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CR160149

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MML TR 78-57c

PETROGRAPHIC AND PETROLOGICAL STUDIES OF LUNAR ROCKS

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(NASA-CR-160149) PETROGRAPHIC AND PETROLOGICAL STUDIES OF LUNAR ROCKS Final Report, Mar. - Dec. 1978 (Martin Marietta Labs., Baltimore, Md.) 47 p HC A03/MF A01 CSCL 03B G3/91 N79-22986 Unclas 15334

December 1978
Final Report: March 1978 to December 1978

Prepared for

NASA Johnson Space Center
Houston, Texas

PREFACE

OBJECTIVES AND SCOPE OF WORK

The objectives and scope of work under this contract were to examine, by optical and scanning electron microscopy and electron microprobe (SEM/EDS system), materials from the lunar highlands (impact melts and breccias) and from terrestrial meteorite impact craters. Studies in these two areas were to be made concurrently to elucidate the process or processes by which the surfaces of planets are formed and modified.

CONCLUSIONS

Examination of polished thin sections from five glass coated breccias were carried out. Sections from the breccias 15465 and 15466 were examined in detail, and the chemical and mineralogical analyses of several of the larger clasts are presented. Bulk analyses, using the SEM/EDS system in scanning mode, have been made of 33 clasts, and analyses of several hundred glass spheres, of which four are partly crystalline, have also been made.

The green glass spheres were found to average close to the typical composition reported by Agrell et al. (1973). Those which had crystallized olinine were found to have a greater variation in bulk composition than those which had not, but three of the four would seem to be directly related to the green glass spheres. Two generations of olivine were found. One, more slowly crystallized, has a forsterite content of 76-78 mol %, while the other, a product of rapid crystallization of the glass itself, is considerably more enriched in iron, and closer to the

composition expected from the normative mineral compositions calculated from the glass. The first group may well be phenocrysts which crystallized from an earlier, larger body of melt. Such an occurrence would strongly support an igneous origin for the spheres.

Mineralogical and bulk chemical analyses of clasts from the breccias suggest that igneous-textured, non plutonic clasts may all be impact melts. A few ANT suite clasts were found, but most were heavily shocked. Some of these clasts contain highly potassic glass (K_2O = 7%) which is of granitic composition overall. The presence of these glasses raises the possibility that these ANT clasts, or the body from which they are derived, has a high KREEP content.

The textural and chemical diversity of the igneous textured clasts from the Apollo 15 glass-coated breccias suggests that, if they are impact melts, they may be the products of smaller, local impacts into a petrologically diverse lunar crust.

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INTRODUCTION

Our work during the period February 1978 to December 1978 has been concentrated on finishing detailed analyses of the remaining Apollo 15 glass coated breccias in our possession. Further samples from the Zhamanshin crater have not yet been received from Florensky in the Soviet Union, thus no work beyond that reported on last year could be done.

Four samples not previously studied or not completed were analyzed by optical microscopy, SEM, and SEM/microprobe to determine the provenance of the breccias and the processes by which they were formed. All four (15465,53; 15465,54; 15466,13; and 15466,27) are polymict breccias with a significant but variable soil component. All contain varying amounts of glass spheres with compositions in the same range as those found in the Apollo 15 soil and in other Apollo 15 breccias. The matrices of the breccias contain clasts apparently representative of extrusive and plutonic igneous rocks and impact melts. Some clasts contain high K glasses, Ba bearing K-feldspars, REE bearing apatites, and iron-rich pyroxenes indicative of highly differentiated rocks.

GLASS CHEMISTRY

Glass chemistry is divided into two groups, green glass spheres and interstitial or mesostasis glasses associated with the different mineral clasts analyzed during the course of this study. Interstitial (mesostasis) glass chemistry will be discussed along with the clast mineralogy; green glasses are discussed below.

Green Glass

Following the discovery of spherical glass droplets in Apollo 15 soils (Reid et al., 1972; Agrell et al., 1973), considerable attention has been paid to the origin of these objects and their relationship to internal or external lunar processes. One of the more recent attempts to ascribe an origin to these spheres is a study by Butler (1978) utilizing S and Zn chemistry to distinguish between internal (igneous) and external (meteorite impact) origins. Butler (1978) mentions that only one droplet which had been found at the Apollo 15 landing site contained a phenocryst, or phenocrysts. This observation refers to Agrell et al. (1973), who report one olivine (Fo_{87}) in devitrified glass containing "scalariform" olivine of lower MgO content (~Fo_{70}).

We have analyzed several hundred glass spheres found in the Apollo 15 glass coated breccias. All cluster about the main composition given in Agrell et al. (1973) (see Winzer, 1977). Four droplets have been found to have produced crystals, and one, or more, include crystals which, by their form, appear indicative of two different cooling rates. Plate 1 shows four SEM photomicrographs of green glass spheres, two from 15466,13 and one from 15466,22. Photos a and b are from 15466,22, and show a 400 μm diameter green glass sphere in the glassy matrix of that section. The composition of the sphere is identical, within analytical error, to the typical green glass sphere given by Agrell et al. (1973), and to those undevitrified spheres we have analyzed.

This sphere consists of olivine (Fo_{73-71}) and glass (see Table 1), of which there are two distinct compositions. One small crystal-like portion of the interstitial glass gives chromium values of 9.8%, and thus

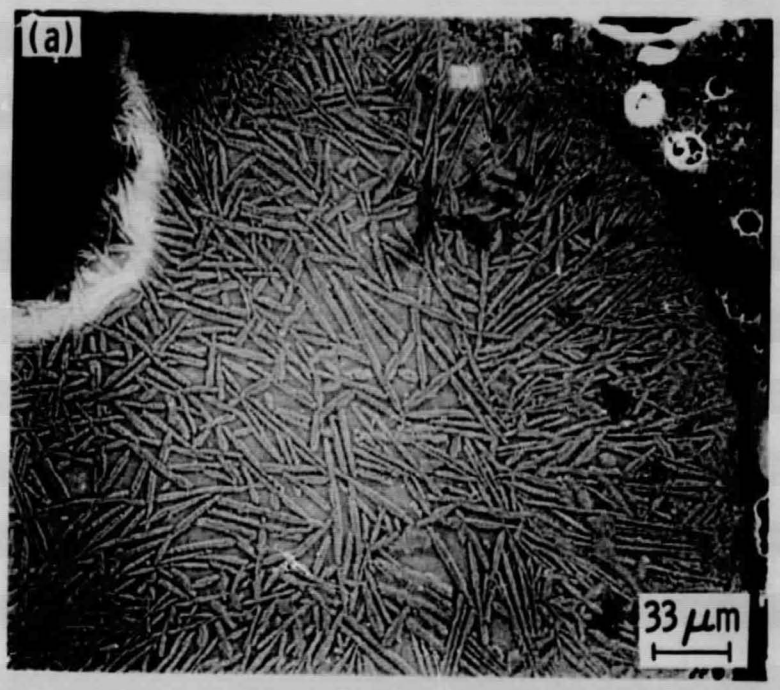
Plate 1. SEM photomicrographs of partly crystallized green glass spheres from Apollo 15 glass-coated breccias.

a,b. 15466,22 400 μm diameter green glass sphere

c. 15466,13 80 μm green glass sphere with two textural forms of olivine. Blocky euhedral to subhedral grains (lower left) have higher Fo contents than skeletal forms (see text for explanation).

d. 15466,13 95 μm green glass sphere. This sphere has a significantly different composition than the others, or the average ggs composition.

Plate 1



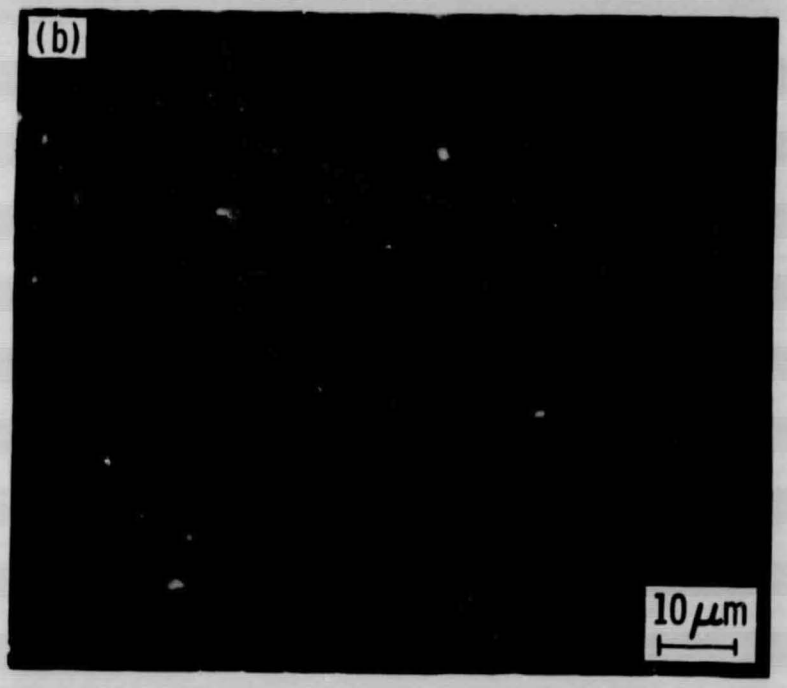
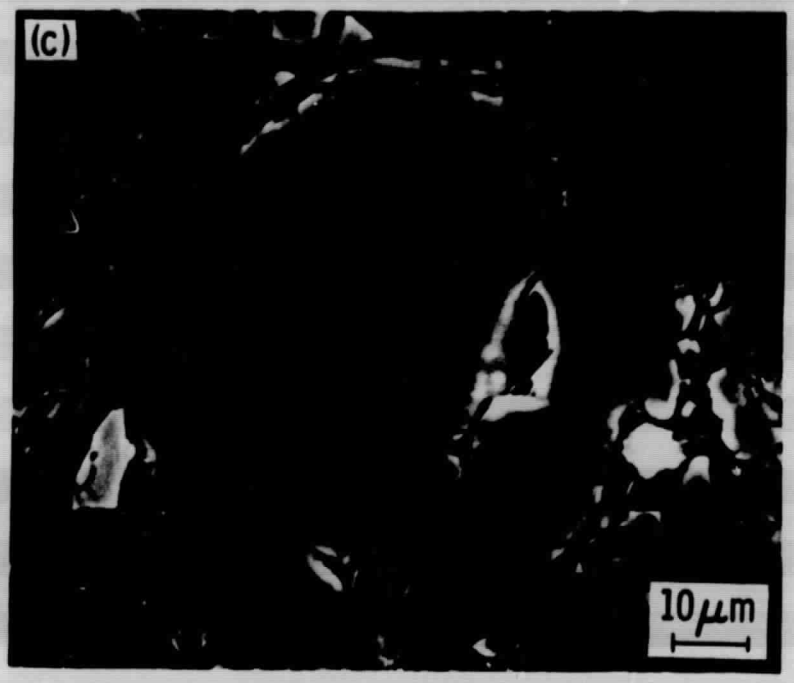


Plate 1



may be a small chromite crystal. The interstitial glass is quartz-normative, with a simple normative mineralogy of 34% An_{100}, 57% pyroxene ($Wo_{27}En_{29}Fs_{45}$), 8% quartz, and 1% ilmenite.

Close examination of the photograph reveals a change in grain size of the olivines crystallizing from this sphere. There is a progressive decrease in grain size outward from the core of the droplet, suggestive of more rapid cooling at the surface of the droplet and slower cooling towards the center. There is no radical change in the crystal form of the olivine (say from dendritic, as in photo d, to the coalesced chain forms seen here), thus it would seem that crystallization probably stopped a little sooner at the edges than in the center. The texture suggests crystallization from the melt while the droplet had its present form (i.e., the crystals were not present in a melt body prior to crystallization).

The texture of the sphere from 15466,13 (photo c, Plate 1) differs from that of a and b in that the olivine here appears in two forms, a blocky euhedral to subhedral form (Fo_{78}) and as partly coalesced chains (Fo_{68}?). Here, the grain size difference from core to rim appears to be absent, but this is a considerably smaller grain (80 μm) than the one from 15466,22. Table 1 contains an area analysis of the sphere, along with an analysis of the interstitial glass. As can be seen from the chemical analyses, there are differences between this and the "typical" green glass sphere in MgO, CaO, and Al_2O_3; however, the affinities are obvious. This sphere most closely resembles the olivine chondrule type glasses discussed by Agrell et al. (1973).

The third partly crystalline sphere differs considerably from the

Table 1

SEM/EDS Analyses of Partly Crystalline Green Glass Spheres

Element	1	2	3	4	5	6	7	8
SiO_2	45.23	48.81	45.03	51.43	46.37	49.01	42.17	44.90
TiO_2	0.35	0.51	0.46	0.57	0.45	0.60	3.26	3.07
Al_2O_3	7.73	10.54	7.17	11.83	10.00	12.20	9.29	13.20
Cr_2O_3	0.50	0.54	0.65	0.57	0.72	0.66	0.43	0.44
FeO	19.77	19.34	20.70	16.22	19.20	17.51	22.90	18.64
MgO	16.66	7.13	17.16	5.67	13.89	6.39	13.15	4.47
CaO	8.42	12.28	8.75	13.91	10.50	14.14	9.51	13.87
Na_2O	0.22	0.20	-0-	-0-	-0-	0.45	0.42	0.57
K_2O	0.07	0.08	0.05	0.03	-0-	-0-	0.07	-0-

1. Typical green glass (Agrell *et al.*, 1973)
2. Olivine "chondrule" interstitial glass (Agrell *et al.*, 1973)
3. 15466,22 Devitrified olivine bearing green glass sphere (area analysis)
4. 15466,22 Interstitial glass from Ol bearing green glass sphere
5. 15466,13 Devitrified olivine bearing green glass sphere (area analysis)
6. 15466,13 Interstitial glass from Ol bearing green glass chondrule
7. 15466,13 Glass ovoid, partly devitrified
8. 15466,13 Interstitial glass from partly devitrified glass ovoid

other two, although it resembles the other green glasses texturally (photo d, Plate 1). Like the second sphere, this is an ovoid, 95 μm in maximum dimension. Very small, dendritic olivine "spears" have begun to crystallize from one end of the ovoid. These "spears" appear to be more iron rich (Fo_{59} - Fo_{67}) than those in the other two spheres studied. Chemically, this sphere is also quite different, the principal difference being the TiO_2 content (see Table 1). FeO is also higher, and SiO_2 lower, but the remaining elements fall into the range of other green glasses analyzed.

The fourth sphere studied is not shown on the plate, but is similar in composition to that shown in Plate 1c. This sphere, found in 15465,53, has three euhedral to subhedral crystals of olivine which appear to have crystallized slowly. Their composition (Fo_{76}) is nearly identical to the subhedral, blocky olivine from 15466,16 (photo c, Plate 1).

Petrogenesis of Crystalline Glass Spheres

The principal arguments over the origin of the glass spheres have revolved around whether or not they are igneous, and therefore derived from the moon by internal processes, or whether they are impact melts, either derived by impact into a lava lake or by total melting of other lunar rock types. Some discussion of these hypotheses can be made from the data presented here, and from the studies of the glass-coated breccias discussed in previous papers (Winzer et al., 1978; Winzer, 1977).

All four crystalline glass spheres have olivine on the liquidus, but crystallize olivine of higher MgO content than predicted by the normative calculations from the bulk analysis of the sphere. The normative

olivines can be 10-20 mol % lower in the forsterite end member than those actually crystallized. The blocky olivines deviate the furthest, while the most rapidly crystallized dendritic or interrupted chain olivines come the closest. This suggests that the olivines which crystallized from the melt were not in equilibrium with it. Two hypotheses can be presented to account for these differences. First, the rapidly crystallizing olivines did not have time to equilibrate with the melt due to kinetic restrictions involving the movement of Mg and Fe through the melt to the growing olivine crystal and preferential incorporation of Mg over Fe^{2+} in the olivine (see Philpotts, 1978; Leeman, 1978). The kinetic hypothesis would most likely apply to the rapidly crystallized olivines whose compositions are closest to the normative olivines for the melts, however, it would seem less likely to apply to the equant olivines whose composition can deviate by as much as 20 mol %. Texturally, these equant, blocky olivines would appear to be products of slower crystallization, and would be expected to crystallize more nearly in equilibrium with the melts. If this is true, the most logical hypothesis is that these blocky olivines are phenocrysts which formed prior to droplet formation, and the olivines showing rapid formation appear to be related directly to cooling of the droplet (Plate 1a). These observations do not in themselves rule out either hypothesis for formation of the droplets, but tend to support more strongly an internal igneous origin, at least for the original liquid from which the phenocrysts formed.

A second line of evidence bearing on the formation of the spheres lies in the chemistry of the melt rocks and glass rinds in the breccias themselves. The rimming glasses found on the breccias studied here are

quite different from those of the spheres, and have more in common with the local soils in the areas from which they were returned (see Winzer et al., 1978). Impact melts included in the clast population in the breccias themselves are significantly more aluminous than the spheres (Winzer, 1977, and this report). Most impact melts from the Apollo 15 breccias which can be positively identified as such have feldspar or ilmenite on the liquidus rather than olivine. The green glass spheres do not, therefore, resemble most of the identifiable impact melts found along with them in the breccias. This suggests, although it does not prove, an origin other than by impact melting.

PETROLOGY OF CLASTS IN APOLLO 15 GLASS-COATED BRECCIAS

15465

Part of 15465 was reported on in Winzer, 1977; the remainder of our work on this breccia is included in this report.

15465,53

This section does not include the glass rind. 15465,53 is a fragment-rich, glass poor breccia containing two relatively large (71 mm) clasts and several smaller lithic clasts. This section also contains an abundance of green glass spheres, a few as large as 500 μm. The matrix is comp sed of mineral fragments, glass spheres, and a small amount of matrix glass binding the sample together.

Clasts 7-10 are reported on here. We have analyzed clasts 1-10 using the area scan technique, and these analyses are discussed later in

the report. Analyses of pyroxene, plagioclase, and olivine from three of the four clasts studied are presented in Figures 1 and 2. Clast 7 is composed of a single large, poikilitic cristobalite enclosing small anhedral to subhedral ilmenite.

Clasts 8 and 9 are similar. Both are relatively coarse-grained plagioclase-pyroxene rocks containing small amounts of olivine, chrome spinel, ilmenite, and glass of variable composition. Both have been shocked, clast 8 more than clast 9. Clast 8 has the wider range of compositions of the two. Feldspars are generally homogeneous or slightly zoned ($An_{80} \rightarrow An_{86}$), but pyroxene shows a wide compositional range. Two pyroxenes appear to be present (Figure 2): a subcalcic augite ($Wo_{5-9}En_{31}Fs_{34}$) to less calcic, more iron-rich rims ($Wo_{16}En_{33}Fs_{51}$), and the reverse. Many of these textures, and the resulting minerals, appear to be related to melting and recrystallization resulting from the shock event which affected the clast. Clast 8 contains, in addition to two pyroxenes and plagioclase, chrome spinel (15.5% Cr_2O_3), ilmenite and mesostasis glass which ranges from 74-94% SiO_2 and from 0-7% K_2O. The high K glasses contain 74% SiO_2 and ~12% Al_2O_3; thus their normative compositions are similar to granite (K, feldspar, quartz, and pyroxene).

Clast 9 has a smaller range of compositions than clast 8, but these compositions overlap those of clast 8. Feldspar compositions show less of a range than those of clast 8 (ranging from An_{85} to An_{89}) and are generally unzoned (Figure 1). The pyroxenes are orthopyroxenes zoned from $Wo_3En_{80}Fs_{17}$ to $Wo_5En_{57}Fs_{38}$. Normative clinopyroxenes appear in the glass, which is lower in K_2O (0.6%) and shows less range than the glasses

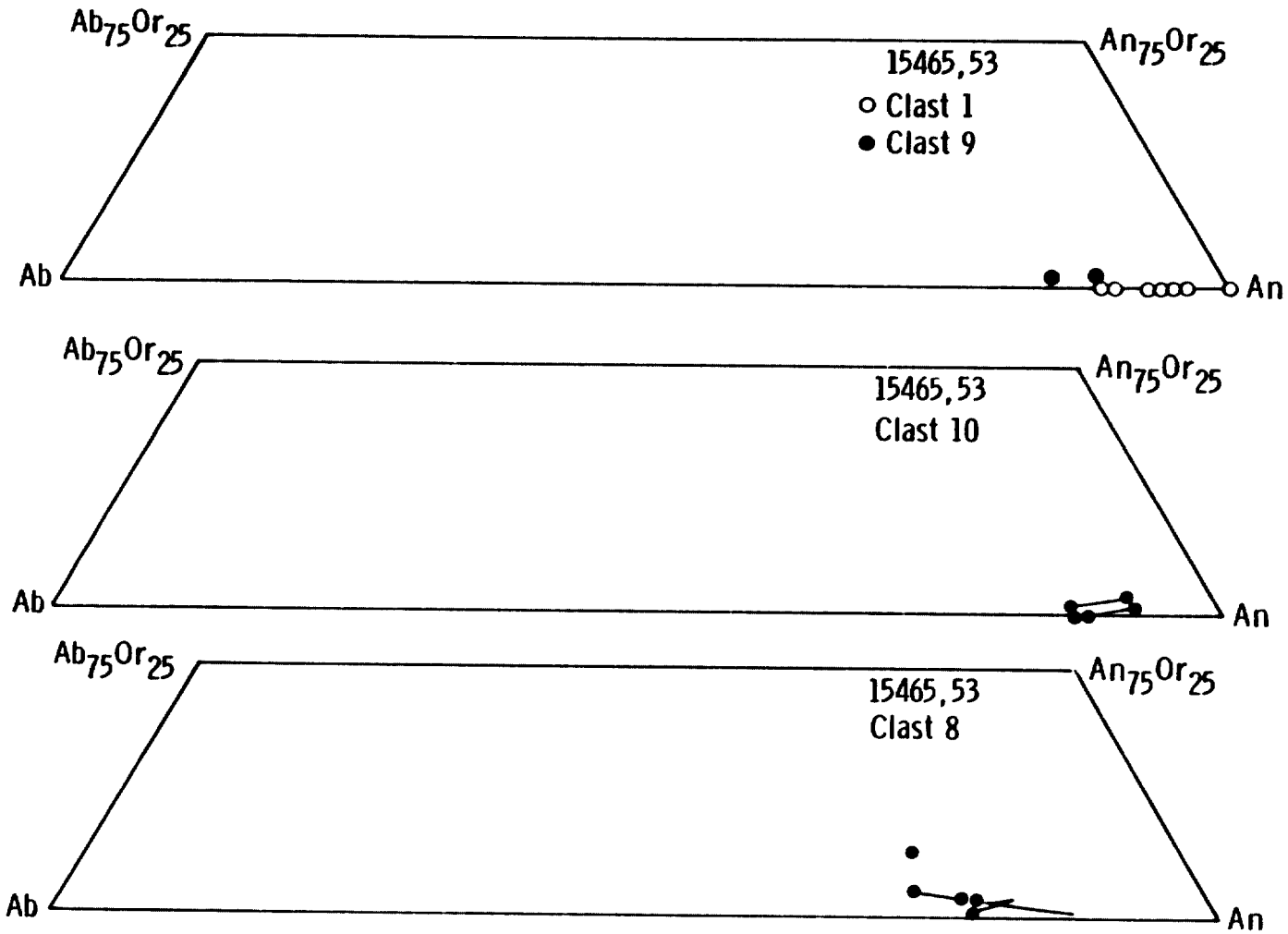


Figure 1. Compositions of feldspars in clasts from 15465,53. Each point represents several analyses.

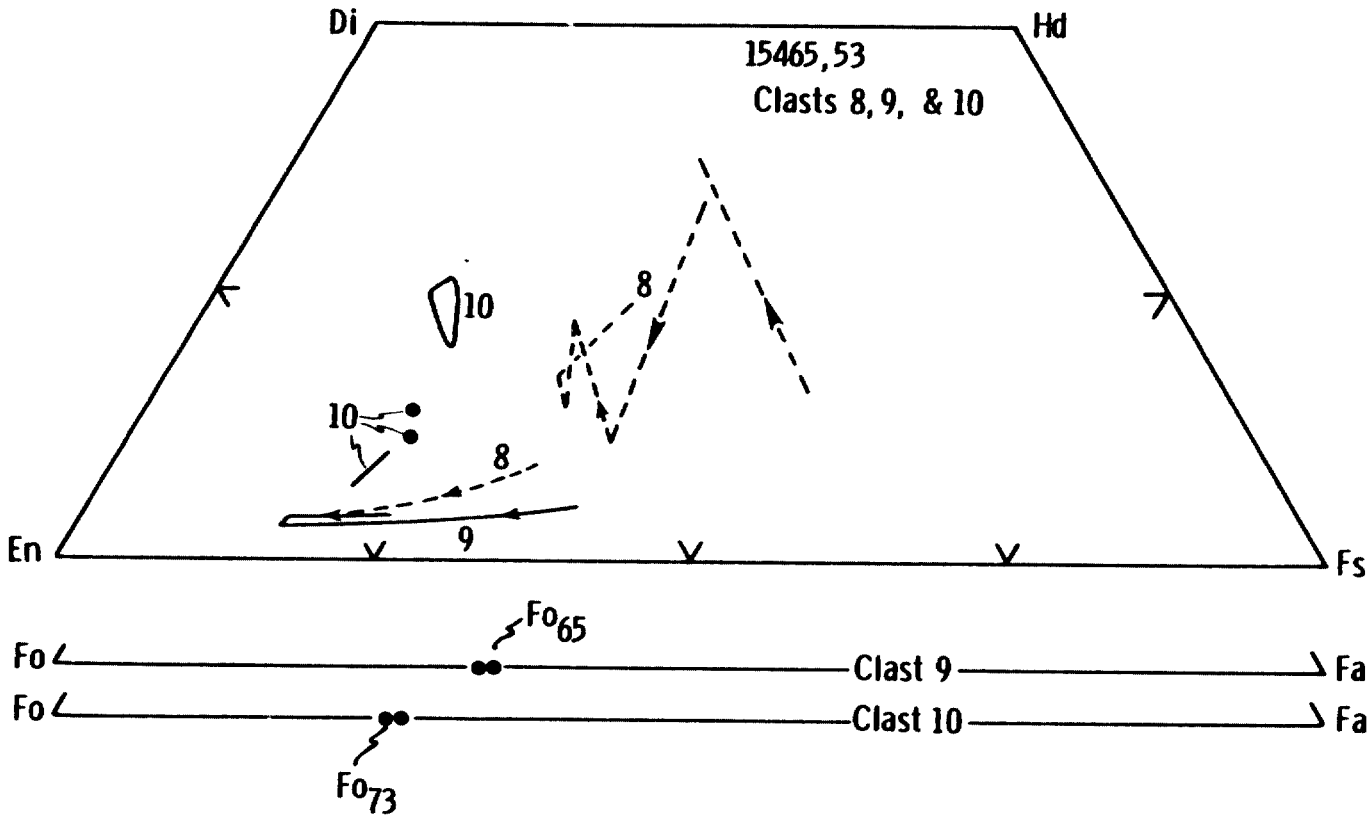


Figure 2. Compositions of pyroxene in clasts from 15465,53. Single points or areas represent multiple analyses. Arrows on lines represent direction of compositional zoning. Arrow points toward the core composition.

found in clast 8.

Clast 10 differs from clasts 8 and 9 in that it has a texture similar to eruptive igneous rocks or more slowly cooled impact melts, and it appears undisturbed by shock. Texturally it consists of small euhedral plagioclase feldspars (An_{87} - An_{94}, unzoned), which are occasionally enclosed in anhedral pyroxene. Subhedral to anhedral plagioclase, which is larger and not enclosed in pyroxene, comprises about 50% of the clast (visual estimate). Small euhedral olivine, which also encloses plagioclase, is enclosed in, or rimmed by, the pyroxene. The crystallization sequence, on textural grounds, is plagioclase, olivine + plagioclase, pyroxene + plagioclase + ilmenite.

Origin of the Clasts

Clasts 8 and 9 appear to be fragments from a larger ANT suite rock. This rock would have been heavily shocked prior to or perhaps at the time of formation of 15465. What is interesting about both clasts is the presence of glass with elevated K_2O content. It is not possible to determine with certainty whether or not these glasses were part of the original rock prior to the shock event which altered it, but, texturally, these glasses would appear to be mesostasis remaining after crystallization of the principal minerals rather than melt injected from another source. Clast 10, although having the texture of a basalt, is highly aluminous (see Table 2), and is more likely to be explainable as an impact melt (see section on clast bulk chemistry).

15466

Three sections from 15466 have been examined during the course of study of the Apollo 15 glass-coated breccias. One, 15466,22, was reported on in our last report (Winzer, 1977). The other two will be discussed here.

15466,13

This section does not include the rind glass which coats 15466, but is only of the breccia itself. This portion of 15466 is a glassy clast and fragment-poor breccia containing green glass spheres, fragmental feldspar, pyroxene, and minor olivine in a vesicular glass matrix. Unlike 15466,22, the range of mineral compositions from the clasts studied is considerably smaller, although one poikilitic K-feldspar "clast" has been found which contains barium-bearing K-feldspar, REE bearing apatite, high K glass, Mg bearing ilmenite, troilite and plagioclase (clast 13).

Figures 3a, 3b, and 4 show the range in chemistry of feldspar, pyroxene, and olivine from the 13 clasts studied in detail.

Clasts can be categorized on the basis of their texture and the chemistry of the principal minerals, however, these two criteria do not always produce consistent results. Clasts 1, 6, and 9 are brecciated, coarse grained fragments consisting of feldspar and/or pyroxene or olivine. Feldspars are usually unzoned or very slightly zoned (Figure 3). Ferromagnesian minerals are, likewise, of restricted composition and generally unzoned. Pyroxenes are magnesian, with En contents above

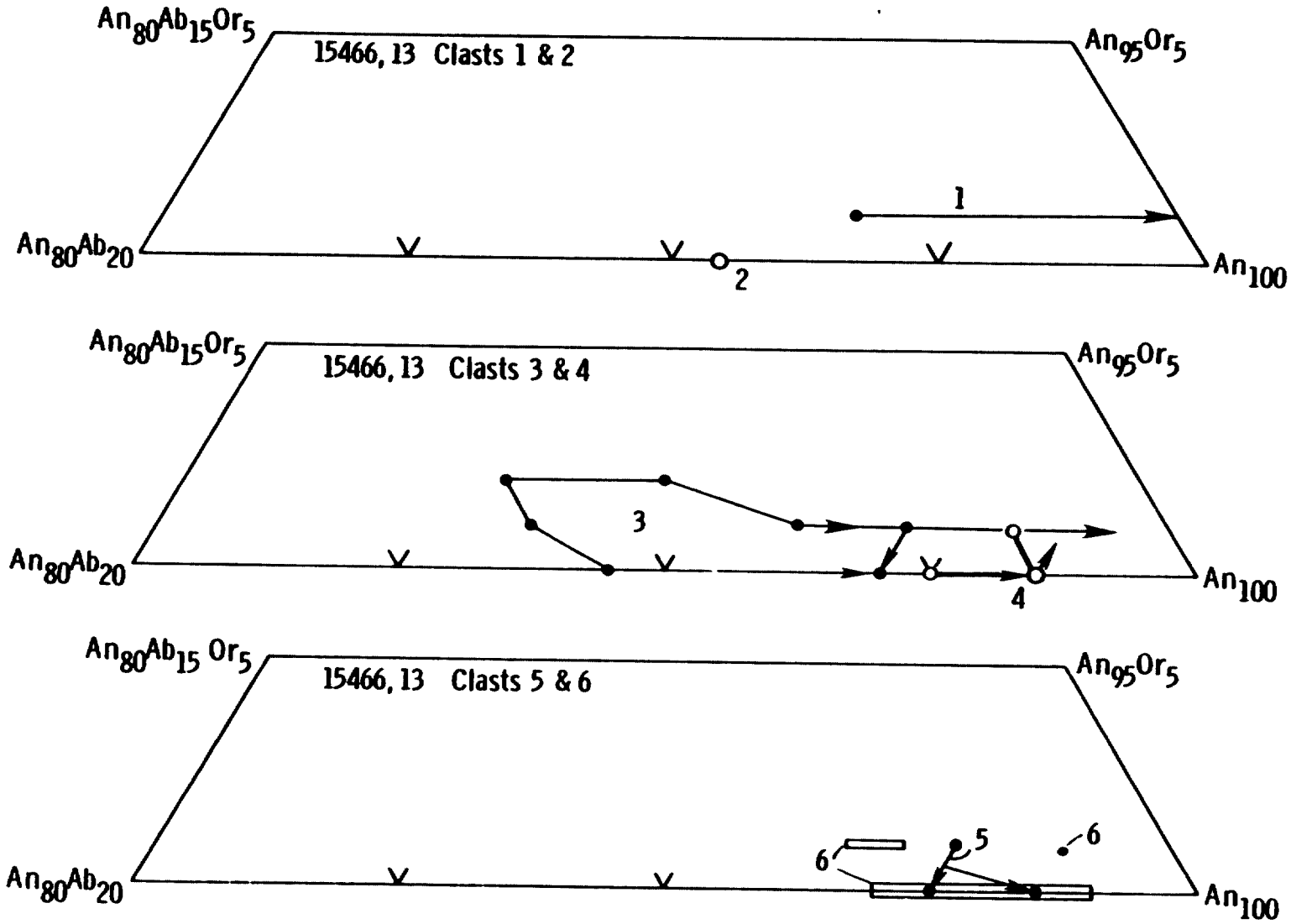


Figure 3a. Compositions of feldspars from clasts in 15466,13. Symbols as in Figures 1 and 2.

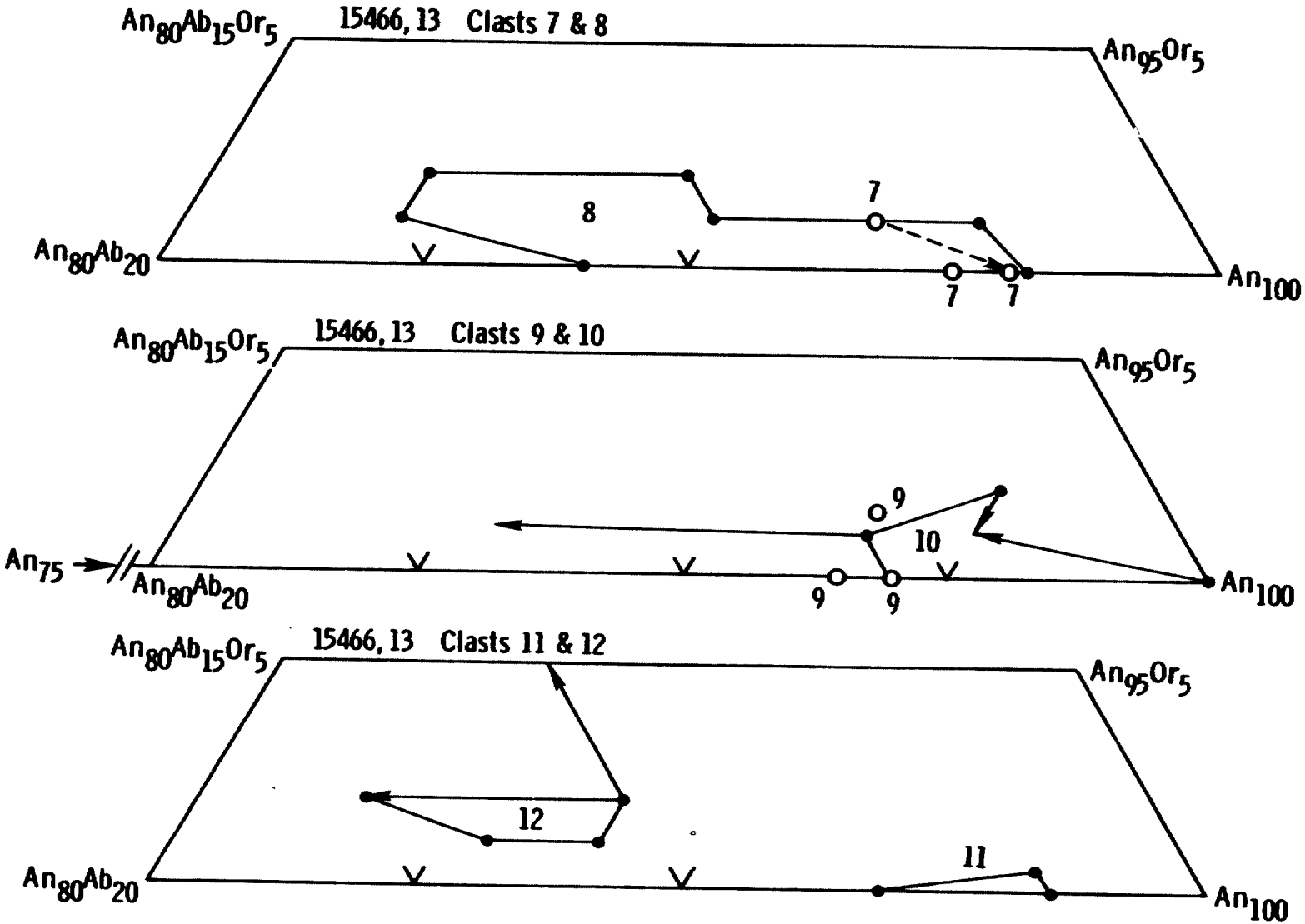


Figure 3b. Compositions of feldspars from clasts in 15466,13. Symbols as in Figures 1 and 2.

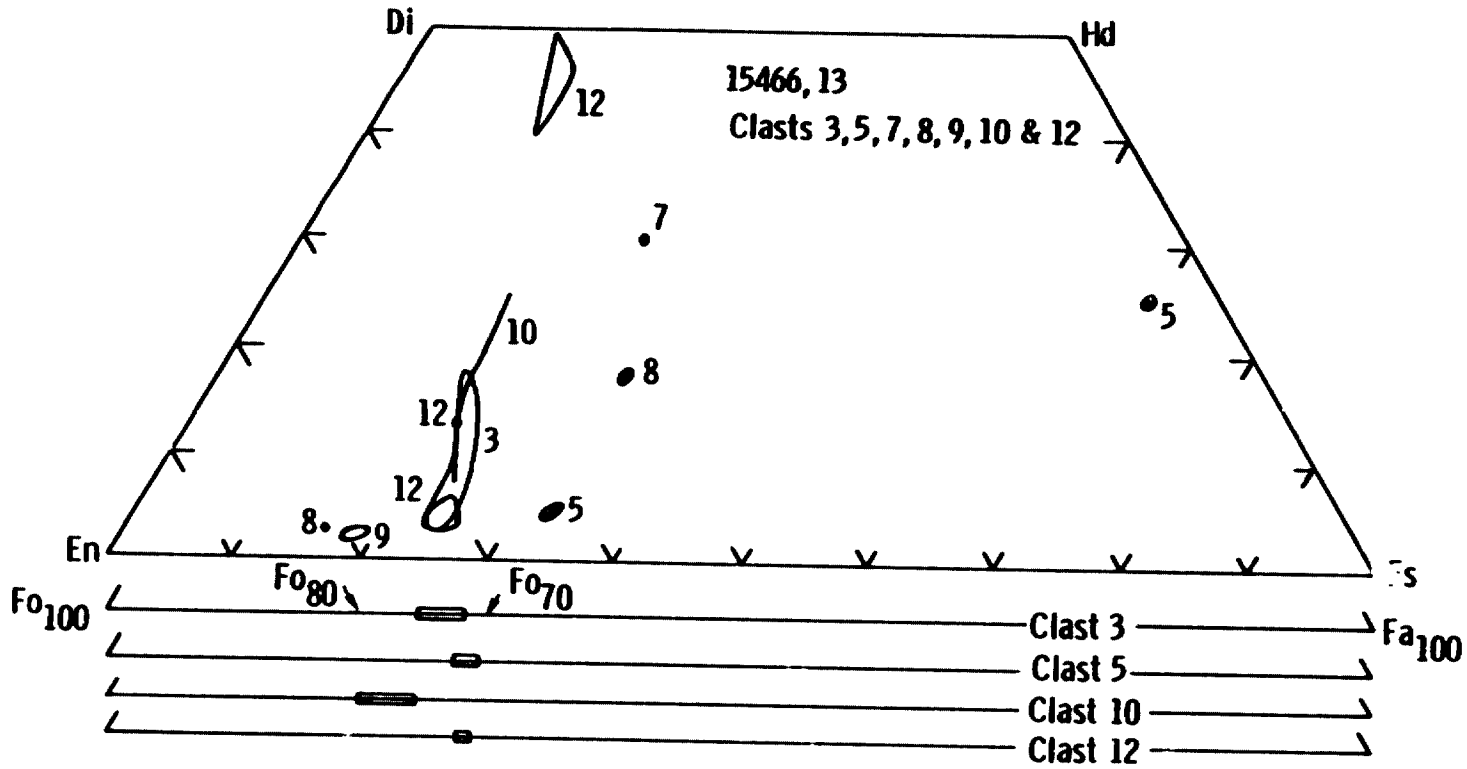


Figure 4. Compositions of pyroxene and olivine in clasts from 15466,13. Symbols as in Figures 1 and 2.

65 mol %. Olivine is present in one of the three clasts, and at Fo_{77} fits with the magnesian character of the pyroxenes. Only clast 9 contains any glass (Figure 5); the others are glass-free. These three clasts are almost certainly plutonic, and may be fragments derived from a larger body of ANT suite rock. All three clasts are too small to be reliably classified as a single rock type.

Differentiating by grain size and degree of crystallinity, the remaining clasts can be divided into three groups. Clasts 4 and 5 are vesicular glassy clasts comprising the first group. Clast 4 appears to be a single maskelynite or plagioclase glass grain, while clast 5 is a sintered breccia containing, in addition to low Ti glass, orthopyroxene ($Wo_{4-5}En_{62-64}Fs_{32-33}$), hedenbergite ($Wo_{25}En_{6}Fs_{69}$), and anorthite ($An_{75}$ - An_{85} and An_{55}). This would appear to be a disequilibrium assemblage, and is most likely the product of incorporation of xenocrysts of ANT suite feldspar and, possibly, opx into an impact melt. Textural relationships suggest that the low An plagioclase and the hedenbergite crystallized from the vesicular melt matrix, while the larger, subhedral, partly brecciated crystals of higher An plagioclase and orthopyroxene are xenocrysts incorporated at the time of formation.

The second group, more coarsely crystalline and with less glassy mesostasis than group 1, consists of clasts 2, 7, and 11. Texturally these clasts are composed of plagioclase "phenocrysts," usually 10-50 µm in longest dimension, set in a fine, cryptocrystalline groundmass which is usually olivine or pyroxene normative. These clasts contain no mineral large enough to analyse other than feldspar. Where feldspars

can be analyzed reliably, they show considerable compositional range, from An_{81} to An_{95}. Zoning, often reverse, generally covers 4-5 mol percent An, but clast 7 contains feldspars ranging from An_{81} to about An_{95}. This clast also contains glassy, cryptocrystalline mesostasis with a considerable compositional range (the greatest range of all clasts studied) (Figure 5).

The third, and largest, group (clasts 3, 8, 10, and 12) are the most crystalline (least glass), and are generally slightly coarser than those of group II. All four are texturally similar, containing large pyroxene xenocrysts in a fine-grained matrix of plagioclase, olivine, pyroxene, ilmenite, troilite and minor mesostasis glass. The crystallization sequence, from textural evidence, is plagioclase followed by or along with olivine, followed by pyroxene with ilmenite and high K, barium bearing mesostasis glass. Ilmenite may crystallize along with, or before, pyroxene in clast 12. This group of clasts has the greatest variability in mineral composition of all the groups. In pyroxene, in the less "developed" clasts (in terms of differentiation), zoning is restricted, and two pyroxene compositions (a magnesian orthopyroxene and a subcalcic augite) may be present (clast 8). In clast 10, a continuous compositional range from augite ($Wo_{25}En_{56}Fs_{19}$) to magnesian pigeonite ($Wo_{7}En_{69}Fs_{24}$) is present. Both of these clasts (8 and 10) coexist with olivines with limited compositional range. Clast 12, which contains the high K barium bearing glasses, contained a clinopyroxene zoned from augite ($Wo_{42}En_{45}Fs_{13}$) to diopside ($Wo_{49}En_{41}Fs_{10}$) coexisting with an unzoned orthopyroxene ($Wo_{3-5}En_{71-73}Fs_{23-26}$) and olivine ($Fo_{72}$). Clast 12 also contains reverse zoned

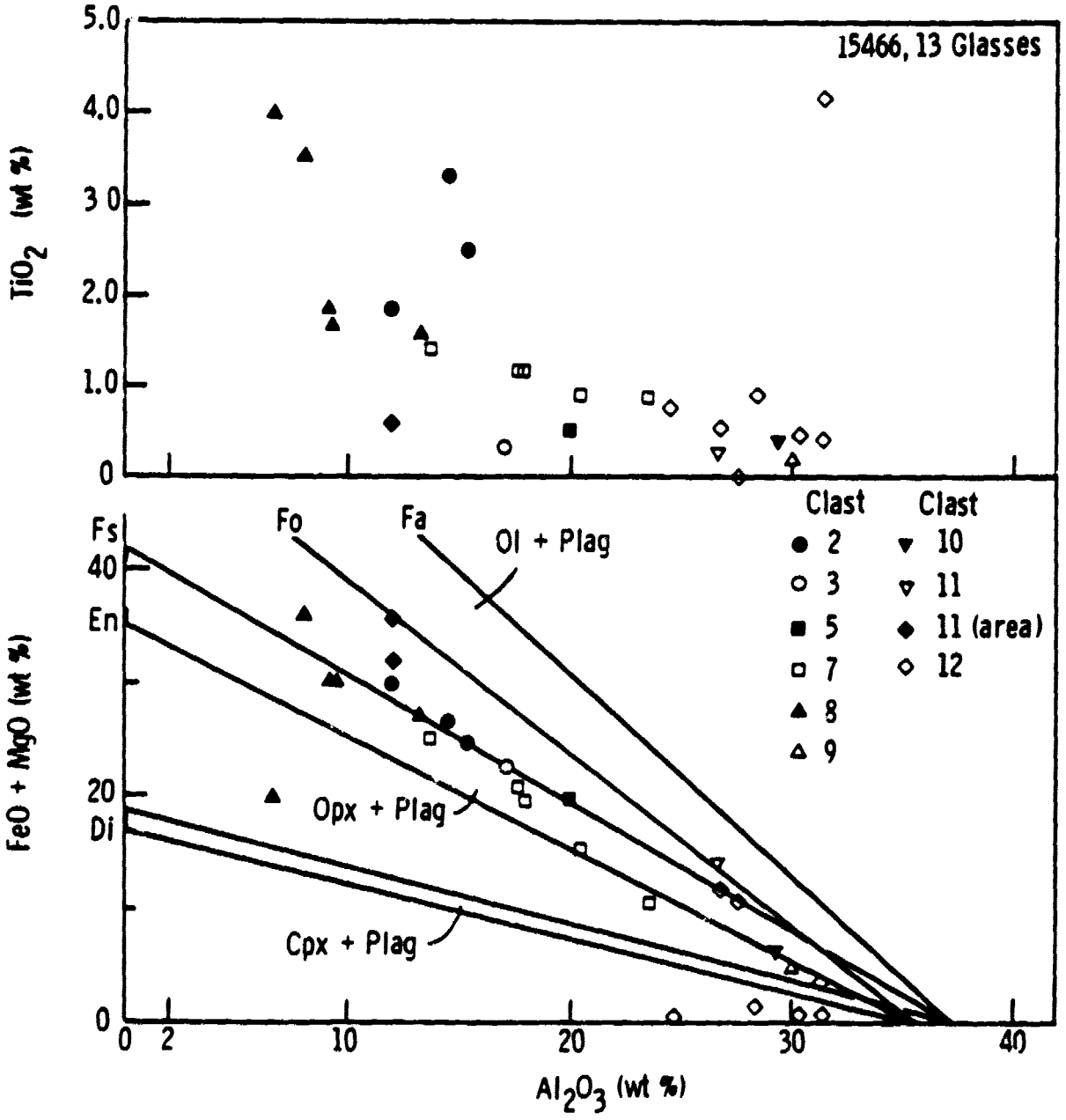


Figure 5. Plot of FeO + MgO (wt. %) and TiO_2 (wt. %) against Al_2O_3 (wt. %) for interstitial glasses from clasts found in 15466,13. Lines join pure mineral endmember compositions.

plagioclase (An_{75} [core] to An_{79} [rim]).

The glasses in all the above clasts are highly feldspathic, with generally low Ti, Fe, and Mg contents, and elevated K contents (Figure 5). All clasts in the third group are feldspathic, and contain more ilmenite (by visual estimate) than groups I and II. This group of clasts is the most likely to be formed by endogenous processes, although the presence of xenocrysts could indicate derivation by impact melting.

Groups I and II are most likely to be impact melts which have been quickly quenched following their formation. Clasts of group III could be either impact melts or extrusive igneous rocks but, with the data presently available, no strong case can be made for either.

15466,27

This section, unlike 15466,22, has much less matrix glass and a higher fragment and clast population. This portion of the breccia contains green glass, both as whole and fragmented spheres, impact melts, and a few larger, igneous-textured clasts. Six clasts have been analyzed in detail. The chemistry of the principal minerals, olivine, pyroxene, and plagioclase, are given in Figures 6 and 7.

The clasts in 15466,27 can be broken down into three groups on the basis of texture. The first group, containing clasts 4 and 6, is made up of large, almost monomineralic, fragments (clast 4 is a plagioclase; clast 6 is a pyroxene) which have been heavily shocked and partly melted. Clast 4 is ~1.5 mm in largest dimension and is composed of unzoned plagioclase (An_{94} - An_{100}) (Figure 6) which encloses small (30 μm), anhedral,

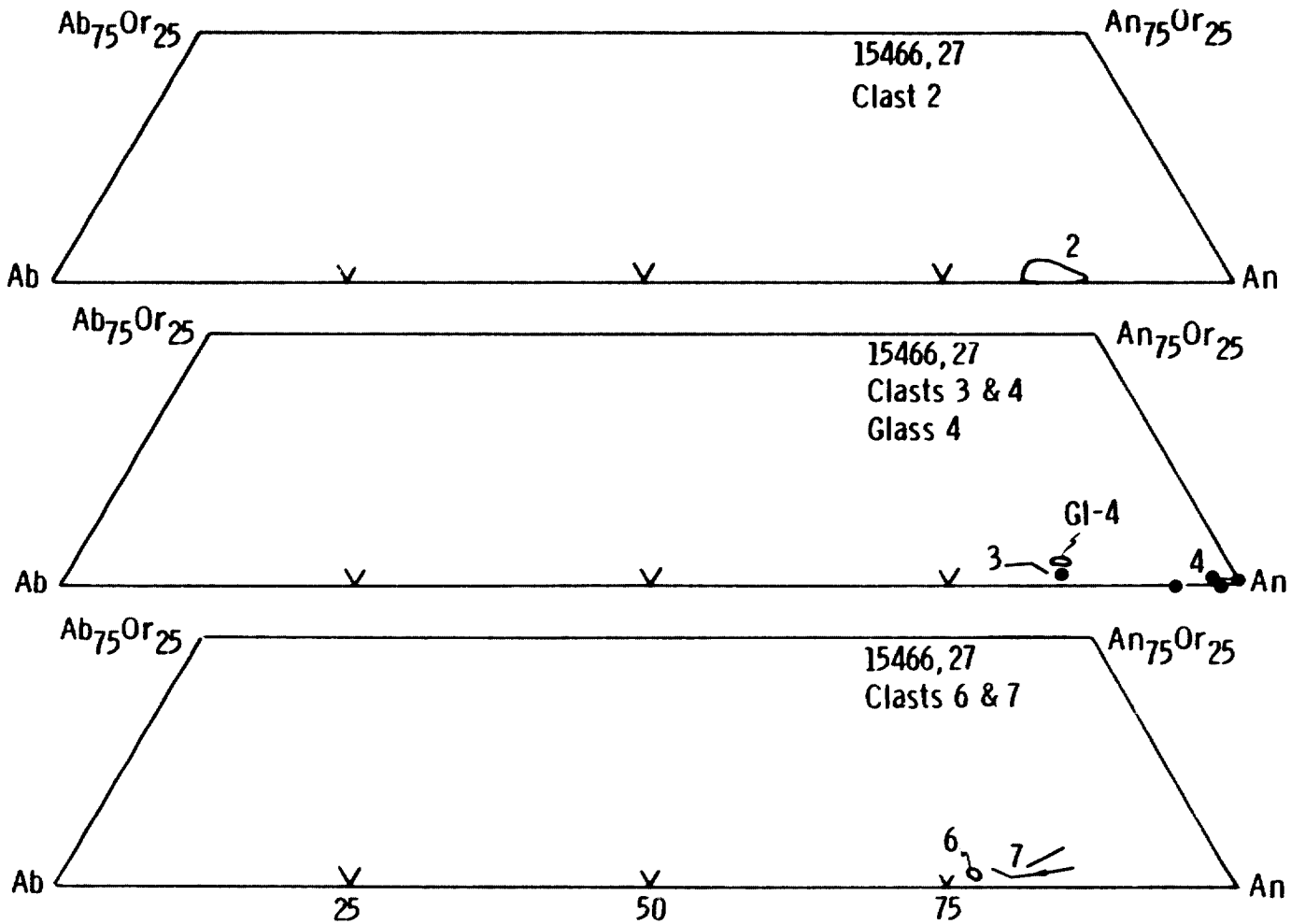


Figure 6. Compositions of feldspar in clasts from 15466,27. Symbols as in Figures 1 and 2.

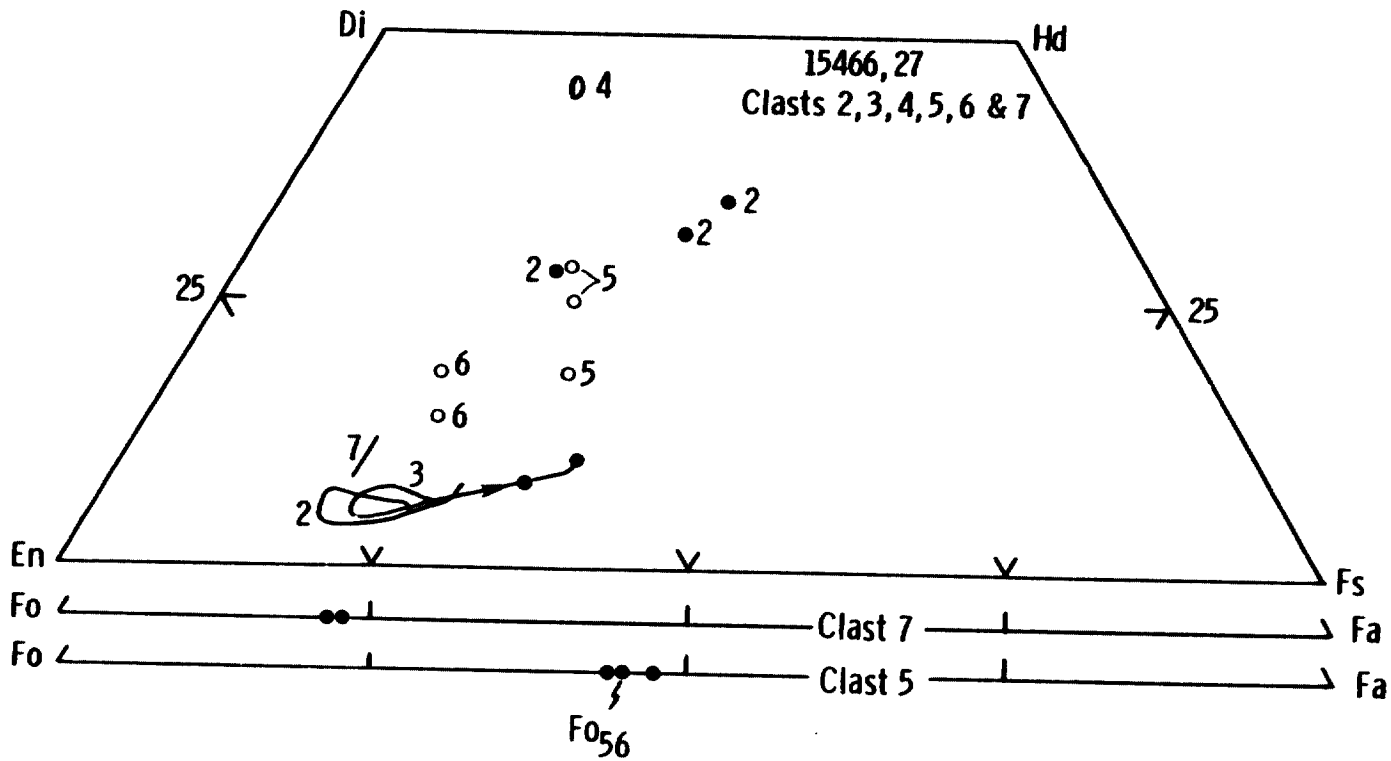


Figure 7. Compositions of pyroxene and olivine in clasts from 15466,27. Symbols as in Figures 1 and 2.

unzoned diopside (Figure 7). Clast 6, by contrast, is an irregularly shaped, partly recrystallized pyroxene about 350 μm in longest dimension. Parts of the clast are melt, and parts are crystalline. The crystalline portion is augite ($Wo_{9-23}En_{38-63}Fs_{21-44}$) while the melt is pyroxene normative with the normative pyroxene composition in the same range as the crystalline pyroxene. The melt areas have crystallized small subhedral plagioclase (An_{78}). Normative plagioclase calculated from the melt chemistry has, again, the same composition. These two clasts are little more than large fragments, probably from a plutonic rock or rocks, which were heavily shocked and disaggregated prior to incorporation in the breccia.

The second "group" has only one member, clast 5. The clast is a small (140 μm), devitrified fragment of impact melt containing olivine, augite, and glass, Augite appears to have crystallized along with olivine, but the textural relationships are obscured by the fineness of the grains (3-5 μm). The vesicular glass matrix shows considerable compositional range (see Figures 8 and 9) in Al_2O_3 and MgO + FeO.

Group III is the largest, containing clasts 2, 3, and 7. These clasts have a definite igneous texture, with euhedral plagioclase, either enclosed in or surrounded by pyroxene (clasts 3 and 7), or with small anhedral olivine and euhedral plagioclase enclosed in pyroxene. Clast 2 differs from 3 and 7 texturally in that it consists of anhedral plagioclase and pyroxene, with a very fine grained mesostasis, and has been moderately shocked. All three clasts contain ilmenite.

One of the more striking observations which can be made from these

data is that the mineral compositions of all three clasts are nearly identical. This fact is most clearly illustrated by the feldspars, which range from An_{81} to An_{88}. All three show zoning of about 5 mol % An from core to rim. Pyroxene compositions are a little more variable. All are subcalcic augites, the principal difference between them being the degree of zonation (Figure 7). Only clast 7 contains olivine large enough to be reliably analyzed. Olivine (Fo_{88}) occurs as small subhedral grains rimmed by (or enclosed in) subcalcic augite ($Wo_{8-12}En_{69-73}Fs_{19}$).

Glass compositions from clasts 2 and 7 have been obtained, and although both overlap, there are differences in the trends shown and the Al_2O_3 contents (Figures 8 and 9). Clast 7 contains glasses of essentially anorthite composition, in addition to the lower Al_2O_3, higher TiO_2, and FeO + MgO glasses. Both clasts contain glasses with up to 2% K_2O, and clast 7 contains FeNi spheres in the mesostasis areas.

Origin of the Clasts

Clasts of group I are clearly shocked fragments of ANT suite rocks, while the single member of group II is an impact melt. Members of group III are more enigmatic. These clasts are texturally and chemically similar to high alumina basalts, but they bear many similarities to impact melts from Apollo 16 breccias and other Apollo 15 breccias. Clast 2 has been shocked to sufficient levels to product melting of grains at margins, but the precourser to clast 2 was, quite possibly, an ANT suite rock judging by the texture of the less damaged part of the clast. Clast 7, by presence of Ni(Fe) and Fe metal droplets in the glass, as well as

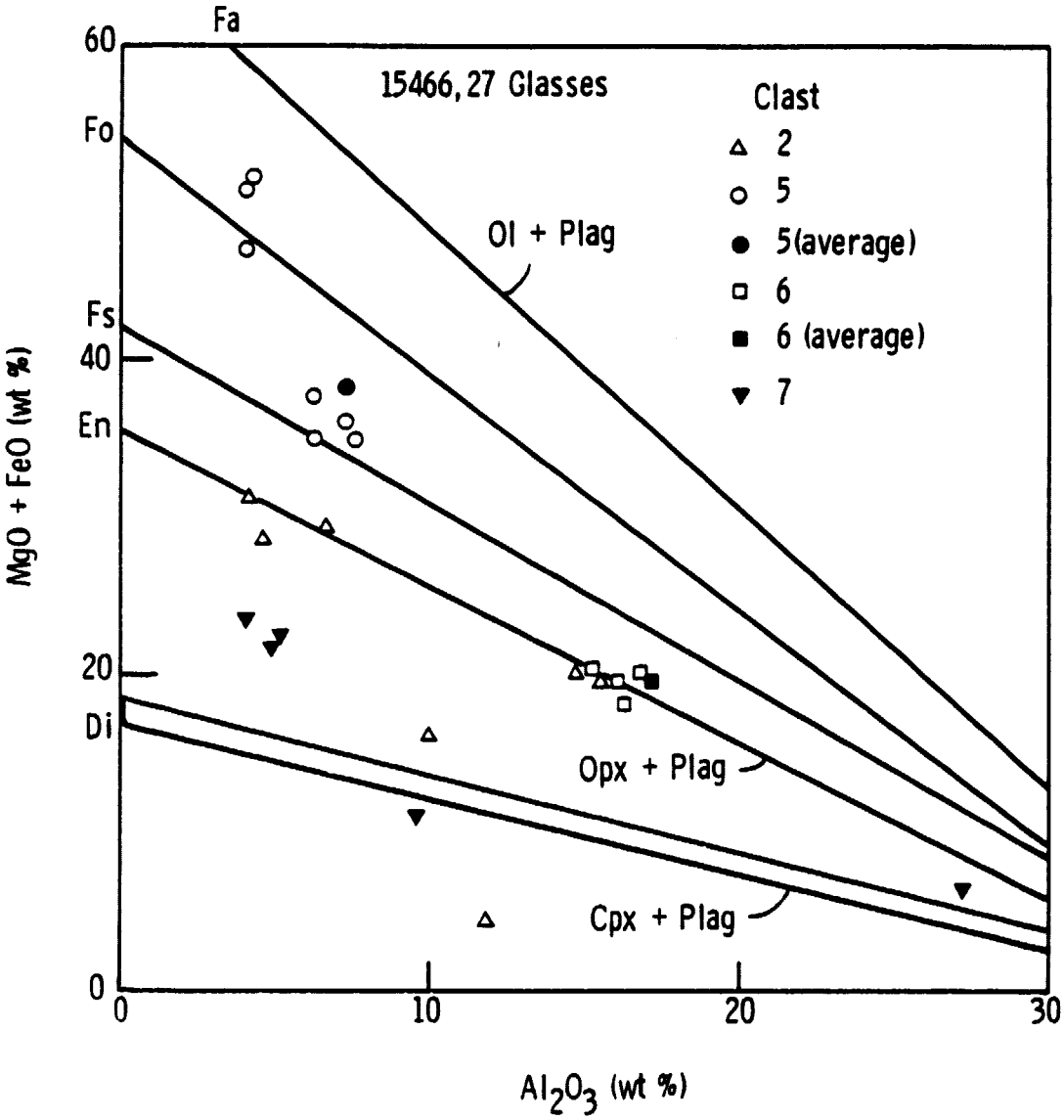


Figure 8. MgO + FeO (wt. %) plotted against Al_2O_3 (wt. %) for interstitial glasses found in clasts from 15466,27. Lines connect major mineral endmember compositions.

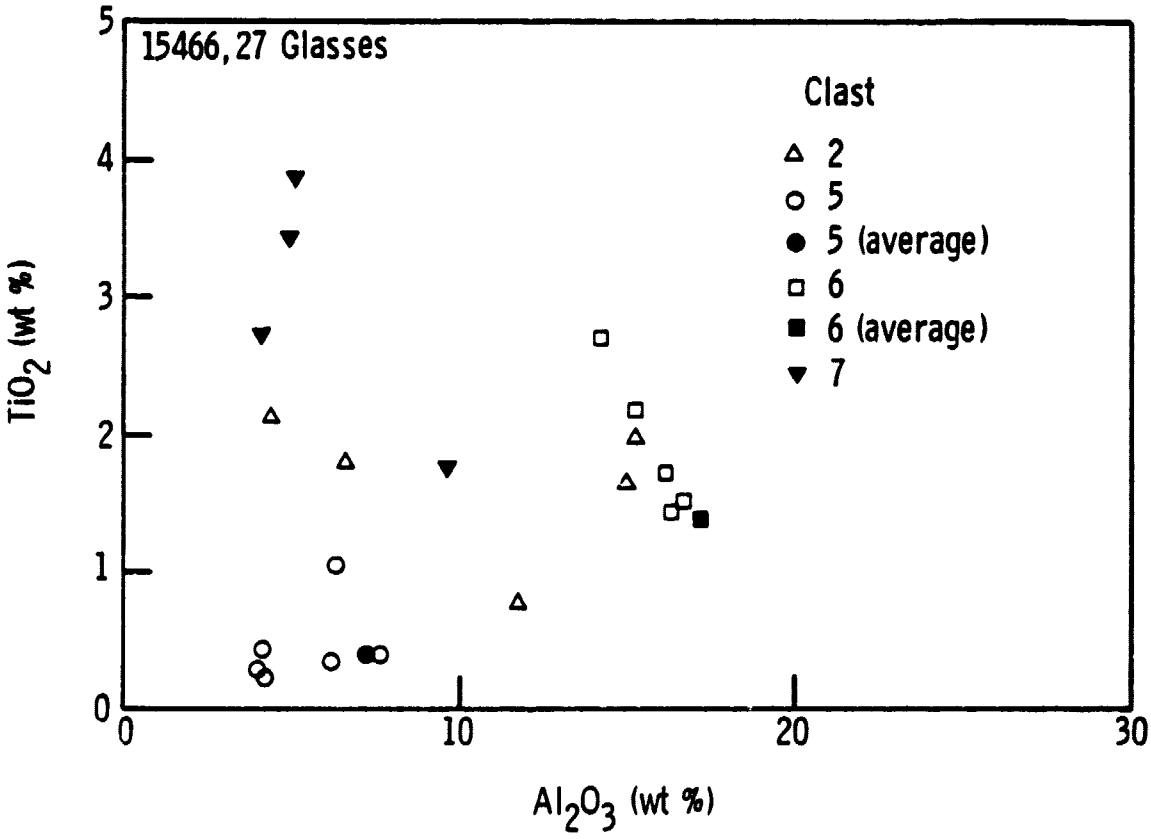


Figure 9. Plot of TiO_2 (wt. %) against Al_2O_3 (wt. %) for interstitial glasses found in clasts from 15466,27

its feldspathic composition is likely to be an impact melt. No criteria exists to so distinguish clast 3, except its similarity in mineralogy and mineral chemistry to the other two clasts.

CLAST CHEMISTRY

In order to gain some insight into the relationships of clasts to one another and to other well established lunar rock types, a majority of the clasts reported in Winzer, 1977 and those discussed in this report have been analyzed using the area scan technique. This approach is similar to the expanded beam technique, except that the beam is focussed and scanned across the area to be analyzed while an X-ray spectra is analyzed. The same technique was used to analyze clasts from 61175 (Winzer et al., 1977), and details of the technique and the correction procedure are reported there. The analyses presented here have not been corrected beyond use of the Bence-Albee correction prodecure, as the program is not yet integrated with our analytical facility, thus higher errors than normally quoted for this laboratory may be expected in certain of the elemental compositions (see Albee et al., 1977). Normative mineral composition derived from these analyses were compared with actual compositions of the minerals occurring in the clasts obtained by SEM/EDS analysis. Where clasts are well crystallized, both agree within 5-8 mol % of the end members; thus, the analyses are not believed to be grossly in error. Analyses from thirty-three clasts are presented in Table 2.

Comparison of the clasts to one another, and comparison of mineral chemistry and crystallization sequence, raises the same question we have

Table 2

Area Analyses of Clasts from Apollo 15 Glass Coated Breccias

Sample #	15255,38 Clast 1	15255,77 Clast 1	15255,77 Clast 2	15255,77 Clast 3	15255,77 Clast 4	15255,77 Clast 5	15255,77 Clast 6	15255,77 Clast 7
SiO_2	45.32	45.57	45.01	44.74	47.47	45.67	48.59	47.27
TiO_2	2.43	3.00	0.42	0.71	0.43	1.55	2.30	0.90
Al_2O_3	12.58	7.83	7.33	30.85	22.04	25.17	15.55	18.30
FeO	20.59	21.84	20.24	3.54	11.74	6.48	22.04	14.25
MgO	7.50	11.88	17.86	2.76	3.35	5.56	0.86	5.08
Cr_2O_3	0.78	0.53	0.65	0.15	0.16	0.24	0.05	0.30
CaO	11.17	9.37	8.42	17.24	14.75	14.52	10.64	13.91
Na_2O	0.21	0.13	0.00	0.18	0.54	0.61	0.43	0.16
K_2O	0.06	0.11	0.00	0.00	0.04	0.59	0.10	0.06
Niggli Norm								
Il	3.54	4.34	0.60	1.00	0.62	2.16	3.44	1.30
Ab	2.00	1.20	----	1.60	4.95	5.50	4.15	1.50
Or	0.40	0.65	----	----	0.25	3.50	0.65	0.35
An	34.65	21.28	20.18	83.70	58.88	64.23	43.08	50.68
Wo	----	----	----	0.82	6.37	----	5.39	8.24
En	13.80	20.12	16.91	7.64	9.46	7.87	2.54	14.48
Fs	19.92	18.65	10.90	4.72	18.22	4.22	33.22	21.94
Qtz	----	----	----	0.51	1.26	----	7.53	1.51
Di	18.56	21.66	17.58	----	----	6.30	----	----
Fo	3.00	6.27	20.61	----	----	4.08	----	----
Fa	4.26	5.82	13.23	----	----	2.19	----	----

Table 2 (continued)

Area Analyses of Clasts from Apollo 15 Glass Coated Breccias

Sample #	15255,77 Clast 8	15255,77 Clast 9	15286,29 Clast 1	15286,29 Clast 2	15286,29 Clast 3	15286,29 Clast 5	15286,29 Clast 6	15465,54 Clast 1
SiO_2	49.86	50.72	45.79	44.62	48.08	43.15	46.75	47.45
TiO_2	1.50	1.06	0.64	2.36	0.63	0.29	0.63	0.37
Al_2O_3	18.20	2.63	24.24	23.32	25.02	25.52	25.64	23.79
FeO	9.33	19.37	5.54	7.47	5.70	4.75	6.56	6.42
MgO	8.69	16.83	10.51	9.20	6.17	13.16	5.35	8.79
Cr_2O_3	1.50	0.75	0.16	0.20	0.17	0.17	0.23	0.28
CaO	11.42	9.34	13.33	12.70	14.21	13.26	14.88	12.82
Na_2O	0.68	0.00	0.00	0.25	0.22	0.00	0.20	0.21
K_2O	0.40	0.00	0.13	0.16	0.11	0.00	0.09	0.21
Niggli Norm								
Il	2.10	1.50	0.88	3.28	0.94	0.38	0.86	0.50
Ab	6.15	----	----	2.25	2.25	----	1.75	1.90
Or	2.40	----	0.75	0.95	0.65	----	0.50	1.25
An	45.68	7.28	64.72	61.85	63.98	63.75	67.10	62.83
Wo	4.51	----	----	----	1.11	1.50	----	0.10
En	24.12	33.01	19.43	17.26	20.32	8.94	10.08	24.08
Fs	12.66	21.05	5.33	5.84	8.90	1.80	10.62	9.36
Qtz	2.38	----	----	----	1.86	----	----	----
Di	----	31.74	0.32	0.80	----	----	3.92	----
Fo	----	3.30	6.75	5.82	----	19.71	2.52	----
Fa	----	2.10	1.83	1.95	----	3.90	2.64	----

Table 2 (continued)

Area Analyses of Clasts from Apollo 15 Glass Coated Breccias

Sample #	15465,54 Clast 2	15465,54 Clast 3	15465,54 Clast 4	15465,53 Clast 1	15465,53 Clast 2	15465,53 Clast 3	15465,53 Clast 4	15465,53 Clast 5
SiO_2	47.38	49.69	50.60	44.37	51.95	45.41	47.27	45.94
TiO_2	2.78	0.87	1.73	0.13	2.30	0.35	0.42	4.58
Al_2O_3	17.03	25.20	16.40	34.46	20.12	7.54	32.31	12.82
FeO	10.76	4.91	9.93	1.27	8.01	20.21	2.16	14.45
MgO	9.34	3.74	9.82	0.61	4.66	17.87	0.00	9.59
Cr_2O_3	0.44	0.04	0.26	0.05	0.25	0.57	0.00	0.54
CaO	12.04	13.92	10.60	18.87	11.45	8.59	16.79	12.04
Na_2O	0.27	1.54	0.53	0.29	1.26	0.00	1.21	0.22
K_2O	0.26	0.29	0.47	0.02	0.28	0.00	0.29	0.17
Niggli Norm								
Il	3.92	1.22	2.42	0.18	3.26	0.50	0.58	6.56
Ab	2.45	13.80	4.80	2.60	11.50	----	10.85	2.05
Or	1.55	1.70	2.80	0.10	1.65	----	1.70	1.05
An	45.10	61.18	41.20	92.75	49.15	20.62	81.78	34.48
Wo	6.18	3.11	4.68	0.38	3.42	----	0.56	10.80
En	26.14	10.32	27.26	1.68	13.06	17.02	----	27.26
Fs	12.98	6.42	13.42	1.88	9.72	10.89	2.78	17.30
Qtz	1.37	2.25	3.41	0.43	8.22	----	1.78	0.49
Di	----	----	----	----	----	17.66	----	----
Fo	----	----	----	----	----	20.28	----	----
Fa	----	----	----	----	----	13.02	----	----

Table 2 (continued)

Area Analyses of Clasts from Apollo 15 Glass Coated Breccias

Sample #	15465,53 Clast 6	15465,53 Clast 7	15465,53 Clast 8	15465,53 Clast 9	15465,53 Clast 10	15466,22 Clast 1	15466,22 Clast 2	15466,22 Clast 3	15466,22 Clast 4
SiO_2	45.42	96.12	54.05	50.36	45.94	45.03	49.48	54.18	48.13
TiO_2	2.19	0.29	1.83	1.34	1.62	0.46	0.72	0.31	0.41
Al_2O_3	29.69	0.63	15.24	13.70	21.73	7.17	28.91	0.64	26.18
FeO	4.40	1.07	10.01	11.31	7.19	20.70	3.22	11.44	5.31
MgO	0.64	0.00	8.46	13.44	10.03	17.16	0.00	30.95	4.86
Cr_2O_3	0.05	0.15	0.49	0.44	0.18	0.65	0.00	0.94	0.40
CaO	16.21	0.12	9.47	9.05	12.87	8.75	16.15	1.53	14.90
Na_2O	1.26	0.47	0.54	0.38	0.38	0.00	1.02	0.00	0.22
K_2O	0.22	0.05	0.23	0.35	0.08	0.05	0.84	0.05	0.06
Niggli Norm									
Il	3.10		2.60	1.86	2.24	0.66	0.98	0.42	0.56
Ab	11.50		4.90	3.40	3.40	----	9.95	----	2.00
Or	1.30		1.40	2.05	0.45	0.30	4.55	0.30	0.35
An	74.52		39.10	34.58	57.08	19.65	73.20	1.52	70.40
Wo	2.88		3.46	4.09	----	----	2.46	----	1.46
En	1.80		23.74	37.02	18.29	15.90	0.34	67.32	13.44
Fs	3.90		13.88	16.26	6.06	10.90	4.16	14.69	8.28
Qtz	0.94		10.92	0.75	----	----	4.36	----	3.50
Di	----		----	----	5.18	19.44	----	4.58	----
Fo	----		----	----	5.49	19.71	----	9.18	----
Fa	----		----	----	1.80	13.44	----	2.01	----

raised previously concerning clasts in lunar breccias (Winzer et al., 1977): namely, what are the origins of many of the clasts which have igneous textures, but are texturally and chemically diverse, and do not correspond to well established lunar igneous rocks like the mare basalts? Do any, or all, of the clasts represent internally derived igneous rocks, or are they all products of impact melting or mixing? Figures 10 and 11 are plots of MgO + FeO and MgO/MgO + FeO against Al_2O_3. The first plot indicates the relationship of clast chemistries to principal end member minerals (Fo-Fa, En-Fs, Di and An). This plot shows the strong tendency of all clasts to lie on anorthite-orthopyroxene "mixing" lines, regardless of mineral chemistry or modal composition. The clasts which are plotted here are similar in composition to those found in 61175 (Winzer et al., 1977), and, where their compositions permit the use of the olivine-anorthite-silica ternary diagram, will fall in the primary plagioclase field of this diagram.

The second plot is a simple index of "differentiation." If all the clasts plotted on this diagram were part of a suite of related igneous rocks, derived by some dominantly equilibrium process such as fractional crystallization or partial melting, a general trend of increasing MgO/MgO + FeO with increasing Al_2O_3 (An) content of the feldspar should be evident. No such trend appears. Perhaps a more sensitive indicator is the total alkali ($Na_2O + K_2O$) content against MgO/MgO + FeO. This is plotted on Figure 12. The error here is larger than for the other two plots, because at low Na or K concentrations, the error of the analyses becomes increasingly large. In general, however, this error would be reflected in horizontal movement of the points, which would have little

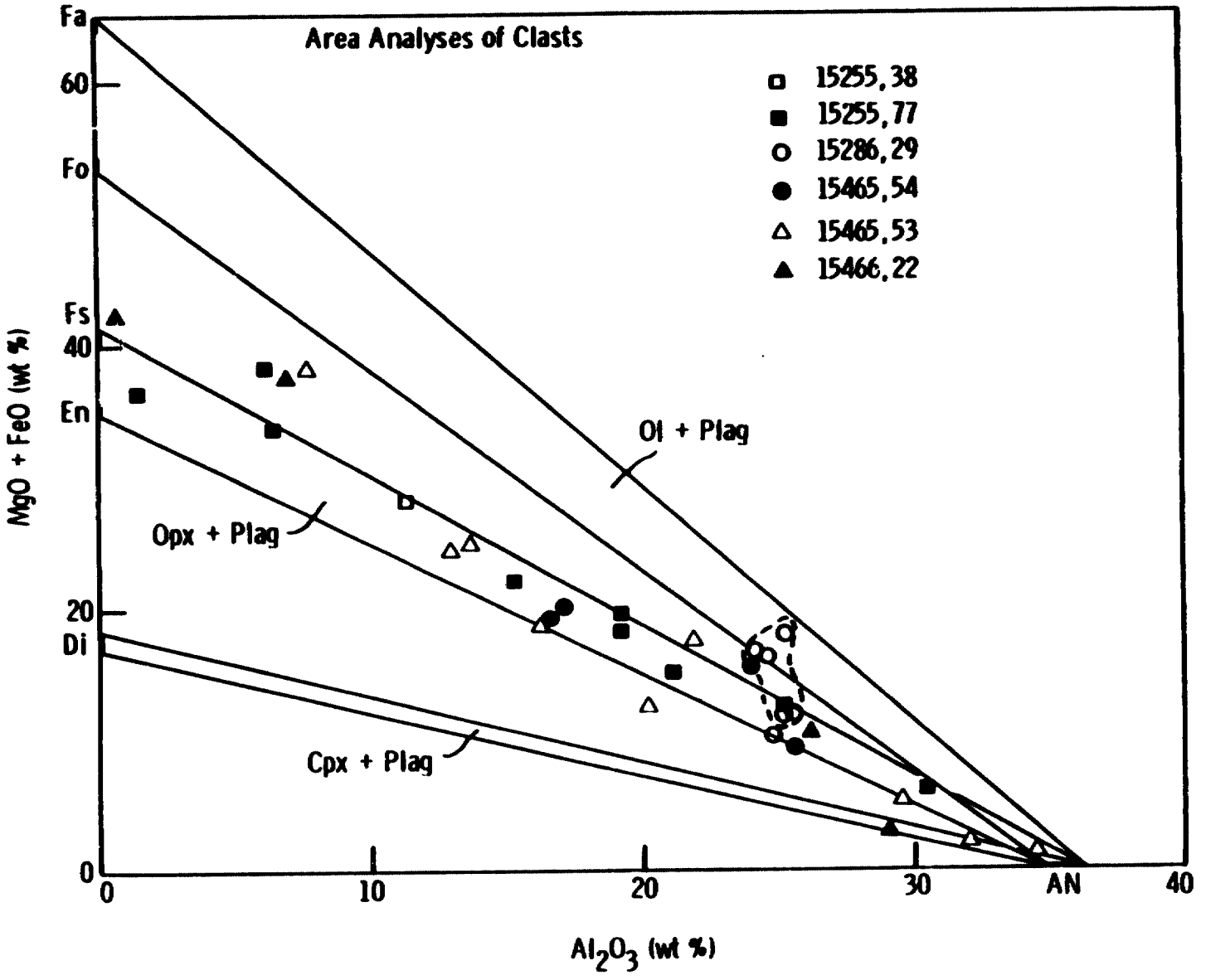


Figure 10. Plot of MgO + Fe O (wt. %) against Al_2O_3 (wt. %) from area analyses of clasts from Apollo 15 glass coated breccias

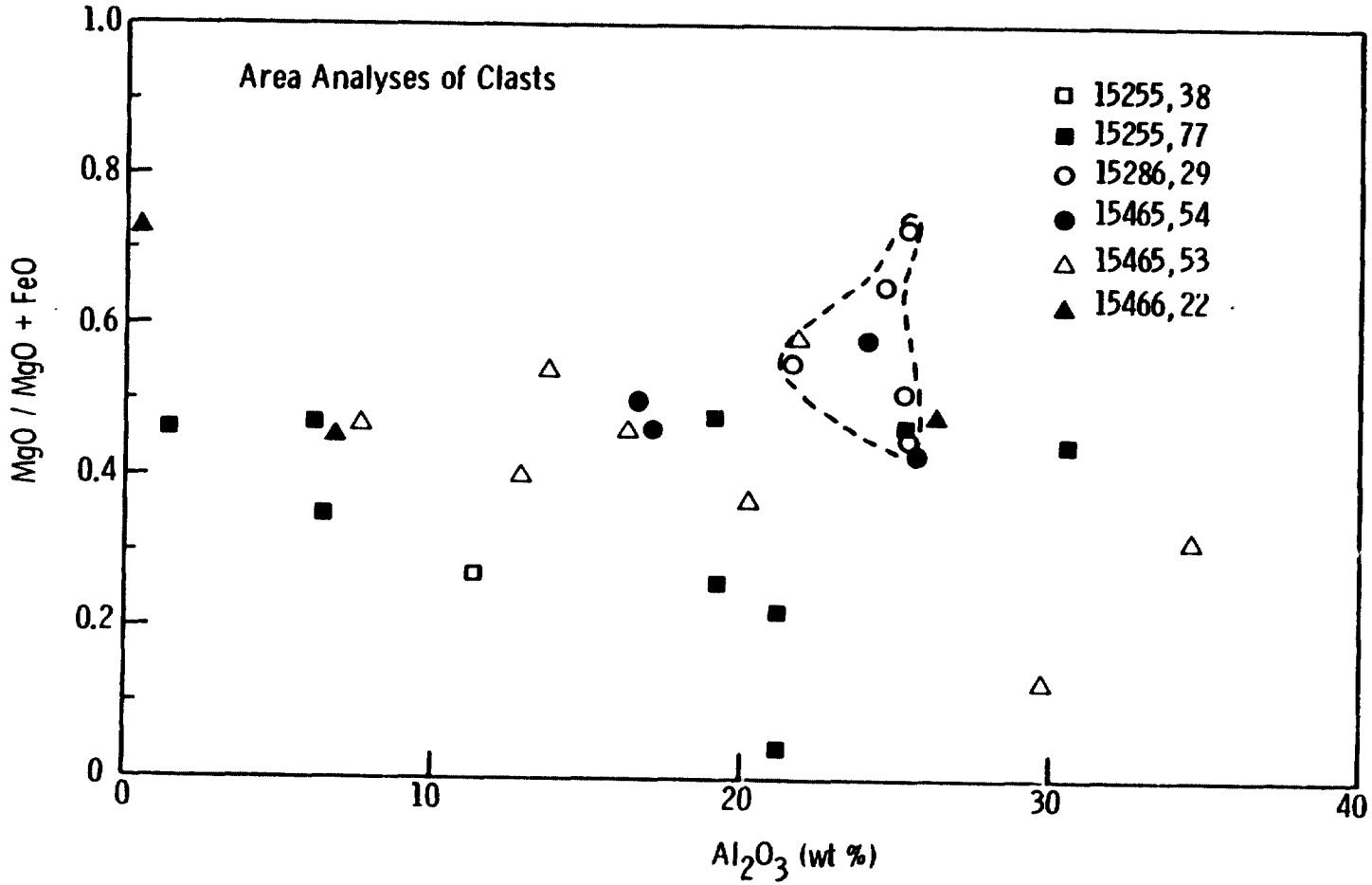


Figure 11. Plot of MgO/MgO + FeO against Al_2O_3 (wt. %) from area analyses of clasts from Apollo 15 glass coated breccias. For details of analytical technique see Winzer et al. (1977).

effect on the general, trend or lack of it. As total $K_2O + Na_2O$ content increases, MgO, and, thus, the ratio MgO/MgO + FeO, should decrease. It appears from examination of Figure 12 that no such trend exists.

Using a combination of all three plots, and by comparison with the results from analysis of clasts in 61175, most of the igneous textured rocks in the Apollo 15 glass coated breccias would appear to be impact melts. The evidence to support this contention is as follows: (1) No trends indicative of fractional crystallization, partial melting, or other equilibrium or semi-equilibrium process are evident in the clast chemistry. (2) Although most of these rocks, by their compositions, should have plagioclase on the liquidus, many crystallize olivine or pyroxene. (3) Several of the igneous-textured rocks contain Fe(Ni) spherules which strongly suggests association with meteorite impact. These rocks are not distinguishable on the basis of bulk chemistry from those which do not contain such spheres. (4) The compositions of the clasts, despite their basaltic igneous textures, are similar to rocks of the ANT suite (Figure 10), suggesting that they may be derived from melting of ANT suite rocks by meteorite impact.

Given the above conclusion, it is interesting to speculate on the origin of the impact melts. In our earlier work on the rind glasses enclosing these breccias, we established the striking similarities between the glass compositions and the compositions of the local soils at the locations from which the breccias were collected (Winzer et al., 1978). This similarity strongly links the last stage of the process by which these breccias were formed to local impacts which fused the soil and

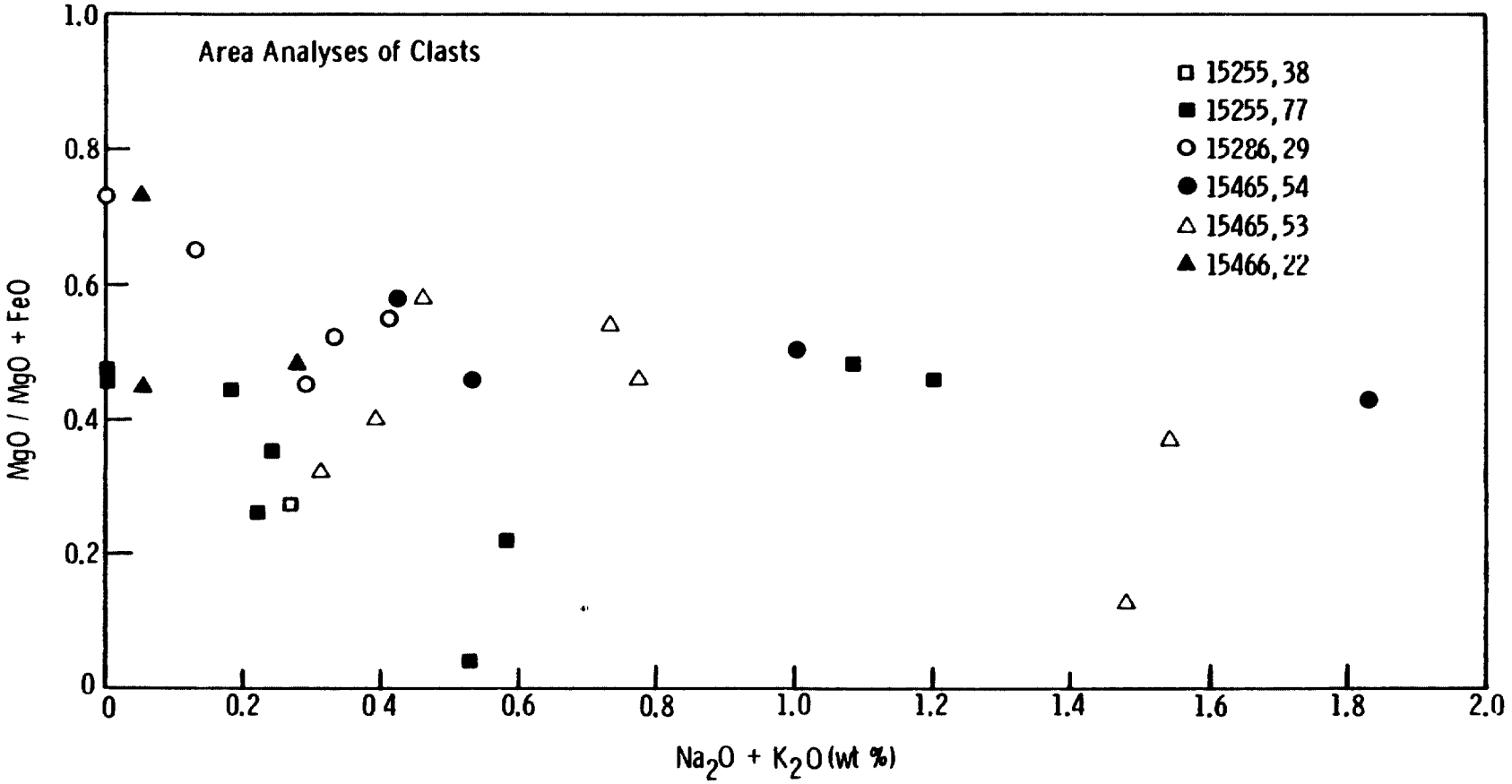


Figure 12. Plot of MgO/MgO + FeO against $Na_2O + K_2O$ (wt. %) from area analyses of clasts from Apollo 15 glass-coated breccias. For details of analytical technique see Winzer et al. (1977).

splashed the resulting fusion product onto the pre-existing breccias. Examination of Figure 10 indicates that clasts from 15286,29 and 15465,54 have relatively restricted compositional ranges; however, this may be only a function of the portion of the breccia sampled. That this is probably the case can be seen by noting that 15465,53, from the same rock, contains clasts which cover the entire range of the plot. It seems, therefore, that we cannot use clast populations as an indicator of the provenance of the breccia. One conclusion can be stated with reasonable certainty, however and this is that it is unlikely that the clasts derive from a single melt sheet. Unlike the situation at the Apollo 17 landing site, where the large boulders sampled can be shown to belong to a single melt sheet (Winzer et al., 1977), the spread in compositions seen here make such an occurrence much less likely. A more reasonable hypothesis is that these impact melts represent many impacts, perhaps smaller local impacts, rather than a large basin-forming event. These would not be the same impacts that formed the rind glasses. From the diversity of clasts and the similarity in the range of clasts found in each sample, the most likely source for the clasts is the soil. The presence of green glass in the breccias already establishes the presence of the soil component in the breccias (Winzer, 1977). It is possible that, despite their dissimilarity to typical soil breccias, the glass coated Apollo 15 breccias are principally derived from the local lunar soil.

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