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INVESTIGATION OF GLASS PARTICLES RECOVERED FROM APOLLO 11 AND 12 FINES: IMPLICATIONS CONCERNING THE COMPOSITION OF THE LUNAR SURFACE

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INVESTIGATION OF GLASS PARTICLES RECOVERED FROM APOLLO 11 AND 12 FINES: IMPLICATIONS CONCERNING THE COMPOSITION OF THE LUNAR SURFACE

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Abstract

Glass particles generally make up from 20 to 40% of the Apollo 11 and 12 fines (<1 mm dia). Regular forms (mostly spherical, elliptical, teardrop or dumbbell in shape) make up from approximately 0.5 to 1% of the fines. Splashed silicate glass, metallic beads and mounds, and impact pits are common surface features on both Apollo 11 and 12 glass particles. Relict silicate and oxide mineral inclusions (mostly pyroxene, plagioclase with some olivine and ilmenite) and metallic spherules are present in almost all of the opaque particles, but are present in only about one-third of the non-opaque glass particles. Nickel-iron octahedral crystals (2-5 μm dia.) have been found in a few glass particles.

Most of the glasses have "basaltic" compositions similar to the rocks or fine material from the respective Apollo sites. The Apollo 12 glasses differ in composition from the Apollo 11 glasses in the same manner that the Apollo 12 rocks differ from the Apollo 11 rocks--i.e. the Apollo 12 glasses generally have higher SiO_2 contents and lower TiO_2 contents than the Apollo 11 glasses. Glasses with "anorthositic" compositions have been found at both the Apollo 11 and 12 sites. "Basaltic" glasses with high K and P contents have been found in the Apollo 12 fines. These glasses are similar in composition to KREEP. Such material may be the cryptic component needed to explain the difference in composition between the Apollo 12 crystalline rocks and the fines and breccias. The

remaining glasses may represent exotic components or partial melting products of known materials. Modification of glass compositions by vapor fractionation seems to have been negligible.

INVESTIGATION OF GLASS PARTICLES RECOVERED FROM APOLLO 11 AND 12 FINES: IMPLICATIONS CONCERNING THE COMPOSITION OF THE LUNAR SURFACE

1. INTRODUCTION

Glass particles make up from 20 to 50 percent of the fines (<1 mm diameter) from the lunar soil at the Apollo 11 and 12 sites. Most of these glass particles were probably formed by impact melting of the local and surrounding regolith. Evidence most quoted for an impact origin of these glasses includes: 1) chemical heterogeneity of some of the glasses, 2) glasses with monomineralic compositions (mostly in Apollo 11 samples), 3) included Ni-Fe spherules, and 4) highly shocked crystalline inclusions. (The reader is referred to Chao et al. [1970a] for a more detailed discussion of the evidence for an impact origin for the lunar glasses.)

Many of these glass particles represent homogenized portions of the lunar rock or soil from which they were formed. A 500 milligram sample of <1 mm fines will yield hundreds or thousands of such particles >50 μm diameter. According to Shoemaker et al. (1970) 50% of the regolith at Tranquillity Base is expected to have come from a distance less than 3.1 km, about 5% from distances greater than 100 km and as much as 0.5% or more from distances greater than 1000 km. Thus the investigation of lunar glass particles from a single sample of <1 mm fines can tell us a great deal about the composition and variability of the lunar surface material within a radius of several hundred kilometers of the collection site.

A short summary of preliminary findings resulting from the investigation of glass particles from Apollo 11 soil sample 10084 was reported in a paper by Adler et al. (1970). In addition, a paper presenting the main conclusions of an investigation of glass particles from Apollo 12 sample 12057 has been published (Glass, 1971). However, because of length restrictions much of the supporting data for the above papers were not included. These data and additional data on glass particles from Apollo 12 sample 12070 are presented in this paper along with a discussion of the main findings and conclusions from these investigations.

2. SAMPLE DESCRIPTIONS

The glass particles discussed in this paper were recovered from an approximately four gram sample of Apollo 11 sample 10084 and approximately 0.5 gram samples of Apollo 12 samples 12057 and 12070. All three samples are <1 mm fines. The Apollo 11 sample is fines collected in the contingency sample. Apollo 12 sample 12057 consists of fines from the bottom of the documented Apollo Lunar Sample Return Container and is thus a mixture of material from several locations at the Apollo 12 site. Sample 12070 is the fines of the contingency sample taken on the rim of a small crater fifteen meters northwest of the LM.

3. ANALYTICAL PROCEDURES

A. Separation Methods

A total of 107 glass spherules were concentrated from the greater than 149 μm size fraction of Apollo 11 sample 10084 in the course of heavy liquid mineral separation. The spherules were obtained from Dr. J.A. Philpotts and the percent recovery is not known. The size, shape, color, transparency, surface features and other outstanding characteristics of each spherule were recorded and the spherules were placed in a container for additional investigations. In addition to the spherules, three angular glassy fragments from 10084 were selected for investigation and a fragment of pale green transparent glass from sample 10084 was obtained from Dr. N.M. Short.

The two Apollo 12 samples (nos. 12057 and 12070) were disaggregated with a sonic vibrator and dry sieved into five size fractions: $>580\ \mu m$, $147\text{-}580\ \mu m$, $74\text{-}147\ \mu m$, $44\text{-}74\ \mu m$ and $<44\ \mu m$. All of the spherules $>74\ \mu m$ diameter were picked out of the sample, described and placed in a container for further investigation. A total of 266 spherules were recovered from sample 12057 and 355 from sample 12070.

B. Petrographic Studies

The refractive indices of eighty-seven glass particles from sample 12057 were determined by the oil immersion method. In general, the precision of measurement is $\pm$ 0.002. Polished sections of each glass particle mounted for microprobe analysis were studied in reflected and transmitted light to determine the abundance of vesicles and crystalline inclusions. Metallic spherules were distinguished from other crystalline inclusions by their shape and reflectivity. Approximatley twenty mineral inclusions in several glass particles were identified by making spectral scans with an electron microprobe analyzer. In addition, mineral species included in or attached to the surface (rock flour) of several glass particles were identified by x-ray diffraction analysis using a Debye-Scherrer camera.

C. Electron Microprobe Analysis

Glass particles showing the widest range in physical properties were picked for electron microprobe analysis. Each particle was mounted in epoxy inside a ¼" metal tube, ground down to expose a section and polished. Coarse polishing was done with diamond paste. The final polish was with cerium oxide. Each particle was analyzed for Si, Ti, Al, Fe, Mn, Mg, Ca, Na and K. In addition, the Cr and P contents of forty glass particles from 12057 were determined.

The analyses were made with an ARL microprobe analyzer. Operating conditions were generally 15 KV accelerating voltage and 0.04 μamp specimen current. Ten to forty second counting times were used. Glasses made up by Corning and analyzed by the USGS were used for standards. Silica and Al_2O_3 standards were used for background counts. The data were corrected for background, instrument drift, absorption, atomic number and fluorescence using a computer program by Goldstein and Comella (1969). Each analysis is an average of five to ten point counts.

4. RESULTS

A. Abundance and Description of Glass Particles

Glassy particles in the lunar fines range from glassy coatings on rock fragments, to dark opaque glassy blebs, to opaque spherules, to transparent spherules, as well as, angular fragments of opaque and non-opaque glass (Fig. 1). Point counts of 1000 grains from the 74-147 μm and 147-580 μm size fractions of the two Apollo 12 samples indicate an average glass content of approximately thirty percent (Table 1). Quaide et al. (1971) report that these samples contain ~40% discrete grains of glass for similar size fractions. The greater than 580 μm size fraction apparently contained less glass, but only twenty-two grains were present in each sample from this size range. Quaide et al. (1971) also report lower glass contents for this size fraction (~25% and ~5% for sample 12057 and 12070, respectively).

Glass spherules (spheres, ovals, dumbbells, teardrops and other regular forms) make up approximately 1 to 5% of the Apollo 11 fines (Duke et al., 1970; Quaide and Bunch, 1970). The percent spherules increases with decreasing size fraction (Duke et al., 1970). Similarly the two Apollo 12 samples 12057 were found to contain approximately one percent spherules (based on point counts of 1000 grains) with a slight indication of an increase in percent spherules with decreasing size fraction (Table 1). Sample 12070 was found to contain only 0.4 to 0.6% glass spherules. However, the number of spherules recovered per gram of sample is greater for 12070 than for 12057 (Table 1). As with sample 12057 there is an indication that the percent spherules in sample 12070 increases with decreasing size fraction down to at least 74 μm. Quaide et al. (1971) report similar values for the spherule content of these two samples, but their data show no indication of an increase in percent spherules with decreasing size fraction.

The 107 spherules recovered from Apollo 11 sample 10084 range in size from 35 μm diameter up to an oval shaped spherule 1280 μm long by 1040 μm wide. (Since the spherules were recovered from the greater than 149 μm size fraction, the spherules with diameters less than 149 μm diameter must have been adhering to larger grains.) The largest spherical shaped glass body recovered from the Apollo 12 samples is ~540 μm in diameter. (However, it should be remembered that the Apollo 12 samples have only a combined weight of approximately one gram as opposed to the Apollo 11 sample which was approximately four grams.)

The size distribution for glass spheres greater than 176 μm diameter is similar for all three samples (Table 2). The number of spheres increases with decreasing size range and greater than half of the spheres occur in the smallest size range observed (Table 2).

Nearly 40% of the Apollo 11 spherules and approximately 50% of the recovered Apollo 12 spherules are opaque black. The non-opaque spherules occur in a wide variety of colors. However, dark wine red spherules are the most common in the Apollo 11 sample (Table 3). In contrast, yellow-brown to dark brown spherules are the most common in the two Apollo 12 samples with deep wine red spherules being fairly rare.

Spherical or elliptical forms make up approximately 90 to 94% of the spherules in all three samples (Table 4). The remainder are mostly dumbbells, teardrops or rod-shaped forms.

B. Surface Features

The following discussion is based mostly on scanning electron microscope (SEM) studies of twenty-four Apollo 12 glass particles (fifteen spherules and nine irregular blebs or fragments). Only seven Apollo 11 glass particles were studied with the SEM. However, comparison of the surface features observed on the Apollo 12 glasses with published descriptions of surface features on Apollo 11 glass particles indicates that there is no significant difference between the two. (For a more complete discussion of surface features observed on Apollo 11 glasses see Carter and MacGregor, 1970; McKay et al., 1970; Frondel et al., 1970.)

The surface of the glass spherules range from smooth and regular to rough and dust covered (Fig. 1E & F). Most of the surface features can be grouped into the following categories:

Rock Flour. Some of the opaque spherules have minute mineral grains or rock fragments (rock flour) embedded in or coating their surface. The dust coating is often only on one side of the spherule suggesting that it was acquired as the spherule landed on the regolith before it was completely solid. Sometimes vigorous agitation with a sonic vibrator will dislodge some of the particles leaving indentations on the surface of the spherule.

Exposed Vesicles. Approximately one-third of the spherules have exposed vesicles which were apparently formed by outgassing (Fig. 2A). Exposed vesicles have been observed only on the opaque spherules. Some of the splashed silicate glass blebs and coatings also have exposed vesicles.

<u>Splashed Silicate Glass</u>. Blebs or coatings of silicate glass (Fig. 2B and Fig. 3) occur on ten of the thirty-one glass particles studied. The silicate glass coating on the spherule shown in Figure 3 has a slightly different composition than the spherule being somewhat richer in Ca and Ti and poorer in Fe and K.

<u>Ni-Fe and Sulfide Beads and Mounds</u>. Beads or mound-like structures are visible on approximately one-third of the glass particles. They range in diameter from less than 1 μm up to approximately 25 μm. In general, the beads or mounds are randomly scattered over the surface of the spherules (Fig. 2C). However, on two of the spherules the beads occur in a geometric pattern (Fig. 4B) and on one the beads have partially coalesced to form an irregular mass (Fig. 5). On two of the spherules some of the beads have fallen out leaving dimple-like depressions (Figs. 4B and 5).

Electron microprobe analysis of the beads shown in Figure 5 shows that these beads are composed predominantly of iron with a minor amount of nickel and a trace of cobalt and sulphur. Other authors have reported troilite and phosphorous-rich mounds (e.g. Carter and MacGregor, 1970).

The geometric pattern shown in Figure 4B consists of large beads (up to ~1.5 μm dia.) each surrounded by a circle of smaller beads (~0.1 μm dia. or less). The circle of smaller beads occurs out from the central bead a distance that is approximately equal to the diameter of the central bead. In many cases the central bead has fallen out leaving a depression that is surrounded by a ring of small beads.

It is suggested that the geometric arrangement of beads discussed above is produced when a spherule is coated with a thin layer of Ni-Fe which draws up into beads due to surface tension. The shallow depression left where beads have fallen out indicates that the beads formed while the glass sphere was still in a molten state. A similar, but more irregular pattern of beads is present on the spherule shown in Figure 5.

Impact Pits. Of the thirty-one glass particles studied only three were observed to have an obvious impact pit on their surface. One pit on an Apollo 11 glass spherule was a small highly fractured area with a large spalled zone on one side. A second pit on an Apollo 12 spherule is a small glass-lined pit with a slightly raised rim. The third impact pit is shown in Figure 2D. This pit has a central melted depression surrounded by an outer fractured zone with radial fracture pattern.

C. Petrography

1. Refractive Index. The refractive indices of eighty-seven glass particles from 12057 range from 1.555 up to 1.690. However, most of the refractive indices fall between 1.580 and 1.670. A histogram of refractive index versus frequency shows a bimodal distribution with one mode at about 1.595 and the second at about 1.650.

In general, the refractive index of the glass is related to its color, and both the refractive index and color are good indications of the composition. The relationship between refractive index, color and SiO_2 content is shown in Figure 6. Two main groups or trends are evident. One group of mostly pale green to greenish-yellow glasses has a wide range in SiO_2 content (38-47%), but almost constant refractive index (~1.595). These glasses are "anorthositic" in composition with low Fe and Ti and high Ca and Al contents. The second group is made up of glasses with an average refractive index of 1.650. They range in color from yellow to green to brown to red. These glasses show a strong inverse correlation between refractive index and SiO_2 content (in general, the darker colored glasses [brown to red] have high refractive indices and low silica contents). These glasses are "basaltic" in composition and generally have higher Ti and Fe and lower Al contents than the lighter colored, "anorthositic" glasses. A similar relation between color and chemical composition was observed for Apollo 11 glasses (see for example Chao et al., 1970b; von Engelhardt et al., 1970, Quaide et al., 1970).

2. Vesicles. Generalized descriptions of five Apollo 11 and 157 Apollo 12 glass particles, mounted for electron microprobe analysis are given in Table 5. It can be seen that out of 162 glass particles approximately one-fourth contain vesicles. This percentage is true for both fragments and spherules. Approximately 72% of the opaque glass particles (seventeen total) contain vesicles whereas only about 21% of the non-opaque glass particles (145 total) contain vesicles.

From the above discussion it appears that the opaque glass particles were not heated as thoroughly as the non-opaque (especially the transparent) glass particles and had not finished outgassing before they solidified. Thus the opaque glass particles generally contain vesicles, whereas the non-opaque glass particles generally do not. This suggestion is supported by data on crystalline inclusions in the glass particles.

3. Inclusions.

a. Relict Silicate and Oxide Inclusions. Mineral grains which appear to be inclusions of pre-existing minerals (Fig. 7A) occur in approximately 38% of the glass particles investigated (see Table 5). X-ray diffraction analysis and electron microprobe analysis of inclusions in twenty glass particles indicate that the most abundant mineral inclusions are pyroxene and feldspar with some olivine and ilmenite.

As with the vesicles, relict mineral inclusions are more abundant in the opaque particles. They were observed in fifteen of the seventeen opaque particles whereas they were only observed in approximately one-third of the non-opaque particles.

b. SiO_2 Glass. One transparent yellow-green glass spherule (140 μm dia.) was found to contain a large (~30 μm dia.) rounded centrally located triangular shaped inclusion of lechatelierite (Fig. 7C). The inclusion is isotropic and electron microprobe analysis indicates that it is composed of nearly pure SiO_2. Frondel et al. (1970) reported rare grains of silica glass with N_d = 1.462 in Apollo 11 samples which they thought were derived from melting or shock vitrification of tridymite or cristobalite.

c. Ni-Fe and Sulfide Spherules. Ni-Fe and/or sulfide spherules (Fig. 7D) were observed in nearly half of the glass particles. They range in size from <1 μm up to approximately 30 μm in diameter. In some particles numerous submicron spherules delineate flow lines. In many of the glass spherules the metallic spherules are located near the outside of the spherule.

Most of the metallic spherules in both the Apollo 11 and Apollo 12 glasses are composed predominantly of iron with a few percent nickel. However, others are rich in Ni or S (Table 6).

The compositions of the metallic spherules are suggestive of meteoritic contamination; and, in fact, many authors have interpreted the presence of these spherules as indicating that the lunar glasses were produced by meteorite impact. However, Ni-Fe blebs have been found in Apollo 12 crystalline rocks. Reid et al. (1970) report that the Ni-Fe blebs in the Apollo 12 crystalline rocks have higher cobalt (up to 8%) than meteoritic Ni-Fe. Spectral scans of the Ni-Fe spherules in the Apollo 12 glasses indicate that they have low Co contents ($<1\%$). Thus those metallic spherules that were investigated are believed to be meteoritic in origin.

In general, those glassy particles containing relict silicate or oxide inclusions also contain Ni-Fe and/or sulfide inclusions and the glass particles without other mineral inclusions do not contain metallic and/or sulfide spherules either. Metallic and/or sulfide spherules were observed in nearly all the opaque glasses and approximately one-third of the non-opaque glasses.

d. Ni-Fe Octahedral Crystals. Black opaque Ni-Fe octahedral crystals (2 to 5 μm dia.) have been found in one Apollo 11 (Fig. 8) and two Apollo 12 glass particles. Electron microprobe analysis indicates that the crystals have the following approximate composition: 94% iron, 6% nickel and a trace of cobalt. The glass particles containing the Ni-Fe crystals are homogeneous and are free of Ni-Fe spherules and other crystalline inclusions.

Black, opaque, cubic crystals (generally 4-5 μm dia.) have been described by other investigators in Apollo 11 glasses (von Engelhardt et al., 1970; Frondel et al., 1970, Chao et al., 1970a). Chao (personal communication) has observed chromite as well as Ni-Fe cubic crystals in both Apollo 11 and Apollo 12 glasses.

Von Engelhardt et al. (1970) suggested that the glass containing the metallic crystals must have cooled in such a manner that the temperature remained close to the crystallization temperature of the metal long enough to allow the growth of a single crystal out of each liquid droplet. Walter (personal communication) states that reduction probably took place since the solubility of iron metal in silicate glass is low. In any event, the conditions under which the crystals are formed must be rather unique, since the Ni-Fe in most of the glass particles is in the form of spherules rather than crystals.

4. <u>Devitrification</u>. Approximatley seven percent of the glass particles investigated were partially or completely devitrified. Most of the devitrified particles are weakly birefringent colorless to grey translucent spherules with rough surfaces. These spherules are anorthositic in composition (see nos. 344, 345, 347, 348 and 350-353, Table 8). Several glass fragments have plagioclase crystals that appear to have been formed by devitrification (Fig. 7B).

5. <u>Transparent Pale Green Glass Fragments</u>. Transparent pale green glass fragments have been found in Apollo 11 and 12 fines. Although they make up less than one percent of the fines

they are conspicuous because of their transparency and bottle-green color. Of the twelve pale green glass fragments investigated all were homogeneous and none were found to contain vesicles or crystalline inclusions (including metallic spherules) except for devitrified plagioclase. These glass particles are anorthositic in composition (e.g. see samples 154-159, Table 8) and their refractive index is generally 1.595 ± 0.002.

6. Discussion. All of the opaque fragments and spherules contain vesicles and/or crystalline inclusions; whereas only 56% of the non-opaque fragments and 44% of the non-opaque spherules contain vesicles and/or crystalline inclusions. The glass in those particles containing vesicles and crystalline inclusions are generally heterogeneous. On the other hand, the glass particles without vesicles and crystalline inclusions are generally homogeneous.

Of the seventeen fragments that do not contain vesicles or crystalline inclusions, twelve are the pale green fragments discussed earlier. The remainder of the fragments do not appear to have any other characteristics in common.

D. Chemical Composition

The chemical compositions of fifteen Apollo 11 and 161 Apollo 12 glass particles are given in Tables 7 and 8, respectively. The glasses have a wide range in composition. However, in contrast to other workers (e.g. von Engelhardt et al., 1970; Chao et al., 1970 a & b) no glasses of monomineralic compositions have been found. The glass analyses, histograms of oxide abundances and various oxide plots have been utilized to divide the analyses into groups. Chao et al. (1970a) have divided both the homogeneous

Apollo 11 and 12 glasses into eight groups. When possible the groups established in this study have been correlated with those established by Chao et al. (1970a). In order to facilitate discussion the Apollo 11 and Apollo 12 glasses will be discussed separately.

1. Apollo 11 Glasses. The compositions of four fragments and eleven glass spherules from sample 10084 are given in Table 7. The Apollo 11 glasses fall into two main groups: "anorthositic" (group 1); and "basaltic" (groups 2-3 and miscellaneous analyses).

Group 1. The glasses in this group are distinguished by their high Al_2O_3 (>25%) and CaO (>15%) and low TiO_2 (<0.5%), FeO (<6%) and MgO (<6%) contents (Table 7). This group is similar to group 2 of the homogeneous Apollo 11 glasses of Chao et al. (1970a). Two glass particles fall in this group. One (sample 11) is a transparent pale green glass fragment devoid of vesicles or crystalline inclusions. The second is a 200 μm diameter clear to cloudy grey spherule with a rough surface.

Group 2. These glasses are distinguished from the group 1 glasses by their lower Al_2O_3 (~11-16%) and CaO (~11-15%) and higher TiO_2 (~6-8%), FeO (~14-17%) and MgO (~7-9%) contents (Table 7). The glasses in this group appear to be most similar to those in Apollo 11 group 4 of Chao et al. (1970a). However, the average FeO content appears to be a little higher and the average Al_2O_3 content a little lower. Approximately half of the glasses fall into this group. Three of the glasses are large (>580 μm) yellow-brown to brown glass fragments that contain numerous relict crystalline inclusions. Only one of the three was observed to contain metallic spherules. The remainder of the glasses in this group are small (<200μ m dia.) reddish-brown to deep wine red glass spherules.

<u>Group 3</u>. Only one particle (no. 122) was assigned to this group. It is placed in a group because it is similar to the glasses in Apollo 11 group 6 of Chao et al. (1970a). It has the highest FeO (23.7%) and TiO_2 (8.4%) and lowest Al_2O_3 content (5.3%) of any of the Apollo 11 glasses in Table 7. It is also distinguished by its low SiO_2 and high MgO content.

<u>Group 4.</u> Again only one particle is assigned to this group (Table 7). It is similar to the two glasses in Apollo 11 group 8 of Chao et al. (1970a). Like the glass particle in group 3 it has a high FeO and MgO and low Al_2O_3 content. However, it is distinguished from the group 3 glass by its low TiO_2 content (0.48%).

<u>Miscellaneous Analyses</u>. The remainder of the glasses cannot readily be assigned to one of the above groups for one reason or another and apparently do not fall into any of the groups defined by Chao et al. (1970a). Samples 125 and 132 are similar to the group 2 glasses except for their lower TiO_2 contents (Table 7). Sample 8 is similar to sample 10 in Table 2 of Chao et al. (1970a). Sample 10 has to the best of the author's knowledge the highest silica content of any Apollo 11 glass particle analyzed. This spherule is also unique in that it is one of three glass particles to contain Ni-Fe octahedral crystals.

2. <u>Apollo 12 Glasses</u>. The chemical compositions of 118 glass particles (fifty-five fragments and sixty-three spherules)

from sample 12057 and forty-three glass particles (eight fragments and thirty-five spherules) from sample 12070 are given in Table 8. A generalized description of each glass particle is given in Table 5. Seven groups have been distinguished. The range and average composition of each group is given in Table 9. Table 10 gives a summary of the distinguishing chemical characteristics of each group and a generalized description of the glasses in each group. Like the Apollo 11 glasses the Apollo 12 glasses can be divided into two main groups--those with "anorthositic" compositions (groups 1 and 2 in Table 8) and those with "basaltic" compositions (groups 3-7 and miscellaneous analyses in Table 8). The relationship between the groups, refractive index and SiO_2 content is indicated in Fig. 9.

<u>Group 1</u>. These glasses are distinguished by their high Al_2O_3 and CaO and low TiO_2, FeO and MgO contents (Tables 8, 9 & 10). They are similar to the group 2 glasses, but are distinguished from them by their lower FeO and MgO content (<5%). The glasses in this group are similar to those in Apollo 12 group 1 of Chao et al. (1970a) but have lower FeO and MgO contents. Only two particles are in this group (both from sample 12057). Both are small (<74 μm dia.) pale yellowish green spherules.

<u>Group 2</u>. The glasses in this group are similar to the group 1 glasses in that they have high Al_2O_3 (>20%) and CaO (>13%) and low TiO_2 (<1%), MgO and FeO contents (Tables 8, 9 & 10). But they are distinguished from the group 1 glasses by their FeO and MgO contents which even though they are low, are greater than 7%. These glasses are similar to those in group 1 of the Apollo 11 glasses. Thirty-four (~21%) of the analyzed glasses were assigned to this group. Approximately one-third of them are the

transparent pale green glass fragments, without vesicles or crystalline inclusions, that were discussed earlier. The remainder are generally colorless to yellow-green transparent or grey frosted spherules without vesicles and with or without crystalline inclusions. Five of the spherules (nos. 2, 227, 233, 244 and 298) have higher SiO_2, TiO_2, Na_2O and K_2O contents than the other glasses in this group (see Table 8). The glasses in group 2 are similar to those in Apollo 12 groups 1 and 2 of Chao et al. (1970a).

The remaining glasses (groups 3-7 and miscellaneous analyses) are "basaltic" in composition and are distinguished from group 1 and 2 glasses by their lower Al_2O_3 and higher TiO_2, FeO and MgO contents (Tables 8, 9 and 10).

Group 3. The distinction between group 3 and group 4 glasses is rather arbitrary as there is a continuous range in compositions between group 3 and 4 glasses. However, a plot of K_2O content versus Na_2O content for Apollo 12 glasses other than those in groups 1 and 2 shows a clustering of values below 0.2% Na_2O and 0.1% K_2O (Fig. 10). Thus the group 3 glasses are distinguished from groups 4-7 by their low alkali content ($Na_2O < 0.2\%$ and $K_2O < 0.1\%$). In addition to their low alkali contents, the glasses assigned to group 3 have lower P_2O_5 and lower average SiO_2 and Cr_2O_3 and higher average TiO_2, Al_2O_3, MgO and CaO contents than the glasses in groups 4-7 (Tables 8, 9 and 10). The glasses in group 3 are nearly all small (<150 μm dia.) yellow-brown spherules without vesicles or crystalline inclusions. Twenty-four (~15%)

of the analyzed glasses were assigned to this group. The glasses in this group are similar to analyses in several of the Apollo 12 groups of Chao et al. (1970a).

Group 4. Group 4 glasses are distinguished from the group 5 glasses primarily by their alkali content. Group 4 glasses have alkali contents intermediate between group 3 and group 5 glasses (see Tables 9 & 10). The glasses in this group exhibit a wide range in composition which does not show any obvious clustering into groups. These glasses are similar to two glasses in Apollo 12 group 4 of Chao et al. (1970a). The glasses in this group are fragments and spherules with a wide range in color and opacity. Most contain crystalline inclusions including Ni-Fe spherules. Those with the highest FeO content are generally brown to red-brown fragments without vesicles. Sixty-six (~41%) of the analyzed glasses were assigned to this group.

Group 5. Twenty (~12%) of the analyzed glass particles fall into this group. The glasses in this group are distinguished from the other "basaltic" glasses by their high alkali content ($0.6\% < K_2O < 0.85\%$; $0.9\% < Na_2O < 1.2\%$) (Fig. 10). The glasses in this group form a distinct grouping with a rather narrow range in composition (see Tables 8 & 9; Fig. 11). Besides their high alkali contents, the glasses in group 5 are generally richer in SiO_2, Al_2O_3 and P_2O_5 and lower in TiO_2, FeO and MgO than the other "basaltic" glasses (see Tables 8 & 9).

The group 5 glasses are generally transparent to translucent yellow-brown fragments without bubble cavities, but with numerous crystalline inclusions. They are similar to the transparent brown potassic glass from Apollo 12 regolith described by Meyer and Hubbard (1970). They are also similar to some heterogeneous Apollo 12 glasses reported by Chao et al. (1970a).

Group 6. The five glasses in group 6 are distinguished from the other Apollo 12 glasses by their high TiO_2 contents (>5%). These glasses also have low SiO_2 and alkali contents. One of these glasses (no. 216, Table 8) has the highest refractive index measured in this investigation. The glass particles in this group are red to reddish brown fragments or spherules without vesicles. Chao et al. (1970a) report only one Apollo 12 glass particle with a TiO_2 content greater than 5% and it is distinguished from the group 6 glasses by its higher SiO_2 content (45.7%) and lower FeO content (15.5%).

Group 7. Only one glass particle is assigned to this group. It is a reddish-brown spherule from sample 12070. It has the lowest Al_2O_3 content (4.12%) among the glasses analyzed in this study. It is also distinguished by a low SiO_2 (38.8%) and CaO (6.4%) and high FeO (29.8%) content. It is placed in a group rather than under miscellaneous analyses because it is similar to Apollo 11 red to black spherules analyzed by Keil et al. (1970) and to red-brown glass from a breccia analyzed by Ware and Lovering (1970). It is also similar to the Apollo 11 group 6 glasses of Chao et al. (1970a) which are dark wine red spherules and to an Apollo 11 spherule (no. 122) discussed in this report (Table 7).

Miscellaneous Analyses. Nine of the glass particles from sample 12057 cannot be assigned to any of the above groups. All have fairly high Na_2O and/or K_2O contents. Two of them (nos. 226 and 234) have unusually high alkali contents compared to other

Apollo 11 and 12 glasses (Table 8, Fig. 10). They also have high SiO_2 contents and low TiO_2 contents. Three others (nos. 174, 175 & 276) have high K_2O contents (~0.9%) but intermediate Na_2O contents. Two of these samples (174 and 276) are quite similar to each other compositionally and all three are opaque. Samples 166, 205 and 219 have higher Na_2O contents than the group 4 or 5 glasses but lower Na_2O and total alkali contents than the group 6 glasses and are intermediate in composition between the group 4 and group 6 glasses. All three are non-opaque fragments from the 147-580 μm size fraction and samples 166 and 219 are both reddish brown and contain crystalline inclusions. Sample no. 230 is a yellow-green spherule with high Na_2O content (1.22%) but intermediate K_2O content (0.32%).

5. DISCUSSION

A. Comparison between Apollo 11 and Apollo 12 Glasses. The glasses from both the Apollo 11 and 12 sites can be divided into two main groups: 1) "anorthositic" and 2) "basaltic". The anorthositic glasses (Apollo 11 group 1 and Apollo 12 groups 1 and 2) from the two sites are quite similar to each other. However, the basaltic glasses (Apollo 11 groups 2-4 and Apollo 12 groups 3-7) from the two sites are for the most part distinct. In general, the Apollo 12 basaltic glasses have higher SiO_2 contents and lower TiO_2 contents than the Apollo 11 basaltic glasses (see Fig. 12). However, the five Apollo 12 glass particles in group 6 (Table 8) are similar to many of the Apollo 11 glasses. Likewise, some of the Apollo 11 basaltic glasses with low TiO_2 contents (e.g. sample 8 in Table 7) are similar to Apollo 12 basaltic glasses.

Glasses with low Al_2O_3 contents (<6%) are fairly common in Apollo 11 samples (von Engelhardt et al., 1970; Chao et al., 1970a & b; Keil et al., 1970; also see sample no. 122, Table 2 of this paper). Only the one Apollo 12 glass particle in group 7 (Table 8) has been found with similar composition. Likewise, basaltic glasses with high alkali content like the Apollo 12 glasses in group 5 are extremely rare in Apollo 11 samples.

Although distinct from each other in many respects, on some variation diagrams (of percent oxides versus each other) the Apollo 12 glasses fall on the same trends as the Apollo 11 glasses (e.g. see Fig. 13).

B. <u>Comparison between Glasses and the Rocks and Soils at the Apollo 11 and 12 Sites</u>. The majority of the Apollo 11 and 12 glasses are similar in composition to the rocks and fines at the respective sites. The seven Apollo 11 glasses assigned to group 2 (Table 7) are similar in composition to published analyses (LSPET, 1969) of Apollo 11 crystalline rocks, breccias and fines. The comparison between these glasses and the average composition of the Apollo 11 fines is particularly striking. Except for the somewhat lower MnO and Na_2O contents of the glasses all of the oxides are generally within the range given for Apollo 11 rocks and fines.

Most of the Apollo 12 glasses assigned to group 4 (Table 8) have compositions within the range given (LSPET, 1970) for the Apollo 12 rocks and fines. However, they seem to have slightly higher average SiO_2 and slightly lower average TiO_2 and FeO contents than the Apollo 12 rocks and fines. In general, they are more similar to the average composition of the fines; however, about one-fifth are more similar to the crystalline rocks because of their high FeO (>17%) and TiO_2 (>3%) and low Al_2O_3 (<12%) contents.

The Apollo 12 group 3 glasses are more similar to the Apollo 12 rocks and fines than the group 4 glasses in some respects and less similar in others. They are more similar because of their slightly lower SiO_2 and higher TiO_2 contents. However, their extremely low Na_2O contents distinguishes them from the Apollo 12 rocks and fines. This suggests that these glasses were derived from another parent material or that their compositions have been modified by some process such as vapor fractionation.

C. <u>Modification of Glass Composition by Vapor Fractionation</u>. The Apollo 12 group 3 glasses differ from group 4 glasses by having higher average TiO_2, Al_2O_3, MgO and CaO contents and lower average SiO_2, FeO, MnO, Na_2O, K_2O and P_2O_5 contents. The observed differences in composition between the group 3 and group 4 glasses are the ones that would be expected if the group 3 glasses were produced from group 4 glasses by vapor fractionation in a reducing environment (see Walter, 1967; Chapman and Scheiber, 1969).

Further support for vapor fractionation is seen in a variation diagram of Al_2O_3 versus MgO for Apollo 12 glasses. Walter (personal communication) points out that Al_2O_3 varies inversely with MgO in igneous differentiation trends, but that Al_2O_3 varies directly with MgO in vapor fractionation trends. A plot of all analyses of

Apollo 12 glasses shows that the main overall trend is for Al_2O_3 to vary inversely with MgO. However, within the main trend Al_2O_3 varies directly with MgO in going from the group 4 to the group 3 glasses as would be expected if the group 3 glasses were produced from group 4 glasses by vapor fractionation.

Also in support of vapor fractionation is the fact that nearly all the group 3 glasses are small (<150 μm dia.) spherules without bubble cavities or crystalline inclusions. The group 4 glasses, on the other hand, generally contain crystalline inclusions. This suggests that the group 3 glasses were heated more intensely than the group 4 glasses.

Since the lunar glasses show distinct clustering according to composition and since the bulk of the glasses from the Apollo 11 and 12 sites are similar in composition to the rocks and fines from the respective sites, it is unlikely that the major element contents of most of the glasses have been changed appreciably by vapor fractionation. Chao et al. (1970a) also conclude that the major element contents of the lunar glasses that they studied have not been appreciably affected by volatilization, and that their present compositions probably closely reflect the compositions of the parent materials.

D. <u>Exotic</u> <u>Glasses</u>. Several groups of glasses from the Apollo 11 and 12 sites do not have compositions similar to the analyzed rocks or soil from the Apollo 11 or 12 site, respectively. These glasses may have been produced by shock melting of materials from other areas of the moon and/or from local rocks that are not abundant.

1. Anorthositic (Apollo 11 Group 1 and Apollo 12 Groups 1 and 2) Glass. The Apollo 11 group 1 glasses (Table 7) and Apollo 12 groups 1 and 2 glasses (Table 8) have compositions similar to the "anorthosite" fragments found in Apollo 11 and 12 samples by Wood et al. (1970) and Wood et al. (1971). Other investigators have also found glasses with similar compositions in Apollo 11 (Smith et al., 1970; King et al., 1970, von Engelhardt et al., 1970; Wood et al., 1970; Short, 1970; Chao et al., 1970a) and Apollo 12 (Chao et al., 1970a) samples. As pointed out by Wood et al., (1970) and other authors, the anorthosite fragments and anorthositic glasses show rather close agreement with Surveyor VII analysis of ejecta from the highland crater, Tycho (see Table 11). Preliminary work shows that glasses with this composition are abundant in Apollo 14 fines. Thus anorthositic glasses appear to be the only type that are common at the first three Apollo landing sites (Apollo 11, 12 and 14).

2. KREEP (Apollo 12 Group 5) Glass. The glasses of group 5 are similar in composition to some feldspathic orthopyroxene-rich rock fragments from Apollo 12 samples that are designated KREEP by Hubbard et al. (1971) because of their high potassium, rare-earth elements and phosphorous contents (Table 12). Glass of KREEP composition has also been described by Meyer and Hubbard (1970) and Meyer et al. (1971) (Table 12).

The type B norite anorthosite fragments described by Wood et al. (1971) and the "gray mottled" fragments described by Anderson et al. (1971) from the Apollo 12 soil and the dark portion of rock 12013 are also similar in composition to KREEP material (Table 12). Based on mineral assemblage Meyer et al. (1971) suggested that Luny Rock 1, described from Apollo samples by Albee and Chodos (1970), is also similar to KREEP material.

Material of KREEP composition appears to be the cryptic component that several authors (e.g. Wakita and Schmitt, 1970; Schnetzler et al., 1970, Hubbard and Gast, 1970) have suggested is needed in the soil to explain the difference in composition between the Apollo 12 fines and the Apollo 12 crystalline rocks. Hubbard et al. (1971) proposed that the Apollo 12 soil samples are essentially a two-component mixture of average crystalline rocks from the Apollo 12 site and KREEP material.

It has been suggested that KREEP material is from the Fra Mauro Formation via a ray from Copernicus (Meyer et al., 1971). Preliminary work has shown that glass of KREEP composition similar to the Apollo 12 group 5 glasses is the most abundant type of glass in the Apollo 14 fines which were returned from the Fra Mauro Formation.

3. Other Possible Exotic Glasses. The Apollo 11 glasses in groups 3 and 4, the Apollo 12 glasses in groups 6 and 7 and the miscellaneous Apollo 11 and 12 glasses may represent glasses produced from parent materials other than those mentioned above or they may simply represent partial melting of the above possible parent materials.

As mentioned earlier glasses similar in composition to those in Apollo 11 group 3 and Apollo 12 group 7 have been reported by several investigators in the Apollo 11 samples. Thus it seems likely that these glasses were produced from a parent material of similar composition rather than being the result of partial melting of analyzed local material from the Apollo 11 or 12 sites. The low SiO_2 and Al_2O_3 content and high FeO and MgO contents of these glasses suggests that the parent material is ultrabasic.

The five Apollo 12 glasses in group 6 are similar in composition to the Apollo 11 rocks and fines except for their somewhat lower TiO_2 content. Therefore these glasses may be derived from a parent material similar to the Apollo 11 rocks or soil. Likewise, Apollo 11 sample no. 8 is similar in composition to the Apollo 12 rocks and may have been derived from a similar parent material.

As mentioned previously, many of the miscellaneous Apollo 12 glasses (Table 8) seem to have compositions similar to glasses in Apollo 14 fines. Thus these glasses may have been produced from a high alkali basaltic rock from the Fra Mauro Formation.

6. CONCLUSIONS

The majority of the glass particles in the fines (<1 mm dia.) from the Apollo 11 and Apollo 12 sites are believed to have been produced by impact melting of the local rocks or soil. Because the chemical analyses cluster into several major groups it is believed that the compositions of the glasses are similar to the bulk composition of the parent material. Glasses produced by partial melting seem to be rare. Although there is evidence that vapor fractionation has modified the compositions of some of the Apollo 12 glasses it seems that the major element contents of most of the glasses have not been appreciably affected by volatilization.

Analyses of Apollo 11 and 12 glasses provide evidence for at least five major rock types on the lunar surface. Glasses produced by impact melting of these rocks and the rock types from which they were probably derived are as follows:

1. High Ti "basaltic" glasses (Apollo 11 group 2 in Table 7 and Apollo 12 group 6 in Table 8) derived from rocks and/or fines similar to those returned from the Apollo 11 site,

2. "Basaltic" glasses (Apollo 12 group 4 in Table 8 and sample 8 in Table 7) derived from rocks or soil similar to that at the Apollo 12 site;

3. "Anorthositic" glasses (Apollo 11 group 1 in Table 7 and Apollo 12 groups 1 and 2 in Table 8) derived from highland (?) "anorthosites";

4. High alkali and phosphorous glasses (KREEP) (Apollo 12 group 5 in Table 8) derived from an orthopyroxene-rich igneous rock (similar to the KREEP material of Hubbard et al. (1971), norite fragments of Wood et al. (1971), the dark portion of lunar rock 12013 and luny rock 1) which may be from the Fra Mauro Formation (Hubbard et al., 1971). Material with this composition is probably the cryptic component needed in the soil in order to explain the difference in composition between the Apollo 12 fines and the Apollo 12 crystalline rocks;

5. "Ultrabasic" (?) glasses (Apollo 11 group 3 in Table 7 and Apollo 12 group 7 in Table 8) with low Al_2O_3 (<6%) and high FeO (>20%) contents. The parent material for this glass is unknown.

Other glasses discussed in this report may be representative of other rock types on the lunar surface. However, more data must be obtained in order to determine if these glasses really represent additional rock types or whether they simply represent mixtures or partial melting of the known rock types.

Glasses are a major component of the lunar fines. A single one gram sample of fines contains thousands of glass particles $>50 \mu m$ diameter. Most of the glasses were produced by impact melting of the local regolith. Other glass particles are apparently exotic and may have been derived from a source area as far away as 1000 km or farther. Thus because of their abundance and mode of formation and distribution lunar glasses provide much useful information concerning the composition and heterogeneity of the lunar surface.

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TABLE 2

SIZE DISTRIBUTION OF GLASS SPHERES >88 μM DIAMETER RECOVERED FROM APOLLO 11 SAMPLE 10084 AND APOLLO 12 SAMPLES 12057 AND 12070

	Sample 10084	Sample 12057		Sample 12070	
Class Limits (μm)	No. Spheres	No. Spheres	%	No. Spheres	%
88- 124	(8)	110	62.9	139	58.5
125- 176	(11)	46	26.2	50	21.0
177- 249	31	13	7.4	32	13.4
250- 353	6	5	2.9	9	3.7
354- 500	6	1	0.6	7	3.0
500-1000	2	0	____	1	0.4
>1000	1	0	____	0	____
TOTAL	65	175	100.0	238	100.0

() Indicates incomplete recovery. This is because the glass spheres from 10084 were separated from the >149 μm size fraction. The smaller spheres must have been adhering to larger grains.

TABLE 1

DISTRIBUTION OF GLASSY PARTICLES IN APOLLO 12 SAMPLES 12057 AND 12070

SIZE FRACTION (μm)	SAMPLE 12057 Wt. (mg)	SAMPLE 12057 % Glassy Particles	SAMPLE 12057 % Spherules	SAMPLE 12057 Spherules /gm	SAMPLE 12070 Wt. (mg)	SAMPLE 12070 % Glassy Particles	SAMPLE 12070 % Spherules	SAMPLE 12070 Spherules /gm
>580	9 4	14	0	0	28.1	9	0	0
147 - 580	100 1	30	0.6	190	82.9	34	0 4	314
74 - 147	98.1	29	0.8	2141	109.0	22	0.5	2633
44 - 74	111.3	n.d.	1.0	n.d.	37 9	n.d.	0.6	n d
<44	115 6	n d	1.1	n.d.	128.5	n d	n.d	n d.

n.d. = not determined

TABLE 4

DISTRIBUTION OF SHAPES AMONG APOLLO 11 AND APOLLO 12 GLASS SPHERULES 74 μM DIAMETER

	Percent Abundance		
	Apollo 11	Apollo 12	
SHAPE	10084	12057	12070
Spherical or elliptical	94	90	93
Dumbbell	0	2	0
Teardrop	1	1	2
Other	5	7	5

TABLE 3

DISTRIBUTION OF COLOR AMONG GLASS SPHERULES > 74 μM DIAMETER FROM APOLLO 11 SAMPLE 10084 AND APOLLO 12 SAMPLES 12057 AND 12070

	Apollo 11 10084		Apollo 12 12057		Apollo 12 12070	
	No.	%	No.	%	No.	%
Colorless to pale green	1	1	5	4	6	4
Yellow to yellow-green	7	11	28	21	30	17
Greenish brown			8	6	1	1
Orange to yellow-brown to brown	15	23	49	38	93	54
Reddish brown	5	8	30	23	21	12
Deep red	36	54	4	3	5	3
Other	2	3	7	5	16	9
TOTAL	66	100	131	100	172	100

TABLE 5

DESCRIPTION OF GLASS PARTICLES MOUNTED FOR ELECTRON MICROPROBE ANALYSIS.

SEE TABLES 7 AND 8 FOR CHEMICAL COMPOSITION

Sample No.	Type Particle*	Size Fraction(μm)	Vesicular	Color+	Silicate Crystalline Inclusions	Metallic Spherules
			Apollo 11 Sample 10084			
3	F	580	Yes	YBr	Partially Devitrified	No
4	F	580	No	YBr	Yes	No
5	F	580	No	B	Yes	Yes
11	F	580	No	BGr	No	No
8	S		Yes	BrG	No	Yes
10	S			YGr	Ni-Fe Octahedral Crystals	
122	S	180		O		
123	S	200		deepR		
124	S	195	Yes	deepR		
125	S	80		YBr		
128	S	80x100		YGr		
129	S	200		GrG		
131	S	100		R		
132	S	100		R		
133	S	100		R		
			Apollo 12 Sample 12057			
154	F	147-580	No	BGr	No	No
155	F	147-580	No	BGr	No	No
156	F	147-580	No	BGr	No	No

TABLE 5 (CONTD.)

Sample No.	Type Particle*	Size Fraction(μm)	Vesicular	Color+	Silicate Crystalline Inclusions	Metallic Spherules
		Apollo 12 Sample 12057				
157	F	147-580	No	BGr	No	No
158	F	147-580	No	BGr	No	No
59	F	147-580	No	Y	No	No
160	F	147-580	No	Br	Yes	Yes
161	F	147-580	Yes	GrG	No	Yes
163	F	147-580	Yes	Y	No	Yes
164	F	147-580	No	Gr	No	Yes
165	F	147-580	No	Gr	No	Yes
166	F	147-580	No	RBr	Yes	Yes
167	F	147-580	Yes	Y	Yes	Yes
168	F	147-580	No	Br	No	Yes
169	F	147-580	No	RBr	No	No
170	F	147-580	Yes	GrG	Yes	Yes
171	F	147-580	No	Br	Ni-Fe Octahedral	Crystals
172	F	147-580	Yes	GrY	No	Yes
173	F	147-580	Yes	GrG	Yes	Yes
174	F	147-580	Yes	O	Yes	Yes
175	F	147-580	No	O	Yes	No
176	F	147-580	No	O	Devitrified	No
177	F	147-580	Yes	O	Yes	Yes
178	F	147-580	No	O	Yes	Yes
179	F	147-580	Yes	O	Yes	Yes

TABLE 5 (CONTD.)

Sample No.	Type Particle*	Size Fraction(μm)	Vesicular	Color+	Silicate Crystalline Inclusions	Metallic Spherules
			Apollo 12 Sample 12057			
180	F	147-580	Yes	O	Yes	No
182	S	147-580	No	Yr	Yes	Yes
183	S	147-580	No	Gr	No	No
184	S	147-580	No	Br	No	No
185	S	147-580	Yes	RBr	Yes	Yes
186	S	147-580	Yes	Y	Yes	Yes
187	S	147-580	No	RBr	No	Yes
188	S	147-580	Yes	G	Yes	Yes
189	S	147-580	Yes	G	Yes	Yes
191	F	147-580	Yes	O	Yes	Yes
192	F	147-580	No	O	No	Yes
194	F	147-580	No	BGr	No	No
195	F	147-580	No	BGr	No	No
196	F	147-580	No	YGr	Yes	Yes
197	F	147-580	Yes	Br	Yes	Yes
198	F	147-580	No	Br	Yes	
199	F	147-580	No	Br	No	No
200	F	147-580	No	Y	Yes	Yes
201	F	147-580	Yes	Y	Yes	Yes
202	F	147-580	No	Br	Yes	Yes
203	F	147-580	No	GrY	Yes	Yes

TABLE 5 (CONTD.)

Sample No.	Type Particle*	Size Fraction(μm)	Vesicular	Color+	Silicate Crystalline Inclusions	Metallic Spherules
		Apollo 12 Sample 12057				
204	F	147-580	No	GrY	Yes	Yes
205	F	147-580	No	YGr	No	Yes
206	F	147-580	Yes	GrY	Yes	Yes
207	F	147-580	No	GrY	Yes	Yes
208	F	147-580	No	GrY	No	Yes
209	F	147-580	No	YGr	Yes	Yes
210	F	147-580	No	YGr	Yes	Yes
211	F	147-580	No	Br	Yes	Yes
212	F	147-580	Yes	Br	Yes	Yes
213	F	147-580	No	YBr	Yes	Yes
214	F	147-580	No	YGr	Yes	Yes
215	F	147-580	Yes		Yes	Yes
216	F	147-580	No	Br	Partially Devitrified	Yes
217	F	147-580	No	Gr	Yes	Yes
218	F	147-580	No	Br	Yes	Yes
219	F	147-580	No	RBr	Yes	No
223	F	147-580	No	R	No	Yes
224	S	74-147	No	GrY	Yes	Yes
225	S	74-147	No	Y	Yes	Yes
226	S	74-147	No	Y	Yes	No
227	S	74-147	No	Gr	No	No
229	S	74-147	No	Y	No	No

TABLE 5 (CONTD.)

Sample No.	Type Particle*	Size Fraction(μm)	Vesicular	Color+	Silicate Crystalline Inclusions	Metallic Spherules
			Apollo 12 Sample 12057			
230	S	74-147	No	YGr	Devitrified	No
231	S	74-147	No	GrY	No	Yes
232	S	74-147	No	YGr	No	No
233	S	74-147	No	YGr	No	No
234	S	74-147	No	YGr	No	No
235	S	74-147	No	Br	Yes	No
236	S	74-147	No	YBr	No	No
237	S	74-147	No	Br	No	No
238	S	74-147	No	Br	No	Yes
239	S	74-147	No	Br	No	No
240	S	74-147	No	Gr	No	No
241	S	74-147	No	YBr	No	No
242	S	74-147	Yes	YGr	Yes	Yes
243	S	74-147	No	YBr	No	No
244	S	74-147	Yes	YGr	Yes	Yes
245	S	74-147	No	YBr	No	No
246	S	74-147	No	Br	Yes	No
247	S	74-147	No	Br	No	Yes
248	S	74-147	No	YBr	No	No
250	S	74-147	No	Br	No	No
251	S	74-147	Yes		Yes	Yes
252	S	74-147	No	YBr	No	No
254	S	74-147	No	YGr	Yes	No

TABLE 5 (CONTD.)

Sample No.	Type Particle*	Size Fraction(μm)	Vesicular	Color+	Silicate Crystalline Inclusions	Metallic Spherules
		Apollo 12 Sample 12057				
255	S	74-147	No	YGr	No	No
257	S	74-147	No	YBr	No	No
258	S	74-147	No	RBr	Yes	Yes
259	S	74-147	No	YBr	No	No
260	S	74-147	No	YBr	No	No
261	S	74-147	No	Br	No	No
262	S	74-147	No	YBr	No	No
263	S	74-147	No	YBr	No	No
265	S	74-147	No	Br	No	No
266	S	74-147	Yes	O	No	Yes
267	S	74-147	Yes	O	Yes	Yes
271	S	74-147	Yes	O	Yes	Yes
275	S	74-147	No	Y	Devitrified	No
276	S	44- 74	Yes	O	Yes	Yes
278	S	44- 74	No	Br	No	No
280	S	44- 74	Yes	Br	No	No
283	S	44- 74	No	BrY	No	No
286	S	44- 74	No	YGr	No	No
287	S	44- 74	No	Br	No	No
289	S	44- 74	Yes	Br	Yes	Yes
290	S	44- 74	No	YGr	Yes	No
291	S	44	No	O	Yes	Yes

TABLE 5 (CONT'D)

Sample No.	Type Particle*	Size Fraction(μm)	Vesicular	Color+	Silicate Crystalline Inclusions	Metallic Spherules
			Apollo 12 Sample 12057			
296	S	44	Yes	Br	Yes	No
298	S	44	No	YBr	Yes	Yes
299	S	44	Yes	Y	No	Yes
300	S	44	No	Br	Yes	Yes
			Apollo 12 Sample 12070			
328	F	147-580	No	BGr	No	No
329	F	147-580	No	BGr	No	No
330	F	147-580	No	BGr	No	No
331	F	147-580	No	BGr	No	No
332	F	147-580	No	YBr	No	Yes
333	F	147-580	No	YBr	No	No
334	F	147-580	No	RBr	No	Yes
335	F	147-580		R		
336	F	147-580		G		
337	F	147-580		RBr		
338	S	147-580	Yes	RBr	No	No
339	S	147-580	No	GrG	No	Yes
340	S	147-580	No	C	No	No
341	S	147-580	No	Y	No	No
342	S	147-580	No	R	No	Yes
343	S	147-580	No	R	No	No

TABLE 5 (CONTD.)

Sample No.	Type Particle*	Size Fraction(μm)	Vesicular	Color+	Silicate Crystalline Inclusions	Metallic Spherules
			Apollo 12 Sample 12070			
344	S	74-147	No	G	Devitrified	Yes
345	S	74-147	Yes	C	Partially Devitrified	No
346	S	74-147	No	C	No	No
347	S	74-147	No	C	Partially Devitrified	No
348	S	74-147	No	G	Devitrified	No
350	S	74-147	No	G	Devitrified	Yes
351	S	74-147	No	G	Devitrified	Yes
352	S	74-147	No	C	Partially Devitrified	Yes
354	S	74-147	Yes	Y	No	No
355	S	74-147	No	YGr	No	No
356	S	74-147	No	YGr	No	Yes
358	S	74-147	No	YGr	No	No
359	S	74-147	No	YBr	No	No
360	S	74-147	No	Y	No	No
361	S	74-147	No	Y	No	No
362	S	74-147	Yes	YBr	No	No
363	S	74-147	Yes	Br	No	No
365	S	74-147	No	Br	No	Yes
366	S	74-147	Yes	Br	No	No
367	S	74-147	No	Br	No	No
368	S	74-147	No	RBr	Yes	No
369	S	74-147	No	RBr	No	No

TABLE 5 (CONTD.)

Sample No.	Type Particle*	Size Fraction(μm)	Vesicular	Color+	Silicate Crystalline Inclusions	Metallic Spherules
			Apollo 12 Sample 12070			
370	S	74-147	No	RBr	No	No
371	S	74-147	Yes	Br	No	No
372	S	74-147	Yes	O	Yes	Yes
373	S	74-147	Yes	O	Yes	Yes
375	S	74-147	Yes	O	Yes	No

*F=fragment, S=spherule

+Color code: O=opaque, BGr=bottle-green, Y=yellow, Br=brown, Gr=green, R=red, G=grey, C=colorless

TABLE 6

COMPOSITION OF METALLIC AND SULFIDE SPHERULES IN GLASS FRAGMENTS FROM APOLLO 12 SAMPLE NO. 12057

Sample No.	Size of Inclusion (μm)	WEIGHT PER CENT (Electron Microprobe Analysis) Fe	Ni	P	S	Total*	Ni/Fe
201	8 x 10	87	1.5	1.6	0.2	90.3	0.017
212 S	9	81	3	2.4	0.2	86.6	0.035
212 I	10 x 24	90	2.5	0.3	0.1	92.9	0.028
207	12	51	11.5	0.1	25	87.6	0.25
217	32	89	6.5	1.6	0.0	97.1	0.073
200	10 x 32	55	3	0.0	30	88.0	0.055
165	8 x 10	79	6.5	2.1	0.4	88.0	0.082
160	6 x 10	12	32.0	0.15	2.4	46.6	2.67
164	8 x 9	80	8	2.6	0.0	90.6	0.10

*The low totals are due to the fact that the electron beam overlapped onto the surrounding silicate glass.

TABLE 7

CHEMICAL COMPOSITION OF APOLLO 11 GLASSES FROM SAMPLE 10084

SAMPLE NO.	GROUP 1		GROUP 2							GROUP 3	GROUP 4	MISC ANALYSES
	11	129	5	4	3	133	124	131	123	122	128	10
OXIDES												
SIO2	48.0	47.7	43.0	43.0	43.0	41.9	40.6	36.3	39.2	37.0	43.0	53.0
TIO2	0.35	0.5	7.0	7.0	7.0	6.3	7.5	6.6	6.8	8.4	0.48	0.5
AL2O3	32.0	24.7	14.0	12.0	11.0	13.3	11.4	15.7	13.9	5.3	8.4	11.4
CR2O3												0.3
FEO	3.5	5.5	14.0	16.0	17.0	16.3	16.1	14.1	15.3	23.7	20.9	9.3
MNO	0.05	0.06	0.16	0.14	0.15	0.20	0.16	0.16	0.17	0.24	0.21	0.12
MGO	4.5	5.1	7.0	9.0	8.0	5.0	7.1	8.2	8.4	14.5	14.8	14.0
CAO	18.0	15.9	11.0	12.0	12.0	13.4	13.2	14.6	13.7	8.1	9.8	8.8
NA2O	0.2	0.75	0.7	0.4	0.4	0.18	0.27	0.07	0.11	0.53	0.26	0.4
K2O	0.06	0.10	0.2	0.2	0.1	0.10	0.16	0.05	0.06	0.17	0.06	0.07
P2O5												0.03
TOTAL	106.66	100.31	97.06	99.74	98.65	96.68	96.49	95.78	97.64	97.94	97.91	97.92
R.I.	1.58		1.66	1.662								

SAMPLE NO.	MISCELLANEOUS ANALYSES		
	8	132	125
OXIDES			
SIO2	46.0	42.6	40.3
TIO2	2.5	4.7	4.4
AL2O3	13.0	13.3	13.4
CR2O3			
FEO	15.0	14.3	17.1
MNO	0.15	0.17	0.17
MGO	11.0	8.1	8.9
CAO	12.0	14.3	13.1
NA2O	0.3	0.21	0.12
K2O	0.1	0.08	0.06
P2O5			
TOTAL	100.05	97.76	97.55

TABLE 8

CHEMICAL COMPOSITION OF APOLLO 12 GLASS PARTICLES FROM SAMPLES 12057 AND 12070

SAMPLE NO.	GROUP 1		GROUP 2									
	299	290	225	227	356	2	233	244	339	298	275	195
OXIDES												
SIO2	46.62	46.31	51.94	49.15	48.75	47.38	47.06	46.93	46.16	46.14	45.68	45.41
TIO2	0.18	0.15	0.21	1.15	0.35	0.96	1.10	0.80	0.42	0.95	0.19	0.35
AL2O3	29.56	34.29	21.23	20.48	27.49	27.04	21.53	20.34	25.33	26.10	22.48	25.47
CR2O3												
FEO	3.93	0.35	6.16	6.84	3.21	4.44	8.28	8.41	3.91	5.69	7.86	6.91
MNO	0.03	0.02	0.08	0.08	0.05	0.06	0.09	0.08	0.06	0.11	0.07	0.08
MGO	1.00	1.19	10.73	9.06	5.69	6.55	8.54	4.92	8.57	3.40	10.72	9.39
CAO	18.20	20.43	13.12	13.11	15.25	16.58	14.13	14.30	14.58	18.57	14.23	16.73
NA2O	0.78	0.83	0.30	0.77	0.59	0.80	0.55	0.65	1.02	0.60	0.65	0.09
K2O	0.27	0.06	0.04	0.35	0.12	0.10	0.17	0.31	0.11	0.18	0.15	0.02
P2O5												
TOTAL	100.57	103.63	103.81	100.99	101.50	103.91	101.45	96.74	100.16	101.74	102.03	104.45
R.I.			1.588	1.588		1.588	1.597					1.596

SAMPLE NO.	GROUP 2											
	330	178	351	328	194	340	154	155	157	158	331	156
OXIDES												
SIO2	45.17	45.13	45.09	45.03	44.96	44.94	44.9	44.89	44.63	44.48	44.29	44.2
TIO2	0.43	0.29	0.31	0.41	0.32	0.36	0.22	0.32	0.29	0.36	0.35	0.31
AL2O3	25.03	23.55	27.23	25.32	25.40	27.46	23.1	24.27	24.57	25.74	25.07	24.4
CR2O3		0.25					0.3	0.2	0.25	0.2		0.25
FEO	6.00	5.78	4.21	5.75	6.12	3.30	4.9	5.85	5.83	4.73	5.56	5.7
MNO	0.08	0.08	0.09	0.08	0.06	0.05	0.06	0.09	0.07	0.24	0.06	0.07
MGO	9.21	10.25	9.41	9.20	8.99	8.12	11.1	8.69	8.24	8.08	8.93	7.5
CAO	14.80	15.98	15.25	14.90	16.46	15.90	14.9	16.39	16.26	17.06	14.85	17.0
NA2O	0.12	0.28	0.70	0.11	0.10	0.57	0.15	0.15	0.18	0.31	0.13	0.23
K2O	0.08	0.03	0.11	0.07	0.03	0 14	0.04	0.03	0.03	0.05	0.12	0.04
P2O5		0.01					0.04	0.01	0.02	0.02		0.03
TOTAL	100.92	101.63	102.40	100.87	102.44	100 84	99.71	100.89	100.37	101.27	99.36	99.73
R.I.					1.594		1.595	1.595	1.595	1.595		1.595

TABLE 8 (CONT.)

GROUP 2

SAMPLE NO.	329	159	346	224	350	344	182	347	348	345	229	352
OXIDES												
SIO2	44.18	44.14	44.03	43.46	43.19	42.34	42.01	41.66	41.40	40.67	38.77	37.10
TIO2	0.41	0.21	0.34	0.30	0.44	0.44	0.44	0.35	0.42	0.32	0.35	0.43
AL2O3	24.99	28.94	29.34	31.96	29.39	30.88	29.05	29.81	31.94	31.39	34.62	35.99
CR2O3		0.1					0.1					
FEO	5.84	3.49	0.67	1.69	3.24	1.91	0.81	2.55	2.91	1.75	1.65	1.15
MNO	0.07	0.05	0.02	0.03	0.06	0.04	0.03	0.04	0.04	0.03	0.02	0.01
MGO	8.99	3.67	8.26	6.10	7.49	4.94	6.73	7.14	6.31	3.75	6.05	5.70
CAO	14.79	18.47	17.85	20.45	16.96	17.91	19.99	17.68	18.08	18.61	22.01	20.61
NA2O	0.14	0.22	0.04	0.22	0.25	0.15	0.10	0.17	0.18	0.15	0.10	0.24
K2O	0.12	0.05	0.05	0.03	0.10	0.09	0.03	0.07	0.09	0.08	0.03	0.11
P2O5		0.01					0.01					
TOTAL	99.53	99.35	100.60	104.24	101.12	98.70	99.30	99.47	101.37	96.75	103.60	101.34
R.I.		1.595		1.588			1.587				1.595	

GROUP 3

SAMPLE NO.	240	232	236	245	250	246	184	286	261	185	255	259
OXIDES												
SIO2	47.97	45.90	45.65	44.74	44.64	43.86	43.65	43.36	42.98	42.84	42.79	42.66
TIO2	1.89	1.75	2.32	3.28	2.85	3.77	2.46	2.23	2.81	2.33	2.89	3.49
AL2O3	17.22	18.58	11.91	11.62	15.73	11.81	15.01	17.33	11.82	14.48	15.81	12.22
CR2O3							0.4			0.5		
FEO	11.74	9.47	16.07	18.56	14.69	18.28	13.59	13.86	18.09	15.75	15.33	18.63
MNO	0.12	0.09	0.17	0.20	0.14	0.18	0.16	0.16	0.18	0.17	0.16	0.19
MGO	11.13	10.31	12.72	8.82	10.14	9.60	9.47	12.66	11.76	9.92	10.94	12.84
CAO	12.21	12.98	10.41	12.27	12.58	11.23	12.20	12.73	11.70	12.00	12.47	11.08
NA2O	0.16	0.13	0.06	0.11	0.18	0.13	0.16	0.07	0.05	0.16	0.08	0.10
K2O	0.11	0.10	0.06	0.07	0.07	0.09	0.08	0.05	0.05	0.08	0.08	0.08
P2O5							0.04			0.03		
TOTAL	102.55	99.31	99.37	99.67	101.02	98.95	97.22	102.45	99.44	98.46	100.55	101.29
R.I.	1.624	1.608	1.641	1.653	1.650	1.659	1.636		1.660		1.643	1.654

TABLE 8 (CONT.)

GROUP 3

SAMPLE NO.	265	237	278	238	247	252	239	248	262	260	263	257
OXIDES												
SIO2	42.50	42.26	42.25	41.69	41.42	41.41	41.11	40.71	40.02	39.77	39.11	38.09
TIO2	2.83	2.98	2.68	3.00	3.65	3.05	2.55	3.79	2.94	2.96	3.82	3.45
AL2O3	12.94	16.32	14.58	15.73	13.95	15.12	15.62	14.75	15.09	15.11	13.71	16.20
CR2O3												
FEO	17.02	13.45	16.43	16.09	16.38	15.52	16.00	16.74	15.62	16.75	17.98	16.86
MNO	0.18	0.15	0.17	0.18	0.17	0.10	0.16	0.19	0.17	0.18	0.18	0.19
MGO	12.10	10.53	10.95	11.05	11.13	10.53	11.65	10.30	10.33	10.86	12.07	12.39
CAO	11.84	13.20	12.91	13.91	12.79	13.40	13.91	13.93	13.99	13.69	12.75	15.05
NA2O	0.08	0.09	0.06	0.09	0.09	0.10	0.05	0.06	0.05	0.07	0.08	0.06
K2O	0.04	0.07	0.04	0.06	0.06		0.04	0.04	0.05	0.04	0.06	0.05
P2O5												
TOTAL	99.53	99.05	100.07	101.80	99.64	99 23	101.09	100.51	98.26	99.43	99.76	102.34
R.I.	1 648	1.642			1.657	1.650	1.652	1.660	1.649	1.655	1.664	1.663

GROUP 4

SAMPLE NO.	341	332	254	163	167	171	160	192	283	242	362	333
OXIDES												
SIO2	51.96	49.90	49.65	48.76	48.12	47.88	47.64	47.60	47.54	47.47	47.46	47.43
TIO2	2.21	2.88	2.21	1.98	2.13	3.00	1.95	2.84	2.81	1.82	3.03	2.83
AL2O3	13.89	14.77	15.59	14.60	14.71	12.03	14.35	10.09	14.66	13.18	13.95	11.73
CR2O3				0.5	0.45	0.6	0.5	0.9				
FEO	11.31	12.14	11.70	12.96	12.23	16.08	13.25	20.24	14.64	14.13	13.78	15.38
MNO	0.14	0.14	0.12	0.14	0.14	0.18	0.14	0.22	0.15	0.15	0.14	0.19
MGO	7.33	7.77	9.29	9.76	9.41	8.83	9.50	9.76	9.32	10.76	8.47	9.76
CAO	9.33	10.02	11.36	11.05	11.28	10.57	11.17	11.40	11.57	11.09	10.39	9.66
NA2O	0.73	0.72	0.67	0.52	0.67	0.60	0.47	0.43	0.25	0.68	0.24	0.60
K2O	0.68	0.60	0.46	0.39	0.42	0.34	0.32	0.24	0.16	0.52	0.26	0.54
P2O5				0.25	0.35	0.1	0.20	0.2				
TOTAL	97.58	98.94	101.05	100.91	99.91	100.21	99.49	103.92	101.10	99.80	97.72	98.12
R.I.				1.613	1.608	1.620	1.616			1.626		

TABLE 8 (CONT.)

GROUP 4

SAMPLE NO.	354	208	372	173	231	338	361	218	217	289	183	334
OXIDES												
SIO2	47.33	47.27	47.12	47.12	47.08	47.08	47.06	46.98	46.87	46.71	46.69	46.58
TIO2	2.14	2.32	1.87	2.44	1.50	3.46	2.39	2.83	3.27	2.80	1.97	3.86
AL2O3	15.20	14.99	16.97	12.97	18.12	12.01	16.31	13.79	11.36	16.65	15.95	9.61
CR2O3				0.6							0.4	
FEO	13.55	12.25	15.68	15.58	10.69	17.52	13.09	13.88	17.20	13.79	12.37	19.20
MNO	0.15	0.14	0.14	0.15	0.12	0.18	0.15	0.14	0.17	0.14	0.15	0.22
MGO	9.03	9.49	8.79	8.06	11.52	8.66	8.44	9.43	11.35	8.38	9.87	8.39
CAO	11.16	11.44	11.86	11.38	12.54	10.27	11.71	11.56	10.69	12.79	12.07	10.25
NA2O	0.28	0.73	0.51	0.75	0.37	0.27	0.19	0.56	0.40	0.64	0.31	0.34
K2O	0.27	0.59	0.33	0.41	0.12	0.22	0.21	0.29	0.24	0.33	0.14	0.26
P2O5				0.55							0.02	
TOTAL	99.11	99.22	103.27	100.01	102.06	99.67	99.55	99.46	101.55	102.23	99.94	98.71
R.I.		1.613		1.628	1.613			1.627	1.643		1.621	

GROUP 4

SAMPLE NO.	199	243	186	300	201	170	188	212	241	177	191	373
OXIDES												
SIO2	46.57	46.55	46.52	46.48	46.36	46.24	46.17	46.10	46.09	46.08	45.85	45.78
TIO2	2.24	2.35	2.87	1.95	2.75	2.45	2.98	2.48	2.61	2.23	2.84	3.40
AL2O3	9.38	13.92	12.66	10.61	12.99	13.88	13.55	12.83	13.18	11.99	13.4	9.27
CR2O3			0.75			0.65	0.6			0.8	0.7	
FEO	21.28	14.56	17.78	20.18	15.41	14.17	15.50	13.63	15.88	15.06	15.91	20.10
MNO	0.19	0.16	0.18	0.23	0.15	0.16	0.19	0.15	0.19	0.16	0.19	0.21
MGO	12.00	9.22	8.03	8.67	8.62	9.08	10.41	8.21	10.28	10.11	10.31	13.05
CAO	10.00	11.30	12.28	12.31	11.38	11.37	11.06	11.58	11.58	10.94	11.30	8.45
NA2O	0.33	0.33	0.41	0.28	0.51	0.65	0.46	0.76	0.28	0.54	0.56	0.36
K2O	0.14	0.18	0.14	0.16	0.26	0.35	0.20	0.28	0.12	0.24	0.27	0.35
P2O5			0.1			0.25	0.2			0.25	0.25	
TOTAL	102.13	98.57	101.72	100.87	98.43	99.25	101.32	96.02	100.21	98.40	101.58	100.97
R.I.	1.654	1.623			1.631	1.625		1.633	1.627			

TABLE 8 (CONT.)

SAMPLE NO.	GROUP 4											
	214	280	210	267	161	169	189	179	271	180	360	266
OXIDES												
SIO2	45.71	45.71	45.57	45.54	45.49	45.32	45.29	45.24	45.19	45.13	45.13	45.12
TIO2	3.05	3.83	2.60	3.16	2.40	4.58	2.38	2.45	2.92	2.10	2.97	3.43
AL2O3	10.54	12.56	13.36	14.05	14.02	11.01	11.96	10.68	11.79	12.59	13.06	13.21
CR2O3					0.6	0.4	0.65	0.7		0.7		
FEO	18.34	16.71	15.24	15.65	14.89	19.97	17.21	17.38	16.85	16.08	16.52	16.55
MNO	0.21	0.17	0.18	0.14	0.15	0.20	0.18	0.19	0.19	0.18	0.18	0.17
MGO	9.54	10.06	9.57	8.89	9.02	6.69	10.17	10.68	8.71	10.06	9.96	9.74
CAO	11.39	11.29	11.74	11.43	12.27	11.89	11.03	12.06	12.17	12.20	11.02	11.34
NA2O	0.47	0.22	0.52	0.54	0.50	0.62	0.58	0.42	0.37	0.45	0.13	0.38
K2O	0.17	0.11	0.24	0.24	0.24	0.20	0.29	0.20	0.19	0.17	0.24	0.16
P2O5					0.25	0.03	0.25	0.2		0.1		
TOTAL	99.42	100.66	99.02	99.64	99.83	100.91	99.99	100.20	98.38	99.76	99.21	100.10
R.I.	1.646		1.618		1.629	1.662						

SAMPLE NO.	GROUP 4											
	363	355	375	359	358	371	291	337	251	366	365	343
OXIDES												
SIO2	45.10	45.09	44.97	44.95	44.77	44.34	44.08	44.07	43.55	43.20	42.89	42.83
TIO2	2.92	1.61	2.80	3.71	3.38	3.39	3.57	3.59	3.00	3.03	2.92	4.22
AL2O3	14.66	12.61	18.07	12.10	10.41	12.34	11.51	9.93	13.87	14.96	14.31	7.64
CR2O3												
FEO	14.97	15.30	13.84	17.54	17.90	17.04	17.19	18.92	16.30	15.97	15.40	23.04
MNO	0.16	0.18	0.15	0.19	0.19	0.19	0.17	0.20	0.16	0.17	0.18	0.21
MGO	9.91	12.65	8.04	10.22	9.74	10.02	10.57	8.70	10.11	10.97	10.74	13.41
CAO	11.31	10.46	12.30	10.71	9.49	10.61	10.54	9.76	12.26	11.57	11.34	7.28
NA2O	0.17	0.20	0.55	0.24	0.32	0.19	0.44	0.56	0.37	0.14	0.12	0.29
K2O	0.24	0.17	0.26	0.23	0.25	0.21	0.20	000.31	0.17	0.20	0.20	0.22
P2O5												
TOTAL	99.44	98.27	100.98	99.89	96.45	98.33	98.27	96.04	99.79	100.21	98.10	99.14
R.I.												

TABLE 8 (CONT.)

SAMPLE NO.	GROUP 4: 197	367	370	296	187	369	GROUP 5: 165	164	172	235	203	216
OXIDES												
SIO2	42.61	42.44	41.69	41.49	40.10	38.18	51.95	51.26	49.64	49.21	49.05	49.02
TIO2	2.45	2.65	4.09	3.02	4.25	3.18	1.42	1.41	1.51	2.04	1.74	1.95
AL2O3	9.67	14.02	12.21	9.14	11.28	15.31	16.12	15.85	17.53	15.83	16.71	15.72
CR2O3					0.7		0.3	0.3	0.4			
FEO	20.39	15.76	18.10	20.72	23.16	15.42	10.48	10.21	10.89	11.19	10.08	11.50
MNO	0.17	0.16	0.19	0.23	0.20	0.18	0.12	0.11	0.11	0.13	0.11	0.14
MGO	13.41	11.24	11.11	14.91	9.34	11.78	5.68	5.86	6.19	8.07	8.10	8.06
CAO	8.54	10.91	10.64	9.62	11.41	12.30	11.67	11.84	12.45	11.67	11.62	11.12
NA2O	0.34	0.12	0.13	0.23	0.24	0.07	0.99	0.94	1.17	1.03	0.94	0.99
K2O	0.21	0.20	0.18	0.15	0.07	0.18	0.84	0.84	0.65	0.76	0.82	0.81
P2O5					0.05		0.45	0.4	0.6			
TOTAL	97.79	97.50	98.34	99.51	100.80	96.60	100.02	99.02	101.14	99.93	99.17	99.31
R.I.							1.589	1.588	1.605	1.616	1.604	1.609

GROUP 5

SAMPLE NO.	213	204	176	200	202	209	336	196	211	207	198	206
OXIDES												
SIO2	48.97	48.91	48.89	48.78	48.69	48.66	48.62	48.50	48.45	48.44	48.40	48.37
TIO2	2.24	1.68	1.92	2.36	2.14	2.24	2.27	1.50	1.98	2.51	2.04	2.05
AL2O3	16.98	16.41	16.97	14.57	14.73	16.04	15.64	16.90	17.06	14.67	16.19	15.16
CR2O3			0.35									
FEO	10.59	10.78	11.26	11.24	12.04	11.11	11.71	9.10	10.25	12.27	10.77	12.58
MNO	0.13	0.11	0.12	0.14	0.13	0.11	0.14	0.11	0.12	0.14	0.12	0.13
MGO	7.80	7.73	7.62	8.12	8.35	8.11	8.47	11.00	7.69	8.76	8.39	7.66
CAO	11.72	11.71	11.91	11.14	11.32	11.62	10.36	11.20	11.62	10.81	11.67	11.51
NA2O	1.09	0.97	1.02	1.04	0.90	1.16	0.96	0.90	1.05	1.00	0.95	1.07
K2O	0.77	0.81	0.69	0.85	0.75	0.75	0.81	0.77	0.73	0.80	0.72	0.80
P2O5			0.7									
TOTAL	100.29	99.11	101.45	98.24	99.05	99.80	98.98	99.98	98.95	99.40	99.25	99.33
R.I.	1.603	1.599		1.605	1.612	1.608		1.595	1.603	1.612	1.604	1.604

TABLE 8 (CONT.)

SAMPLE NO	GROUP 5		GROUP 6					GROUP 7	MISCELLANEOUS ANALYSES			
	215	168	335	223	342	287	258	368	226	234	174	205
OXIDES												
SIO2	48.26	48.26	43.73	41.91	41.76	41.40	39.59	38.82	57.08	51.75	48.54	48.03
TIO2	2.17	2.51	5.29	8.60	5.18	5.62	5.20	3.49	0.39	1.53	2.27	2.41
AL2O3	13.44	14.99	9.14	10.69	10.25	13.39	10.07	4.12	15.76	17.59	15.53	15.10
CR2O3		0.4									0.35	
FEO	11.81	12.00	20.44	17.06	19.82	17.62	21.51	29.78	7.36	8.59	11.60	12.21
MNO	0.12	0.14	0.22	0.20	0.20	0.19	0.23	0.23	0.09	0.09	0.13	0.14
MGO	8.10	8.04	8.49	10.05	8.37	9.76	11.98	12.79	5.42	8.46	7.59	9.84
CAO	10.56	10.87	10.20	11.79	9.84	12.53	10.96	6.36	10.29	11.18	11.55	11.01
NA2O	0.96	1.04	0.44	0.24	0.61	0.05	0.05	0.22	1.84	1.53	0.60	0.85
K2O	0.83	0.67	0.24	0.05	0.31	0.04	0.05	0.24	1.27	0.90	1.13	0.53
P2O5		0.9									0.8	
TOTAL	96.25	99.82	98.19	100.59	96.34	100.60	99.64	96.05	99.50	101.62	100.09	100.12
R.I.	1 605	1.611					1.690		1.555	1.592		1.612

SAMPLE NO.	MISCELLANEOUS ANALYSES				
	166	276	219	175	230
OXIDES					
SIO2	47.82	47.61	46.70	45.88	45.76
TIO2	2.32	3.15	4.15	4.16	1.18
AL2O3	15.46	16.92	11.00	10.85	18.81
CR2O3	0.6			0.6	
FEO	13.19	11.50	18.00	20.01	8.15
MNO	0.14	0.15	0.19	0.20	0.06
MGO	8.47	9.50	6.55	8.24	12.32
CAO	11.64	12.43	11.70	10.85	12.03
NA2O	0.84	0.65	0.87	0.67	1.22
K2O	0.49	1.08	0.45	0.97	0.32
P2O5	0.3			0.45	
TOTAL	101.27	102.99	99.61	102.88	99.85

TABLE 9

RANGE AND AVERAGE COMPOSITION OF VARIOUS GROUPS OF GLASSES GIVEN IN TABLE 8

	Group 1 (2)		Group 2 (19)		Group 3 (24)	
	Range	Ave.	Range	Ave	Range	Ave.
SiO_2	46.31 - 46 62	46 46	38.77 - 51 94	45 33	38 09 - 47.97	42 56
TiO_2	0.15 - 0 18	0.16	0 19 - 1 15	0 48	1 75 - 3.82	2.92
Al_2O_3	29.56 - 34.29	31 92	20 34 - 34 62	25 28	11.62 - 18.58	14.69
Cr_2O_3			0.1 - 0 3	0 2	0 4 -- 0 5	0.45
FeO	0 35 - 3.93	2 14	0 81 - 8 41	5.32	9 47 - 18.63	15.79
MnO	0 02 - 0 03	0.02	0.02 - 0 24	0 08	0 09 - 0.20	0.16
MgO	1 00 - 1.19	1 10	3 40 - 11.1	7 83	8 82 - 12.84	11 01
CaO	18.20 - 20 43	19 32	13.11 - 22 01	16 62	10 41 - 15.05	12.72
Na_2O	0.83 - 0 78	0.80	0 09 - 0.8	0.34	0 05 - 0.18	0.09
K_2O	0 06 - 0 27	0 16	0.02 - 0.35	0 09	0 04 - 0.11	0.07
P_2O_5			0 01 - 0.04	0.01	0.03 - 0.04	0 04
Total		102 08		101 58		100.43

	Group 4 (66)		Group 5 (20)		Group 6 (5)	
	Range	Ave.	Range	Ave.	Range	Ave.
SiO_2	38.18 - 51 96	45 77	48.26 - 51.95	49.04	39 59 - 43 73	41.68
TiO_2	1 50 - 4.58	2.81	1.41 - 2.51	1 97	5.18 - 8.60	5.98
Al_2O_3	7 64 - 18 12	13 00	13.44 - 17 53	15 89	9 14 - 13 39	10.71
Cr_2O_3	0.4 - 0 9	0 6	0 3 - 0 4	0.35		
FeO	10.69 - 23.16	16 07	9 10 - 12.58	11.06	17.06 - 21.51	19 29
MnO	0 12 - 0.23	0 17	0 11 - 0.14	0.12	0 19 - 0 23	0 21
MgO	6.69 - 14 91	9.84	5 68 - 11.00	7.86	8.37 - 11.98	9.73
CaO	7 28 - 12 79	10 90	10 56 - 12.45	11.48	9 84 - 12.53	11.06
Na_2O	0 07 - 0.73	0.42	0.90 - 1 17	1 01	0.05 - 0 61	0.28
K_2O	0.07 - 0.68	0 26	0 65 - 0.85	0 77	0 04 - 0.31	0.14
P_2O_5	0.02 - 0 55	0 20	0 4 - 0 9	0.6		
Total		100 04		100.15		99.08

TABLE 10

SUMMARY OF APOLLO 12 GLASSES

GROUP	NUMBER OF ANALYSES	GENERALIZED DESCRIPTION	DISTINGUISHING CHEMICAL CHARACTERISTICS
1	2	Small (< 74 μm dia.) transparent pale yellow-green spherules Both from sample 12057.	Al_2O_3 > 29%, FeO+MgO < 5%
2	34	Generally colorless to yellow-green transparent spherules without vesicles, or transparent pale-green glass fragments without vesicles or crystalline inclusions.	Al_2O_3 > 20%, FeO+MgO < 7%
3	24	Mostly small (< 150 μm dia.) yellow-brown spherules without vesicles or crystalline inclusions. All from sample 12057.	11% < Al_2O_3 < 20%, TiO_2 < 5%, Na_2O < 0.2%
4	66	Fragments and spherules with a wide range in color and opacity. Most contain crystalline inclusions including Ni-Fe spherules. All from sample 12057.	10% < Al_2O_3 < 20%, TiO_2 < 5%, 0.2% < Na_2O < 0.8%
5	20	Generally translucent to transparent yellow-brown fragments with numerous crystalline inclusions but without vesicles. All but one from sample 12057.	13% < Al_2O_3 < 18%, TiO_2 < 5%, Na_2O < 0.9%
6	5	Generally red to red-brown fragments or spherules.	9% < Al_2O_3 < 14%, TiO_2 > 5%
7	1	Red-brown spherule from sample 12070	Al_2O_3 < 5%
Misc	9	All from sample 12057 No common characteristics.	
Total	161		

TABLE 11

COMPARISON OF PALE GREEN (BOTTLE GREEN) GLASS FROM APOLLO 12 FINES WITH APOLLO 11 ANORTHOSITE AND ANORTHOSITIC GLASS (WOOD ET AL., 1970) AND SURVEYOR VII ANALYSIS OF HIGHLANDS MATERIAL (PATTERSON ET AL., 1969)

	Apollo 12 Pale Green Glasses (8)	Apollo 11 Anorthositic Glasses (10)	Apollo 11 Anorthosites (6)	Surveyor VII
O	60.6	61.0	61.2	58 ± 5
Na	0.2	0.4	0.3	3
Mg	4.7	3.9	2.1	4 ± 3
Al	10.4	10.6	12.9	9 ± 3
Si	16.0	16.6	16.0	18 ± 4
"Ca"*	6.2	5.5	6.3	6 ± 2
"Fe"*	1.9	2.1	1.2	2 ± 1

*"Ca" denotes all elements in the range mass nos. 30-47, including P, S, K and Ca. "Fe" denotes all elements in the range mass nos. 47-65, including Ti, Cr, Mn, Fe and Ni.

TABLE 12

COMPARISON BETWEEN MAJOR ELEMENT COMPOSITION OF APOLLO 12 GROUP 5 GLASSES (THIS REPORT), KREEP GLASS (MEYER ET AL., 1971), NORITE FRAGMENTS (WOOD ET AL., 1971) AND THE DARK PORTION OF SAMPLE 12013 (MEYER ET AL., 1971)

	Group 5 Glasses (19)	KREEP Glass (51)	Norite Fragments	Dark Portion of 12013
SiO_2	49.0	48.2	49.27	54
TiO_2	1.97	1.9	1.75	3.2
Al_2O_3	15.9	15.6	18.07	15
Cr_2O_3	0.35		0.13	
FeO	11.1	10.7	9.30	11
MnO	0.12		0.1	
MgO	7.86	7.8	7.63	9
CaO	11.5	10.9	10.13	9
Na_2O	1.01	0.5	0.98	1.3
K_2O	0.77	1.2	1.07	0.6
P_2O_5	0.6	0.6	1.52	
TOTAL	100.18	97.4	99.95	103

FIGURE CAPTIONS

Fig. 1. Scanning electron microscope photographs of various types of glass from Apollo 12 sample 12057. A. Shiny black opaque glass crust on a rock fragment ~565 μm across. B. Glassy agglutinate composed of rock and mineral grains cemented together with glass, ~1 mm long. C. Shiny dark grey opaque to translucent vesicular glass fragment, ~630 μm long. D. Dense black opaque glass fragment with conchoidal fracture, ~865 μm long. For chemical composition see Table 10 sample 192. E. Irregular black opaque glassy bleb or spherule with rock and/or mineral grains attached to surface, 300 μm diameter. F. Shiny dark brown transparent glass spherule without bubble cavities or crystalline inclusions. R.I. = 1.636, ~250 μm diameter.

Fig. 2. Scanning electron microscope photographs showing surface features found on glass spherules from Apollo 12 sample 12057. A. Black opaque spherule with exposed vesicles and metallic beads on surface, diameter ~170 μm. B. Opaque spherule with silicate glass "splashed" onto its surface, diameter ~135 μm. C. Metallic beads (up to ~3.5 μm dia.) on surface of glass spherule. D. Glass spherule (~145 μm dia.) with large (~50 μm dia.) impact ("zap") pit on surface. The impact pit is characterized by a central depression with a radial fracture pattern surrounding it.

Fig. 3. Scanning electron microscope photograph of 490 μm diameter opaque glass spherule from Apollo 11 sample 10084. The top part has a melted appearance with a radial structure around the margin. It appears that molten silicate material was splashed on the surface

and ran down the side of the spherule. Circular openings in the melted surface are probably due to surface tension. The remainder of the spherule is covered with small (~5 μm dia.) metallic beads (see Fig. 3).

Fig. 4. High magnification scanning electron microscope photographs of spherule shown in Fig. 3. A. "Melted" surface. Note exposed vesicles and shrinkage (?) cracks. B. Original ("unmelted") surface. This surface is covered with numerous small metallic beads in a geometric pattern. The larger beads (up to 2.8 μm dia.) are surrounded by a surface free of beads out to a distance from the bead that is approximately equal to the diameter of the bead. At this distance there is a circle of smaller beads that surrounds the larger central bead. Several of the larger central beads have fallen out leaving depressions.

Fig. 5. Scanning electron microscope photograph of 320 μm diameter opaque glass spherule from Apollo 11 sample 10084 with metallic beads on its surface. The larger beads have coalesced to form an irregular mass. Electron microprobe analysis shows that these beads are composed predominantly of iron with a minor amount of nickel and a trace of cobalt and sulphur. Other beads are surrounded by a chain of smaller beads with the surface in between devoid of beads. In several cases the central bead has fallen out leaving a shallow depression. Note the angular depression on left side of spherule that was left when a mineral or rock fragment was dislodged during cleaning with a sonic vibrator.

Fig. 6. Refractive index versus percent SiO_2 for glass particles from Apollo 12 sample 12057. Note the correlation between color (indicated by symbols), refractive index and SiO_2 content.

Fig. 7. Photomicrographs of polished sections of glass particles from Apollo 12 sample 12057. A. Opaque spherule (~370 μm across) with numerous relict (?) crystalline inclusions and several bubble cavities. Plagioclase, pyroxene, olivine and ilmenite were identified by electron microprobe analysis. The rounded grey areas are exposed bubble cavities. B. Glass fragment (~800 μm across) containing plagioclase laths. For the chemical composition of the fragment see Table 10 sample no. 176. C. Approximately 140 μm diameter transparent yellow-green glass spherule with large (25 x 32 μm) rounded centrally located lechatelierite particle (dark grey) in reflected light. (See Table 10 sample no. 225 for chemical composition.) D. Large (~400 μm across) glass fragment containing numerous crystalline inclusions including metallic spherules (light circular areas). The largest metallic bead is ~32 μm in diameter (see Table 9 sample no. 217 for chemical composition). See Table 9 sample no. 217 for chemical composition of the glass.

Fig. 8. A. Photomicrograph of an irregular transparent pale green glass spherule (~230 μm dia.) from Apollo 11 sample 10084 containing ~25 small (~4 μm dia.) black, opaque octahedral crystals distributed in a plane through the spherule. B. High magnification photomicrograph of one of the octahedral crystals (shown in Fig. 4A) showing one of the octahedral faces in reflected light. Electron microprobe analysis indicates that the crystals are composed of approximately 94% iron and 6% nickel.

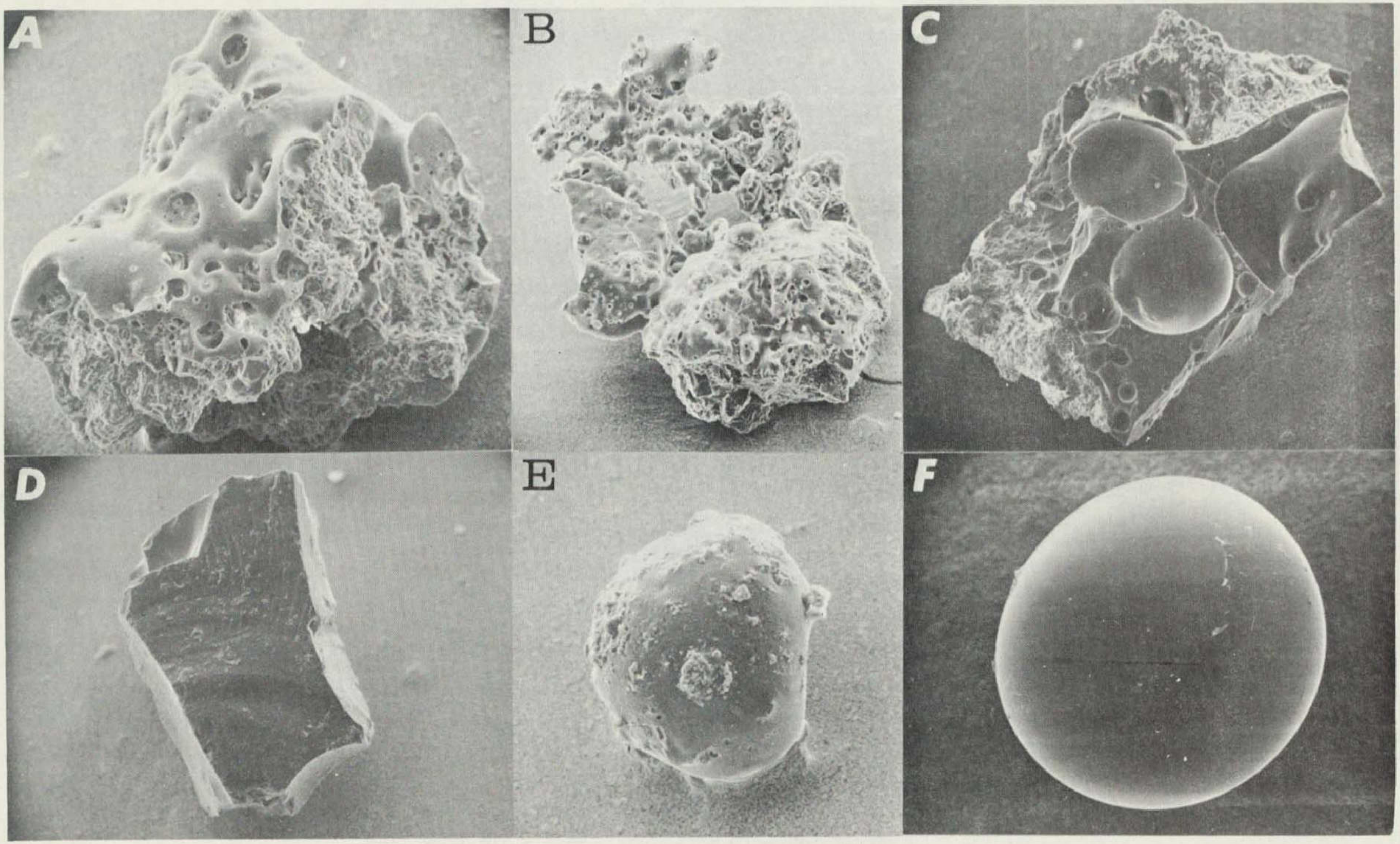
Fig. 9. Refractive index versus SiO_2 content for Apollo 12 glasses. 0 = group 2 glasses, X = group 3, • = group 4, + = group 5, Δ = group 7.

Fig. 10. Percent K_2O versus percent Na_2O for Apollo 12 glasses (groups 3, 4, 5 and miscellaneous analyses [labeled] in Table 8). Glasses from sample 12057 represented by dots and glasses from sample 12070 represented by an X.

Fig. 11. Ternary diagram (Na_2O + K_2O -- CaO + Al_2O_3 -- FeO + MgO + TiO_2) showing relationship between various groups of Apollo 12 glasses in Tables 8, 9 and 10.

Fig. 12. Percent TiO_2 versus percent SiO_2 for Apollo 11 and 12 glasses.

Fig. 13. Percent FeO versus percent Al_2O_3 for Apollo 11 and 12 glasses.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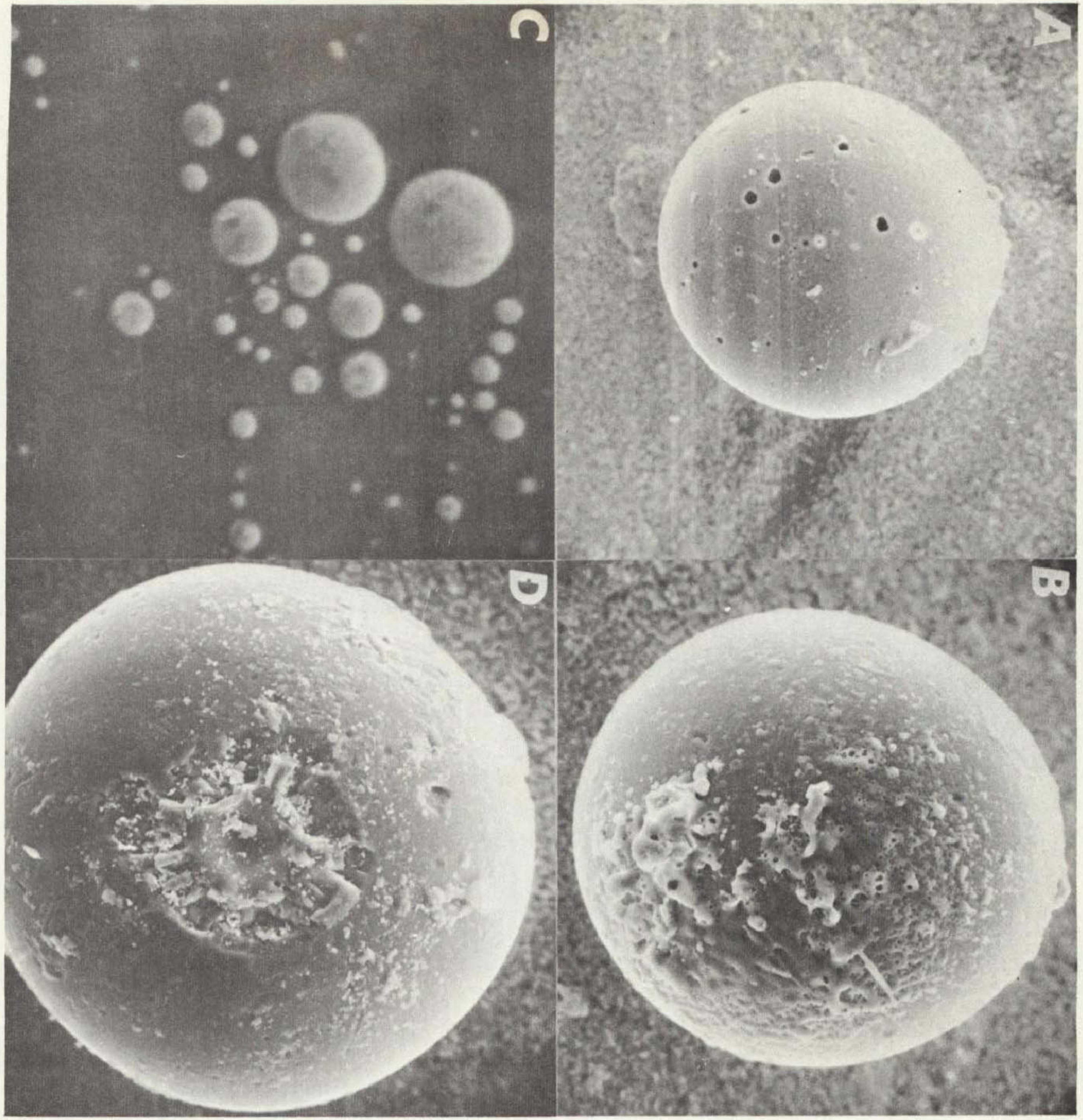
B
C
D
E
F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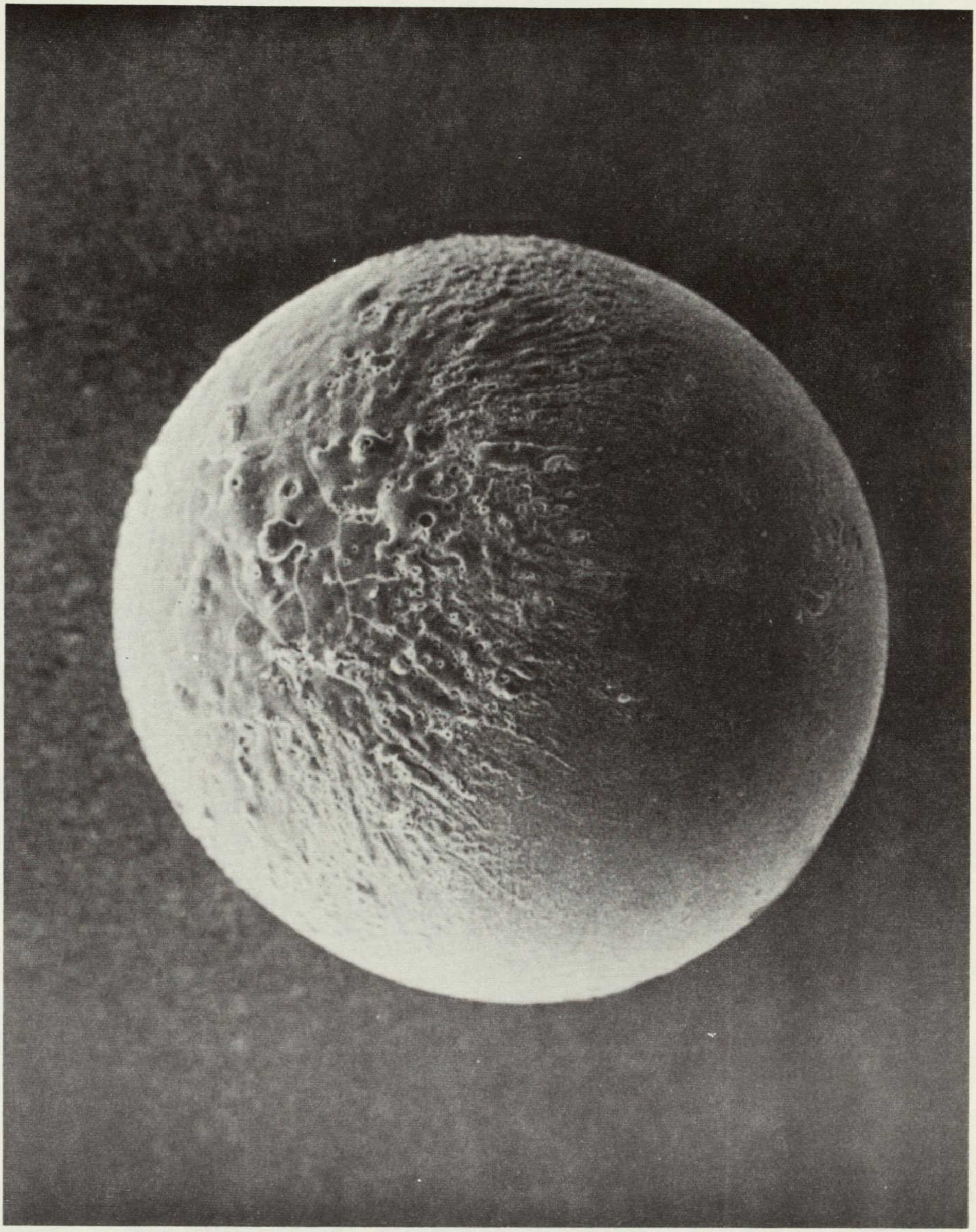
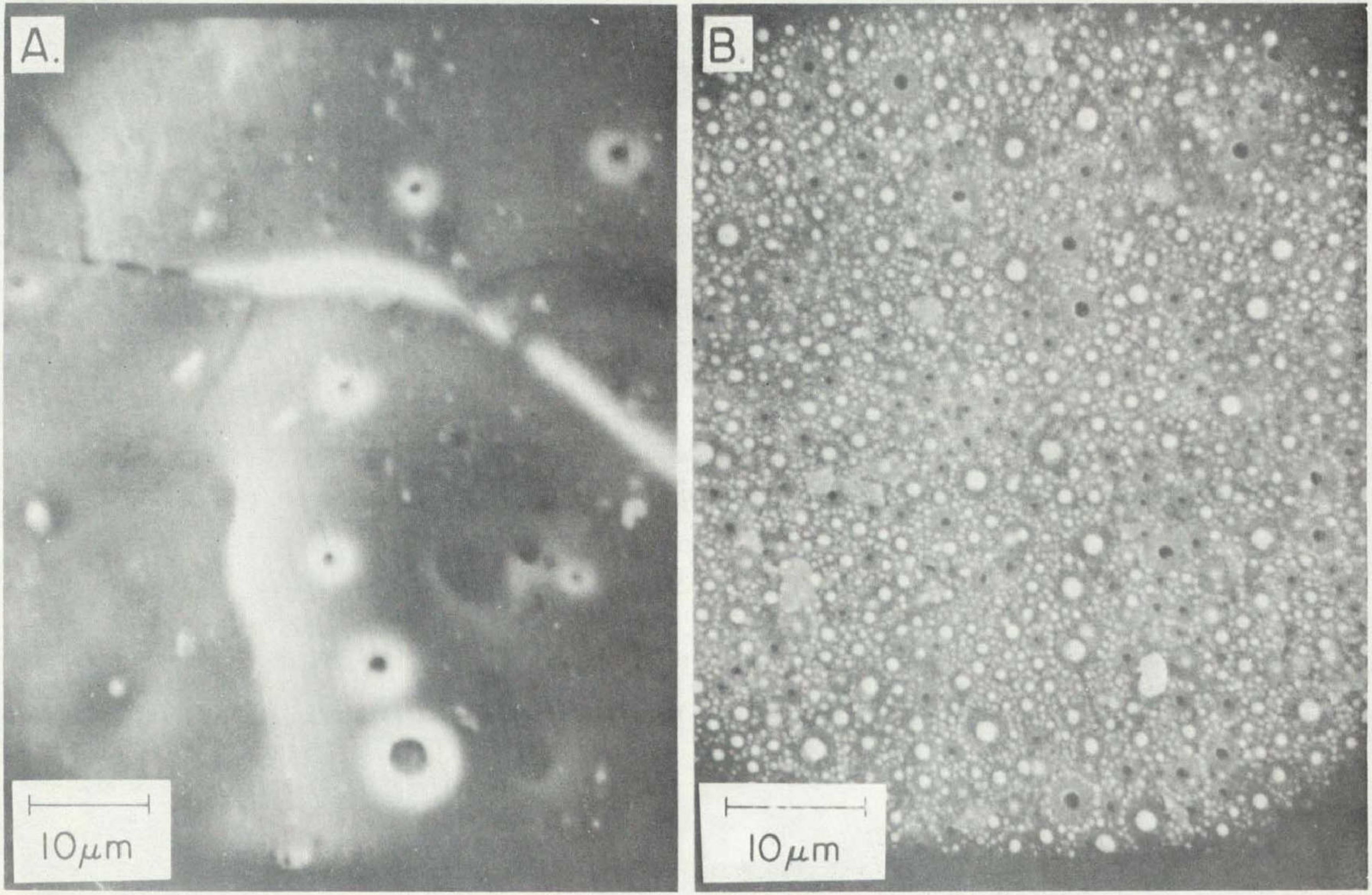
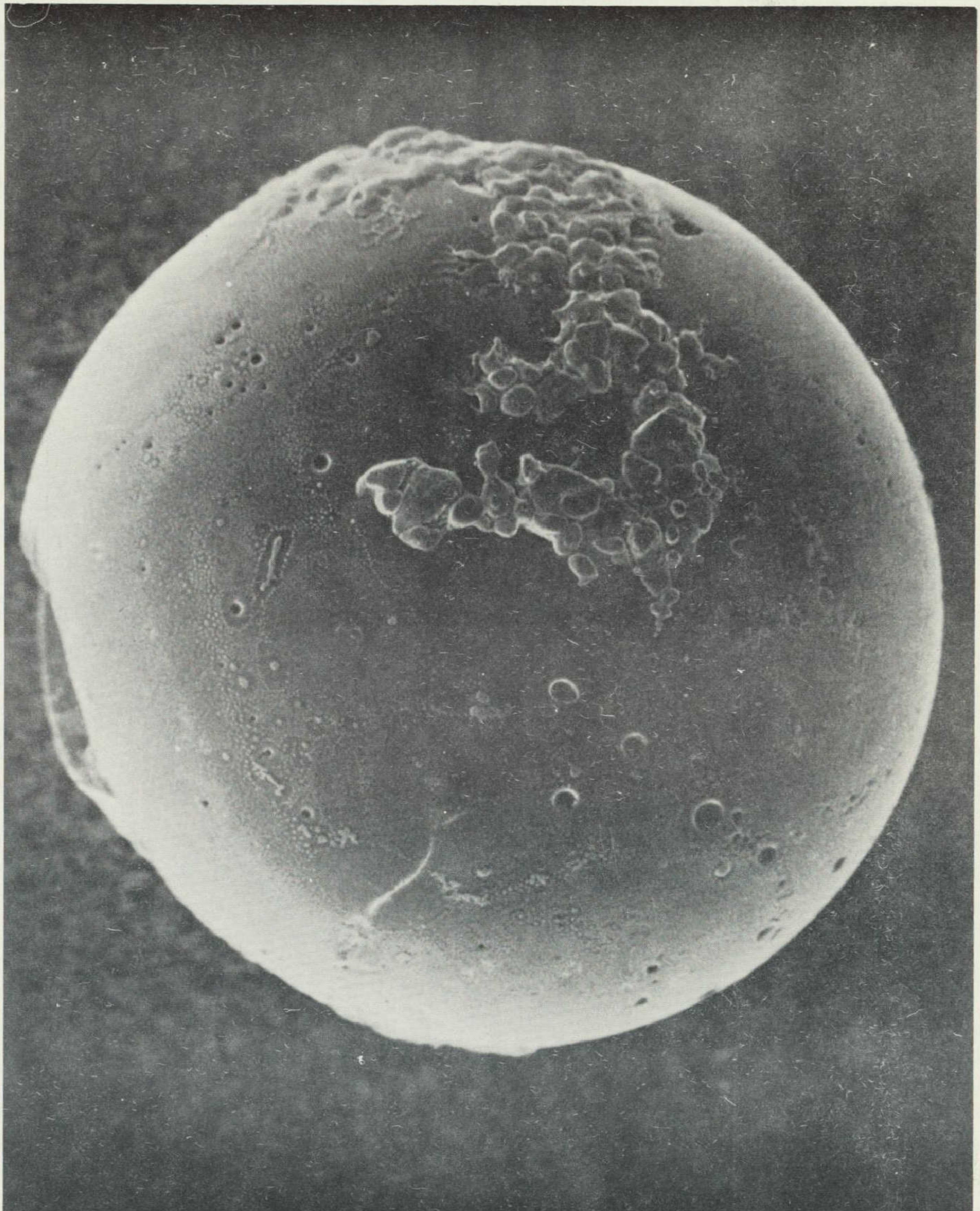
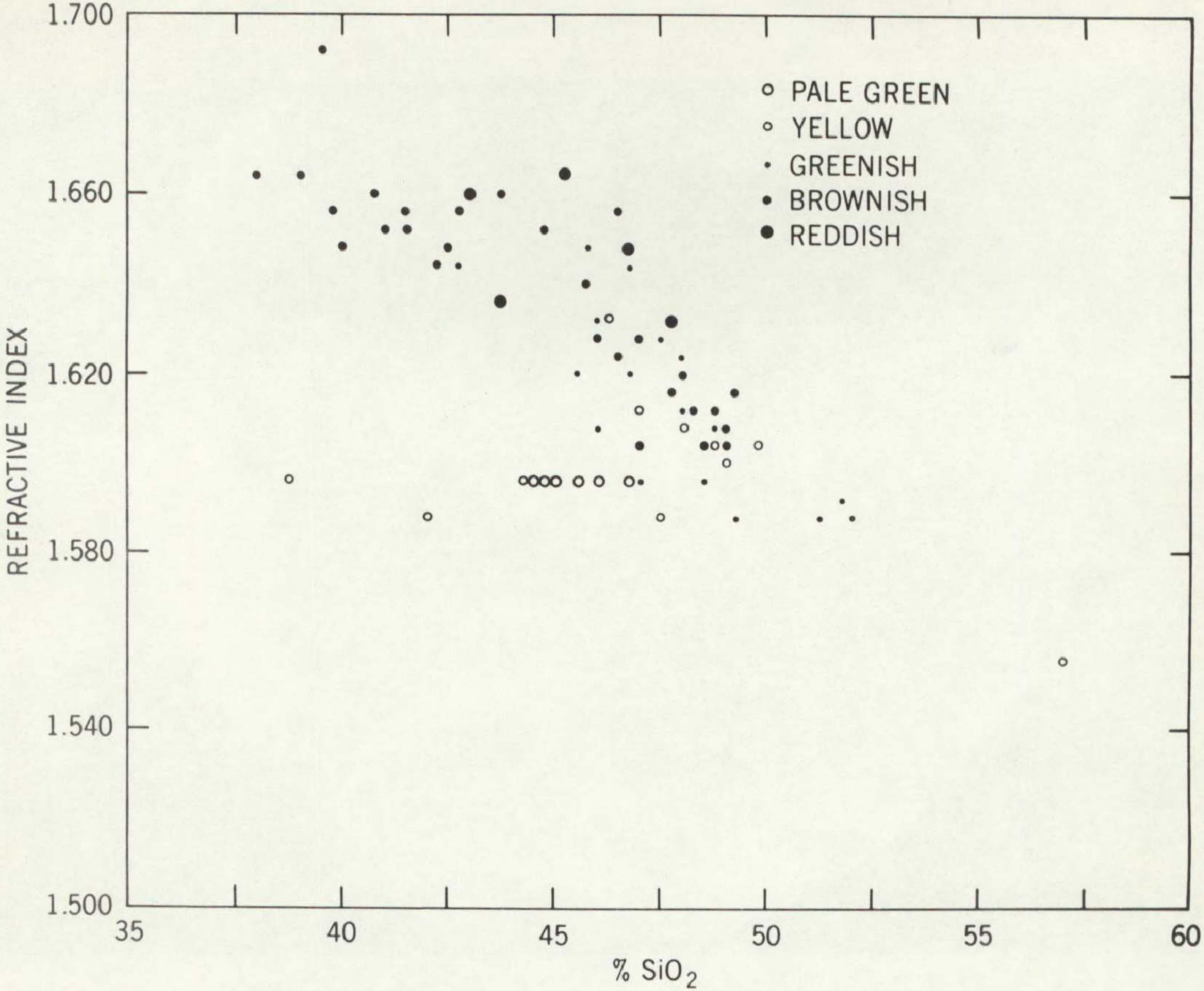
C
D

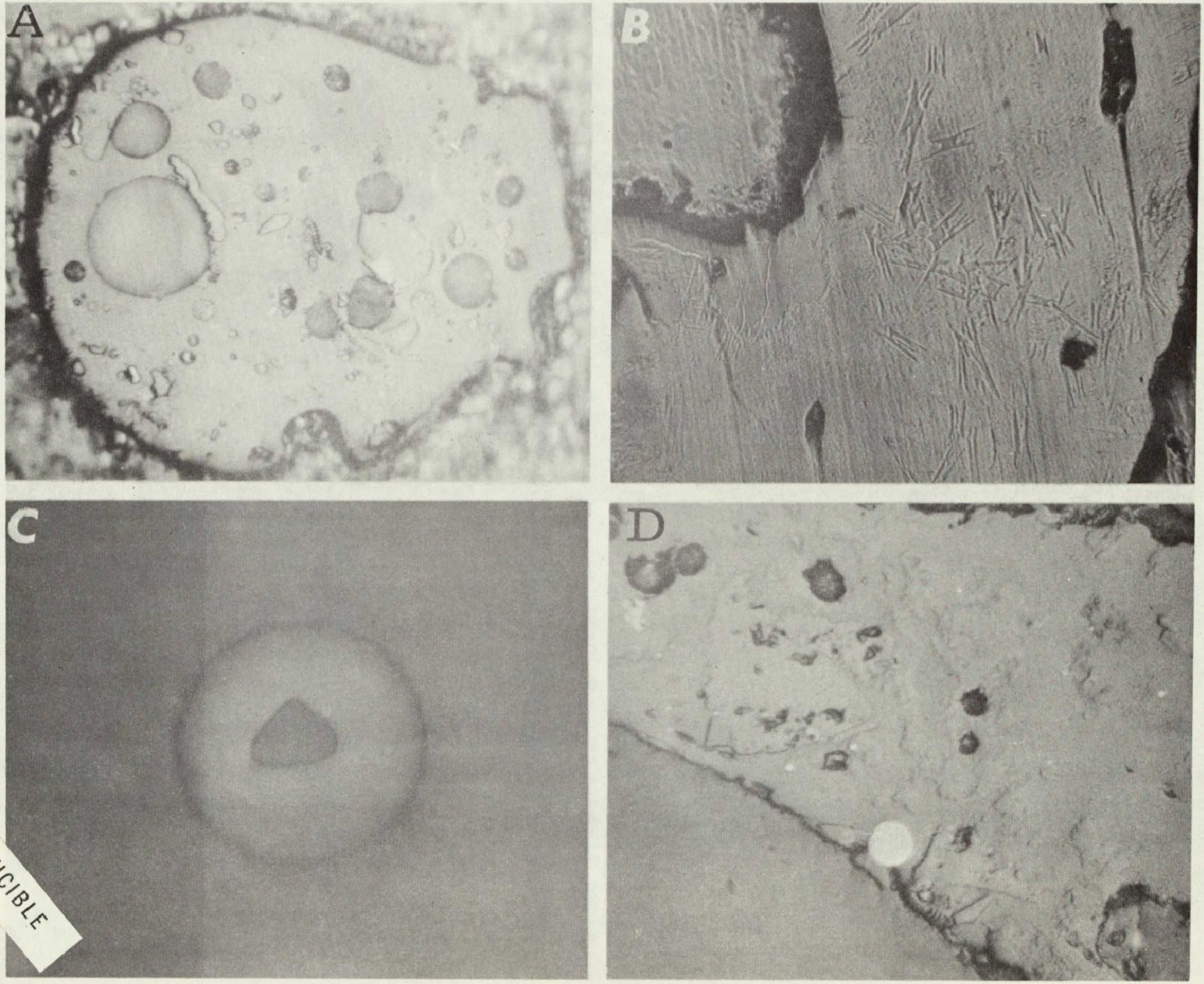


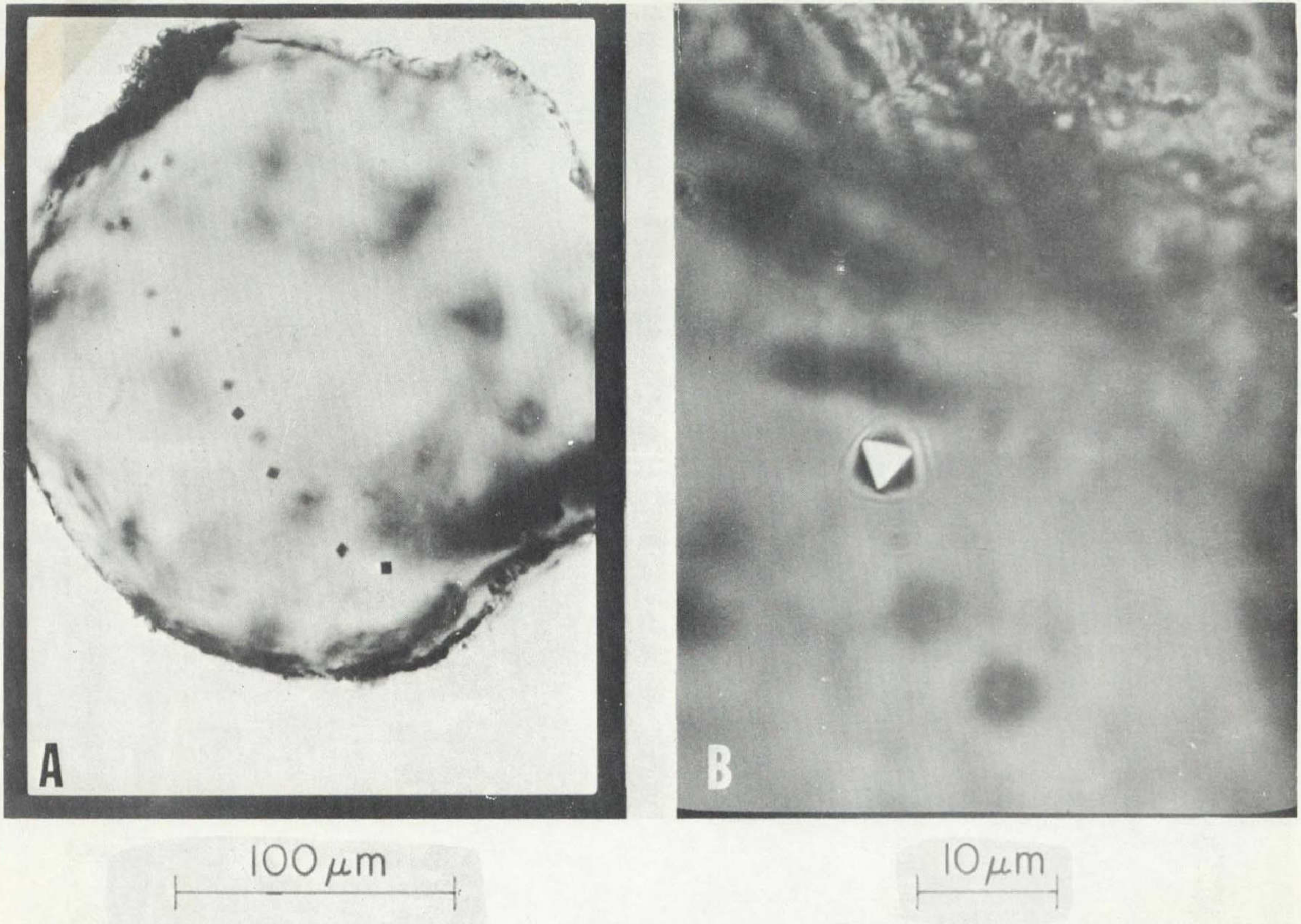

A.
10μm
B.
10μm

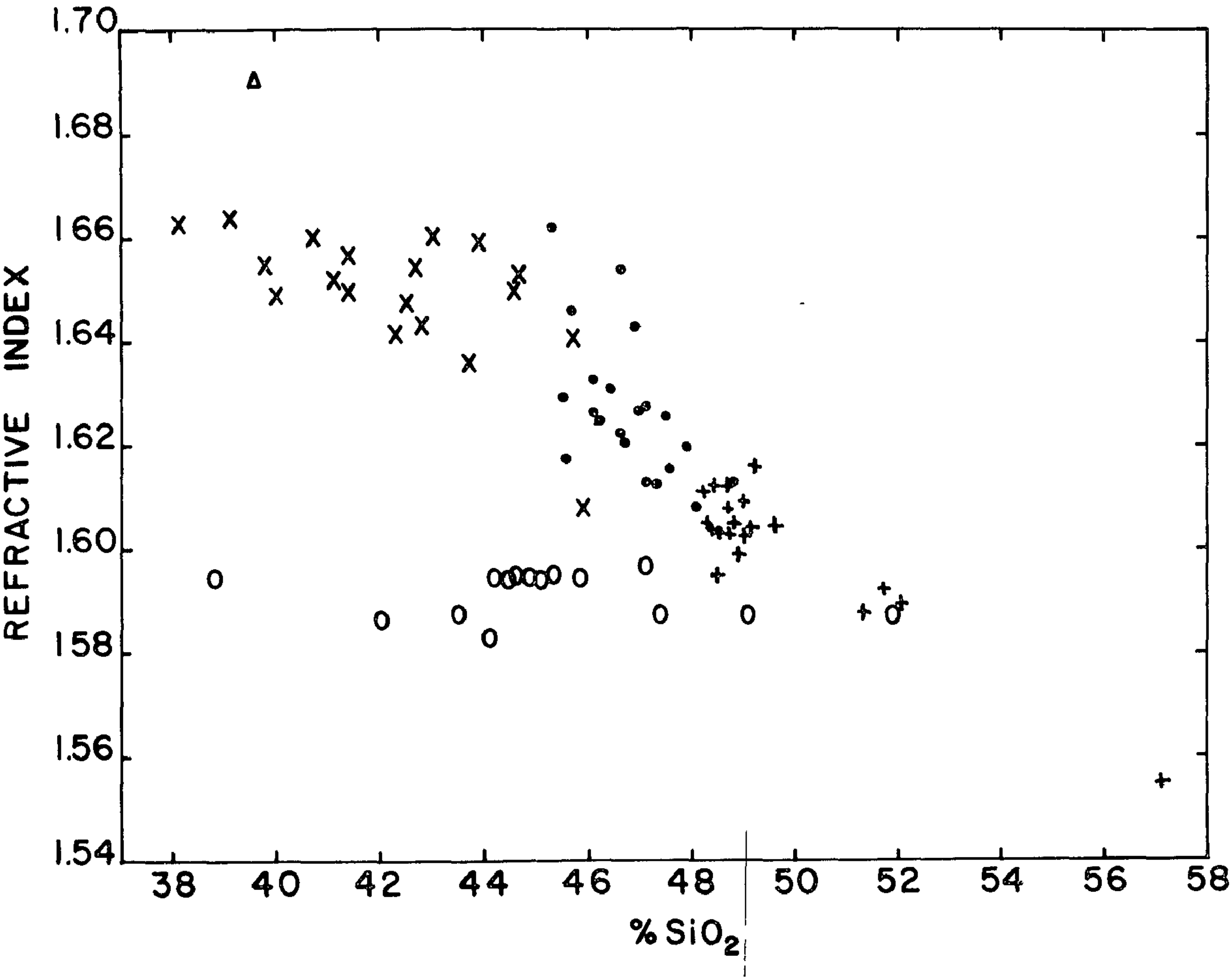


APOLLO 12 SAMPLE NO. 12057

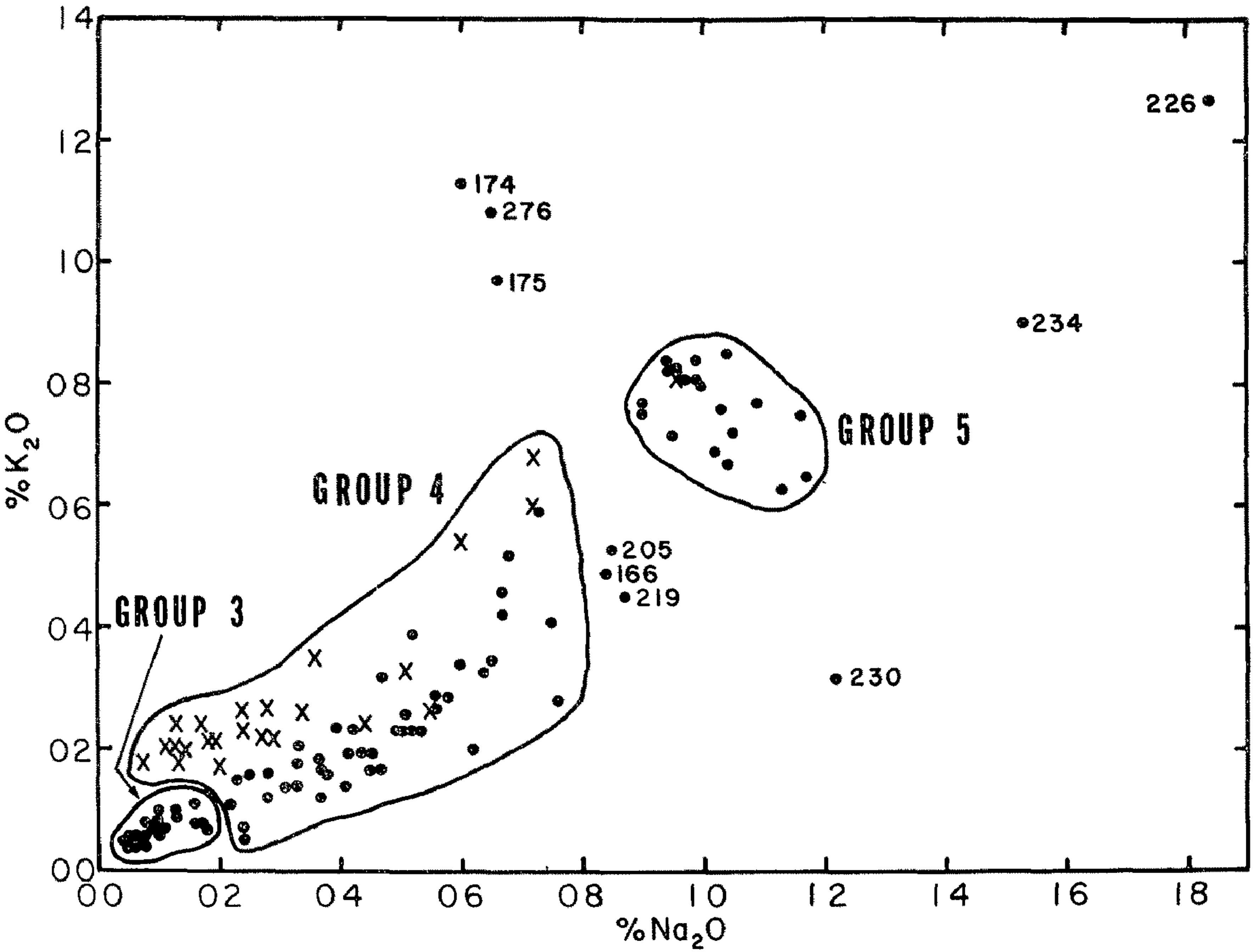



A
B
C
D

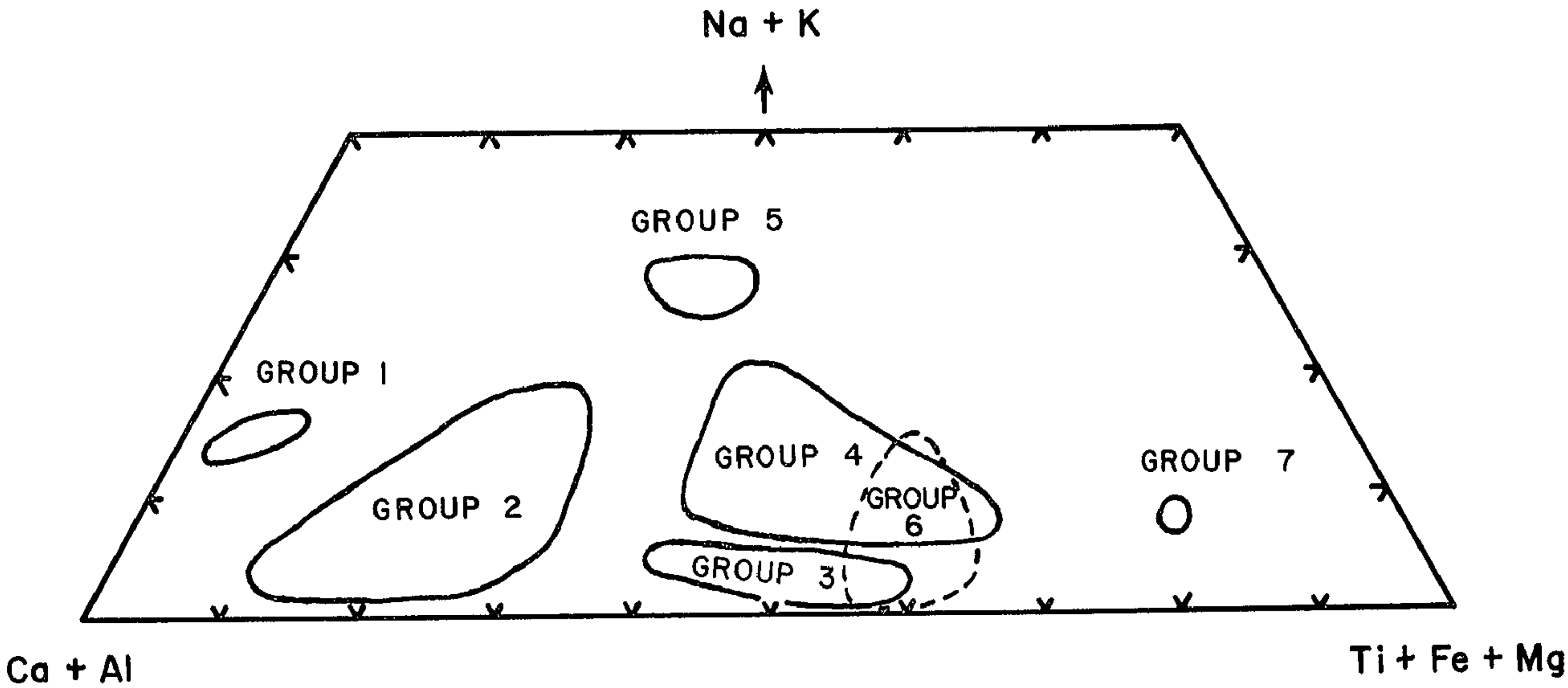

A
B
100 μm
10 μm

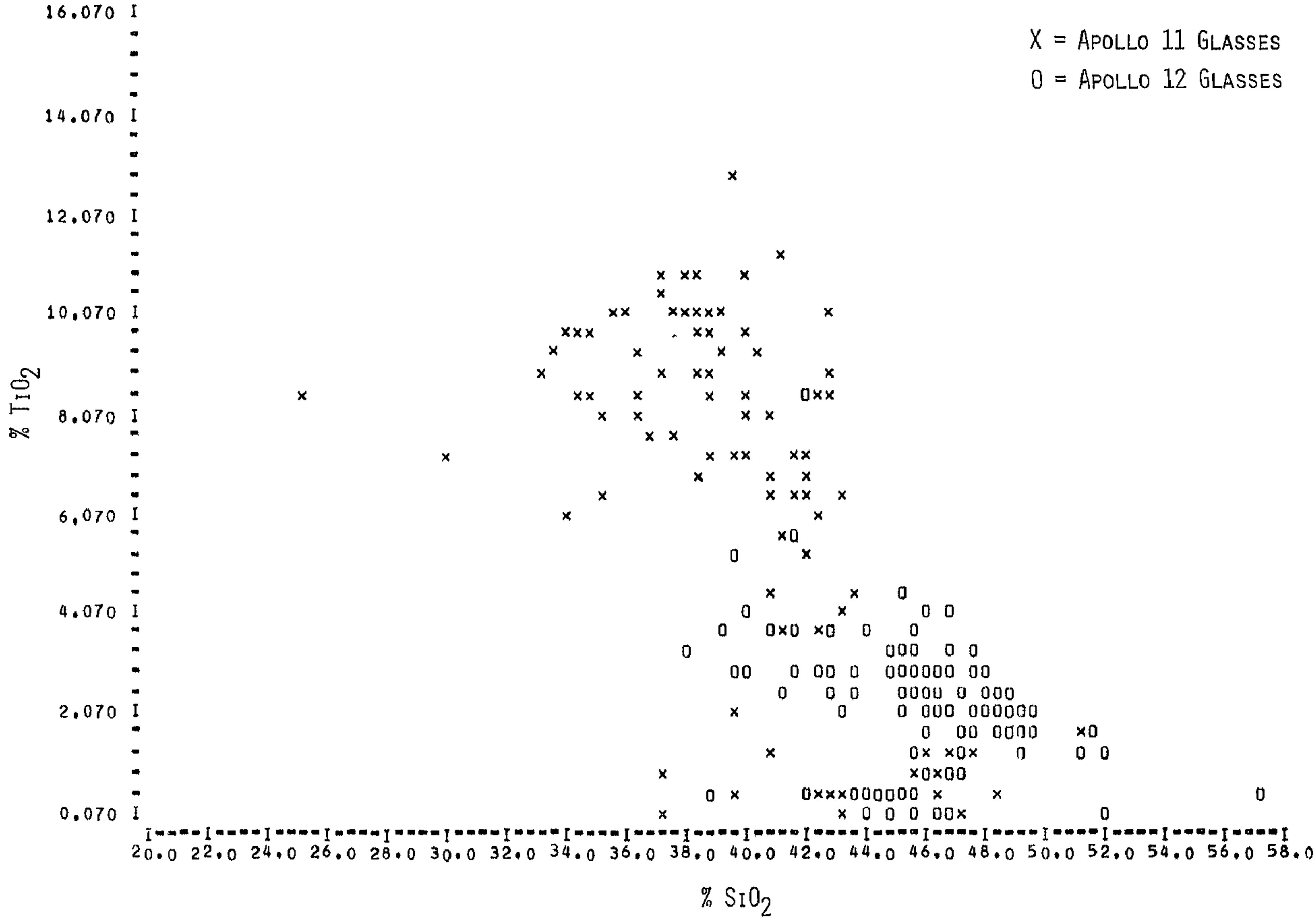


1.70
1.68
1.66
1.64
1.62
1.60
1.58
1.56
1.54
REFRACTIVE INDEX
38
40
42
44
46
48
50
52
54
56
58
% SiO_2

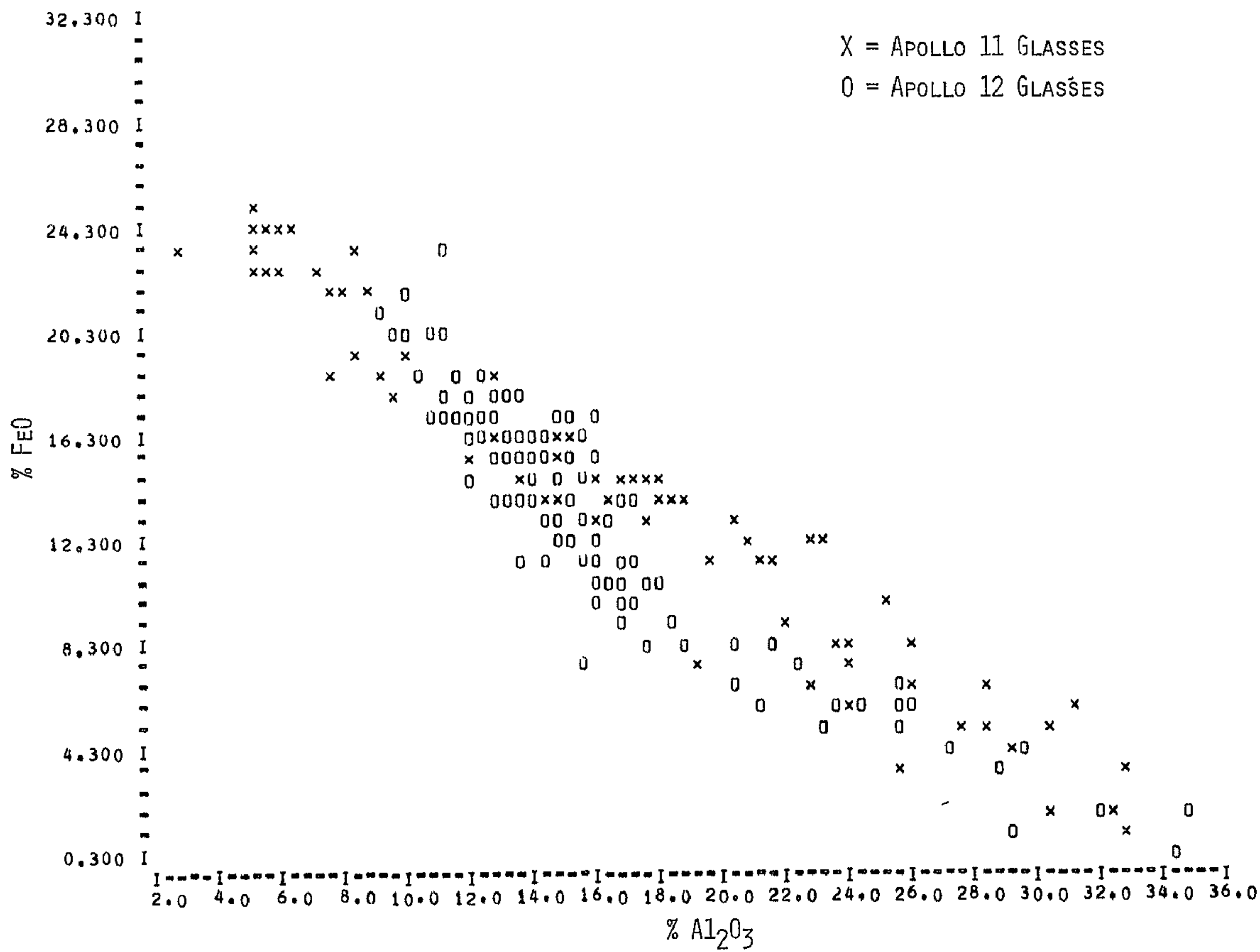


GROUP 3
GROUP 4
GROUP 5
174
276
175
226
234
205
166
219
230
%K_2O
%Na_2O


Na + K
GROUP 5
GROUP 1
GROUP 2
GROUP 4
GROUP 6
GROUP 3
GROUP 7
Ca + Al
Ti + Fe + Mg



X = Apollo 11 Glasses
0 = Apollo 12 Glasses
% TiO2
% SiO2
16.070
14.070
12.070
10.070
8.070
6.070
4.070
2.070
0.070
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
36.0
38.0
40.0
42.0
44.0
46.0
48.0
50.0
52.0
54.0
56.0
58.0



X = Apollo 11 Glasses
0 = Apollo 12 Glasses
% FeO
32.300
28.300
24.300
20.300
16.300
12.300
8.300
4.300
0.300
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
36.0
% Al_2O_3