) (with Mg value of 33.3 and 6.7%  $\text{TiO}_2$ ), are chemically very different from other samples with similar LIL element abundances and each appears to be unique.

Microprobe analysis (I. M. Steele, pers. comm., 1975) of a melt rock clast in breccia 67749 described by Steele and Smith (1973) shows it to have lower Mg value (36.7) and higher  $K_2O$  <sup>(1.2%)</sup> than the Apollo 15 KREEP <sup>-type</sup> basalts.

Another group of melt rocks which have so far been analyzed only by microprobe are the "olivine-normative pigeonite basalts" from Apollo 17 Boulder 1, Station 2 (Stoeser et al., 1974b); these clasts are quite similar to the aluminous mare basalts, although they are lower in  $TiO_2$ .

The poikilitic rocks have a limited compositional range overlapping the ranges for VHA basalt and Apollo 14-type KREEP basalt. Poikilitic sample 77017 has been excluded from consideration because of its much coarser grain-size, unusual texture and very different chemistry (26.3%  $Al_2O_3$ , very low LIL element abundances); these features suggest a different origin to the other poikilitic rocks (see McCallum et al., 1974). Some of the poikilitic rocks (eg. 60315) contain patches of subophitic melt rock which have  $K_2O$  contents (up to 3%) much higher than those of the KREEP basalts from the Apollo 15 site, but which also have higher Mg values of ~67 (Walker et al., 1973a; Bence et al., 1973).

Chondrite-normalized rare earth element (REE) patterns for non-mare melt rocks are summarized in Fig. 4. Several major features are apparent from this diagram:

(1) As observed by Hubbard et al. (1973a,b), Schonfeld (1974) and others, the slopes of trivalent REE patterns for many of the non-mare melt rocks are almost constant within analytical uncertainty over a 30-fold range in trivalent REE abundances. This applies to the anorthositic, VHA, Apollo 17-type KREEP, Apollo 14-type KREEP, and Apollo 15-type KREEP basalts, poikilitic rocks and unique Mg-rich sample 14068 (which has a very similar REE pattern to the most REE-poor Apollo 15-type KREEP basalts). Patterns for the troctolitic basalts also have this same slope at high abundances, but are much flatter at very low abundances. The REE patterns for the aluminous mare basalts, like those for mare basalts, are relatively flat. The REE pattern for unique sample SAO 488-1, although at greater abundances (Ce  $\sim 140 \times$  chondrites) is flat like those of the aluminous mare basalts for the light REE, but has a negative slope for the heavy REE. ANT-suite rocks have a range of trivalent REE patterns from sloping at  $\sim 0.4 \times$  chondrites (for the cataclastic anorthosites) to much flatter at  $\sim 10 \times$  chondrites (for more troctolitic and noritic members).

(2) There is relatively little variation in Eu abundances for melt rocks other than aluminous mare basalts (cf. Hubbard et al., 1973b). Thus, the Eu anomaly is positive for samples with very low trivalent REE abundances, but then passes through zero and becomes increasingly nega-

tive as the trivalent REE abundances increase. Eu abundances for over 95% of these samples are between 0.9 and 3.0 ppm. This is paralleled by a similar limited variation in Sr ( $^{132}_{\wedge}^{140}$  202 ppm - see Table 1), as noted by Gast (1972) and Hubbard et al. (1973).

(3) The Eu variation for the aluminous mare basalts is different. The magnitude of the negative Eu anomaly displayed by these melt rocks is approximately constant over a 4-fold range in trivalent REE abundances. Sample SAO 488-1 also has a similar Eu anomaly despite its higher trivalent REE abundances.

#### Chromium and scandium

The variation of Cr with  $Al_2O_3$  (Fig. 3f) for most of the melt rocks closely resembles that for the LIL elements. This is highly significant because Cr is known to behave very differently to the LIL elements in terrestrial crystal/liquid equilibrium processes (eg. Wager and Mitchell, 1951). It is important to note, however, that the Apollo 17-type KREEP basalts and the aluminous mare basalts stand out as exceptions, and show a lack of coherence between their Cr and LIL element abundances. Both these and the Apollo 15-type KREEP basalts are further distinguished by their extremely high Cr abundances (1810-4300 ppm). Cr and Sc abundances for the melt rocks both show a systematic increase with decreasing Mg value (Fig. 5).

### Siderophile elements

The abundances of the siderophile elements, particularly Au, Ir, Re, and to some extent Ge and Ni, have been used as indicators of meteoritic contamination in both lunar and terrestrial rocks (eg. Morgan et al., 1972, 1974a, 1974b, 1975). The rather limited data available for non-mare melt rocks are summarized in Table 3. Samples of anorthositic basalt, VHA basalt, Apollo 14-type KREEP basalt and most poikilitic rocks have abundances of Au, Ir and Re higher by factors of  $10^2$ - $10^3$  than those in mare basalts and 15415-type cataclastic anorthosites, and also have relatively high Ni contents ( $>130$ ppm). A single poikilitic sample (76215) has Au, Ir and Re abundances only 20-100 times higher than those in mare basalts and also has a much lower Ni content (54 ppm) (Higuchi and Morgan, 1975). The Ni content of 14310 and the Co content of 60315 (Taylor et al., 1972; Haskin et al., 1973) are highly variable in different subsamples, evidently reflecting a heterogeneous distribution of meteoritic metal.

In contrast the aluminous mare basalts and an Apollo 17-type KREEP basalt have much lower abundances of Au, Ir, Re and Ni, and thus appear to be essentially uncontaminated by meteoritic material. This is evidently also the case for Apollo 15-type KREEP basalts. Breccia 15205, which contains

~20% Apollo 15-type KREEP basalt clasts and ~20% pyroxene-phyric mare basalt clasts (Dymek et al., 1974), has bulk Au and Ir abundances ~10 times those in mare basalts and also has a very low Ni content (Baedecker et al., 1973). It can be inferred that the KREEP basalt clasts themselves must be low in siderophiles, since some meteoritic contamination would be expected in the impact-produced fine grained clastic matrix. Morgan et al. (1973) found low siderophile element abundances for a composite sample of six melt-textured particles from 1-2 mm fines 15272,9,22, and deduced from the high Rb, Cs, U and other elements, coupled with petrographic evidence from another portion of the same fines fraction, that the destructively analyzed sample had contained several particles of KREEP basalt of very low siderophile content. The contention that the Apollo 15-type KREEP basalts are essentially devoid of meteoritic contamination is reinforced by the very low Ni abundances of well-documented samples 15386 and 15434,73 (D. P. Blanchard, unpubl. data), as well as the Ni-poor metal characteristic of several other such samples (see below). Ge abundances are not in all cases well-correlated with those of the other siderophile elements, and may be a less useful index of meteoritic contamination (cf. Morgan et al., 1974a).

### TEXTURAL SYSTEMATICS

The intersertal, subophitic, vitrophyric and vario-litic melt rocks can be divided into two distinct groups based on whether or not they contain clasts of relict or xenolithic material (evidently present as suspended solids prior to crystallization of the melts). Such clasts are commonly present in the anorthositic, troctolitic and VHA basalts, and less commonly in the Apollo 14-type KREEP basalts. Some small fragments of these types of melt rock from fines lack clasts, but this may be a result of the scale of sampling. Calcic plagioclase, cataclastic anorthosite and granulitic ANT-suite rocks are the most common relict, xenolithic or xenocrystic debris observed, although fragments of spinel troctolite, feldspathic microbreccia, spinel, magnesian olivine, and pigeonite are present in some samples. These materials commonly show evidence of shock and of reaction with the melt matrix containing them, thus attesting to their exotic nature. In contrast, the aluminous mare basalts, Apollo 15-type KREEP basalts and Apollo 17-type KREEP basalts universally lack obvious xenolithic clasts. In addition, there is a much greater tendency for melt rocks of the first four groups to display substantial small-scale variations in grainsize suggestive of locally irregular cooling rates (even in lithic fragments from 1-2 mm fines).

Typical textures of examples from each of the major melt



rock groups are illustrated in Figs. 6 to 8. Most of the samples selected have been analyzed for both trace and major elements, but few have been previously documented by photographs in the literature. The diagnostic textural features of the first four groups (namely, the presence of clasts and small-scale grainsize variations) have been well-documented in many other samples. Good examples are: (1) anorthositic basalts 68415 (Gancarz et al., 1972; Helz and Appleman, 1973; Walker et al., 1973a; Nord et al., 1973), 67559 (Steele and Smith, 1973) and 60618, 1-2 (Dowty et al., 1974a); (2) troctolitic basalts 60666 (Dowty et al., 1974a) and 72502, 19, A-14 (Steele et al., 1974); (3) Apollo 14-type KREEP basalts 14310 (James, 1973; Gancarz et al., 1971; Bence and Papike, 1972; Longhi et al., 1972; Ridley et al., 1972; Dence and Plant, 1972) and 65785, 1-2 (Keil et al., 1975); and (4) VHA basalts 60335 (Walker et al., 1973a; Nord et al., 1973), 62295 (Walker et al., 1973a; Agrell et al., 1972; Hodges and Kushiro, 1973; Nord et al., 1973), 61016 (Drake, 1974), 65779 and 60615 (Dowty et al., 1974a), clasts in breccia 66055 (Fruchter et al., 1974) and clasts in breccia 66035 (Grieve et al., 1974). The textures of the Apollo 15-type KREEP basalts, Apollo 17-type KREEP basalts and aluminous mare basalts have been well-documented by, for example, Dymek et al. (1974), Powell et al. (1973), Phinney et al. (1972), Simonds et al. (1975); Stoesser

et al. (1974a,b); Gancarz et al. (1971), Grieve et al. (1972) and Albee et al. (1972). Rare porphyritic textures have been observed in Apollo 15-type KREEP basalts (Powell et al., 1973; Dymek et al., 1975), and nearly all samples of Apollo 17-type KREEP basalt (known only as clasts from a single boulder) show slight fracturing and brecciation. Unique melt rock sample 14068 contains a variety of xenolithic materials (Helz, 1972), whereas sample SAO 488-1 has a relatively homogeneous porphyritic intersertal texture (Drake et al., 1973).

The poikilitic rocks have been the subject of much controversial discussion (eg. Albee et al., 1973; Simonds et al., 1973, 1974; Bence et al., 1973). There is now abundant evidence for a textural and chemical gradation between poikilitic rocks and certain types of intersertal melt rock. A continuous gradation in texture is observed in a number of the Apollo 17 examples (Simonds et al., 1974), in 64567 (Simonds et al., 1973) and in clasts from breccia 66035 (Grieve et al., 1974). There is also a continuous variation from sample to sample in the shape of feldspar chadacrysts from equant to lath-like (Simonds et al., 1973). A fragment with well-developed lath-shaped feldspar chadacrysts strongly suggestive of crystallization from a melt is illustrated in Fig. 8c. More discrete areas of subophitic-intersertal

("diabasic") melt rock occur in some poikilitic rocks, such as 60315 (Bence et al., 1973; Walker et al., 1973a), 65015, and the fragment illustrated in Fig. 8d. As suggested by Simonds et al. (1973), the variations from poikilitic to subophitic-intersertal texture may result from locally irregular cooling rates, which also appear to be a common phenomenon in the crystallization history of melt rocks of the first four groups discussed above. Another well-known feature in common with these particular melt rocks is the presence of angular fragments of ANT-suite debris (see Figs. 8c, 8d), which isotopic and trace element studies (Papanastassiou and Wasserburg, 1972c; Jessberger et al., 1974; Meyer et al., 1974) indicate to be relics from a much older equilibrium than recorded by the poikilitic matrices containing them.

## MINERALOGICAL SYSTEMATICS

### Silicates and oxides

The systematic variations in the bulk chemistry of the melt rocks are not unexpectedly accompanied by systematic variations in the nature and chemistry of constituent silicate and oxide mineral phases. These features can be useful as a guide to classification and bulk chemistry, however the differing proportions and compositions of mesostasis in

these rocks (resulting from differences in cooling rate) must be taken into consideration. Nevertheless, the compositions of pyroxenes, olivines and plagioclases are quite diagnostic for most of the melt rock groups, as summarized in Fig. 9. Pyroxenes in the troctolitic and VHA basalts display minimal iron enrichment, and the bimodal distribution of calcic and subcalcic pyroxenes in the poikilitic rocks is very distinctive. Pyroxenes in the aluminous mare basalts display similar compositional variations to pyroxenes in mare basalts. Olivine is almost universally absent from KREEP basalts, although rare olivine ( $\text{Fo}_{70-80}$ ) has been observed in one clast of Apollo 15-type KREEP basalt (Dymek et al., 1974) and one clast of Apollo 17-type KREEP basalt (Stoeser et al., 1974a).

Spinel is distinctive as an early-crystallizing phase in many of the troctolitic basalts (eg. Reid et al., 1974; Weiblen et al., 1974 ) and also in the most magnesian VHA basalts, such as 62295 (eg. Walker et al., 1973). These spinels are generally euhedral to subhedral (see Fig. 6d), colorless to pink in thin section, and range in composition from pleonaste to almost pure  $\text{MgAl}_2\text{O}_4$ , with varying Cr contents. Ilmenite is present in many of the melt rocks, but is most abundant in the aluminous mare basalts.

Several interesting melt rock samples can be tentatively classified from mineralogical data. A unique intersertal basalt clast in poikilitic rock 76055 illustrated by Albee et al. (1973, Fig. 4a) contains plagioclase of composition  $An_{85-90}$ , subcalcic pyroxenes as magnesian as  $Wo_4En_{83}Fs_{13}$  and no olivine (A. L. Albee, unpubl. data), and thus may be an Apollo 15-type KREEP basalt. Another unique sample (1407-11) from Apollo 14 1-2 mm fines described by Powell and Weiblen (1972) consists largely of plagioclase and very magnesian olivine ( $Fo_{88}$ ) with minor mesostasis and aluminous pyroxene as magnesian as  $Wo_{45.0}En_{49.8}Fs_{5.2}$ , and is very probably a troctolitic basalt. The pyroxene compositional variations found by Bence et al. (1974) for intersertal-subophitic melt rocks from Apollo 17 2-4 mm fines (including "feldspathic basalt" 76503,6,9), and by Powell et al. (1975) for similar (but virtually clast-free) Apollo 16 particles, suggest that all are VHA basalts.

### Metals

Iron-rich metal occurs within the major silicate minerals and/or the mesostasis of non-mare melt rocks as both discrete grains and intergrowths with troilite or schreibersite. The Ni and Co contents of such metals have been compared with those of metals in modern meteorites (eg. Goldstein and Axon, 1972) in an attempt to detect meteoritic contamination in

lunar rocks, although the non-specific nature of this criterion has been pointed out (eg. El Goresy et al., 1973). The partial re-equilibration of meteoritic metal during the crystallization of impact melts has been discussed by Hewins and Goldstein (1975). Available Ni and Co data for metals from melt rocks are summarized in Fig. 10. The compositions of known indigenous lunar metals from mare basalts are much more suitable as genetic indices than the compositions of metals from modern meteorites, since there is evidence from siderophile element abundance patterns (eg. Morgan et al., 1974b) that most of the ancient meteorite classes are not represented among modern terrestrial collections. Using this criterion, two distinct groups are evident from Fig. 10.

Data for metals in anorthositic basalts, troctolitic basalts, VHA basalts, Apollo 14-type KREEP basalts, 14068 and poikilitic rocks collectively occupy a large area of the diagram. Metals in some individual samples show less compositional variation than others, but metals in both 14310 and 68415 show as much variation as those in all the other samples combined. The significant observation is that the metals in these samples all have Ni contents greater than 1.5%, and are, with the exception of a few grains in 14310 and 68415, dissimilar in Ni-Co content to the metals in Apollo 11, 12, 15 and 17 mare basalts. Thus, despite the fact that many of these metals are

are also dissimilar to those in modern meteorites, there is reasonable evidence that they are of extralunar origin.

In contrast, the metals in five samples of Apollo 15-type KREEP basalt (15382, SAO 490-53, SAO 490-65, SAO 416-3 and a clast in 15205) and in several clasts of Apollo 17-type KREEP basalt have very low Ni contents (generally less than 1%) and Ni-Co variation within the ranges for metals in mare basalts (see Fig. 10). Particle SAO 416-3 is from the same 1-2 mm fines fraction (15272,9,22) which was found by Morgan et al. (1973) to have very low siderophile element abundances. In addition, the single analyzable metal grain in the unique intersertal melt rock clast in 76055 contains 0.24% Ni, <0.01% Co and 0.1% P (A.L. Albee, unpubl. data). Axon and Goldstein (1973) also noted a high proportion of Co-rich metal particles in Apollo 15 Apennine Front soils which may have been derived from both the KREEP basalts and low-Ti mare basalts characteristic of that site (cf. Phinney et al., 1974; Simonds et al., 1975; Powell et al., 1973; Cameron et al., 1973b). The Ni contents of most of the metals analyzed by El Goresy et al. (1972) in aluminous mare basalts 14053 and 14072 are very low (less than 1%), but since no Co data are reported it is difficult to evaluate the significance of other metals with up to 6.1% Ni also present in these samples.

## DISCUSSION

On the basis of a number of the criteria discussed above, the non-mare melt rocks can be divided into three distinct classes:

- (1) anorthositic, troctolitic, VHA and Apollo 14-type KREEP basalts, unique sample 14068 and poikilitic rocks
- (2) aluminous mare basalts and unique sample SAO 488-1
- (3) Apollo 15-type KREEP basalts and Apollo 17-type KREEP basalts.

The genesis of these rocks is discussed below in three separate sections. In doing this, an emphasis has been placed on mutual petrogenetic consistencies from multiple lines of evidence. The hypotheses presented are not necessarily the only ones permissible and certain aspects remain unresolved, but they appear to be the most likely compromises from our present state of knowledge.

### Origin of anorthositic, troctolitic, VHA and Apollo 14-type KREEP basalts and poikilitic rocks by impact melting of KREEP-ANT mixtures

These particular non-mare melt rocks are collectively characterized by locally heterogeneous textures, xenolithic ANT-suite debris, relatively high siderophile element abundances and metal with non-lunar (meteoritic) Ni-Co contents. Melt rocks at terrestrial impact craters display identical



textural features, including poikilitic textures (eg. Grieve et al., 1974; Grieve, 1975), and many also have high siderophile element abundances (Morgan et al., 1975). The evidence is compelling that these particular lunar rocks are also products of impact melting. The existence of substantial volumes of impact melt associated with lunar craters and basins has been convincingly demonstrated by photogeologic studies (eg. Howard and Wilshire, 1975; Head, 1974). Judging from the observed relict clasts, ANT-suite material constituted an important component of the target regions where these melt rocks were produced. It has been argued by Grieve et al. (1974) and Grieve (1975) that terrestrial meteorite impacts produce essentially total melting of a given volume of the target material(s) and negligible primary partial melting. The xenolithic debris is not unfused relict target material, but instead local brecciated material from outside the melt zone engulfed by the melt as it moves out of the expanding crater. If total melting is also produced in lunar impact events, then components other than the observed ANT-suite material, particularly a component rich in lithophile elements, must also have been present in varying amounts to explain the observed variations in bulk chemistry. Schonfeld (1974) and Schonfeld and Meyer (1972) have presented multi-element mixing models for some of the rocks considered here using "KREEP" "anorthosite" and troctolite or dunite as major end-members.

Dowty et al. (1974a,b) and Keil et al. (1975) have also argued that these melt rocks, and in particular the VHA basalts, are impact-melted mixtures of KREEP and ANT components. Dunite, which is apparently very rare amongst returned samples, is not the most likely magnesian end-member. Troctolite is probably more reasonable and furthermore is present as xenoliths or a xenocryst assemblage in some melt rocks. The inverse correlation of Mg value with  $Al_2O_3$  content for the anorthositic and troctolitic basalts of similar LIL element contents is readily understood in the impact melting hypothesis as a reflection of the same general correlation present in ANT-suite rocks (eg. Schonfeld, 1975; Prinz et al., 1973b; Dowty et al., 1974c).

The general increase in LIL element abundances with decreasing Mg value for these melt rocks is that expected if they were related by different degrees of partial melting. However, there are two significant chemical features not predicted by a partial melting hypothesis which are readily explained by the hypothesis of impact total melting of mixtures of ANT-suite materials and KREEP-rich material (eg. Apollo 15-type KREEP basalt):

(1) Schonfeld (1974), using partial melting models calculated by Gast (1972), has pointed out that the remarkable constancy of slope of trivalent REE patterns for these melt rocks would be very coincidental if they were inter-related

by partial melting processes as suggested by Hubbard et al. (1973), since it would require an unlikely variety of source regions. On the other hand, the constant slope is expected for nearly all mixtures of Apollo 15-type KREEP basalt and ANT-suite rocks (Philpotts et al., 1973; Schonfeld, 1974), because of the dominant effect of the REE-enriched KREEP basalt component. Only if troctolitic-noritic materials (with nearly flat REE patterns at  $\sim 10 \times$  chondrites) constitutes almost the whole mixture will the net slope be flatter (as in the case of the most REE-poor troctolitic basalts).

(2) The general increase in Cr abundances with decreasing Mg value, and the general positive correlation between Cr and LIL elements, are converse to what is observed for terrestrial crystal/liquid equilibria, but are expected from the mixing hypothesis because of the high Cr contents of Apollo 15-type KREEP basalts.

Experimental phase equilibrium studies also provide important constraints on the origin of these rocks. High-pressure experimental studies of anorthositic basalt 68415 (Walker et al., 1973a), VHA basalt 62295 (Walker et al., 1973a; Hodges and Kushiro, 1972) and Apollo 14-type KREEP basalt 14310 (Walker et al., 1972; Green et al., 1972; Kushiro et al., 1972; Ford et al., 1972) indicate a lack of multiple phase liquidus saturation to pressures of at least 12kb. As discussed in detail by Walker et al. (1973a,b) and Green et al. (1972),

these experimental results are more consistent with generation of these melt rocks at low pressures (including the lunar surface region), because the lunar mantle mineralogy at pressures of 10-12kb (200-240 km) inferred from experimental work on mare basalts is incapable of also yielding the non-mare basalts by partial melting.

Origin of aluminous mare basalts by partial melting in the lunar interior and implications for mantle heterogeneity

The small-scale textural homogeneity, lack of xenoliths, low siderophile element abundances and non-meteoritic metal in aluminous mare basalts argue against an impact origin. Instead, it is possible that they represent truly volcanic magmas generated by partial melting in the lunar interior. Their low Mg values, high Cr abundances, and the features of their REE patterns, suggest an affinity with the mare basalts.

Reid and Jakeš (1974) have pointed out that the high Cr contents preclude extensive near-surface fractionation of aluminous mare basalt liquids by subtraction of pyroxene, and suggest that they may be derived from a source region transitional between the aluminous crust and mafic mantle. Schonfeld and Meyer (1972) suggested that aluminous mare basalt 14053 might be a mare basalt "contaminated at depth" with ~7% KREEP basalt. High-pressure experimental studies of aluminous mare basalt 14072 by Walker et al. (1972) indicate

that a liquid of such composition would be multiply saturated with olivine and aluminous low-Ca pyroxene at about 10kb, 1320°C. Although 14072 itself may have accumulated a little olivine (cf. Longhi et al., 1972) and thus may not represent a liquid of exactly the same bulk composition, it is sufficiently similar to other examples of aluminous mare basalt to suggest an origin for such magmas by partial melting of an olivine+aluminous low-Ca pyroxene source at depths of around 200 km (although this should be corroborated by further experiments). The unique Apollo 15 sample SAO 488-1, which may be volcanic and which in some ways resembles the aluminous mare basalts but has higher Fe/Mg and LIL element abundances, could be derived by lower degrees of partial melting of a similar source region. These inferred depths of melting are similar to those at which high-Ti and low-Ti mare basalts may be generated (eg. Green et al., 1975). If the aluminous mare basalts are volcanic rocks, they have apparently erupted at various times in the interval 3.3 to 4.0 b.y. (see Table 4).

The apparent tendency for some concentration of the aluminous mare basalt magmas at certain landing sites (eg. Luna 16, Apollo 14, Apollo 16) which lack other types of mare basalt may reflect a lateral and/or radial heterogeneity in Al and other elements within the lunar mantle. Green et al.

(1975) have also inferred that the high-Ti and low-Ti mare basalts may be derived from similar depths from similar source mineralogies differing in Ti content, and mantle heterogeneity in K and other LIL elements is a plausible explanation for the observed variations in these elements in Apollo 11 and Apollo 15 mare basalts (Compston et al., 1970; Rhodes and Hubbard, 1973).

Origin of Apollo 15- and Apollo 17-type KREEP basalts by partial melting in the shallow lunar interior?

Like the aluminous mare basalts, these two types of KREEP basalt consistently display small-scale textural homogeneity, do not contain xenolithic clasts, and lack meteoritic contamination (as judged from their low Au, Ir, Re, Ni abundances and Ni-poor metal). Their relatively low Mg values (<60) and high Cr contents are features they share with both the aluminous mare basalts and mare basalts.

Since the features typical of impact melts (discussed above) are characteristically absent from these melt rocks, the hypothesis that they are partial melts of the lunar interior (eg. <sup>Walker et al., 1973b</sup> Gast, 1972) must be seriously considered. Weill and McKay (1975) have demonstrated that small degrees (~1%) of partial melting of a source composed of 61% olivine ( $\text{Fo}_{86}$ ) + 20% orthopyroxene ( $\text{En}_{84}$ ) + 19% plagioclase ( $\text{An}_{100}$ ) can yield a liquid closely matching KREEP basalt 15386 in Mg value, Sr

and REE (including Eu). High pressure experimental studies by Green et al. (1972) of a model Apollo 15-type KREEP basalt composition (slightly richer in  $K_2O$  and poorer in  $SiO_2$  than natural samples) reveal that such a liquid would be multiply saturated with olivine, aluminous low-Ca pyroxene and plagioclase at about 6kb, 1250°C. The Apollo 15-type KREEP basalts could thus be generated by partial melting of an olivine+low-Ca pyroxene+plagioclase source at depths of about 120 km. Weill and McKay's one atmosphere experiments should remain relevant to pressures of 5-6 kb, because they predict little pressure effect on partition coefficients, and because phase relations in this system (especially the position of the olivine-pyroxene-plagioclase peritectic point) are virtually unchanged to such pressures (D. Walker, pers. comm., 1975). The Apollo 17-type KREEP basalts could be generated from a similar (but probably slightly different) source region at similar depths, but slightly greater degrees of partial melting would be required to explain their lower LIL-element abundances. Melt rocks like the clast in breccia 67749, which have higher K and Fe/Mg than the Apollo 15-type KREEP basalts, could be products of smaller degrees of partial melting of similar source regions.

Assuming such a partial melting model, the data on Cr partition coefficients given by Weill and McKay (1975) can be used to calculate Cr abundances in the source regions of these

magmas. The composite solid/liquid Cr partition coefficient for their preferred source mineralogy at 1250°C (the 6kb liquidus) is 1.35 (as determined from their Table 1). Assuming an average Cr abundance of 2100 ppm for Apollo 15-type KREEP basalts and 1% partial melting, the source region Cr abundance calculated from Weill and McKay's mass balance equation is 2800 ppm, and the subcalcic pyroxene of the source would contain ~2% Cr<sub>2</sub>O<sub>3</sub>. If the same source mineralogy were appropriate for an Apollo 17-type KREEP basalt (containing 3140 ppm Cr), then the source Cr abundance would be greater than 4000 ppm, even for 5% or more partial melting. Although the latter calculation is not entirely valid, it would imply that there be more pyroxene (and probably both calcic and subcalcic pyroxenes) in the source region of Apollo 17-type KREEP basalts in order to accommodate such high bulk Cr abundances.

As attractive as the partial melting model seems to be, it is difficult to reconcile with <sup>isotopic</sup> Rb-Sr evidence. Two samples of Apollo 15-type KREEP basalt yield 3.91 - 3.94 b.y. internal isochrons with very high initial ratios (Nyquist et al., 1974, 1975). Another sample has an <sup>40</sup>Ar/<sup>39</sup>Ar plateau age of 3.90 - 3.91 b.y. (Stettler et al., 1973; Turner et al., 1973). As discussed in detail by Nyquist et al. (1974), it is impossible to generate the Apollo 15-type KREEP basalts by partial melting



(with consequent fractionation of Rb from Sr) at  $\sim 3.9$  b.y., but it is possible to do so at  $\sim 4.3$  b.y. (which is the average Rb-Sr model age and fission track age (Haines et al., 1974) for Apollo 15-type KREEP basalts). If the latter is correct, then it is necessary to explain the 3.9 b.y. age, which is also the average crystallization age for melt rocks interpreted above to be impact-produced (see Table 4). The Rb-Sr model age of the single analyzed sample of an Apollo 17-type KREEP basalt is 4.12 b.y. (Gray et al., 1974), which is closer to, yet also distinct from, its 4.01 b.y. internal age. These Apollo 17 rocks remain somewhat of an enigma, since they are apparently confined to a single boulder and are very different from the non-mare melt rock fragments found in local soils (Steele et al., 1974 and unpubl. data; Bence et al., 1974).

The close proximity of the three regions of highest gamma-ray activity around Mare Imbrium (Metzger et al., 1973) to the Apollo 14 and 15 sites strongly suggests that they are the sources for the Apollo 15-type KREEP basalt fragments found particularly at those sites. Schonfeld and Meyer (1973) have suggested that considerable quantities of Apollo 15-type KREEP basalt might be buried beneath the mare basalts now filling Mare Imbrium. Thus, the 3.9 b.y. age could represent a total remelting (without mixing) of pre-existing KREEP basalt by the Imbrium event, and the lack of siderophile con-

tamination could be a consequence of the composition of the impacting body or the very large scale of melting (cf. Morgan et al., 1974a). Production of impact melt on such a large scale would also readily permit segregation of granitic material like that in 15405, which appears to be a differentiate from Apollo 15-type KREEP basalt liquid (Ryder, 1975).

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If this is correct, then we must still explain the ultimate origin of the KREEP basalts. Three main types of hypotheses have been suggested:

- (1) impact partial melting of ANT-suite materials (Warner et al., 1974)
- (2) internal segregation as a residual liquid from early (eg. ~4.3 b.y.) lunar differentiation (eg. Steele and Smith, 1973)
- (3) internal partial melting at ~4.3 b.y. as discussed above.

The first hypothesis is perhaps least likely because of the evidence for total rather than partial melting during impacts (eg. Grieve, 1975), and the difficulties of segregating very small amounts of partial melt on a scale large enough to be detectable by the orbital gamma-ray experiment. The uneven distribution of KREEP-rich material on the lunar surface presents problems for all hypotheses. Solomon (1975) has noted that KREEP basalt liquids have densities substantially less than that of the highland crust, which emphasizes the need for

local rather than moon-wide solid-liquid processes in order to explain their distribution. The chemically-equivalent residual liquid and partial melt hypotheses for the ultimate origin of the Apollo 15- and Apollo 17-type KREEP basalts appear to be most likely, but at present there are no grounds for choosing between them.

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## APPENDIX

### A. Classification of samples for which trace element data are given in Table 1

Anorthositic basalts 70182,1(1); SAO 686-5; 15303,3,7;  
65505; 63549; 68415; 68416; 67559; 78222,2(7-3); SAO 687-2

Troctolitic basalts SAO 689-23; 65702,3(5B); 15273,4,2

VHA basalts 78222,2(6-2); 62295; 61016,143; 63545; 60335;  
64455; 67937; 78222,2(7-1); 66095; SAO 688-26; SAO 687-31;  
SAO 687-30; 66055,6-10; 66055,6-4; 66055,4-7; 66055,5-7;  
SAO 685-16; 66055,6-3; 15314,77

Apollo 14-type KREEP basalts 14276; 14152,5,102; 14310; 14073

Apollo 17-type KREEP basalts 72275,91; 72275,171

Apollo 15-type KREEP basalts 15304,25; 15314,81; 15434,73;  
15024,13(4); 15023,2,5; 15273,4,9; 15382; 15273,4,10; 15564,  
17(5); SAO 490-53; 15386; 15434,67(7); SAO 490-65; 15003,454

Aluminous mare basalts 14072; 15103,3,4; 14053; 12038; B-1  
(Luna 16); A-31 (Luna 16); A-29 (Luna 16); 15059,13-11;  
14321 clasts; G-27 (Luna 16); C-29 (Luna 16)

Unique melt rocks 14068; SAO 488-1

Apollo 16 poikilitic rocks 61156; SAO 686-10; 64567; 60625;  
SAO 688-28; SAO 689-22; 65702,3(7A); SAO 689-24; 65702,3(2A);  
64815; 65702,3(7B); 60315; 65702,3(7C); 65702,3(2B); SAO 687-3;  
65015; 62235; SAO 688-27

Apollo 17 poikilitic rocks 73235; 76055; 72315; 72435; 76215;  
73275; 76295; 77135; 76015; 72355; 76315; 72395

B. Classification of samples for which only major element data are available

Anorthositic basalts 65795, 60618,1-2, 60635 (Dowty et al., 1974a); 65702,1(1), 66035,3(3) (Grieve et al., 1974); 10019, 22-5\*(Prinz et al., 1971); SAO 532-3 (Luna 20), SAO 228-8\*(Apollo 14), SAO 316-158\*(Luna 16) (J. A. Wood, unpubl. data)

Troctolitic basalts 60666 (Dowty et al., 1974a); 65702,1(10) (Grieve et al., 1974); SAO 514-6, SAO 514-21 (Luna 20) (Reid, 1972); SAO 506-4 (Luna 20) (Roedder and Weiblen, 1973); average of 2 Luna 20 particles (Kridelbaugh and Weill, 1973); SAO 532-1, SAO 532-10 (Luna 20) (J. A. Wood, unpubl. data); SAO 795-9 (clast in 72215) (G. Ryder, unpubl. data).

VHA basalts 65779, 60615 (Dowty et al., 1974a); 20 particles from Apollo 16 2-4 mm fines (J. W. Delano, unpubl. data); 3 clasts from 66035 (Grieve et al., 1974); 10 clasts from 68115,4 (R.A.F. Grieve, unpubl. data); SAO 602-8, SAO 602-22, SAO 606-4, SAO 606-7, SAO 228-7 (Apollo 14) SAO 316-71 (Luna 16), SAO 532-5 (Luna 20) (J.A. Wood, unpubl. data); 14301,10-8 (Prinz et al., 1973a); SAO 794C1, SAO 794C2, SAO 803C5 (Stoeser et al., 1974b).

Apollo 14-type KREEP basalts 14301,10-11, 14161,15,48-1, 14318,4,2 (Prinz et al., 1973a); 65785,1-2 (Keil et al., 1975); SAO 504-7 (Luna 20) (Cameron et al., 1973a);

SAO 236-18 (Apollo 14) (J.A. Wood, unpubl. data)

Apollo 17-type KREEP basalts 6 clasts from 72275

(Stoeser et al., 1974a,b)

Apollo 15-type KREEP basalts 15434,63(4) (B. N. Powell, unpubl. data); 15103,2,20 (Cameron et al., 1973b); clast

in 15358 (Hlava et al., 1973); SAO 411-3, SAO 465-5, SAO 465-12 (Apollo 15), SAO 239-8, SAO 236-9\* (Apollo 14) (J.A. Wood, unpubl. data);

14162,16,56-1, 14162,16,60-1, 14259,45,4-1 (Prinz et al., 1973a); clast in 67749\* (I. M. Steele, unpubl. data);

subophitic patch in 60315\* (Walker et al., 1973a)

Aluminous mare basalts 13 Luna 16 particles (J. A. Green et al., 1972); 3 Luna 16 particles (Grieve et al., 1972);

1 Luna 16 particle (Vinogradov, 1971); G37 (Luna 16)

(Steele and Smith, 1972); average of several clasts in

14063 (Ridley, 1975); clast in 60639 (Dowty et al., 1974a);

SAO 417-8 (Apollo 15) (J. A. Wood, unpubl. data)

\* Samples with unusual chemical features



## FIGURE CAPTIONS

Fig. 1 Sm vs.  $\text{Al}_2\text{O}_3$  plot for non-mare melt rocks and ANT-suite rocks. Symbols are explained in Fig. 2. Numbers in parentheses are 100 Mg/Mg+Fe ratios. The field for ANT-suite rocks in Figs. 2 and 3 is essentially the same as shown here.

Fig. 2  $\text{K}_2\text{O}$  vs.  $\text{Al}_2\text{O}_3$  plot for non-mare melt rocks. The compositional range of poikilitic rocks has been omitted for clarity, but mostly overlaps that of VHA basalt. Data sources other than Table 1 are given in the Appendix. Data for the Apollo 17 "olivine-normative pigeonite basalts" (Stoeser et al., 1974b) have not been plotted, but generally fall in the field for aluminous mare basalts.

Fig. 3 Plots of  $\text{Al}_2\text{O}_3$  vs. Hf, Ba, Th, U, Rb and Cr for non-mare melt rocks. Symbols as in Fig. 2.

Fig. 4 Chondrite-normalized rare earth element patterns for non-mare melt rocks and ANT-suite rocks. Sources of data for melt rocks are given in Table 1. Data for ANT-suite rocks are from Drake et al., (1974), Hubbard et al. (1971, 1974), Haskin et al. (1973, 1974), Laul and Schmitt (1973), Wakita and Schmitt (1970) and Philpotts et al. (1973).

Fig. 5 Plots of 100 Mg/Mg+Fe vs. Sc and Cr for non-mare melt rocks. Symbols as in Fig. 2.

Fig. 6 (a) Anorthositic basalt 70182,1(1-1), composed mainly

of plagioclase laths with very fine-grained interstitial pyroxene and olivine. Note the xenocrysts of deformed plagioclase (upper left and bottom). Crossed nicols. Width of field is 1.02 mm.

(b) Anorthositic basalt SAO 686-5 (61283), composed mainly of plagioclase laths and angular plagioclase xenocrysts with interstitial glass. Note the finer-grained zone extending across the fragment about one third of the way from the bottom. Crossed nicols. Width of field is 2.33 mm.

(c) Troctolitic basalt SAO 689-23 (60503), composed mainly of plagioclase laths and olivine (both enclosing tiny euhedra of spinel) with minor mesostasis. Crossed nicols. Width of field is 2.55 mm.

(d) Troctolitic basalt 65702,3,(5B), composed mainly of irregularly-distributed plagioclase laths enclosing spinel euhedra (eg. upper left) and feathery olivine, with minor pyroxene and mesostasis. Crossed nicols. Width of field is 1.02 mm.

Fig. 7 (a) Typical VHA basalt SAO 686-26 (68823), composed mainly of fine grained plagioclase laths, olivine, pyroxene and mesostasis, with larger relics of plagioclase and recrystallized anorthosite (bottom center). Crossed nicols. Width of field is 2.33 mm.

(b) VHA basalt 78222,2(6-2), composed mainly of skeletal plagioclase laths with fine-grained interstitial pyroxenes.

olivine and glass. Note the large, blocky plagioclase xenocrysts. Crossed nicols. Width of field is 1.90 mm.

(c) Apollo 14-type KREEP basalt 14276, composed mainly of plagioclase laths and pigeonite with minor mesostasis. Crossed nicols. Width of field is 2.10 mm.

(d) Typical Apollo 15-type KREEP basalt 15304,25 (thin section # 15304,15,46), composed mainly of plagioclase laths, pigeonite and interstitial dark mesostasis. Plane light. Width of field is 1.15 mm.

Fig. 8 (a) Apollo 17-type KREEP basalt clast in breccia 72275, 136, composed mainly of plagioclase laths, pigeonite and mesostasis. Note the minor fracturing typical of these clasts. Crossed nicols. Width of field is 1.81 mm.

(b) Aluminous mare basalt 14072, composed mainly of pigeonite, olivine (lower left), plagioclase laths and ilmenite (center). Crossed nicols. Width of field is 2.10 mm.

(c) Poikilitic rock SAO 607-4, showing portions of two pyroxene oikocrysts (one at extinction) enclosing plagioclase chadacrysts with well-developed lath shapes as well as angular plagioclase xenocrysts. Crossed nicols. Width of field is 1.02 mm.

(d) Poikilitic rock SAO 688-27 (68823), showing two irregular pyroxene oikocrysts (one at extinction) enclosing relatively equant plagioclase chadacrysts and angular xenocrysts. Note the two areas with lath-shaped plagioclase and subophitic texture at top center and lower left.

Crossed nicols. Width of field is 2.55 mm.

Fig. 9 Compositional variations of pyroxene, olivine and

plagioclase from non-mare melt rocks. Data sources

are as follows: (a) Helz and Appleman (1973), Walker et al., (1973a), Hodges and Kushiro (1973), Warner et al. (1973), Steele and Smith (1973), Taylor et al. (1973), Dowty et al. (1974a), Drake et al. (1974).

(b) Weiblen et al. (1974), Drake et al. (1974), Kridelbaugh and Weill (1973), Roedder and Weiblen (1973), Dowty et al. (1974a)

(c) James (1973), Bence and Papike (1972), Ridley et al. (1972), Gancarz et al. (1971), Brown et al. (1972), Powell and Weiblen (1972), Klein and Drake (1972)

(e) Stoesser et al. (1974a, 1974b)

(f) Phinney et al. (1972), Meyer (1972), Dymek et al. (1974), Dowty et al. (1973), Hlava et al. (1973), Powell et al. (1973), Steele et al. (1972), Cameron et al. (1973b), Cameron and Delano (1973), Drake et al. (1973)

(g) Bence and Papike (1972), Gancarz et al. (1971), Bence et al. (1972), Grieve et al. (1972), Albee et al. (1972), J. A. Green et al. (1972), Keil et al. (1971)

(h) Steele and Smith (1973)

(i) Drake et al. (1973)

(j) Simonds et al. (1973, 1974), Bence et al. (1973), Albee et al. (1973), Walker et al. (1973a), Hodges and Kushiro (1973), Drake et al. (1974)

Fig. 10 Ni-Co variation for iron-rich metals from non-mare melt rocks. Data from James (1973), El Goresy et al. (1972, 1973), Gooley et al. (1973), Taylor et al. (1973a, 1973b), Albee et al. (1973), Agrell et al. (1973), Dowty et al. (1974<sup>a</sup>), Misra and Taylor (1975), Hlava et al. (1973), A. L. Albee (unpubl.) and D. B. Stoesser (unpubl.). New data for three Apollo 15-type KREEP basalts (SAO 490-53, SAO 490-65, SAO 416-3) were kindly obtained by Janice F. Bower at the Smithsonian Astrophysical Observatory.

Other data (reported only as ranges or few analyses) for anorthositic basalts (Dowty et al., 1974a), troctolitic basalts (Dowty et al., 1974a (60666)), VHA basalts (Dowty et al., 1974a; McKay et al., 1973; Grieve and Plant, 1973 (64455); J. A. Wood, unpubl. (SAO 602-8)), and unique melt rock 14068 (Nelen et al., 1972; Helz, 1972) plot within the main area of data with Ni >1.5%.

The box at lower left corner encloses data for metals in Apollo 11 mare basalts, the upper line is the lower bound of data for metals in Apollo 12 and 15 mare basalts, and the two lower lines limit data for metals in most types of modern meteorites (all after Goldstein and Axon, 1972). The longer box at far left encloses data for metals in Apollo 17 mare basalts (Taylor and Williams, 1974).

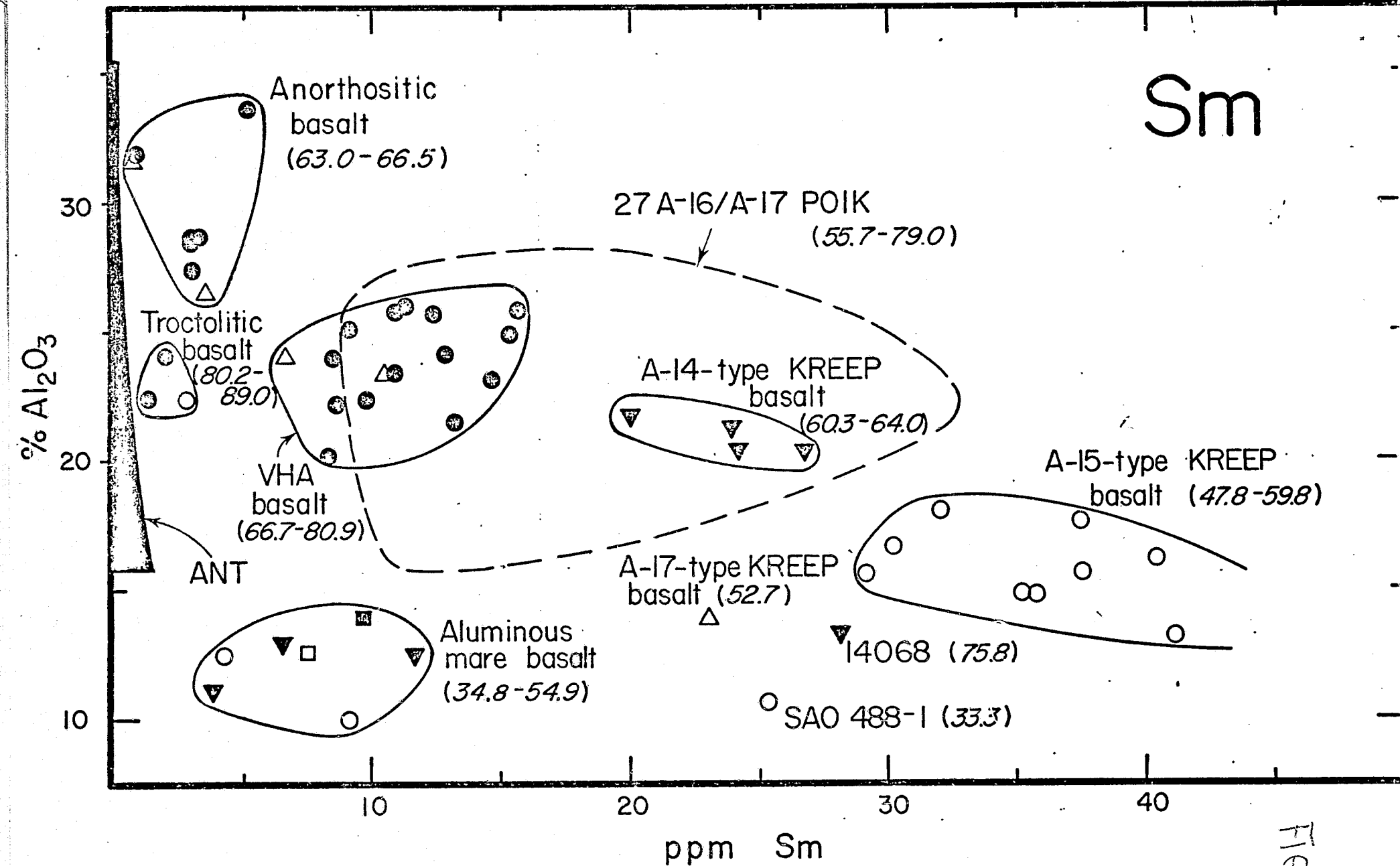


Fig. 1

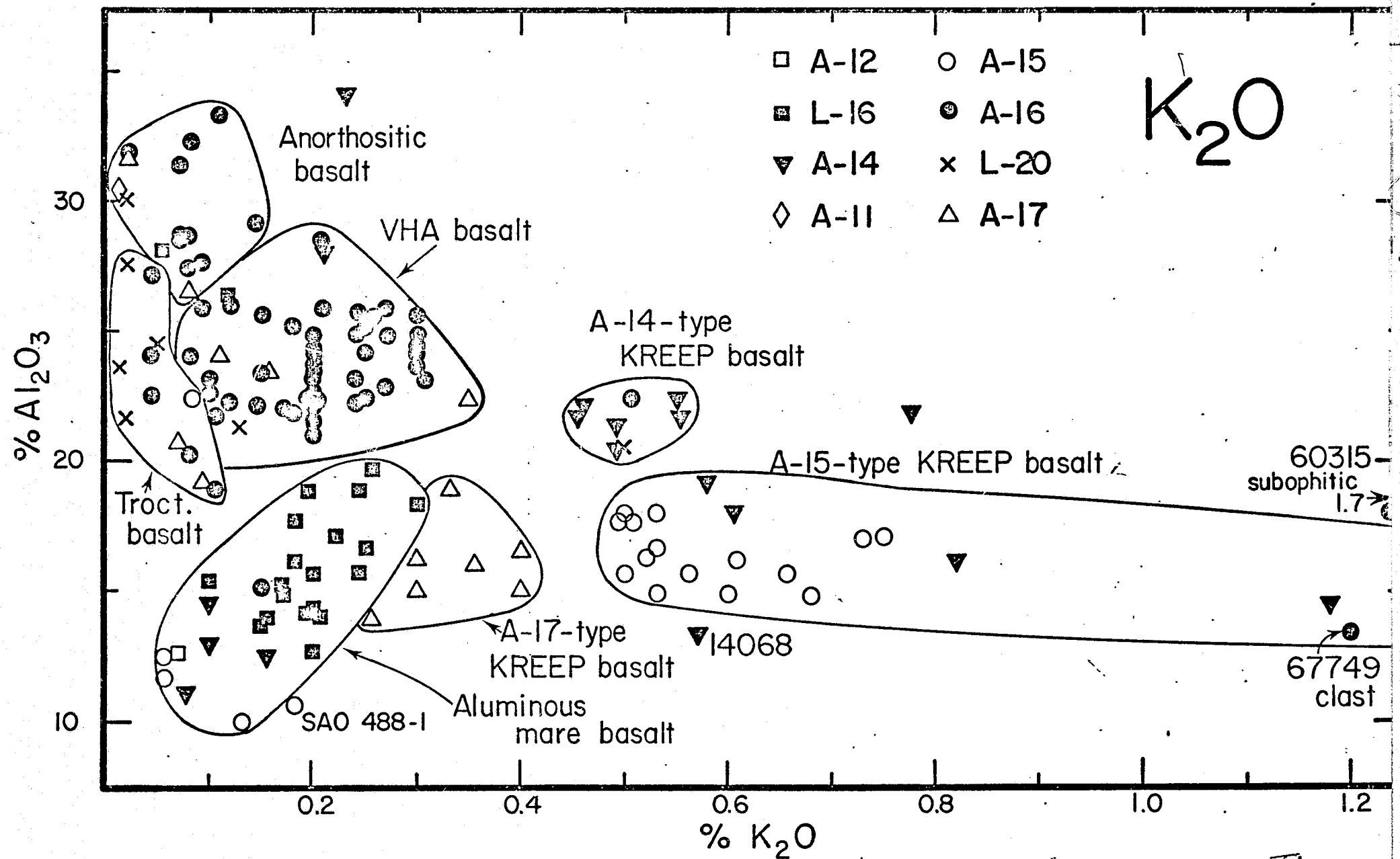


FIG. 2

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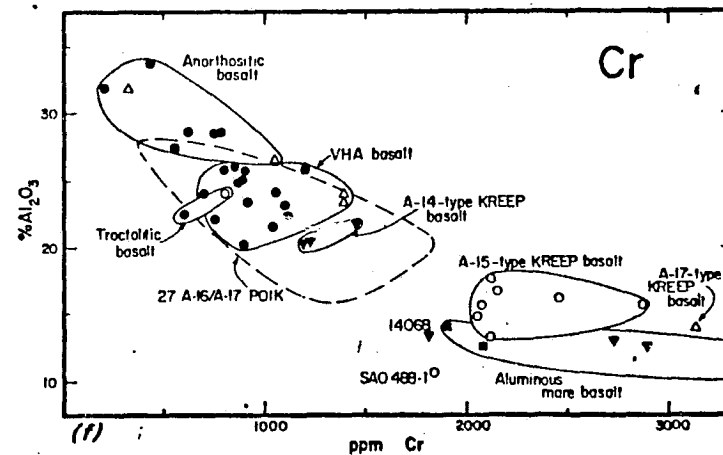
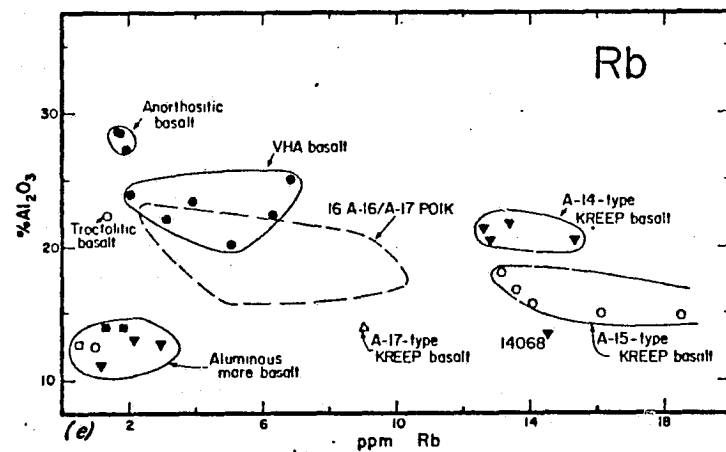
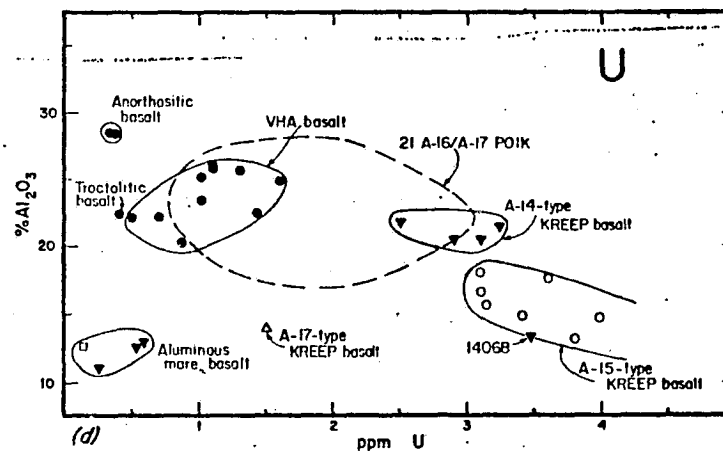
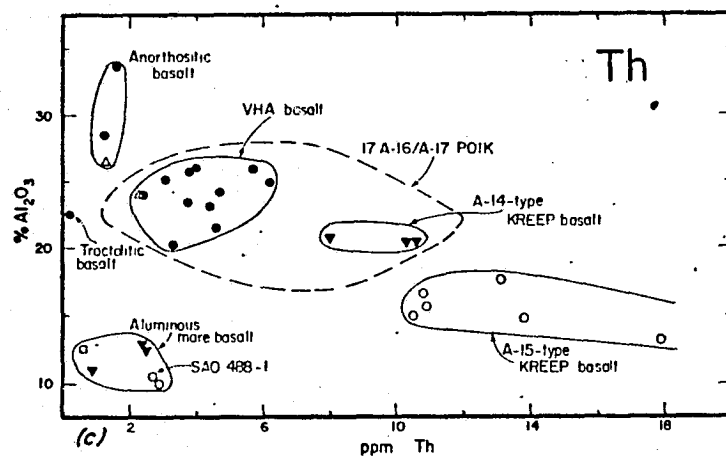
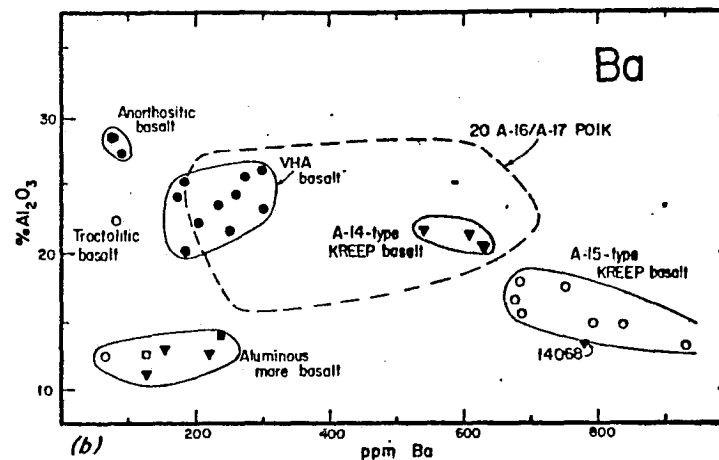
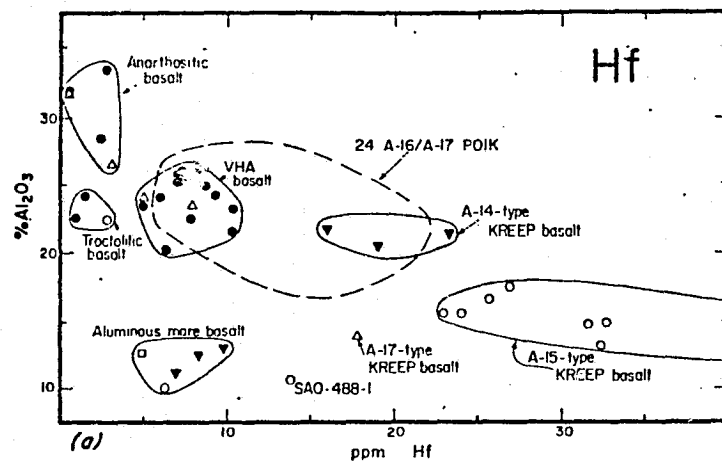
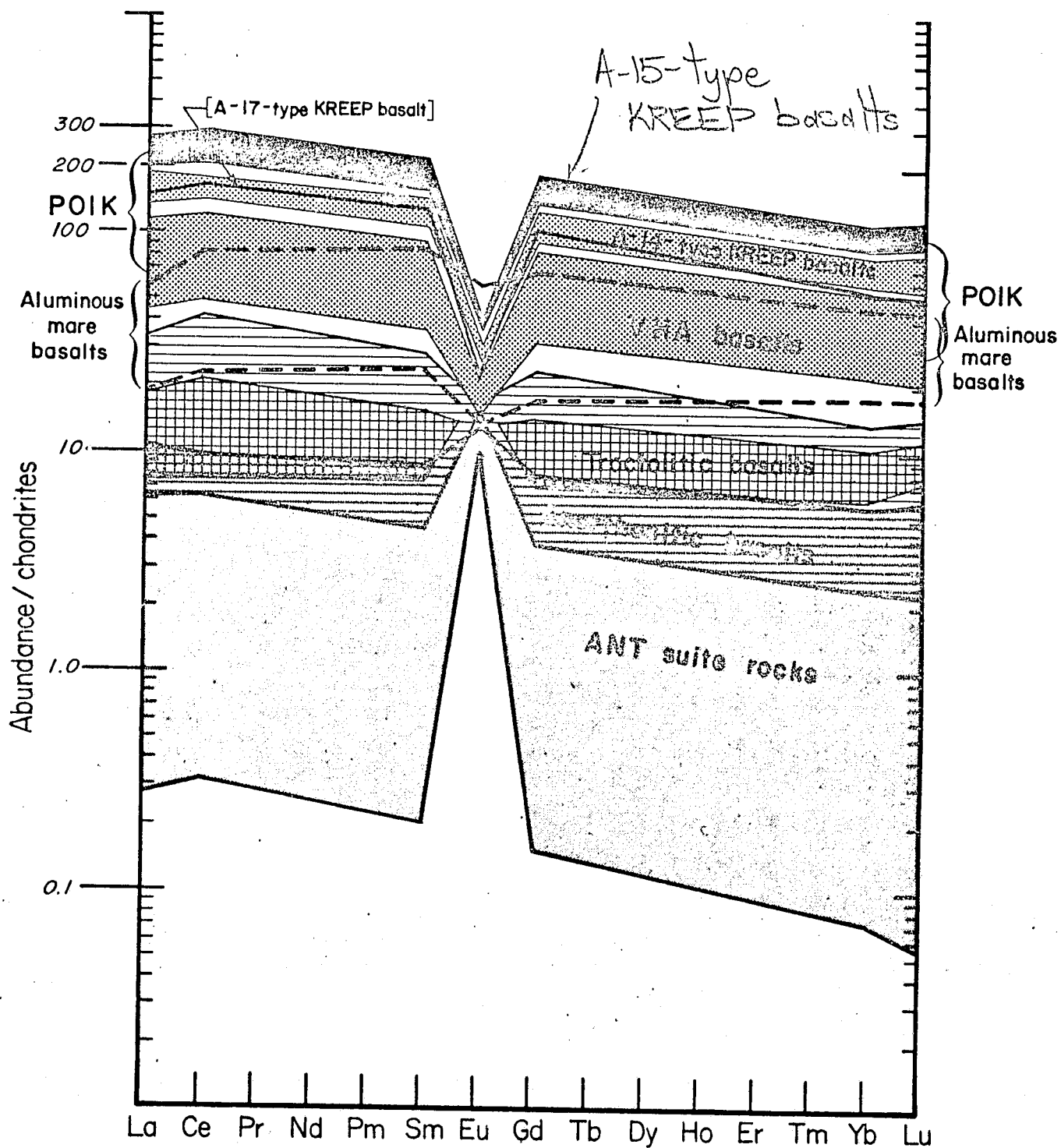


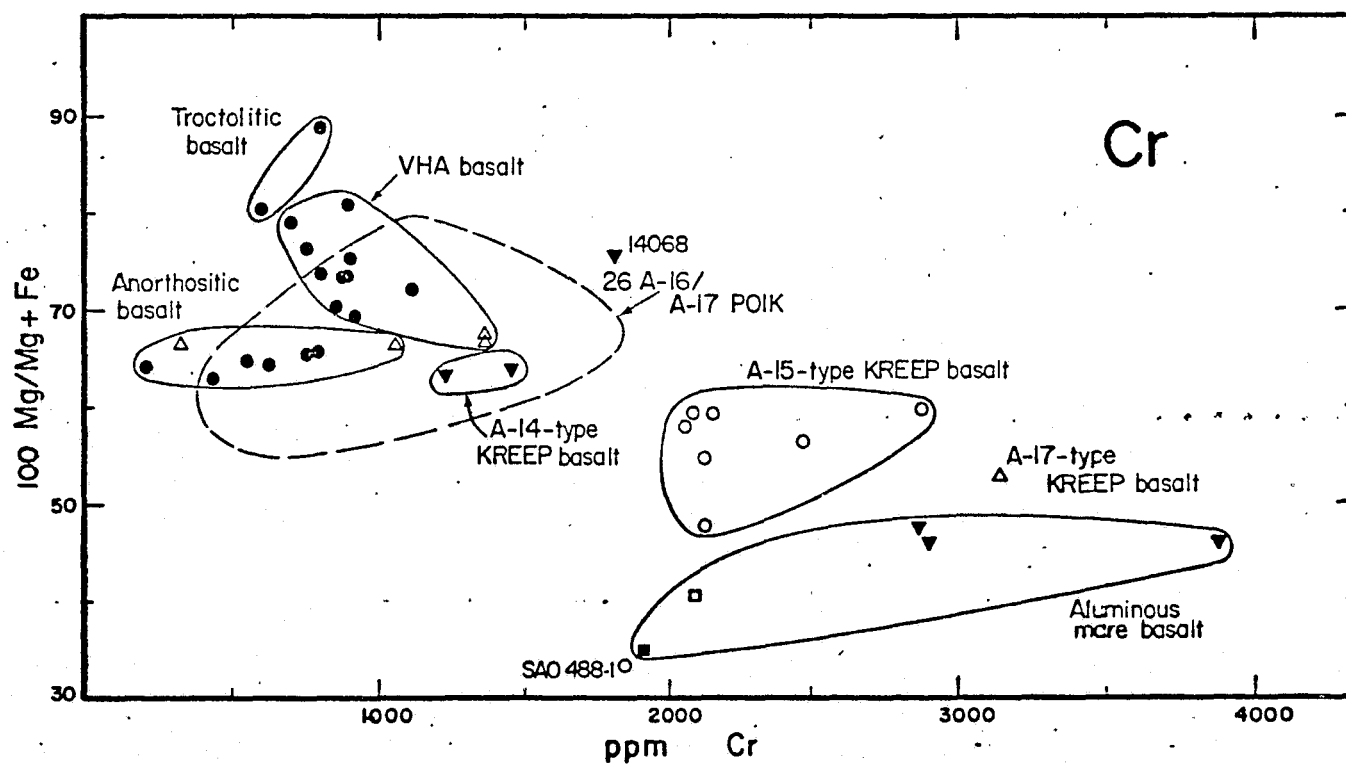
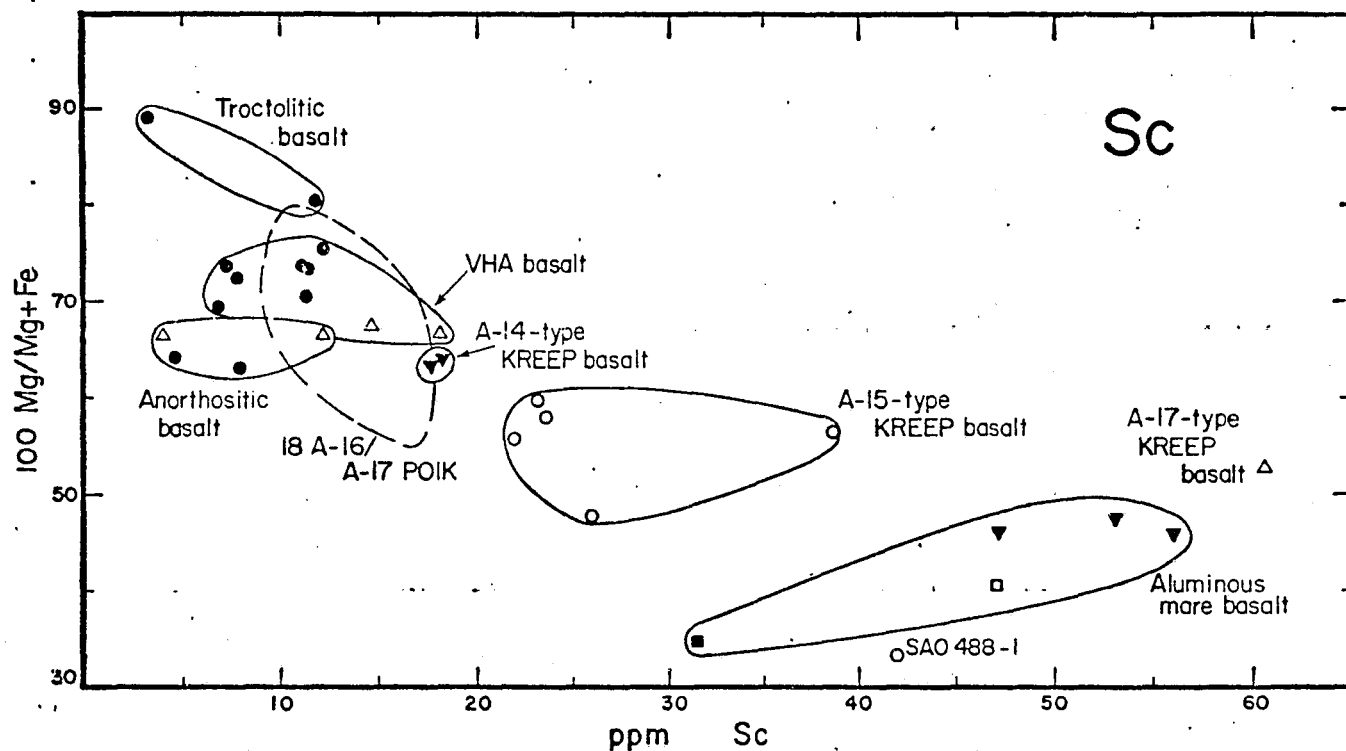


FIG. 4



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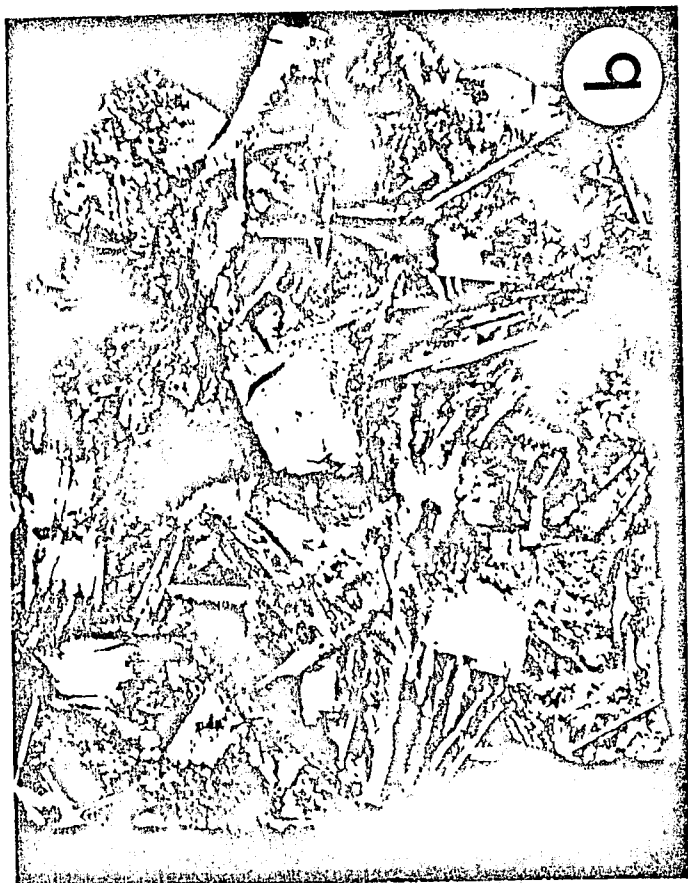
FIG. 5



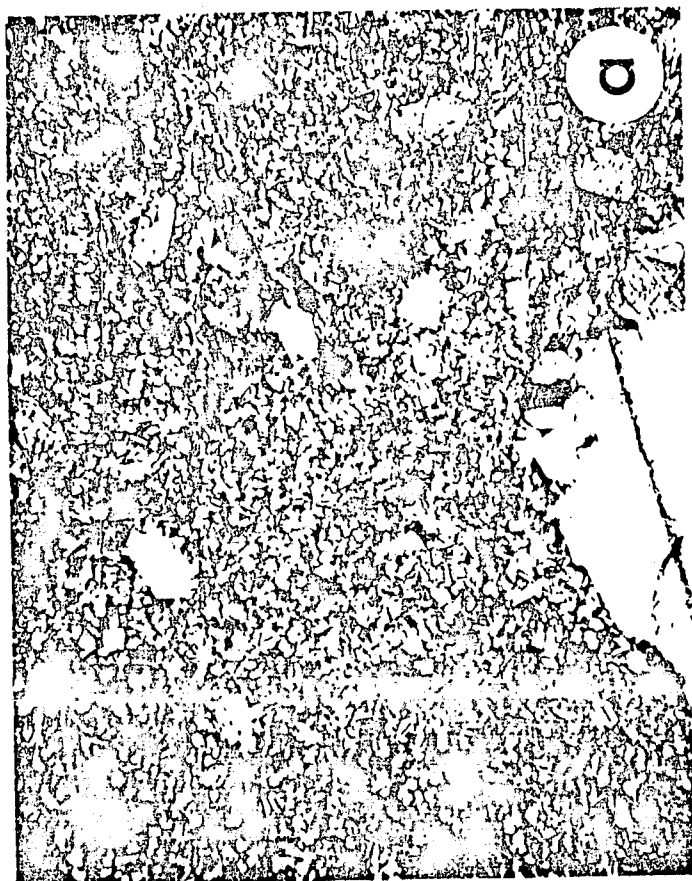


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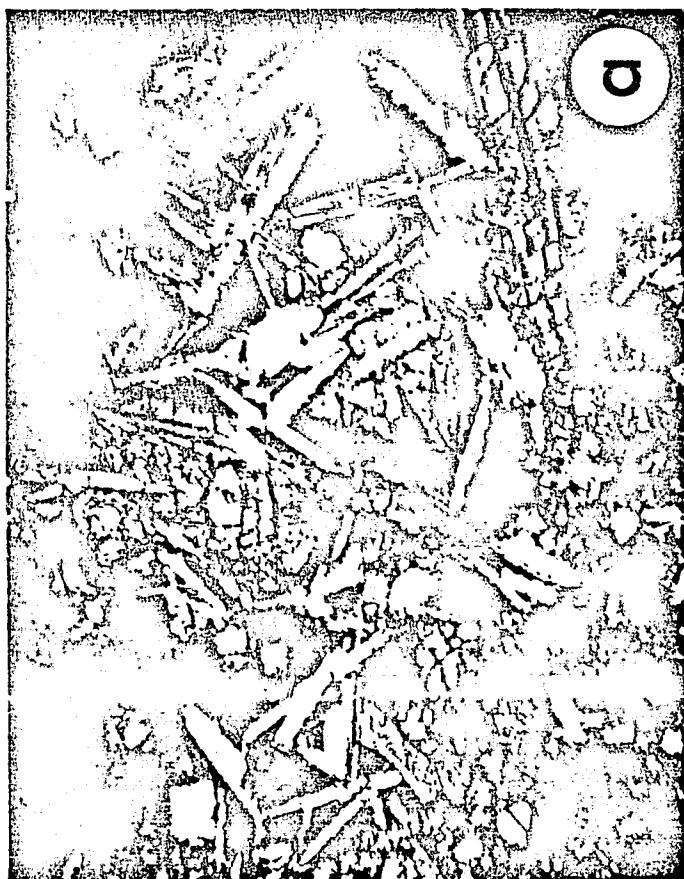


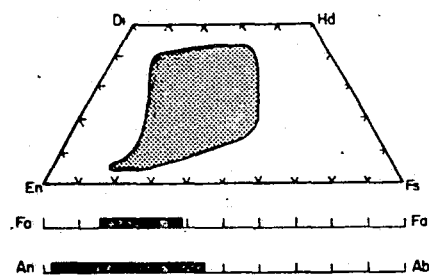
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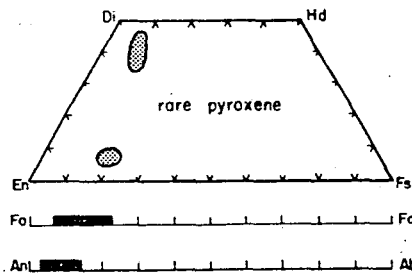


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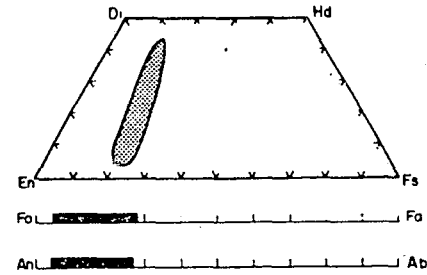




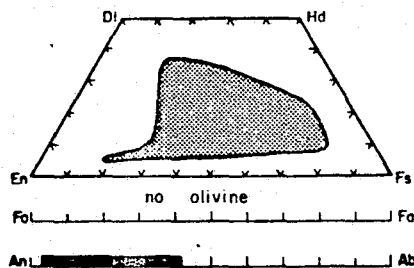
(a) Anorthositic basalts



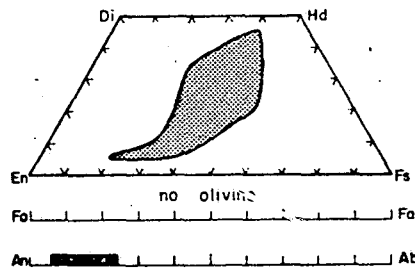
(b) Troctolitic basalts



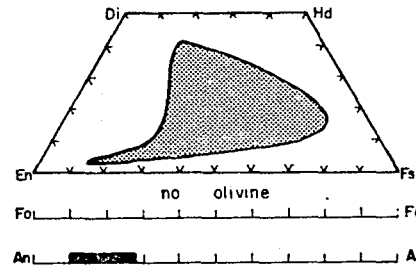
(c) VHA basalts



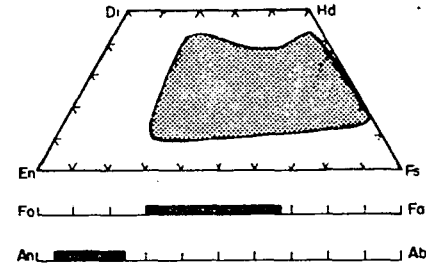
(d) Apollo 14-type KREEP basalts



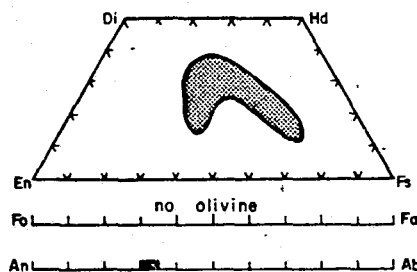
(e) Apollo 17-type KREEP basalts



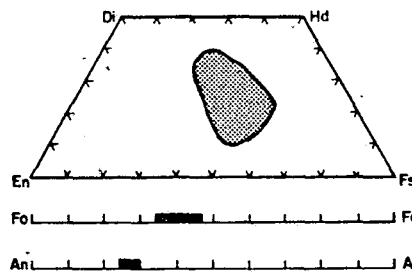
(f) Apollo 15-type KREEP basalts



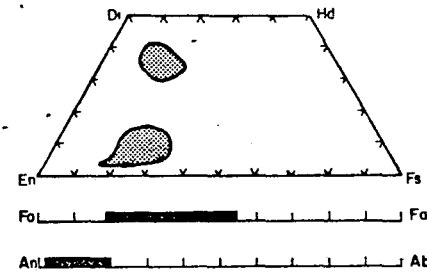
(g) Aluminous mare basalts



(h) KREEP basalt clast in 67749



(i) Iron-rich basalt SAO 488-1



(j) Poikilitic rocks

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FIG. 9

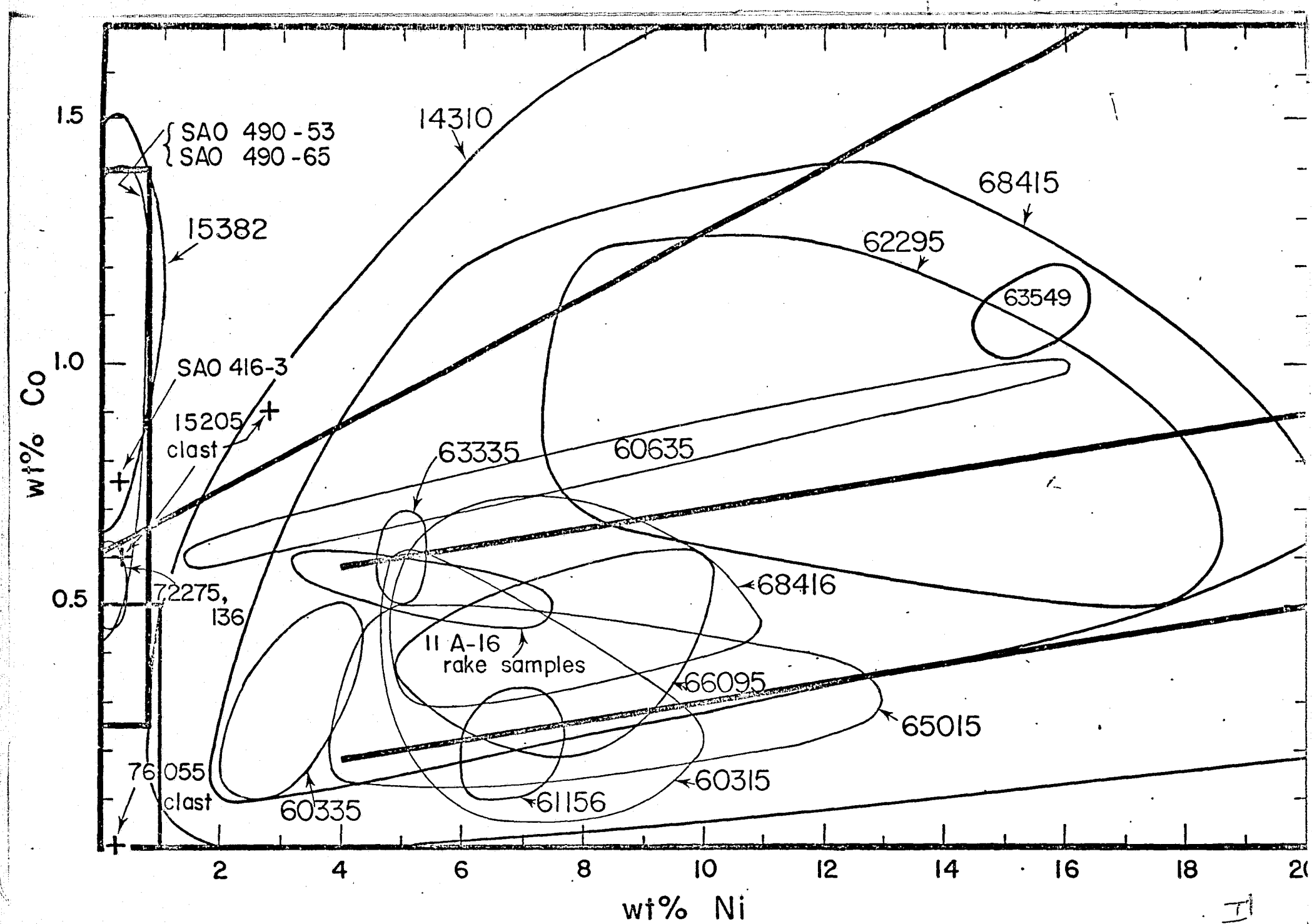


FIG. 10



**TABLE 2** Distribution of major types of non-mare melt rocks at lunar landing sites. Major sites for each group are in italics. The footnotes contain information not covered in the text.

Anorthositic basalt	<u>Apollo 16</u> , <u>Apollo 17</u> , <u>Apollo 11</u> (10019,22-5) <sup>1</sup> , <u>Apollo 15</u> (15303,3,7), <u>Apollo 14</u> (SAO 228-8) <sup>2</sup> , <u>Luna 20</u> (SAO 532-3), <u>Luna 16</u> (SAO 316-158) <sup>3</sup>
Troctolitic basalt	<u>Apollo 16</u> , <u>Apollo 17</u> , <u>Luna 20</u> , <u>Apollo 15</u> (15273,4,2), <u>Apollo 14</u> ? (1407-11)
VHA basalt	<u>Apollo 16</u> , <u>Apollo 17</u> , <u>Apollo 14</u> , <u>Luna 16</u> (SAO 316-71) <sup>4</sup> , <u>Apollo 15</u> (15314,77), <u>Apollo 12</u> ? <sup>5</sup>
Apollo 14-type KREEP basalt	<u>Apollo 14</u> , <u>Luna 20</u> (SAO 504-7), <u>Apollo 16</u> (65785,1-2) <sup>6</sup>
Apollo 15-type KREEP basalt	<u>Apollo 15</u> , <u>Apollo 14</u> , <u>Apollo 16</u> (67749 clast), <u>Apollo 17</u> ? (76055 clast)
Apollo 17-type KREEP basalt	<u>Apollo 17</u> (Boulder 1, Station 2 only)
Aluminous mare basalt	<u>Luna 16</u> , <u>Apollo 14</u> , <u>Apollo 15</u> , <u>Apollo 16</u> (60639 clast) <sup>7</sup> , <u>Apollo 12</u> (12038)
Poikilitic rocks	<u>Apollo 16</u> , <u>Apollo 17</u> , <u>Apollo 15</u> <sup>8</sup> , <u>Luna 20</u> <sup>9</sup> , <u>Apollo 14</u> (eg. SAO 236-6)

1. This sample has an unusually high Mg value of 81.1 (Prinz et al., 1971) Other texturally-similar Apollo 11 samples are 10085-12-75 (Chao et al., 1970, Fig. 15), SAO 37-12 and SAO 41-1
2. This sample has an unusually high K<sub>2</sub>O content of 0.22% (J. A. Wood, unpubl. data)
3. This sample has an unusually high Mg value of 72.3 (J. A. Wood, unpubl. data)
4. Some of the Luna 16 particles described by Cimbalníková et al. (1973) may also be VHA basalts
5. Samples SAO 130-10 and SAO 130-12 (Wood et al., 1971, Figs. IIB-3 and IIB-4) may be VHA basalts
6. This sample has an unusually high Mg value of 78.1 (Keil et al., 1975) and is transitional to VHA basalt
7. Further Apollo 16 samples are described by Delano (1975)
8. See Simonds et al. (1975)
9. For example, SAO 517-5 (Roedder and Weiblen, 1973)



**TABLE 3** Abundances of siderophile elements in non-mare melt rocks (in pph, except Ni in ppm). Numbers of determinations averaged are given in parentheses.

Sample	Au	Ir	Re	Ge	Ni	REFERENCES
<u>Anorthositic basalts</u>						
68415	12.7(2)	4.1(2)	0.434	86(2)	153(2)	Krähenbühl et al., 1973; Baedecker et al., 1974
68416	-	-	-	-	147	Juan et al., 1973
78222,2(7-3)	-	-	-	-	190	D. P. Blanchard, unpubl.
<u>VHA basalts</u>						
62295	3.10	3.58	0.336	642	215	Krähenbühl et al., 1973
66095	17.3(2)	20.1(2)	2.22(2)	2140	905(2)	Krähenbühl et al., 1973; Hughes et al., 1973; Brunfelt et al., 1973
61016 <sup>1</sup>	9.4(3)	11.9(3)	0.841	497(2)	485(3)	Krähenbühl et al., 1973; Wänke et al., 1973; Baedecker et al., 1974; Brunfelt et al., 1973
64455	1.56	2.25	0.284	62	310(2)	Ganapathy et al., 1974; Haskin et al., 1973
60335	-	-	-	-	317(2)	Barnes et al., 1973; Haskin et al., 1973
78222,2(6-2)	-	-	-	-	160	D. P. Blanchard, unpubl.
<u>Apollo 14-type KREEP basalt</u>						
14310	4.31	9.2(2)	1.02	110(2)	184(11)	Morgan et al., 1972; Baedecker et al., 1972; Taylor et al., 1972; Juan et al., 1972
<u>Apollo 17-type KREEP basalt</u>						
72275,91	0.045	0.023	0.0066	1290	55	Morgan et al., 1974a
<u>Apollo 15-type KREEP basalts</u>						
15272,9,22 <sup>2</sup>	0.048	0.047	0.014	65	-	Morgan et al., 1973
15205 <sup>3</sup>	0.41	0.14	-	84	28	Baedecker et al., 1973
15386	-	-	-	-	<40	D. P. Blanchard, unpubl.
15434,73	-	-	-	-	65±25	D. P. Blanchard, unpubl.
<u>Aluminous mare basalts</u>						
14053	0.11	0.017	0.0066	-	14	Morgan et al., 1972; Helmke et al., 1972
14321 clasts	0.30	0.044	0.0051	640	37.5(2)	Morgan et al., 1972; Wänke et al., 1972; Baedecker et al., 1972;
12038	0.36	0.06(2)	-	18	14	Anders et al., 1971; Baedecker et al., 1971; LSPET, 1970
14072	-	-	-	-	31	Helmke et al., 1972
Luna 16 (mean)	-	-	-	-	79	Vinogradov, 1973
<u>Poikilitic rocks</u>						
65015	10.8(3)	11.2(3)	1.16	442(2)	490(2)	Krähenbühl et al., 1973; Baedecker et al., 1974; Hughes et al., 1973; Haskin et al., 1973
60315	24(2)	23(2)	1.36	625	1100(2)	Ganapathy et al., 1974; Laul et al., 1974
62235	16	20	-	-	875(2)	Laul et al., 1974; Brunfelt et al., 1974
77135	6.45	10.5	1.06	618	438	Morgan et al., 1974b
72395	5.8	8.0	0.79	-	290	Laul et al., 1974
72315	4.5(2)	6.7(2)	0.70(2)	-	260(2)	Laul et al., 1974
73235	2.31	3.71	0.385	230	144	Morgan et al., 1974b
73275	3.34	5.71	0.494	265	182	Morgan et al., 1974b
76315	3.21	5.42	0.507	346	256	Morgan et al., 1974b
76015	1.89	3.41	0.315	164	135	Higuchi and Morgan, 1975
76215	0.526	0.829	0.070	31.5	54	Higuchi and Morgan, 1975

<sup>1</sup>Data are for melt rock portion of this composite sample. The cataclastic anorthosite portion has very low siderophile abundances (Krähenbühl et al., 1973)

<sup>2</sup>Projected abundances from bulk analysis of 6 melt-textured particles (mostly mare basalt) from 1-2 mm fines (see text)

<sup>3</sup>This sample is a breccia rich in clasts of Apollo 15-type KREEP basalt and pyroxene-phyrlic mare basalt (see text)

TABLE 4 Summary of Rb-Sr internal ages and  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  plateau ages for non-mare

melt rocks			
Sample	Rb-Sr age (by)	$^{40}\text{Ar}$ - $^{39}\text{Ar}$ age (by)	References
<u>Anorthositic basalts</u>			
68415	3.84 ± 0.01	3.80 ± 0.04 3.85 ± 0.04 3.85 ± 0.06	Papanastassiou and Wasserburg, 1972a; Stettler et al., 1973; Huneke et al., 1973; Kirsten et al., 1973
68416	-	4.00 ± 0.05	Kirsten et al., 1973
<u>VHA basalts</u>			
62295	4.00 ± 0.06	3.89 ± 0.05	Mark et al., 1974; Turner et al., 1973
66095	-	3.6 - 3.8	Turner et al., 1973
68503,16,31	-	3.86 ± 0.07	} Schaeffer and Husain, 1973
68503,16,33	-	3.95 ± 0.06	
66043,2,4	-	4.13 ± 0.05	
66043,2,5	-	4.01 ± 0.05	
63503,15,3	-	3.95 ± 0.06	
72503,8,12	-	3.96 ± 0.02	Schaeffer and Husain, 1974
<u>Apollo 14-type KREEP basalts</u>			
14310	3.87 ± 0.04 3.93 ± 0.04 3.93 ± 0.06 3.94 ± 0.03	3.87 ± 0.03 3.88 ± 0.06 3.89 ± 0.04 3.91 ± 0.05	Papanastassiou and Wasserburg, 1971; Compston et al., 1972; Mark et al., 1974; Murthy et al., 1972; Husain et al., 1972; Stettler et al., 1973; Turner et al., 1971; York et al., 1972
14073	3.88 ± 0.04	-	Papanastassiou and Wasserburg, 1971
14276	3.88 ± 0.01	-	Wasserburg and Papanastassiou, 1971
<u>Apollo 17-type KREEP basalt</u>			
72275,171	4.01 ± 0.04	-	Gray et al., 1974
<u>Apollo 15-type KREEP basalt</u>			
15386	3.94 ± 0.04	-	Nyquist et al., 1975
15434,73	3.91 ± 0.04	-	Nyquist et al., 1974
15382	-	3.90 ± 0.05 3.91 ± 0.05	Stettler et al., 1973; Turner et al., 1973
<u>Aluminous mare basalts</u>			
14053	3.96 ± 0.04	3.92 ± 0.05 3.93 ± 0.06 3.94 ± 0.04 3.94 ± 0.05	Papanastassiou and Wasserburg, 1971; Husain et al., 1972; Stettler et al., 1973; Turner et al., 1971
14072	3.99 ± 0.09	4.04 ± 0.05	Compston et al., 1972; York et al., 1972
14321 clasts	3.95 ± 0.05 3.99 ± 0.14 4.01 ± 0.12 4.05 ± 0.08	3.91 3.92 3.94 3.99	Papanastassiou and Wasserburg, 1971; Mark et al., 1973, 1975; Compston et al., 1972; Turner et al., 1971; York et al., 1972
B-1 (Luna 16)	3.42 ± 0.18	3.45 ± 0.04	Papanastassiou and Wasserburg, 1972; Huneke et al., 1972
12038	3.28 ± 0.21	-	Compston et al., 1971
<u>Poikilitic rocks</u>			
65015	3.93	3.92 ± 0.04 3.98	Papanastassiou and Wasserburg, 1972c; Kirsten et al., 1973; Jessberger et al., 1974
60315	-	3.94 ± 0.05 4.03 ± 0.03	Husain and Schaeffer, 1973; Kirsten et al., 1973
76055	-	4.05 ± 0.07	Kirsten and Horn, 1974