Mineral Sciences Investigations 1976-1977

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EDITOR

ABSTRACT

Fudali, Robert F., editor. Mineral Sciences Investigations 1976–1977. *Smithsonian Contributions to the Earth Sciences,* number 22, 73 pages, 22 figures, 20 tables, 1979.—This volume is comprised of six short contributions reporting the results of some of the research carried out by the Department of Mineral Sciences, Smithsonian Institution, during the period 1976–1977. Included are: a comparison of impact breccias and glasses from Lonar Crater (India) with very similar specimens from the moon; petrographic descriptions and chemical analyses of virtually all the known pyroxene-plagioclase achondrite meteorites and a discussion of the relationships within this class; a comparative chemical study of sixty Australian tektites from widely separated localities; a description of a new, rapid technique of sample preparation for whole-rock analyses using the electron microprobe; an interlaboratory comparison of the precision and accuracy of electron microprobe analyses; and a tabulation of the chemical compositions of some electron microprobe reference samples.

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Petrology, Mineralogy, and Distribution of Lonar (India) and Lunar Impact Breccias and Glasses

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ABSTRACT

Chemically and mineralogically, the shock meta-morphosed breccias and melt rocks at Lonar Crater (India) are the closest terrestrial analogs to the impact-generated rocks and soils of the moon. Comparative studies reveal a wide range of virtually identical forms and textures between Lonar and lunar samples. Thus, the advantage of knowing the unshocked target rocks at Lonar, especially with regards to alternating layers of different competency, may yield invaluable insights into lunar impact processes. Also, chemical differences reported herein between Lonar basalts and impact glasses suggest some probable trends in lunar analogs. Conversely, the isochemical nature of much of the Lonar glass and basalt demonstrates that lunar glasses may often be chemically equated to their parent rocks.

Introduction

As the importance of meteorite impacts as a mechanism producing lunar land forms, rocks, and soils is more clearly recognized, the existence of Lonar Crater, India, is coming to be seen as one of earth's more fortuitous catastrophes. This impact crater is located in the Deccan Trap basalts of India (19°58'N, 76°31'E), and affords unique opportunities for earthbound scientists to study analogs to lunar processes. We report herein a comparative study of the petrography, morphology, and chemistry of shocked Lonar and lunar materials.

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General Geology

The Lonar crater is an almost circular depression, 1830 m in diameter, approximately 150 m deep. Lonar Lake, a shallow saline lake, occupies most of the crater floor. The rim of the crater is raised approximately 20 m above the surrounding plain. A smaller circular depression in the traps, 300 m in

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diameter and about 700 m north of Lonar Crater, apparently is a second crater, probably excavated after throwout from the main crater landed, but during settling of fallout. Various data on general morphology, conclusive evidence for the impact origin, and preliminary studies of petrography, stratigraphy, and the chemistry of the impact rocks have been published elsewhere (Fredriksson et al., 1973). Recent fission track dating of Lonar shock-melted glasses indicates an age less than ~50,000 years (Wilkening, pers. comm.). Carbon–14 dating shows an age of more than 30,000 years for organic material recovered 50 m down in one of the ~90 m thick sediment columns in the lake (Suess, pers. comm.). The crater's age then lies between 30 and 50 thousand years.

The Geological Survey of India has drilled a series of five boreholes approximately on a line trending NE–SW in the floor of the crater. Each drillhole encountered 90 to 100 m of lake sediment, which was found to contain small amounts of impact glass in the form of fragments and spherules, and also rounded lithic fragments exhibiting varying degrees of shock metamorphism. This material was probably eroded from the crater rim. After penetrating the sediment, each of the drillings returned cores of coarser breccia apparently composed of blocks up to meters in size which are unshocked or slightly shocked and contain crude shatter cones. Beneath the coarse breccia, the first four drillings encountered a layer that yielded essentially no core recovery, apparently because it was composed of unconsolidated to extremely friable microbreccia. The assumption was confirmed in the fifth hole for which an improved core catcher was used, resulting in approximately 100% core recovery. In addition, one deep (~100 m) and several shallower holes were drilled in the smaller crater and on its rim. Current evidence indicates that the structure, although artificially modified by former dams and ditches, for purposes of irrigation, is of impact origin.

Comparative Petrography, Morphology, and Chemistry

The Deccan Trap basalts at Lonar exhibit two main textural varieties: (1) "hard" trap which has euhedral plagioclase phenocrysts with strong oscillatory zoning, often glomero-porphyritic, in an aphanitic groundmass; and (2) medium to coarse-grained, slightly to moderately vesicular or amygdaloidal basalt which has weathered to "soft" trap. Major minerals in both textural types are plagioclase (An 50–70) 33%–48%, clinopyroxene (augite ± pigeonite) 17%–34%, and opaques (ilmenite and/or magnetite) 2%–12%. Olivine may be present in small amounts. Alteration minerals include chlorite minerals, iron oxides, serpentine, and epidote. In addition, within both groups more coarse-grained sub-ophitic basalt may contain 20%–30% interstitial fresh glass or palagonite.

In contrast, lunar basalts range in grain size from coarse to fine to vitrophyric, and are often vesicular. In coarse lunar basalts pyroxene may occur as poikilitic grains in plagioclase. Plagioclase constitutes 25%–30%, clinopyroxene 45%–55%, and opaques 15%–20% (including ilmenite, armalocolite, chromespinel, ulvöspinel, rutile, metallic iron, nickel-iron, and troilite). Minor olivine may also be present. Many of the observed differences between Lonar and lunar impact-produced rocks and glasses discussed below may be explained by the chemical differences between the target basalts (see Table 1).

Shockwaves generated by a hypervelocity impact cause a variety of deformations and changes in the targets. Thus, slight shocking of Lonar basalt (≤250 kb) produces minor cataclasis in plagioclase and pyroxene, wavy extinction in pyroxene, and shock-induced twinning in plagioclase. Increasing pressures within this range produce closely spaced twins in pyroxene (this twinning seems to be related to possible strong shear loci). Large plagioclase and pyroxene crystals also tend to recrystallize or granulate into smaller domains, optically independent. In some cases planar elements in plagioclase are also produced, often accompanied by strong cataclasis, warping of the grain, and reduced birefringence. In "moderately" shocked basalt (~250–450 kb), plagioclase is converted to disordered maskelynite in which the original oscillatory zoning is preserved. Moderately strong shocking (~450–600 kb) produces microbreccia clasts in which maskelynite exhibits incipient flow. With intense shock, (≥800 kb), the basalt may be converted to glass. The mechanisms involved and necessary pressures for these various transformations with special reference to Lonar basalts have been studied in great detail by Kieffer et al, 1976, and Schaal and Hörz, 1977.

Ejecta on the rim of the main Lonar crater consist of two contrasting types of debris. The lower

TABLE 1.—Chemical compositions of some lunar and Lonar basalts; Lonar tabulations are electron microprobe analyses, done by this laboratory, using powders fused to a glass with lithium tetraborate flux

Constituent	Apollo 17[a]			Lonar	
	75055,6	70035,1	70215,2	Average[b] Lonar basalt	LNR shocked basalt
SiO_2	41.27	37.84	37.19	50.13	50.35
Al_2O_3	9.75	8.85	8.67	13.69	15.08
FeO	18.24	18.46	19.62	14.09[c]	12.74[c]
MgO	6.84	9.89	8.52	5.80	5.99
CaO	12.30	10.07	10.43	10.20	11.55
Na_2O	0.44	0.35	0.32	2.52	1.70
K_2O	0.09	0.06	0.04	0.55	0.25
TiO_2	10.17	12.97	13.14	2.72	2.31

[a] Apollo 17 PET, 1973:659–692.

[b] Average of 9 basalt samples.

[c] All Fe as FeO; average $Fe_2O_3/(FeO + Fe_2O_3) = 0.42$.

unit ("throw-out") is crudely stratified and shows no evidence of shock. The overlying unit ("fallout") contains clasts from different bedrock units, Flädle-like bombs, glass spherules, and fragments. The lithic clasts show varying degree of shock from barely perceptible through medium to (rarely) intense. As a practical matter the ejecta can be assigned to only two bedrock units representing the two basalt types described above: (1) hard, fresh trap exposed in the upper 50 m of the crater wall; and (2) soft, weathered trap exposed in the lower 50 m which presumably continues downward almost to the lake level and is probably followed by another dense basalt. Ejecta patches dominantly of one or the other unit are juxtaposed throughout the ejecta blanket with, at best, a weak tendency toward inverted stratigraphy. The patches vary widely in size, but are characteristically on the order of 100 m across near the rim and decrease to several meters across near the outer edge.

The hard trap typically forms breccia of small angular clasts; the soft trap is in large masses that have much less internal disruption. Concentrations of ejecta relatively abundant in glass and shocked fragments were found up to ~2 crater radii from the rim expecially to the E and ESE.

The ejecta blanket does not feather out evenly at the margin, but breaks into clumps increasingly scattered in ejecta-free terrain. Some of these are composites of hard and soft trap or even polymict breccias which, surprisingly, cohered during a flight of two or more kilometers. Some clumps remain intact; others are spread out inside secondary craters they have excavated. By analogy, secondary cratering on the moon depends neither on ejection of large individual blocks nor absence of atmosphere (Milton and Dube, 1977).

In Figures 1–6 the similarities between Lonar and lunar shocked basalts and breccias are illustrated. Lithic clasts in the Lonar microbreccias may exhibit severe cataclasis without reduction of birefringence in the plagioclase, or may show little or no cataclasis and still contain plagioclase completely converted to maskelynite. Deformation of plagioclase in lunar breccias is directly analogous to that found in Lonar samples including cataclasis, increased density of twin lamellae, granulation or development of a mozaic texture, development of
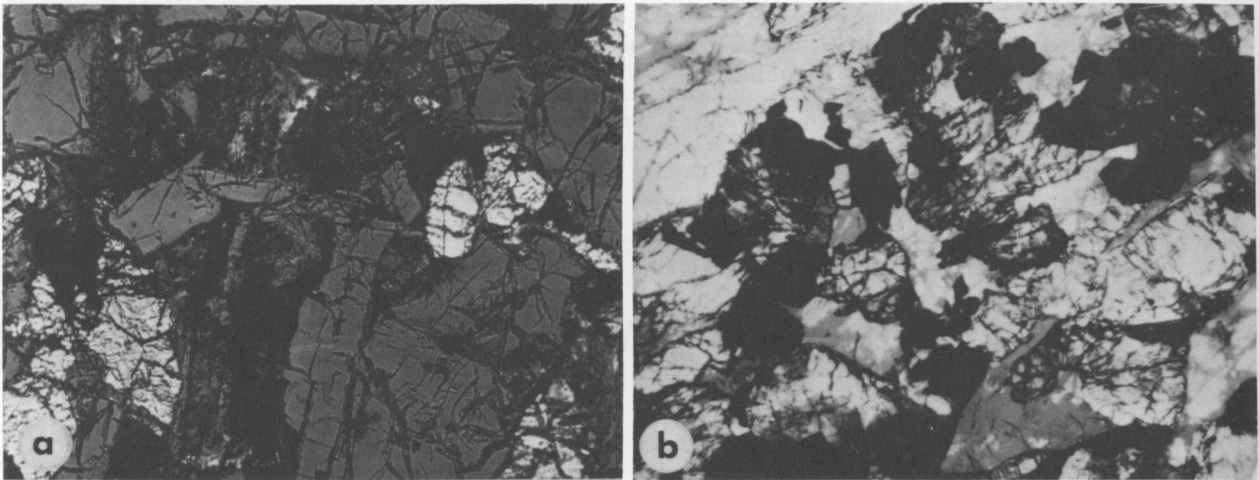
FIGURE 1.—a, Lonar trench sample LRT 18VII-1, a medium-grained basalt with plagioclase totally converted to maskelynite; pyroxenes exhibit moderate cataclasis; section is ∼0.9 mm in length. b, Apollo 17, #79155,68, a coarse-grained basalt with plagioclase partially converted to maskelynite (lower right); pyroxene exhibits moderately strong cataclasis; length of section is ∼3 mm.
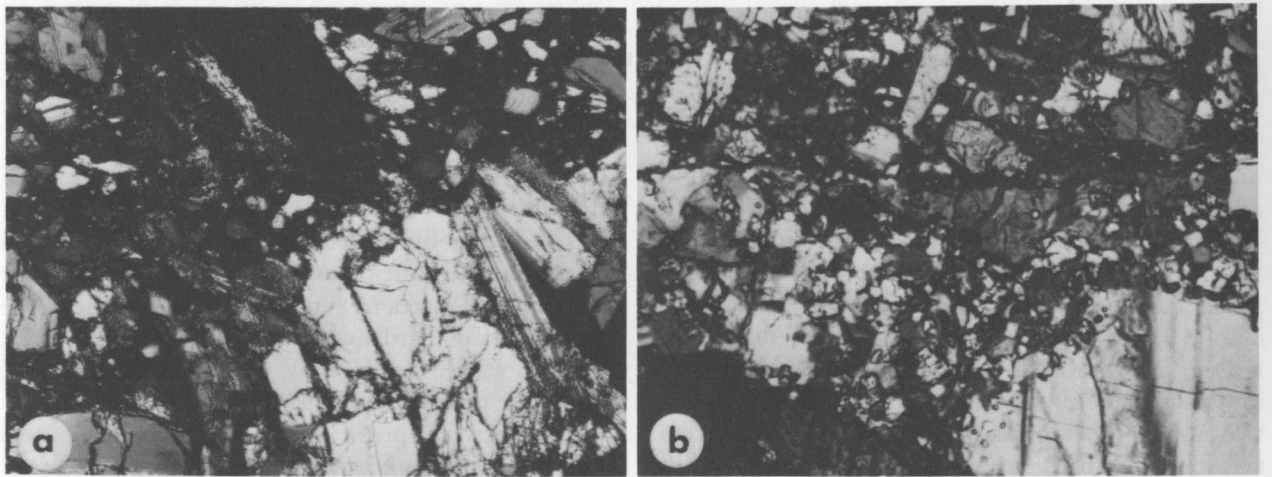
FIGURE 2.—a, Lonar core sample LNR-2-317, ∼460 m below crater rim; note contact between coarse-grained ophitic basalt and area of strong brecciation; section is ∼0.9 mm in length. b, Apollo 17, #78155,7; note contact between coarse-grained plagioclase and pyroxene crystals and strongly brecciated area; section is ∼0.9 mm in length.

planar features and conversion to maskelynite. Lunar pyroxenes exhibit close-spaced twins, granulation, and wavy extinction as do their Lonar counterparts (Figures 1, 2).

Lonar microbreccias from both cores and trenches consist of lithic and crystal fragments embedded in a generally fine semi-opaque rock flour (Figures 3–5). The lithic fragments vary in size from several centimeters to approximately 0.2 mm. Small lithic frag-

ments tend to be more abraded than large fragments. Lithic fragments in a single thin section may all exhibit similar shock characteristics or may exhibit a wide range of shock features (e.g., a slightly shocked fragment juxtaposed to a moderately shocked one). Fragments may also be very similar in texture and grain size ("monomict" breccia) or extremely dissimilar ("polymict" breccia) within one thin section. Occasionally, abraded breccia frag-
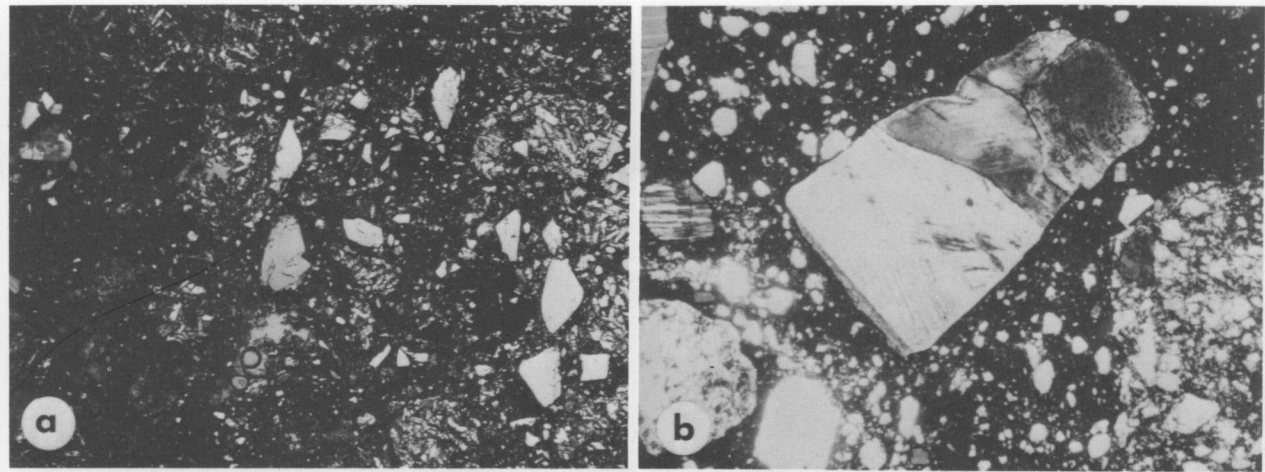
FIGURE 3.—a, Lonar core sample LNR–2–319 is a microbreccia with angular to subangular crystal fragments and rounded lithic fragments; length of section is ~3.2 mm. b, Apollo 17, #73235,63, also with angular to subangular crystal fragments and rounded lithic fragments; length of section is ~3.6 mm.
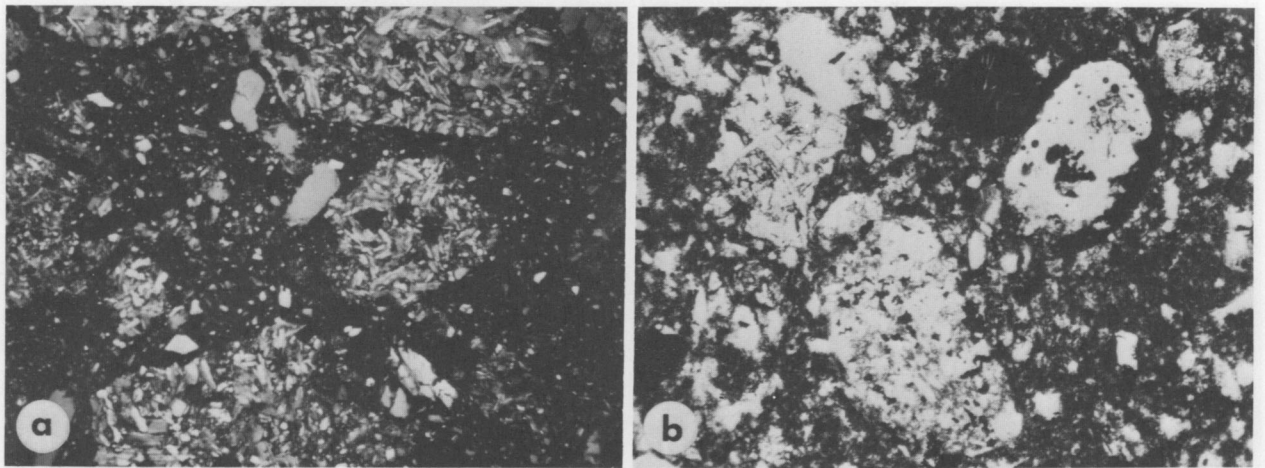
FIGURE 4.—a, Lonar core sample LNR–3–300, ~440 m below crater rim, has abraded lithic fragments in fine-grained rock flour; fragment at lower edge has plagioclase partially transformed to maskelynite; section is 3.4 mm in length. b, Apollo 16, #68822,1; note abraded lithic fragments in fine-grained rock flour and partially devitrified glass spherule; section is 0.9 mm in length.

ments are observed along with normal lithic fragments indicating a process of brecciation, consolidation, abrasion, and final disposition. Apparently, one impact can produce a kind of the breccia-within-a-breccia texture so common in lunar samples (Figure 5). One notable lithic fragment type consists almost entirely of plagioclase; similar lunar "anorthosite" breccia clasts may, thus, not always represent individual rock types. Microbreccia rock flour matrix material often shows evidence of flow, and

may contain turbid shock glass (Figure 6). Crystal fragments in the matrix are usually angular to subangular and exhibit shock effects ranging from mild to moderately strong. The unconsolidated variety of microbreccia appears to contain little or no rock flour matrix, a major component of consolidated microbreccia, and instead, consists almost entirely of small crystal fragments of a fairly uniform size. Shock effects in these fragments are generally slight, occasionally moderate. Lithic and breccia fragments
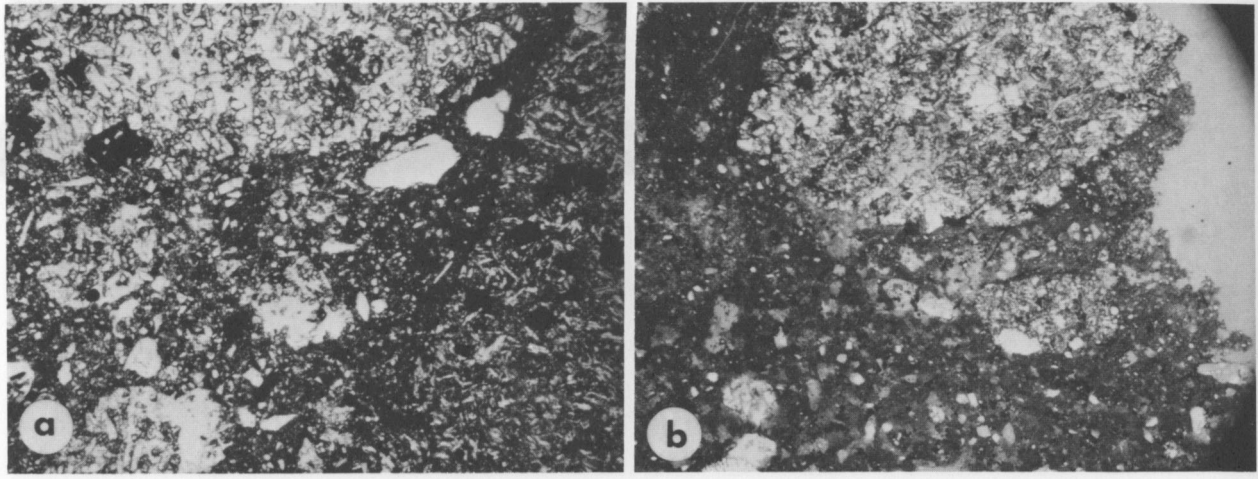
FIGURE 5.—a, Lonar core sample, LNR–2–319A, with abraded lithic fragments in fine-grained rock flour; note high degree of crystal angularity in matrix contrasting with roundness of the lithic fragments; length of section is 3.4 mm. b, Apollo 16, #67943,1–J; note abraded lithic and breccia fragments in fine-grained rock flour; length of section is 1.7 mm.
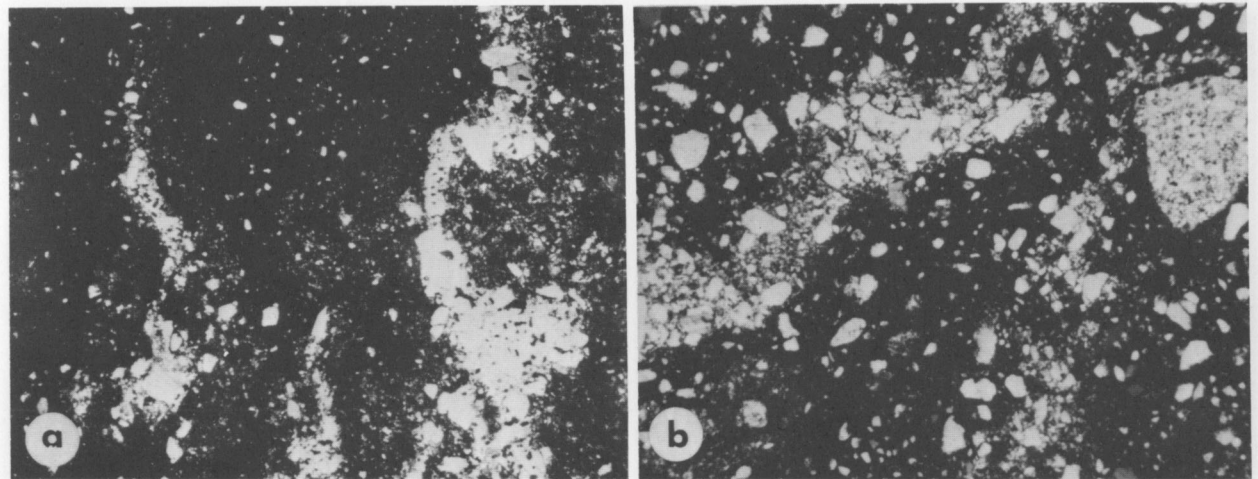
FIGURE 6.—a, Lonar core sample LNR–2–138, ~280 m below crater rim, is a layered microbreccia; light areas are plagioclase crystal fragments; section is 3.4 mm in length. b, Apollo 17, #72215,7, also a layered microbreccia; note subangular breccia fragment; section is 3 mm in length.

are small and uncommon. Crude stratification suggests flow or sedimentation rather than brecciation in situ.

The material found in core 5 between ~200 and 300 m below the lake level ("no core" zone in previous holes) is indeed best characterized as microbreccia, although it is mostly unconsolidated. Mineralogically it resembles the microbreccias described in the previous paragraph. Occasionally more indurated (whether by shock or later diagenetic processes is uncertain) sections of core (up to tens of centimeters) are found. Thin sections show these breccias to resemble simple lunar soil breccias and to contain unshocked to moderately shocked minerals and rock fragments.

Lonar glass ejecta consist of bombs, spherules, and fragments. Black glassy bombs, evidently still soft when deposited, are 10–15 cm in diameter and generally have a dense outer shell and a vesicular core. Spherules, millimeters in diameter and smaller, and similar in appearance to microtektites, consist of droplets of brown to colorless glass, often with flow
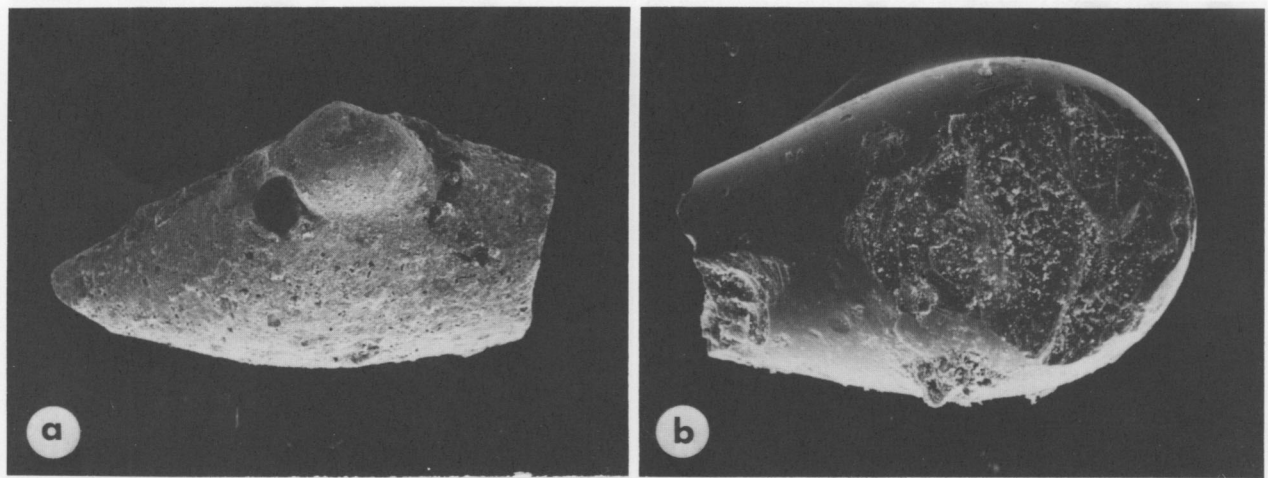
FIGURE 7.—a, Part of a glassy teardrop from Lonar trench sample LRT 18IVB-3 #2. SEM photo; analysis in Table 3; note microcrater and mound of glass; sample is ~2 mm long. b, Apollo 17, #74220,86 (>60 mesh) #1, a teardrop-shaped spherule; note internal structure; SEM photo; sample is 0.5 mm long.
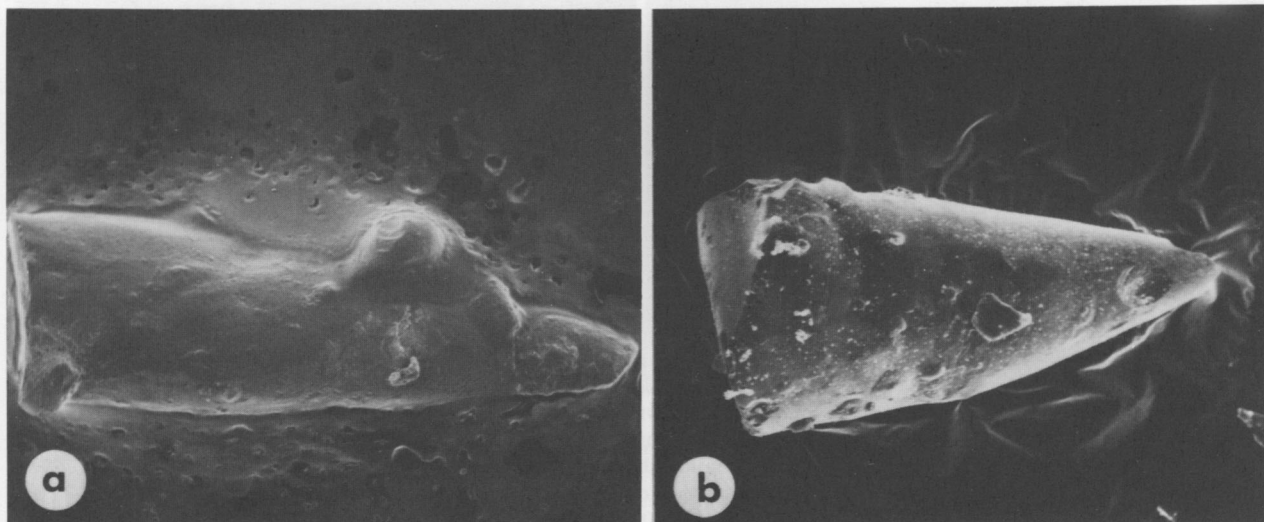
FIGURE 8.—a, A cone-shaped fragment from Lonar trench sample LRT 18VA-4 #1; SEM pho.o; note mound of glass, probably extruded upon cooling; sample is 1.3 mm long. b, Apollo 17, #74220,86 (>100 mesh) #1, a cone-shaped fragment; SEM photo; analysis in Table 4; sa·aple is 0.6 mm long.

banding indicated by contorted schlieren. Feathery recrystallization in the spherules occurs rarely. Though most Lonar spherules seem to be compositionally homogeneous, several were found with compositional zoning. The trends most often observed include progressive alkali depletion (particularly Na_2O) accompanied by FeO enrich nent from the center to the edge of the spherules. Glass shards and angular fragments mostly consist of turbid, brown to colorless glass, often vesicular and containing contorted schlieren. The production of shock melts requires intense shocking, ≥ 800 kb (Schaal and Hörz, 1977), and yet glass shards frequently include crystal fragments or rarely entire lithic fragments that are only slightly shocked.

Lunar glass spherules and fragments have been studied by a number of authors (see especially Carter, 1971). Figures 7–10 show some characteristic
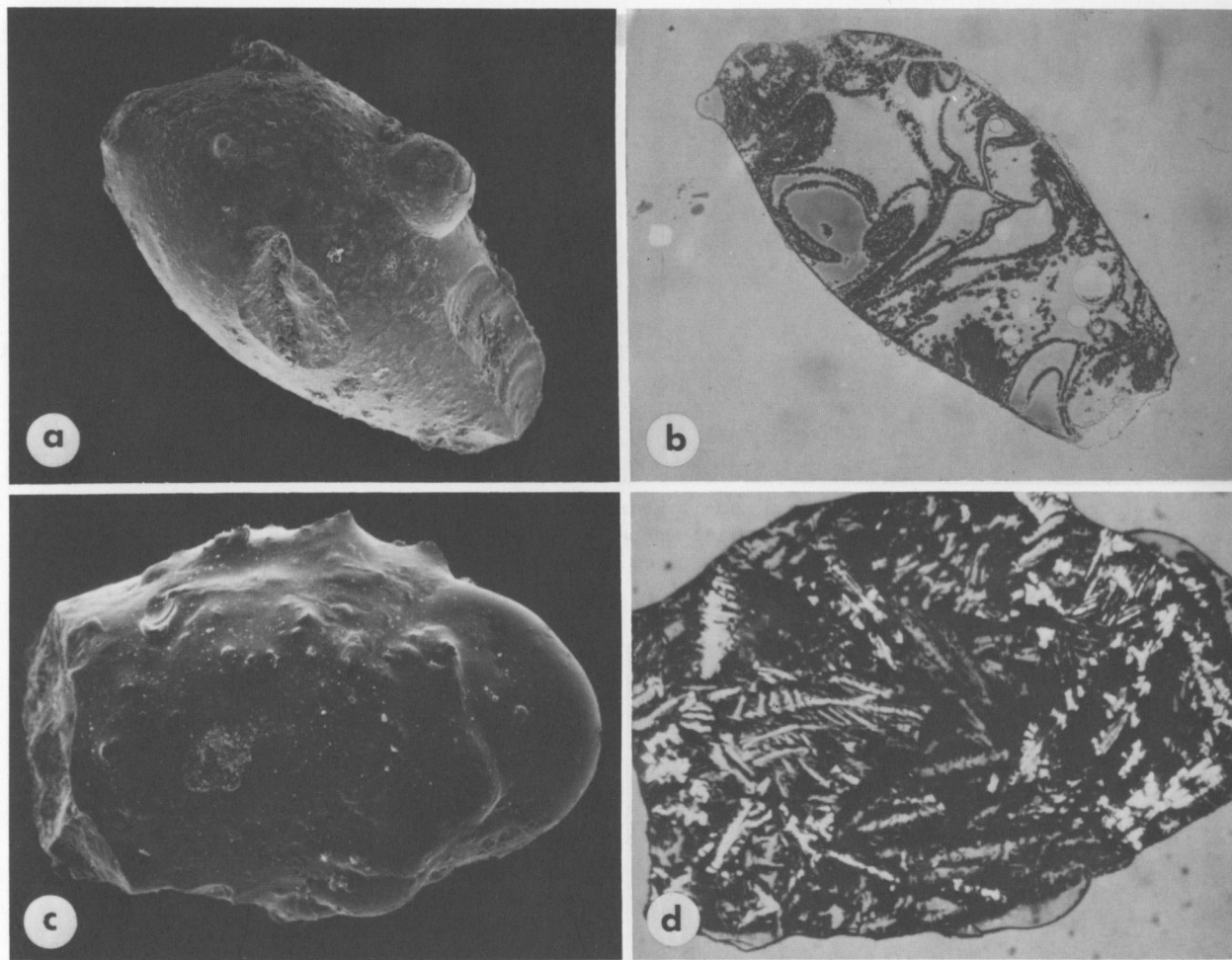
FIGURE 9.—*a*, A spherule from Lonar trench sample LRT 18IIIA-4 #1; SEM photo shows small mound of glass possibly extruded as spherule cooled; analysis in Table 3; spherule is 1 mm in long dimension. *b*, Thin section of spherule shown in a; note apparent inhomogeneity of internal structure; the glass, however, has almost constant (basaltic) composition; the skeletal crystallites decorating flow lines are titanomagnetite; length of section is 1 mm. *c*, Apollo 17, #74220,86 (>100 mesh); SEM photo illustrates similarities in surfaces features of lunar and Lonar spherules (also of many meteoritic chondrules); sample is 0.4 mm long. *d*, A thin section of sample shown in *c* reveals a partially devitrified texture.

types illustrating the similarities between Lonar and lunar glass particles. A few chemical analyses are given in Tables 2–4.

A large number of electron probe analyses were made to determine trends in composition among Lonar basalts, "bombs," and the other glass particles. The glasses were subdivided into two somewhat arbitrary groups based on composition and/or morphology: (1) "normal" glasses (Table 2), the compositions of which were comparatively uniform and resemble the basalts; and (2) "selected" glasses

(Table 3) mostly with compositions deviating from the "normal" glasses. Observed trends were various degrees of alkali, water, and sometimes silica depletion in the spherules and some "unusual" glasses. The majority of analysed glasses, however, closely approximate a homogeneous basalt melt although they appear somewhat depleted in $FeO+MgO$ and enriched in Al_2O_3 relative to the parent basalt (Figure 11, Tables 1, 2). In addition, ferrous iron is more prevalent in the glasses, indicating a reduction upon melting of the parent basalt
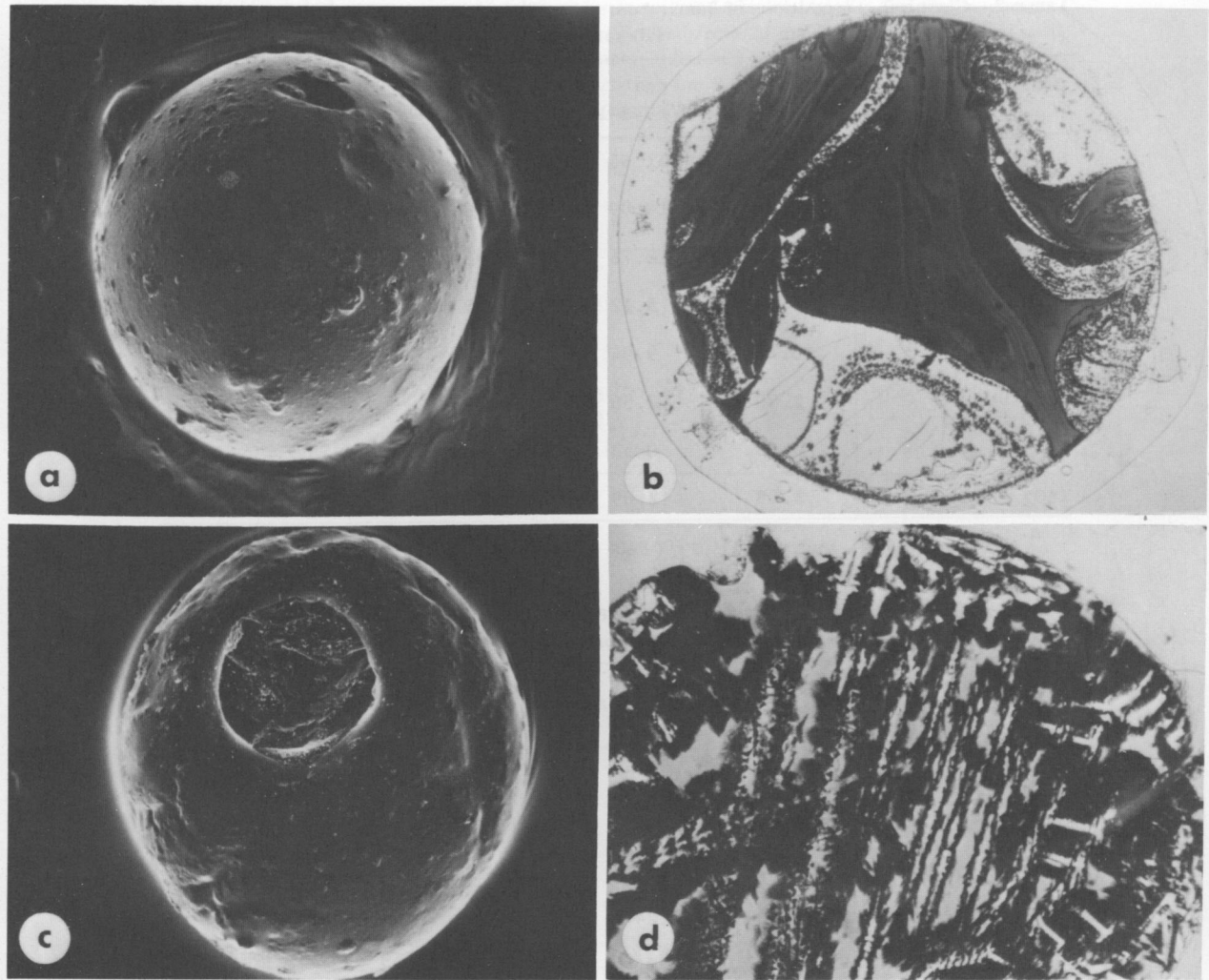
FIGURE 10.—a, Almost perfectly round spherule from Lonar trench sample LRT 18VA–4 #2;
SEM photo; note microcrater; spherule is 0.8 mm in diameter. b, Thin section of Lonar trench
sample LRT 18IIA–3 #3, a spherule similar to that shown in a; analysis in Table 3. c, Apollo
17, #74220,86 (>60 mesh), a spherule; SEM photo; note microcrater; sample is ~0.43 mm in
diameter. d, Thin section of spherule shown in c, showing almost complete devitrification; length
of section is 0.25 mm.

$(Fe_2O_3/(FeO+Fe_2O_3)$ is ~0.42 in the basalts, ~0.37 in the glasses). According to Morgan (1978) the heavy volatile elements Se and Cd are also significantly depleted in the glasses.

Lunar trends, though inherently more difficult to discern (e.g., initially low alkalies) seem also to indicate a depletion in alkalies in glasses relative to the parent basalts (Fredriksson et al., 1971). As at Lonar some heavy volatile elements, such as Pb (Silver, 1975), may also have been redistributed in the lunar rocks and soils by impact volatilization. If lunar fractionation trends are indeed analogous to Lonar trends (even ignoring the "unusual" Lonar glasses which were likely produced by complete or partial melting of individual phenocrysts) then lunar glass fragment chemistry may or may not represent unaltered lunar rock types.

Interpretation of impact cratering and ejecta stratigraphy has been attempted throughout the Apollo missions. The results of the present study are certainly relevant to such questions as the extent, homogeneity, and composition of lunar ejecta blan-

TABLE 2.—Chemical compositions of Lonar "normal" glasses; electron microprobe analyses, this laboratory

Constituent	LRT 19VB–1	LRT 19VB–1	LRT 19VB–1	D 215–4	SL–3 1.5–4
SiO_2	52.02	51.65	52.61	50.48	51.59
Al_2O_3	13.84	14.89	14.36	13.99	14.53
FeO [a]	13.58	12.76	12.91	12.96	13.45
MgO	5.43	5.12	4.95	5.46	4.85
CaO	10.27	9.94	10.40	10.13	9.97
Na_2O	2.30	2.56	1.99	2.59	2.32
K_2O	0.63	0.53	0.47	0.53	0.46
TiO_2	2.69	2.09	2.27	2.23	1.90

[a] All Fe as FeO; average $Fe_2O_3/(FeO + Fe_2O_3) = 0.37$.

TABLE 3.—Chemical composition of Lonar "selected" glasses (note that LRT 18IVB–3 is a "normal" glass); electron microprobe analyses, this laboratory

Constituent	LRT 19VIB–3	LRT 18IIA–3 [a]	LRT 18111A–4 [b]	LRT 19VB–1	LRT 18IVB–3 [c]
SiO_2	37.69	49.1	47.79	51.81	51.78
Al_2O_3	22.22	12.8	12.69	5.27	13.43
FeO [d]	28.41	16.5	15.88	18.30	13.55
MgO	4.82	7.24	7.67	11.64	5.08
CaO	6.96	9.0	9.13	12.13	9.41
Na_2O	0.02	1.76	1.49	0.62	2.31
K_2O	0.02	0.28	0.23	0.29	0.65
TiO_2	0.10	2.34	2.29	1.95	2.38

[a] See Figure 10b.   [c] See Figure 7a.

[b] See Figure 9a,b.   [d] All Fe as FeO.

kets. Thus the mechanisms involved in reworking the lunar regolith (e.g., Gault et al., 1974) may deserve reconsideration. Secondary impacts played an important role in mixing and reworking pre-existing Lonar soils with ejecta of both basalt fragments and loosely consolidated microbreccias. This should be considered in the interpretation of the evolution of the lunar regolith. Secondary cratering may also explain the discrepancy between the long exposure ("suntan") ages of lunar soil relative to excavated rock fragments (Gold and Williams, 1974). Detailed descriptions and maps of the Lonar ejecta distribution are being prepared by the Geological Survey of India in cooperation with some of us, and will be published elsewhere.

Some findings near the bottom of the fifth and last drillcore may justify also a reevaluation of current concepts of the impact effects in rock com-

TABLE 4.—Chemical compositions of selected lunar soil and glasses (Apollo 17); electron micro-probe analyses, this laboratory; bulk soil analyses derived from 20 mg splits fused to a glass with lithium tetraborate flux (A, B, C, and D designate individual glass analyses that appear to be representative of distinctive groupings; it appears that the B glasses generally correspond to the local bulk soils, but the other groupings are not readily identifiable)

Constituent	700019,72			74220,86
	Bulk Soil	A	B	A
SiO_2	41.4	38.1	40.1	39.9
Al_2O_3	12.8	6.1	12.7	6.0
FeO	16.3	24.4	16.8	22.3
MgO	9.9	14.2	10.1	14.8
CaO	10.6	7.2	10.8	7.1
Na_2O	0.28	0.30	0.34	0.33
K_2O	0.15	0.22	0.11	0.10
TiO_2	7.2	8.7	7.9	8.8

Constituent	79035,29				
	Bulk Soil	A	B	C	D
SiO_2	41.2	39.4	41.9	41.4	44.0
Al_2O_3	13.0	6.2	13.8	22.0	36.0
FeO	15.7	22.7	15.8	6.4	0.1
MgO	9.9	14.6	10.0	14.7	0.1
CaO	10.7	7.6	11.3	13.1	20.1
Na_2O	0.39	0.32	0.33	0.11	0.25
K_2O	0.10	0.09	0.11	0.03	0.02
TiO_2	6.4	9.0	7.4	1.20	0.03

Constituent	79135,71				
	Bulk Soil	A	B	C	D
SiO_2	42.0	38.6	42.0	45.2	43.6
Al_2O_3	15.1	5.8	13.6	21.5	35.5
FeO	14.3	22.4	14.3	8.1	0.1
MgO	10.0	14.7	10.5	11.7	0.3
CaO	11.1	7.4	10.8	13.3	19.6
Na_2O	0.44	0.42	0.40	0.04	0.24
K_2O	0.20	0.10	0.06	0.01	0.08
TiO_2	4.7	9.1	6.0	1.16	0.02

plexes with layers of different competency (chemically similar or not). At ~450 m below the rim solid basalt was encountered as in previous drillings. At about 470, 490, and 520 m, however, rock flour layers apparently up to ~1 m thick were encountered between several meters of solid basalt with essentially no shock features. The rock flours in these horizons differ in grain size but are all relatively well sorted. Whether these loose layers represent a peculiar kind of shock veins or injected material or explosively disrupted porous or weathered basalt layers of low competency is unclear. Ongoing studies should yield a better understanding of this and also give more realistic comparisons (scaling factors) between real, large impacts and artificial experiments on small targets (e.g., Gault et al., 1974).
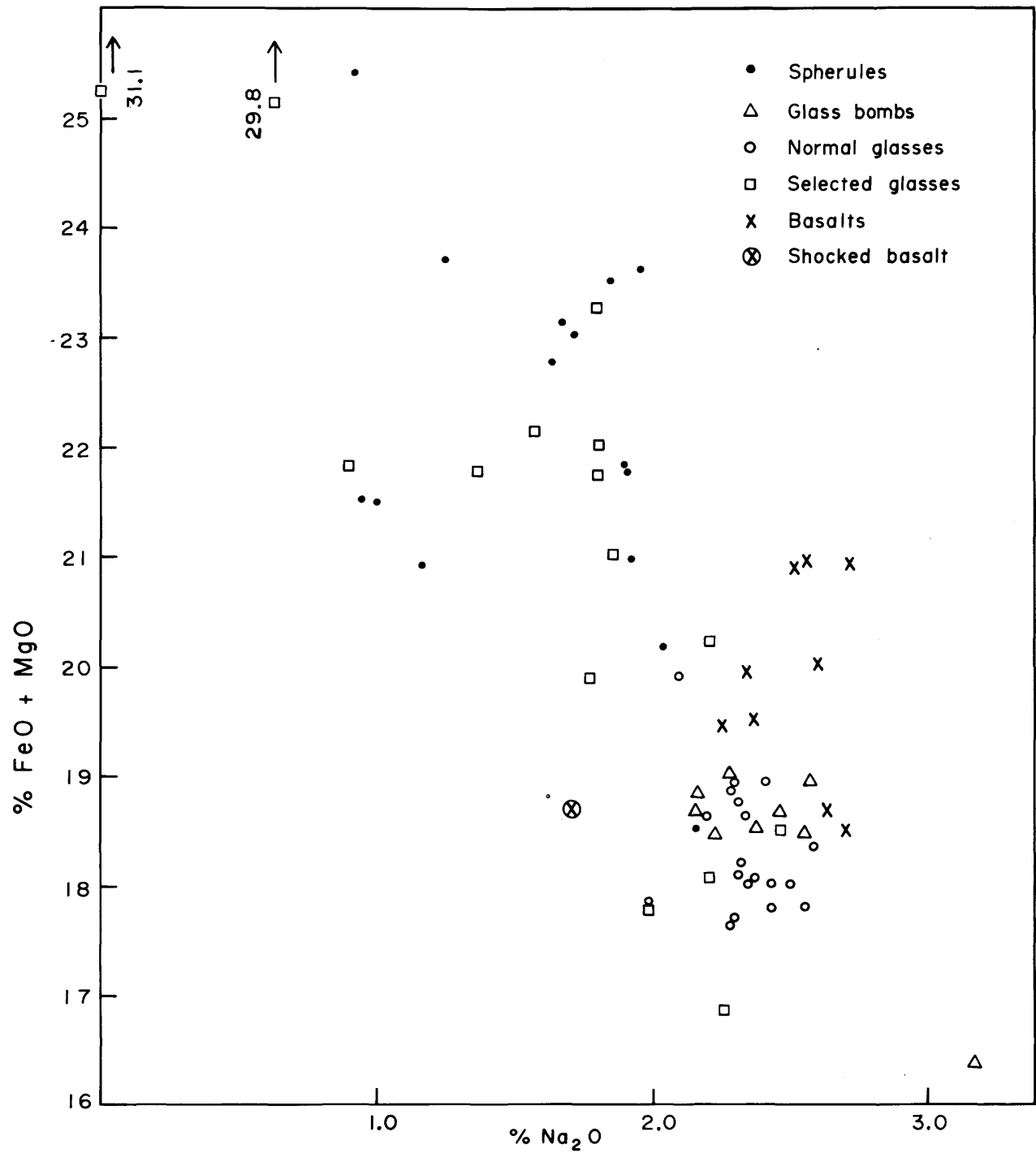
FIGURE 11.—Plot of Na₂O versus FeO+MgO, both in weight percent, for Lonar basalts and glasses; note that two "selected" glasses with high FeO+MgO plot outside the diagram.

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Chemical Variation among Australian Tektites

Brian Mason

ABSTRACT

Microprobe analyses for major components of 60 australites from specific locations covering most of the strewnfield show a wide range of composition. Regional variations are seldom clearly defined, and australites of closely similar composition may be found at widely separated locations. Three distinctive geographic-compositional groups can, however, be distinguished: (1) a group with high Fe and Mg from the Lake Wilson–Mt. Davies region in northwest South Australia; (2) a group with high Ca/Al ratio centered around Charlotte Waters on the South Australia–Northern Territory border and extending into southwest Queensland; (3) a group with high Al and low Si from Pindera in New South Wales (australites from elsewhere in New South Wales analyzed by other investigators also show this feature). Australites show a relatively restricted composition range, whereas microtektites from deepsea sediments south and west of Australia show a much more extensive composition range; thus claims for a common origin of these contrasted materials are not supported by compositional comparisons.

Introduction

Beginning in 1963 and continuing for some years, Mr. R. O. Chalmers of the Australian Museum, Dr. E. P. Henderson of the Smithsonian Institution, and I travelled widely throughout Australia (except Tasmania) for the purpose of collecting tektites (australites) and establishing the limits of the strewnfield. The results of these travels are reported in Chalmers et al. (1976). An important result was the acquisition of large collections from clearly-defined locations; one scientific drawback of many collections of australites is the vagueness of geographic attribution, such as "Nullarbor Plain," "Birdsville Track," etc. Our collections from clearly defined locations (Figure 1) thus provide the opportunity to investigate compositional variations within a specific location, and to make comparisons between locations. By virtue of the fact that individual tektites are glassy objects usually of uniform composition and that australites exhibit a limited range of compositions (67%–79% SiO_2), australites are especially suitable for microprobe analysis.

TECHNIQUES USED.—From a single-locality collection, individual specimens were selected for analysis by separation according to specific gravity. The specific gravity of australites (except for the rare and enigmatic HNa/K group) ranges from about 2.36 to 2.52, and is inversely related to SiO_2 content, 79% to 67% (Chalmers et al., 1976, fig. 17). Collections were processed by flotation in bromoform-acetone mixtures of progressively increasing specific gravity, and individual specimens were selected to cover the whole range. This provided a group of specimens fairly evenly spaced over the total range of SiO_2 content for that locality. A total of 60 specimens representing 11 localities were selected for analysis.

A polished thin section was prepared from each selected specimen. Another portion of the same specimen was crushed and the refractive index of the crushed material determined by the immersion method. This determination also provided an opportunity to evaluate the homogeneity of the individual australite. Thin sections of australites frequently show schlieren of slightly differing refractive index (see, e.g., Chalmers et al., 1976, fig. 16). Most of the analyzed australites showed only minor variation (±0.001) in the refractive index of crushed fragments, and this limited variation was confirmed

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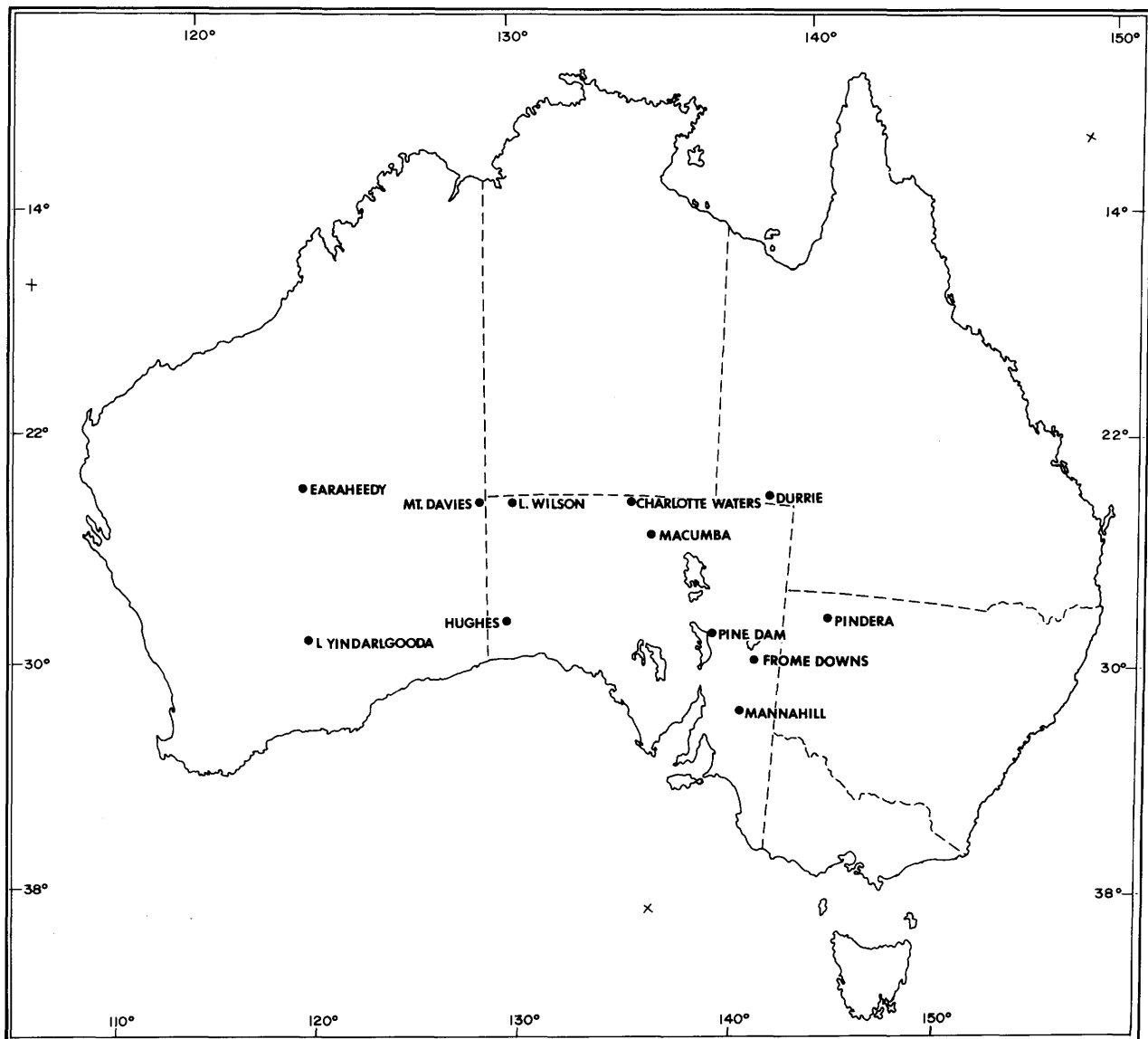
FIGURE 1.—Map showing locations of analyzed australite collections.

by the limited variation between individual spots in the microprobe analysis. A few, specifically some with high SiO_2 content (>75%), showed a greater variation in refractive index, sometimes as much as ±0.003. Although Glass (1970) reports large compositional variations (SiO_2 60%–85%) within a single australite, it must be noted that he specifically selected small, rare inclusions (two high-silica and three low-silica in two thin sections) to establish this extreme range, and also that he states (p. 241),

"The bulk of the glass has an average composition of about 76% SiO_2."

The polished thin sections of the individual australites were analyzed with an ARL-SEMO electron microprobe using an operating voltage of 15 kV and a sample current of 0.15 μA; a broad beam (approximately 0.05 mm diameter) was used to counter the local inhomogeneities discussed in the preceding paragraph. A previously analyzed australite containing 68.35% SiO_2 (Chalmers et al.,

1976, tbl. 8) was used throughout as a reference sample. Measured intensities were adjusted by computer using Bence-Albee factors. The following components were determined: SiO_2, Al_2O_3, FeO (all Fe reported as FeO) MgO, CaO, K_2O, Na_2O, TiO_2, MnO; MnO is not reported in the analyses, since it was uniformly at or near the lower limit of measurability, approximately 0.1%.

Results

The analytical results are set out in Table 1 and are plotted in Figures 2, 3. The results for specific locations are discussed below.

EARAHEEDY.—The collection from this locality comprised 97 specimens. The specific gravity range was from 2.432 to 2.459, most specimens (87) falling in the range 2.455–2.459. The four specimens analyzed (Table 1, columns 1–4) cover the full specific gravity range, which is relatively small; the analyses show a correspondingly small composition range.

LAKE YINDARLGOODA.—The collection from this locality near Kalgoorlie comprised 61 specimens. The specific gravity range was from 2.432 to 2.467, with practically all the specimens (57) having specific gravities between 2.450 and 2.460. The three specimens analyzed (Table 1, columns 5–7) cover almost the full specific gravity range.

A considerable number of analyses of australites from the Kalgoorlie region have been published, most of them by Taylor (1962) and Taylor and Sachs (1964). These analyses confirm the restricted range of australite composition in this region. Of Taylor's 13 analyses, 11 have SiO_2 contents ranging from 70.34% to 72.13%; the remaining two have 75.17% and 77.39% respectively.

HUGHES.—This collection, from the Nullarbor Plain close to the South Australia–Western Australia border, comprised 248 specimens, ranging in specific gravity from 2.398 to 2.473 (two specimens, described in columns 9 and 11 of Table 1, had interior bubbles and their specific gravities were less than 2.398). Of the total collection of 248 specimens, 203 had specific gravities between 2.440 and 2.460.

The three collections from Hughes, Lake Yindarlgooda, and Earaheedy all show very similar specific-gravity distribution patterns, with a single peak at 2.45–2.46 on the frequency curve. The largest collection, that from Hughes, shows the greatest range in specific gravity, as might be ex-

pected. Chapman et al. (1964) have shown that this specific-gravity distribution pattern is uniform for all collections they examined from the Kalgoorlie and Nullarbor Plain locations. The Earaheedy collection shows that this uniformity extends far to the north. Within this vast area australites with comparable SiO_2 content generally show a close correspondence in other components; compare for example in Table 1, analyses 1 and 5, 3 and 9, 7 and 12.

CHARLOTTE WATERS.—A small collection of 33 specimens from Charlotte Waters showed a wide range in specific gravity, 2.390–2.483, with a rather ill-defined frequency peak at 2.440. Chapman et al. (1964), who examined a much larger collection (420 specimens), found a specific-gravity range of 2.395–2.495, with a peak at 2.445. The analyzed specimens (Table 1, columns 14–20) show SiO_2 ranging from 69.0% to 77.6%; a significant feature is a relatively high CaO content compared to australites of similar SiO_2 content from the Nullarbor Plain and Western Australia. Taylor (1962) and Taylor and Sachs (1964) published six analyses of australites from Charlotte Waters; SiO_2 ranged from 71.26% to 75.10%, CaO from 3.11% to 5.49%, figures similar to those obtained in this investigation.

DURRIE.—This collection is of considerable interest, since it is closest to the northern and eastern margin of the strewnfield. The 99 specimens in the collection ranged in specific gravity from 2.384 to 2.489, with a mean of 2.440. Six specimens covering the full range of specific gravity were analyzed (Table 1, columns 21–26), and show a range of SiO_2 from 69.2% to 78.9%. The compositions are similar to those of Charlotte Waters, but extend to a higher SiO_2 content; it is significant that the low-SiO_2 australites from Durrie also show the high CaO contents of Charlotte Waters australites (cf. analyses 14 and 21).

MACUMBA.—This small collection (19 specimens) is of particular interest because it has a wide range of specific gravity (2.386–2.461), and the specific-gravity distribution plot shows two peaks, one at 2.395 and one at 2.440 (Chalmers et al., 1976, tbl. 7). This two-peaked specific-gravity distribution plot is characteristic of australite collections from the Lake Torrens–Lake Eyre region of South Australia and is not found elsewhere. The six specimens analyzed (Table 1, columns 27–32) cover an SiO_2 range of

TABLE 1.—Analysis of 60 selected australites for major constituents and for specific gravity and refractive index (locality of analyzed specimens, by column: 1–4, Earaheedy, USNM 5796; 5–7, Lake Yindarlgooda, USNM 5733; 8–13, Hughes, USNM 2548; 14–20, Charlotte Waters, USNM 2537; 21–26, Durrie, USNM 5799; 27–32, Macumba, USNM 2535; 33–38, Pine Dam, USNM 5802; 39–45, Mannahill, USNM 4831; 46–51, Lake Wilson, USNM 2534; 52–56, Mount Davies, USNM 2536; 57–60, Pindera, USNM 2242)

Constituent	1	2	3	4	5	6	7	8	9	10
SiO_2	69.9	70.2	71.8	73.0	69.9	70.6	74.3	70.2	71.7	72.4
Al_2O_3	14.5	14.2	12.8	12.9	14.1	14.0	11.4	13.4	12.6	12.7
FeO^a	5.24	5.01	4.54	4.60	5.06	4.99	4.02	4.93	4.64	4.55
MgO	2.34	2.16	2.15	2.02	2.31	2.31	1.69	2.39	2.14	1.98
CaO	3.24	2.51	3.70	3.14	3.36	3.15	2.89	4.63	3.63	3.20
K_2O	2.74	2.77	2.29	2.63	2.49	2.48	2.44	2.62	2.62	2.71
Na_2O	1.54	1.74	1.14	1.37	1.32	1.35	1.27	1.42	1.43	1.43
TiO_2	0.80	0.84	0.72	0.78	0.80	0.79	0.67	0.78	0.68	0.70
Total	100.3	99.4	99.1	100.4	99.3	99.7	98.7	100.4	99.4	99.7
SG	2.459	2.452	2.445	2.432	2.464	2.454	2.432	2.467	--	2.445
n	1.517	1.514	1.513	1.511	1.517	1.514	1.509	1.518	1.515	1.513

Constituent	11	12	13	14	15	16	17	18	19	20
SiO_2	73.3	74.3	75.2	69.0	70.8	73.3	73.6	74.3	75.6	77.6
Al_2O_3	12.0	12.0	11.0	12.9	13.3	10.9	10.6	10.1	9.95	10.6
FeO	4.64	4.42	4.27	4.78	4.74	4.11	4.16	3.98	3.91	3.65
MgO	2.04	1.81	1.80	2.29	2.22	1.86	1.93	1.77	1.70	1.58
CaO	3.52	2.23	2.79	5.93	3.80	4.40	5.03	5.00	4.19	2.17
K_2O	2.74	2.39	2.71	2.34	2.43	2.40	2.37	2.35	2.39	2.23
Na_2O	1.51	1.10	1.35	1.12	1.26	1.20	1.23	1.19	1.16	1.08
TiO_2	0.71	0.73	0.65	0.74	0.77	0.64	0.57	0.59	0.54	0.60
Total	100.5	99.0	99.8	99.1	99.3	98.8	99.5	99.3	99.4	99.5
SG	--	2.410	2.398	2.483	2.455	2.442	2.439	2.429	2.417	2.390
n	1.508	1.504	1.500	1.522	1.514	1.512	1.512	1.508	1.506	1.499

TABLE 1.—Continued.

Constituent	21	22	23	24	25	26	27	28	29	30
SiO_2	69.2	70.3	71.7	73.1	76.1	78.9	70.9	71.4	72.3	74.9
Al_2O_3	12.9	12.5	13.1	12.8	10.9	10.0	10.8	12.9	10.8	10.1
FeO	5.26	4.72	4.90	4.73	4.44	4.08	4.42	4.65	4.24	3.90
MgO	2.42	2.28	2.10	2.04	1.65	1.49	2.03	2.12	1.82	1.80
CaO	5.79	5.81	4.05	3.12	2.40	1.89	5.91	3.51	5.10	3.97
K_2O	2.36	2.41	2.40	2.45	2.55	2.36	2.44	2.44	2.51	2.41
Na_2O	1.08	1.28	1.20	1.31	1.15	1.00	1.27	1.37	1.33	1.21
TiO_2	0.74	0.69	0.72	0.74	0.68	0.59	0.58	0.77	0.64	0.58
Total	99.8	100.0	100.2	100.3	99.9	100.3	98.4	99.2	98.7	98.9
SG	2.489	2.473	2.452	2.429	2.404	2.384	2.461	2.454	2.442	2.422
n	1.522	1.519	1.514	1.510	1.504	1.499	1.515	1.514	1.513	1.507

Constituent	31	32	33	34	35	36	37	38	39	40
SiO_2	76.0	77.3	68.9	70.1	72.0	74.2	76.3	78.3	69.5	70.6
Al_2O_3	10.1	9.48	13.8	13.4	12.9	12.0	10.9	10.3	14.5	14.1
FeO	3.76	3.55	5.10	4.91	4.74	4.52	4.42	3.83	5.04	4.92
MgO	1.64	1.46	2.35	2.26	2.21	1.94	1.70	1.31	2.41	2.28
CaO	3.31	3.10	5.19	4.18	4.05	3.06	3.00	1.57	3.97	3.59
K_2O	2.34	2.33	2.60	2.54	2.45	2.25	2.55	2.44	2.48	2.35
Na_2O	1.20	1.20	1.43	1.36	1.28	1.09	1.25	1.14	1.22	1.13
TiO_2	0.59	0.53	0.74	0.76	0.71	0.57	0.66	0.61	0.77	0.72
Total	98.9	99.0	100.1	99.5	100.3	99.6	100.8	99.5	99.9	99.7
SG	2.406	2.398	2.476	2.466	2.454	2.416	2.400	2.371	2.468	2.460
n	1.504	1.503	1.520	1.518	1.514	1.507	1.502	1.496	1.518	1.515

TABLE 1.—Continued.

Constituent	41	42	43	44	45	46	47	48	49	50
SiO_2	72.3	73.5	75.2	76.0	76.8	68.7	70.7	71.1	72.2	74.1
Al_2O_3	12.5	12.5	12.0	11.7	11.5	13.0	12.8	12.0	11.8	11.6
FeO	4.55	4.45	4.28	4.08	4.32	6.10	5.85	5.39	5.33	5.26
MgO	2.02	1.85	1.70	1.64	1.54	3.53	3.33	2.92	2.70	2.98
CaO	3.71	3.49	2.11	2.07	1.60	3.91	3.28	3.59	3.40	2.51
K_2O	2.49	2.41	2.52	2.32	2.55	2.28	2.16	2.37	2.48	2.08
Na_2O	1.26	1.25	1.13	1.09	1.10	1.29	0.97	1.18	1.16	0.91
TiO_2	0.71	0.67	0.69	0.67	0.65	0.79	0.72	0.65	0.64	0.65
Total	99.5	100.1	99.6	99.6	100.1	99.6	99.8	99.2	99.7	100.1
SG	2.446	2.434	2.399	2.391	2.377	2.489	2.466	2.446	2.437	2.420
n	1.513	1.510	1.501	1.500	1.498	1.522	1.519	1.513	1.513	1.507

Constituent	51	52	53	54	55	56	57	58	59	60
SiO_2	74.9	69.0	69.9	70.6	71.4	73.0	67.3	68.2	68.9	69.3
Al_2O_3	10.9	13.2	13.2	13.1	12.5	12.2	15.9	15.7	15.3	15.4
FeO	4.75	5.50	5.76	4.99	5.33	5.25	5.57	5.37	5.27	5.25
MgO	2.41	3.30	3.13	2.47	2.96	2.99	2.68	2.57	2.33	2.45
CaO	2.68	4.14	3.22	3.59	2.92	2.87	3.22	3.08	2.99	2.90
K_2O	2.37	2.33	2.52	2.66	2.37	2.16	2.78	2.56	2.61	2.55
Na_2O	1.11	1.17	1.26	1.41	1.21	1.10	1.38	1.30	1.13	1.38
TiO_2	0.64	0.75	0.72	0.74	0.66	0.66	0.85	0.83	0.83	0.82
Total	99.8	99.4	99.7	99.6	99.4	100.2	99.7	99.6	99.4	100.1
SG	2.415	2.493	2.477	2.460	2.445	2.425	--	--	--	--
n	1.506	1.523	1.520	1.515	1.512	1.506	1.519	1.518	1.518	1.518

[a] All Fe as FeO.

70.9%–77.3%, similar to but somewhat less extensive than that for Durrie. Other components are comparable for those recorded for australites of similar SiO_2 content from Charlotte Waters and Durrie; in particular, the low-SiO_2 (<75%) australites from Macumba also show relatively high CaO (except for analysis 28).

PINE DAM.—Australites from Pine Dam, near Lake Torrens, show a specific-gravity range of 2.368–2.476, with peaks at 2.395 and 2.462 (Chalmers et al., 1976, tbl. 7). Six specimens, covering practically the full specific-gravity range, were analyzed (Table 1, columns 33–38). These analyses resemble those of similar SiO_2 content from Macumba, except that they are generally lower in CaO and higher in Al_2O_3.

MANNAHILL.—A collection of 89 australites from Mannahill was available for study. The specific-gravity range was 2.377 to 2.468, with a single peak at 2.419 in the distribution curve. This single peak at 2.40 to 2.42 is characteristic of collections from southeast South Australia and Victoria (Chalmers et al., 1976, tbl. 7). Seven specimens, covering the whole specific-gravity range, were analyzed (Table 1, columns 39–45). The analyses are comparable to those of Pine Dam australites with similar SiO_2 contents, although the Mannahill australites appear to have somewhat lower CaO contents.

FROME DOWNS.—A small collection (14 specimens) from Frome Downs station was acquired after the main part of this manuscript was completed. It is of considerable significance because of its approximately equidistant position between three locations (see Figure 1) with distinctly different australite populations, as indicated by specific gravity ranges and peaks (in parentheses): Mannahill (2.377–2.468, peak 2.419); Pine Dam (2.368–2.476, peaks 2.395, 2.462); Pindera (2.270–2.470, peak 2.450). The 14 Frome Downs australites have a specific gravity range of 2.380–2.429; no peak is evident, probably because of the small number of specimens, but the mean is 2.402. The Frome Downs collection clearly differs in specific gravity range and therefore in chemical composition from the Pine Dam and other collections in the Lake Torrens region to the west, and to the nearest location in the east, the Pindera area in New South Wales. A search of the region between Frome Downs and Pindera in August 1978 found no australite occurrence, although the terrain appeared favorable in many places. I conclude therefore that a significant chemical hiatus exists between these two locations. The Frome Downs occurrence seems to be the farthest north location for the low specific gravity Victoria-type australites unmixed with the higher specific gravity population, as around Lake Torrens and Lake Eyre.

LAKE WILSON.—This location, in the far northwest of South Australia, is known to carry australites of unusual composition. This was first recognized by Taylor and Sachs (1964:250), who analyzed one specimen and commented: "Sample No. 26 is unusual in possessing, in addition to the high value for nickel, the highest amounts of Mg, Fe, Co and Cr. The concentrations of the other elements are normal for the silica content (69.8 per cent)." Chapman et al. (1964) published a specific-gravity distribution diagram for Lake Wilson australites and noted that it was different from those of all other australite locations, with a more extensive specific-gravity range (2.395–2.505) and the highest peak (2.465).

Six specimens from Lake Wilson were analyzed (Table 1, columns 46–51), ranging from 2.415 to 2.489 in specific gravity and 74.9% to 68.7% in SiO_2 content. The data plotted in Figure 2 show that the Lake Wilson australites are uniformly higher in FeO and MgO than other australites of similar SiO_2 content. It was on this basis that Chapman and Scheiber (1969) established their HMg group of tektites; they recognized tektites belonging to this group not only in Australia but in Indonesia and at one locality in the Philippines. Chapman and Scheiber (1969) and Chapman (1971) published analyses of HMg australites from the following locations: Lake Margaretha (25°26′S, 125°14′E), West Serpentine Lakes (28°50′S, 128°35′E), near Young Range (25°06′S, 125°15′E), and Giles Creek (25°02′S, 128°18′E). These locations, together with the Mt. Davies collection mentioned below, define a triangular area straddling the South Australia–Western Australia border and extending over about 4° of both latitude and longitude. Hughes, with australites of "normal" composition, is about 140 miles south of West Serpentine Lakes, and Earaheedy, also with australites of normal composition, is about 150 miles west of Young Range; at Charlotte Waters, 300 miles to the east of Lake Wilson, the australites are also of normal composition except for relatively high CaO. The HMg

tektites thus occupy a defined geographic field, and although its limits remain to be precisely defined, they do not appear to overlap into surrounding areas of normal compositions.

Mt. Davies.—Mt. Davies is a geographical area centered around the Western Australia–South Australia–Northern Territory conjunction, about 40 miles west of Lake Wilson. Many thousands of australites have been collected from this area by aborigines and sold through the Department of Aboriginal Affairs, Adelaide. I obtained a small collection of 12 specimens directly from the local aborigines in 1965. Five of these were analyzed (Table 1, columns 52–56), and these analyses are very similar to those of the Lake Wilson australites of comparable SiO_2 content.

Pindera.—This is an isolated location in northwestern New South Wales, rather far removed from other areas of tektite concentration. Australites from this location have a unique appearance, with pitted surfaces resulting from the presence of small internal bubbles, a feature rare in australites from other localities. As a result, specific gravities of Pindera australites show a wide range (2.270–2.470 in a collection of 155 specimens) according to Chapman (in Chalmers et al., 1976, tbl. 6). This range is, however, almost entirely a function of bubble content,

since the ten specimens I analyzed all had very similar compositions, with SiO_2 ranging from 67.3% to 69.3% and Al_2O_3 ranging from 15.9% to 15.3%; four of these analyses, covering the full range of composition, are given in Table 1 (columns 57–60). Chapman and Scheiber (1969) report a similar composition for the Pindera specimen they analyzed.

Chapman and Scheiber note that their Pindera specimen and two other analyzed australites from New South Wales have uniquely high Al_2O_3 contents ($>14.9\%$), and this may be related to their unusually low SiO_2 contents (66.8%–68.5%). Figure 2 shows that apart from the low SiO_2 and high Al_2O_3 contents, the only other distinguishing feature in the analyzed Pindera australites is a relatively low CaO content. Nevertheless, it is possible that the New South Wales portion of the strewnfield does have a distinctive chemical composition; more analyses from additional locations are needed to establish this.

Discussion of Analyses

Most of the available analyses of australites have been published by Taylor (1962), Taylor and Sachs (1964), Chapman and Scheiber (1969), and Chapman (1971). Table 2 compares the results ob-

Table 2.—Compositional range, in weight percent, of australites; (source of data by column: 1, this paper, 60 analyses; 2, Taylor (1962) and Taylor and Sachs (1964), 32 analyses for SiO_2, Al_2O_3, FeO and 43 analyses for other components; 3, Chapman and Scheiber (1969) and Chapman (1971), 23 analyses)

Constituent	1	2	3
SiO_2	67.3 – 78.9	69.6 – 78.7	66.9 – 79.7
Al_2O_3	9.5 – 15.9	9.35 – 14.0	9.9 – 16.1
FeO [a]	3.55 – 6.10	3.83 – 5.38	3.57 – 6.06
MgO	1.31 – 3.53	1.49 – 2.49	1.31 – 4.28
CaO	1.57 – 5.93	2.13 – 5.09	1.72 – 5.62
K_2O	2.08 – 2.78	2.07 – 2.57	2.00 – 2.62
Na_2O	0.91 – 1.74	1.05 – 1.52	1.00 – 1.58
TiO_2	0.59 – 0.85	0.55 – 0.90	0.48 – 0.93

[a] All Fe as FeO.

tained by these investigators with those reported in Table 1. Table 2 excludes the HNa/K austra-lites of Chapman and Scheiber; these are very rare (Chapman and Scheiber found nine during the specific-gravity screening of approximately 47,000 tektites), and their identification as tektites has been questioned by Chalmers et al. (1967:37–38).

The comparison shows that the ranges of composition for the major components are very similar in each of the three groups. It can therefore be stated with some confidence that the compositional range of australites is now well established, and specimens falling outside this range are unlikely to be found.

The extent of the variation in major components is clearly demonstrated in Figure 2, in which the percentages of the individual components in each analysis are plotted against the SiO_2 percentage of that analysis. The first impression is the limited scatter within each component. This is especially characteristic for FeO, MgO, K_2O, and Na_2O (note that the vertical scale for K_2O and Na_2O is twice that for the other components, which tends to emphasize the scatter for the alkalies). Another obvious feature is the general decrease in Al_2O_3, FeO, MgO, and CaO with increasing SiO_2 content; however, this trend is not marked for Na_2O and may be absent in K_2O.

Taylor and Sachs (1964) computed correlation coefficients for their 32 analyses for which SiO_2 determinations were available. The correlation coefficients with SiO_2 were Al, −0.907; Mg, −0.955; Ti, −0.842; Fe, −0.817; Na, −0.805; K, −0.764; Ca, −0.221. For all these elements except Ca, the negative correlation is significant at less than 0.01 per cent.

Chapman has used his analyses of Australasian tektites to establish a chemical classification of these objects. Within the Australian strewnfield he has distinguished the following classes: normal, HCa, HMg, HAl, HNa/K (not considered here). His definitions of these classes are not unequivocal; in fact they vary somewhat from time to time, as the following quotations show.

Normal: The predominant type in Western Australia and the Philippines, with a restricted range of CaO and MgO respectively about 3.1% and 2.2% (Compston and Chapman, 1969:1024).

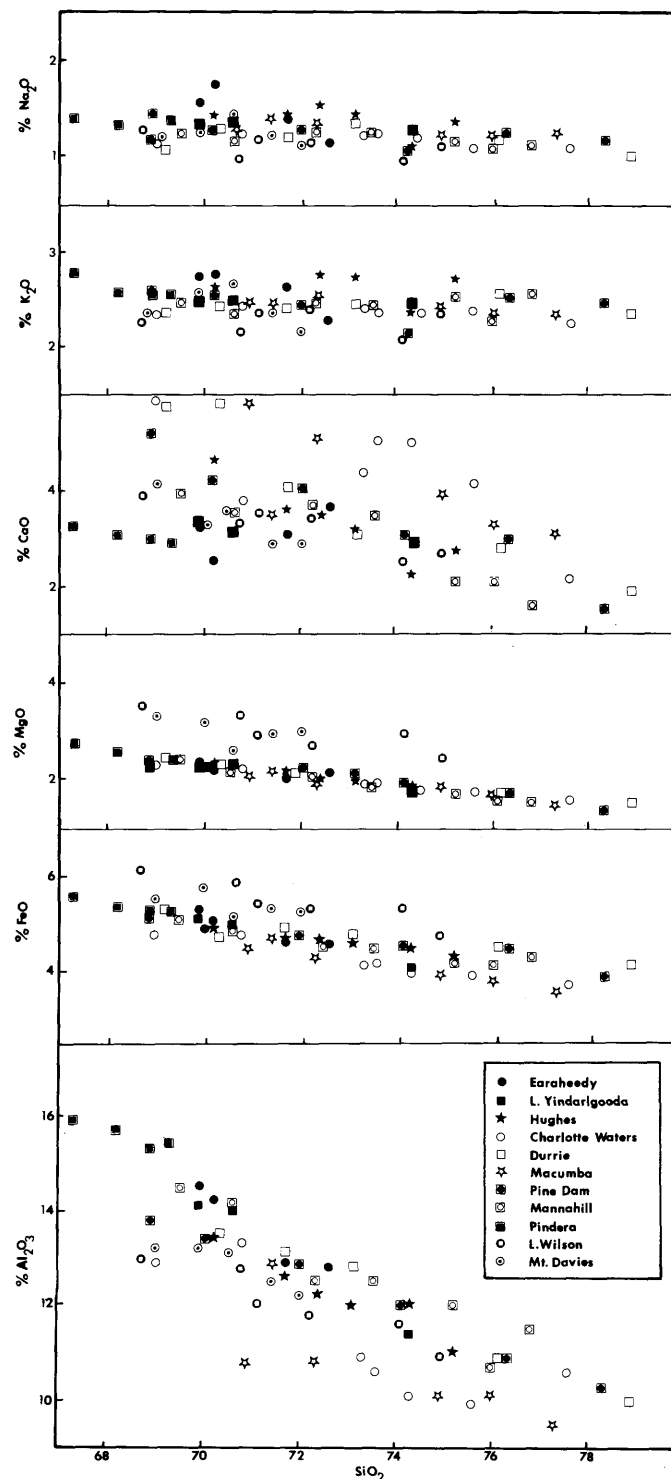SiO_2 70% to 73%, alkalies higher than in, for example, the

FIGURE 2.—Plot of SiO_2 versus Na_2O, K_2O, CaO, MgO, FeO, and Al_2O_3, all in weight percent, for australite analyses in Table 1.

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HCa group (Chapman and Scheiber, 1969:6761).

CaO > MgO and Ni ≤ 41 ppm (Chapman, 1971:6313).

HCa: CaO varying from about 2.0 to 10.0% and MgO from 1.3 to 2.5% (Compston and Chapman, 1969:1024).

FeO 3.5–4.9%, Ni 14–42, Cr 56–110, Co 7–18 ppm, Cr/Ni 2.0–4.9 (Chapman and Scheiber, 1969:6741).

LSG–HCa streak . . . stretching from Tasmania to Central Australia . . . low modal SG (≤ 2.41); Na₂O < 1.25% (Chapman, 1971:6312).

Nearly HCa: CaO near lower boundary and with Na₂O > 1.25% (Chapman, 1971:6313).

HMg: MgO varying continuously from 1.5 to 8.0% and comparatively restricted variation in CaO (Compston and Chapman, 1969:1024).

MgO > 3.4%, Ni ≥ 210 ppm, Cr ≥ 210 ppm (Chapman, 1971:6312).

FeO 3.9–8.6%, Ni 91–390 ppm, Cr 100–460 ppm, Co 14–63 ppm (Chapman & Scheiber, 1969:6741).

Nearly HMg: MgO > 2.8%, Ni ≥ 200 ppm, Cr ≥ 190 ppm (Chapman, 1971:6312).

HAl: Al₂O₃ ≥ 14.9% (Chapman, 1971:6312).

Some comments may be made on these criteria. The criterion CaO>MgO given for normal australites applies to all australite analyses except for a few in the HMg class. The criterion CaO varying from about 2.0% to 10.0% and MgO from 1.3% to 2.5% for the HCa class applies to practically all australites; reference to Table 1 and Figure 2 shows only three australites with less than 2% CaO, and the only australites with MgO>2.5 belong to the HMg class. Australites generally contain less than 6% CaO; tektites with CaO greater than 6% seem to be limited to the Philippines.

Chapman (1971) presented a map (his fig. 2) showing the distribution of his chemical classes of australites. Practically all his normal australites are confined to Western Australia. The HMg australites define a streak extending northwest from the Lake Wilson–Mt. Davies region. The HCa australites define a streak from Victoria through South Australia to Charlotte Waters and Henbury. The HAl australites are found only in New South Wales, with the exception of one from Tasmania.

Figure 2 provides the opportunity to try to fit the analyses of this investigation into Chapman's classification scheme. The only class that can be unequivocally recognized is the HMg class; the analyses of australites from the Lake Wilson and Mt. Davies regions are consistently higher in MgO (and FeO) than other australites of similar SiO₂ content. The utility of an HAl group is doubtful; few are

known, and their Al₂O₃ content (≥14.9%) being coupled with low SiO₂ content puts them on the same Al₂O₃–SiO₂ trend as other australites (Figure 2). Figure 2 shows that some australites, specifically most of those from Charlotte Waters, Durrie, and Macumba, are significantly higher in CaO than the remainder. Thus an HCa class can possibly be recognized, but as pointed out above the criteria given for this class by Compston and Chapman (1969) apply to practically all analyzed australites except those of the HMg class.

Robert Fudali has demonstrated to me that a plot (Figure 3) of Al₂O₃ versus CaO values from the analyses in Table 1 shows a well-defined hiatus. All the values plotting above the hiatus are of australites from Charlotte Waters, Durrie, and Macumba. This pattern defines a coherent and restricted geographical region extending from north-central South Australia to adjoining southwest Queensland. Not all analyses from these locations, however, yield values that plot above the hiatus; two of seven from Charlotte Waters, four of six from Durrie, and one of six from Macumba plot below it. The values which plot above the hiatus probably all represent HCa australites according to Chapman, but many of those plotting below the hiatus also belong to this class. The values from five analyses of HCa australites published by Chapman and Scheiber (1969) have been plotted on Figure 3; three (all from the Charlotte Waters area) plot above the hiatus, one (from Victoria) plots below it, and one (from near Macumba) plots just within its lower limit.

One purpose of this research was to see whether australites from a specific locality showed a distinctive range of chemical composition. Table 1 and Figure 2 show that this is not generally the case, although some regional trends can be distinguished. The Lake Wilson–Mt. Davies group in the far northwest of South Australia are uniformly somewhat higher in MgO and FeO than other australites of similar SiO₂ contents, but for the other major components they fall within the range of most australites. The Pindera australites have uniquely high Al₂O₃ contents. Some but by no means all the australites from localities extending from Mannahill to Charlotte Waters in South Australia and Durrie in Queensland have high CaO (>4%); some of these also have lower Al₂O₃ contents than most
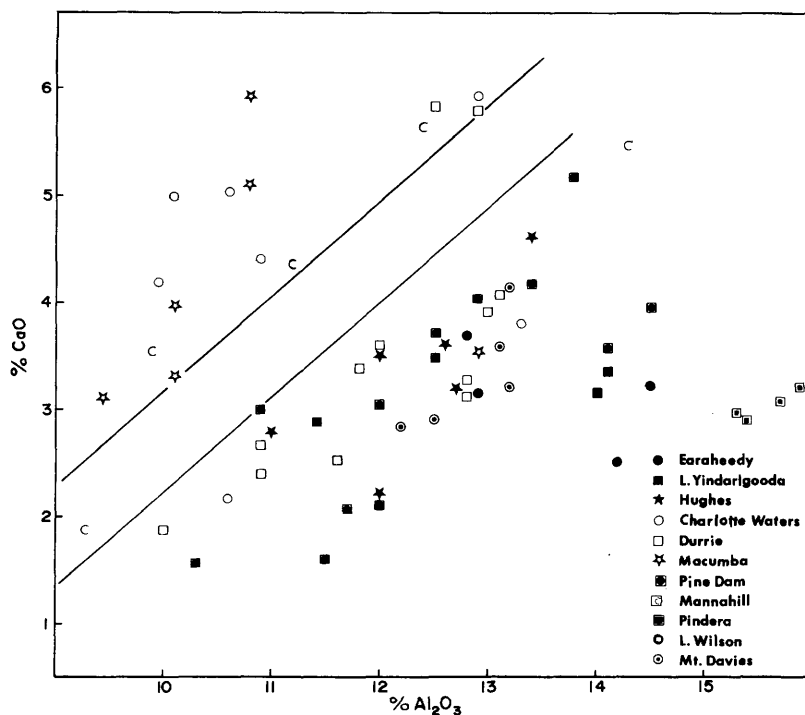
FIGURE 3.—Plot of Al_2O_3 versus CaO, both in weight percent, for the analysis in Table 1 (c = HCa australites by Chapman and Scheiber (1969); diagonal lines define locality-related hiatus).

other australites. Australites from Western Australia and adjacent parts of the Nullarbor Plain tend to be slightly higher in K_2O and Na_2O than australites from other localities.

These results may be compared with the observations of Taylor and Sachs (1964:241). They detected regional differences between average australite compositions from localities near Kalgoorlie, Charlotte Waters, and in Victoria. They commented:

Compared to the Charlotte Waters group (II), the Kalgoorlie group (I) have a distinctly lower average for SiO_2 and are higher in those elements which show significant negative correlations with SiO_2 ... The Victorian group (III), although containing low values for the alkali elements, are generally intermediate in average composition. It thus appears that two distinct groups, at Kalgoorlie and Charlotte Waters, may be distinguished. Perhaps a mixture of these two types is found in Victoria.

My results are consistent with these comments. I did not analyze any Victorian australites, but many of my analyses of Pine Dam and Mannahill australites can be matched with published analyses of Victorian australites.

Australites and Microtektites

In 1967 Glass announced the discovery of microscopic (<1 mm diameter) glassy objects in deep-sea sediments from south and west of Australia: "On the basis of their geographical distribution, appearance, physical properties, and age of deposition, it is concluded that the glassy objects discussed in this report are microtektites, and that they constitute a portion of the Australasian strewn field which extends from Thailand to Tasmania" (Glass, 1967: 374). Not all tektite researchers have accepted the identity of microtektites with tektites; a summary of opposing viewpoints is provided by Chalmers et al. (1976:16).

Cassidy et al. (1969) published microprobe analyses of 60 microtektites and Glass (1972b) reported 44 analyses of a particular variety which he calls "bottle green microtektites." Cassidy et al. and Glass both conclude that their chemical analyses support the identification of these microtektites with Australian tektites. A rigorous comparison, however, of their analyses of microtektites with the

analyses of australites reveals many inconsistencies and may negate their conclusion.

The range of composition of microtektites is much wider than that for australites. For the principal component, SiO_2, the range for microtektites is 48.1% to 77.0%; of the 104 microtektite analyses from the Australian region, only 46, or less than half, fall within the SiO_2 range of australites (66%–79%). Cassidy et al. claimed that the "normal" microtektites (excluding the bottle green ones) showed concordant compositional trends with the Australasian tektites and served to extend the known composition range of tektites. Glass claimed that the bottle green microtektites overlap and extend all major-element trends found for the HMg tektites of Chapman and Scheiber (1969). Even if this claim were valid, the non-existence of australites with less than 66% SiO_2 renders it of little relevance.

When the data, however, for microtektites within the australite composition range of 66%–79% SiO_2 are studied closely, the correspondence between

australite and microtektite compositions can only be described as poor. Discordances are particularly prominent for Na_2O (most microtektites have less than 1%, most australites more than this amount); for K_2O, where only four microtektites fall within the field for australites and two of these are discordant with australites in other components; and for MgO, where practically all the bottle green microtektites have much higher contents than the HMg australites with which they are claimed to correspond. The chemical discordance between microtektites and australites is clearly displayed in Figure 4, which plots FeO versus MgO percentage for australites and microtektites. The australites show a very limited range in FeO and MgO contents and an extremely strong positive correlation between these two components. Note the contrast in the microtektites, which show a very wide range in FeO and MgO contents, and essentially no correlation between these components.

The extreme scatter of microtektite analyses, compared to the relatively restricted composition of australites, argues against rather than for a common source material. If one is to claim that microtektites and australites are cogenetic, the evidence must be from sources other than chemical composition.

FIGURE 4.—Plot of FeO versus MgO, both in weight percent, for australites (Table 1) and microtektites (Cassidy et al., 1969; Glass, 1972b) (trapezoid defines scatter of australites).

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The Pyroxene-Plagioclase Achondrites

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ABSTRACT

The pyroxene-plagioclase achondrites (also known as eucrites and howardites, as calcium-rich achondrites, and as basaltic achondrites) form the largest class of achondrite meteorites, and are of special interest because they are the closest meteoritic analogs of lunar rocks. In this paper we provide chemical analyses for 20 of them, and have selected analyses of 31 others from the literature. Brief accounts are provided for them, together with microprobe analyses of their principal minerals, pyroxene and plagioclase. We have adopted the structural distinction between eucrites (unbrecciated and monomict breccias) and howardites (polymict breccias). Shergotty and Zagami, although eucrites by this difinition, are distinct in their chemical and mineralogical composition, and the term shergottite should be retained for them. A large number of eucrites (which we call main-group) have almost identical chemical and mineralogical composition; they are silica-oversaturated, having excess SiO_2 in both the mode and the norm. Howardites are not mechanical mixtures of eucrites and diogenites; their individual mineral and rock clasts belong to a differentiation sequence that is compositionally more extensive than the eucrites and diogenites.

Introduction

The pyroxene-plagioclase achondrites are a group of meteorites consisting essentially of pyroxene and calcic plagioclase, the pyroxene usually dominant over plagioclase. They compose a majority of the achondrites, totalling over 50 of approximately 90 known. Prior (1920) grouped them together with Angra dos Reis and the nakhlites as calcium-rich

achondrites. Urey and Craig (1953) preferred to call the calcium-rich achondrites the basaltic-type achondrites (now generally shortened to basaltic achondrites), to emphasize their general similarity to terrestrial basalts (although the latter are clearly different in the amount and composition of the plagioclase).

Prior recognized three classes of pyroxene-plagioclase achondrites: (1) eucrites or clinohypersthene-anorthite achondrites; (2) shergottites or clinohypersthene-maskelynite achondrites; and (3) howardites or hypersthene-clinohypersthene-anorthite achondrites. (Clinohypersthene in Prior's usage is the mineral now known as pigeonite.) In the current British Museum catalog (Hutchison et al., 1977) the eucrites are defined as plagioclase-pigeonite achondrites and the howardites as plagioclase-hypersthene achondrites (the two shergottites, Shergotty and Zagami are included with the eucrites).

Thus the distinction between eucrites and howardites was originally made on the basis of the nature of the pyroxene, the dominant pyroxene being pigeonite in eucrites and orthopyroxene (hypersthene) in howardites. Mason (1962) noted that this distinction could be correlated with the bulk chemistry of these meteorites, most clearly with the CaO content and the $FeO/(FeO+MgO)$ molecular percentage; he suggested that a dividing line could be drawn at $FeO/(FeO+MgO) = 50$, eucrites showing a higher ratio, howardites a lower one.

Lacroix (1926) felt there were insufficient grounds for separating eucrites and howardites, but that if such separation were desired, it would be better made on structural grounds, howardites being classed as brecciated eucrites. Wahl (1952) introduced the terms monomict and polymict breccias, and classed the eucrites as unbrecciated or monomict, howardites as polymict pyroxene-plagioclase

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achondrites. This distinction was adopted by Duke and Silver (1967) and several other researchers. Bunch (1975) provided a comprehensive account of the large variety of rock and mineral clasts found in the polymict pyroxene-plagioclase achondrites, and clearly demonstrated the desirability of distinguishing these meteorites as howardites.

It is noteworthy that either the structural or the mineralogical criterion is usually sufficient to classify unambiguously a pyroxene-plagioclase achondrite as a howardite or a eucrite, since meteorites with dominant orthopyroxene are also polymict breccias (except Binda), and most monomict breccias have pigeonite as the dominant pyroxene (polymict breccias with dominant pigeonite are Macibini, Bialystok and Nobleborough). In using the terms howardite and eucrite, however, it is desirable to state in what sense these terms are used; in this paper we use them in the structural sense. We also distinguish Shergotty and Zagami from the eucrites on account of their distinctive chemical and mineralogical composition.

In discussing the eucrites and howardites, frequent reference will be made to the diogenites (also known as hypersthene achondrites). The diogenites, although classed by Prior as calcium-poor achondrites, occupy one end of a spectrum of chemical and mineralogical compositions extending through howardites to eucrites. Prior did not specify a limiting value of CaO between the calcium-poor and calcium-rich achondrites; currently the most calcium-rich diogenite is Garland with 2.60% CaO (Fredriksson et al., 1976), and the most calcium-poor howardite is Yamato-7307 (also known as Yamato(1) with 3.83% CaO (Wänke et al., 1977). The amounts of the other major components are equally close. Nevertheless, these two meteorites are easily differentiated both macroscopically and microscopically, Garland being an aggregate of pale-green orthopyroxene clasts with only trace amounts of other minerals, whereas Yamato-7307, while containing a large amount of pyroxene similar in composition to that in Garland, also has a considerable eucritic component (pigeonite + plagioclase). One characteristic of howardites is that they frequently contain clasts of diogenite composition. A close relationship, therefore, exists between these two classes, which will be further discussed later in this paper.

Interest in the pyroxene-plagioclase achondrites

has increased greatly in recent years, largely because they are the closest analogs to lunar rocks. Indeed, Duke and Silver (1967) presented arguments suggesting that the eucrites, howardites, and mesosiderites were actually lunar rocks. The results of the Apollo missions have negated this suggestion, and therefore established that these meteorites prove the previous existence of at least one other body in the Solar System with analogous chemical and mineralogical composition (and presumably similar evolutionary history) to the moon. The nature and composition of this body ("eucrite parent body") has been the subject of intensive research (see, for example, Dreibus et al., 1977; Consolmagno and Drake, 1977; Allègre et al., 1977; Stolper, 1977; Anders, 1977).

In view of this great interest in the pyroxene-plagioclase achondrites, we have collected the published major-element analyses of these meteorites and supplemented them with analyses of as many previously unanalysed meteorites as possible. Where published analyses are either incomplete or show inconsistencies with the mineralogical composition we have attempted to rectify this. Some of the new analyses (by E. J.) are by classical wet-chemical techniques; where only small samples were available the material was fused with lithium tetraborate and the resulting glasses analysed with the electron microprobe (by J. N.).

Results

The analyses are presented in Table 1. In this tabulation K_2O and P_2O_5 are omitted (recent analyses show that K_2O is consistently below 0.05% and P_2O_5 is usually less than 0.1%); free nickel-iron is also omitted, since it is a rare and erratically distributed accessory and is seldom determined; FeS, if determined, is given in the table key.

The analyses are arranged in order of increasing FeO/(FeO+MgO) mole percentage. This is a

useful factor in distinguishing eucrites and howardites in the chemical sense (howardites have $FeO/(FeO+MgO)$ 30–45, eucrites 40–69, there being a slight overlap). The ratio also correlates positively with CaO and Al_2O_3, and negatively with MgO. Other parameters derived from the analytical data are the composition and amount of normative plagioclase, the composition and amount of normative pyroxene, and the amount of normative olivine or silica. From a consideration of texture the meteorites are classified as unbrecciated, monomict breccias, and polymict breccias; if texture is used as the discriminant factor between eucrites and howardites, then unbrecciated meteorites and monomict breccias are eucrites, while polymict breccias are howardites.

Notes on the individual meteorites (bearing the analysis numbers used in Table 1) follow.

1. YAMATO-7307.—This meteorite, also known as Yamato(1), was collected by the Japanese Antarctic Expedition in 1973, and is of special interest since it has the lowest $FeO/(FeO+MgO)$ mole percentage of any of these meteorites. As such, it is compositionally very similar to the diogenites. The diogenites, however, are essentially monomict breccias (a small eucritic component has been recognized in a few), with uniform pyroxene composition (Fs 25–27). Sections of Yamato–7307 which we have examined show that it is a polymict breccia, with a wide range in pyroxene composition (Fs 19–49); two grains of olivine were seen (Fa 17, 37), and a diogenite enclave consisting essentially of pyroxene with uniform composition (Fs 27).

2. MÄSSING.—The analysis shows that this meteorite is very similar in composition to Yamato-7307; an incomplete analysis by Fukuoka et al. (1977) confirms this. It is a polymict breccia with a wide range of pyroxene compositions (Fs 22–46); plagioclase also shows a considerable range in composition (Ab 4–21). It should be mentioned that specimens of a chondrite mislabelled as Mässing have been distributed (the specimens in the Museum d'Histoire Naturelle, Paris, and Eidgenössische Technische Hochschule, Zurich are such); the analytical data on Mässing A reported by Schmitt et al. (1972) are probably of this mislabelled material.

3. CHAVES.—Thin sections of this meteorite show that it is a typical polymict breccia. The groundmass consists largely of comminuted orthopyroxene enclosing larger shocked clasts of the same mineral;

eucrite enclaves (unbrecciated, with ophitic texture) are not uncommon, and one fragment of diogenite was seen. Jérémine (1954) has provided a thorough petrographic description of this meteorite; she noted the presence of accessory tridymite and quartz, which we have confirmed with the microprobe (note the 0.5% of free SiO_2 in the norm). Our microprobe analyses show that the pyroxene consists largely of orthopyroxene, with lesser amounts of pigeonite; the Fs mole percent ranges from 20 to 51. Plagioclase also shows a range of composition, Ab 9–24.

4. FRANKFORT.—This meteorite has been described by Mason and Wiik (1966a). It is a polymict breccia, with pyroxene clasts (mainly orthopyroxene, some pigeonite) in a comminuted groundmass; one small eucrite enclave was observed. Our microprobe analyses show pyroxene compositions ranging from Fs 24 to Fs 39; similar results were reported by Takeda, Miyamoto, Ishii, and Reid (1976).

5. ZMENJ.—Thin sections show a typical polymict breccia, consisting largely of clasts of hypersthene (major) and pigeonite (minor) in a comminuted groundmass. Our microprobe analyses show pyroxene compositions ranging from Fs 23 to Fs 44, and plagioclase ranging from Ab 4 to Ab 10 (normative plagioclase is Ab 13, which suggests that the Na_2O in the analysis may be a little too high). Desnoyers and Jérome (1973) analysed a number of grains of olivine in Zmenj, and found compositions ranging from Fa 15 to Fa 39.

6. BINDA.—This meteorite, originally classified as a howardite because the pyroxene is largely hypersthene, was reclassified by Duke and Silver (1967) as a eucrite because it is a monomict breccia. The pyroxene in Binda has been described by Takeda and Ishii (1975); they comment (page 500):

The bulk composition of low-Ca pigeonite $Ca_{6.9}Mg_{62.2}Fe_{30.9}$ suggests the crystallization temperature is above 1110°C. The temperature where augite blebs $Ca_{44.7}Mg_{42.4}Fe_{12.9}$ developed in the host orthopyroxene $Ca_{2.4}Mg_{64.4}Fe_{33.2}$ is about 970°C. The Binda howardite contains the most magnesian pigeonite among the basaltic achondrites, and these pyroxenes are interpreted to be crystallized from magma and not the mechnical mixture of diogenite and eucrite pyroxenes. The Binda meteorite may be classified as the most Mg-rich and Ca-poor eucrite.

7. PAVLOVKA.—Thin sections show a polymict breccia largely of mineral grains (hypersthene with minor pigeonite and plagioclase), but small- to medium-sized eucrite enclaves are not uncommon; some plagioclase grains are unusually large, larger

than could be derived from common eucrites, suggesting a possible anorthositic parent. Our probe analyses indicate an unusually wide range of pyroxene compositions; orthopyroxene is dominant, with Fs ranging 14–36, with lesser amounts of pigeonite, Fs 36–55, and a few grains of ferrohedenbergite, averaging $Wo_{38}Fs_{47}En_{15}$; a single grain, $Wo_{19}Fs_{72}En_9$, possibly pyroxferroite, was analyzed. Plagioclase ranged Ab 7–13, average 9. Two grains of olivine, Fa 33, 35 were analyzed. Desnoyers and Jérome (1973) analyzed 15 grains of olivine in Pavlovka, with Fa ranging 36–49.

An incomplete analysis by Fukuoka et al. (1977) is very similar to that given in Table 1.

8. WASHOUGAL.—Jérome and Michel-Lévy (1972) describe this meteorite as a very heterogeneous polymict breccia. From the refractive indices, they give the range of composition of the pyroxenes as Fs 20–47. They describe several kinds of lithic clasts, among them eucritic fragments with an ophitic or subophitic texture, and a cm-sized dunite xenolith (olivine composition Fa 12.8).

9. BHOLGATI.—A thin section shows a breccia with numerous clasts of orthopyroxene up to 1 mm across, small less numerous clasts of pigeonite and plagioclase, and rare grains of chromite, in a fine-grained groundmass. Our microprobe analyses show a range of Fs 23–62 in orthopyroxene and pigeonite

KEY TO TABLE 1
Identification of Analyses by Columns

1. Yamoto-7307, also known as Yamoto(1); Wänke et al., 1977 (FeS = 0.30%).
2. Mässing; J. Nelen, analyst.
3. Chaves; McCarthy et al., 1972.
4. Frankfort; Mason and Wiik, 1966b (FeS = 0.69%).
5. Zmenj; Wiik, 1969 (FeS = 0.48%).
6. Binda; McCarthy et al., 1973.
7. Pavlovka; J. Nelen, analyst.
8. Washougal; Jérome and Michel-Lévy, 1972 (FeS = 0.99%).
9. Bholgati; E. Jarosewich, analyst.
10. Luotolax; Wiik, 1969 (FeS = 1.08%).
11. Yurtuk; J. Nelen, analyst.
12. Bununu; Mason, 1967a. (TiO₂, revised, 0.51%).
13. Medanitos; Symes and Hutchison, 1970.
14. Le Teilleul; J. Nelen, analyst.
15. Molteno, non-magnetic fraction; Frost, 1971.
16. Moama; Lovering, 1975.
17. Jodzie; J. Nelen, analyst.
18. Serra de Magé; E. Jarosewich, analyst.
19. Kapoeta; Mason and Wiik, 1966a (FeS = 0.98%).
20. Malvern; McCarthy et al., 1972.
21. Pomozdino; Kvasha and Dyakonova, 1972 (FeS = 2.79%).
22. Brient; Dyakonova and Kharitonova, 1961 (FeS = 0.55%).
23. Petersburg; E. Jarosewich, analyst (FeS = 0.74%).
24. Nagaria; J. Nelen, analyst.
25. Moore County; Hess and Henderson, 1949 (FeS = 0.82%).
26. Shergotty; Duke, 1968.
27. Macibini; McCarthy et al., 1973.
28. Bialystok; E. Jarosewich, analyst (FeS = 0.55%).
29. Yamoto-74450; Wänke et al., 1977 (FeS = 0.65%).
30. Ibitira; Wänke et al., 1974.
31. Jonzac; J. Nelen, analyst.
32. Sioux County; Duke and Silver, 1967 (FeS = 0.45%).
33. Allan Hills No. 5; E. Jarosewich, analyst (FeS = 0.27%).
34. Nobleborough; J. Nelen, analyst.
35. Chervony Kut; Zavaritskii and Kvasha, 1952 (FeS = 0.25%).
36. Cachari; McCarthy et al., 1973.
37. Kirbyville; J. Nelen, analyst.
38. Juvinas; Duke and Silver, 1967 (FeS = 0.53%).
39. Millbillillie; J. Nelen, analyst.
40. Mount Padbury enclave; J. Nelen, analyst.
42. Adalia; J. Nelen, analyst.
43. Palo Blanco Creek; J. Nelen, analyst.
44. Peramiho; Berwerth, 1903 (FeS = 0.80%).
45. Stannern; Von Engelhardt, 1963 (FeS = 0.72%).
46. Haraiya; E. Jarosewich, analyst (FeS = 0.27%).
47. Pasamonte; Duke and Silver, 1967 (FeS = 0.06%).
48. Bereba; McCarthy et al., 1973.
49. Emmaville; Mason, 1974.
50. Nuevo Laredo; Duke and Silver, 1967 (FeS = 0.21%).
51. Lakangaon; McCarthy et al., 1974, with Cr_2O_3 and Na_2O by J. Nelen.

Table 1.—Analytical data on pyroxene-plagioclase achondrites (a = mole percent FeO/(FeO+MgO); b = mole percent Ab in normative plagioclase; c = weight percent normative plagioclase; d = mole percent Wo, Fs in normative pyroxene; e = weight percent normative pyroxene; f = weight percent normative olivine (ol) or silica (q); g = texture (u = unbrecciated, m = monomict breccia, p = polymict breccia); key to identification of analyses by columns on facing page)

Constituent	1	2	3	4	5	6	7	8	9	10
SiO_2	50.82	51.1	51.79	49.48	50.47	50.41	49.9	50.22	49.35	50.42
TiO_2	0.23	0.31	0.37	0.46	0.46	0.23	0.29	0.32	0.41	0.64
Al_2O_3	4.27	4.1	6.84	5.10	6.97	6.95	6.0	6.70	8.30	9.03
Cr_2O_3	1.02	0.91	0.61	1.34	1.04	0.75	0.86	0.83	0.71	0.87
FeO	16.46	17.6	15.33	17.39	16.22	16.83	18.1	17.34	16.27	16.09
MnO	0.52	0.49	0.48	0.53	0.55	0.54	0.52	0.47	0.53	0.52
MgO	21.37	21.3	18.39	20.50	17.85	17.75	17.8	16.95	15.56	14.97
CaO	3.83	4.1	5.64	4.02	5.35	5.82	5.3	5.60	6.14	6.83
Na_2O	0.13	0.08	0.22	0.17	0.29	0.20	0.17	0.18	0.27	0.37
a	30.2	31.7	31.8	32.2	33.8	34.8	36.3	36.5	37.1	37.6
b	10	6	10	10	13	9	9	8	10	13
c	12	12	20	15	20	20	17	19	24	26
d	4,29	4,30	5,30	3,31	5,32	5,33	5,35	5,35	5,35	6,35
e	80	80	78	73	75	76	76	77	72	71
f	5.1 ol	6.4 ol	0.5 q	8.9 ol	1.8 ol	3.8 ol	4.6 ol	0.5 ol	0.2 ol	0.6 q
g	p	p	p	p	p	m	p	p	p	p

Constituent	11	12	13	14	15	16	17	18	19	20
SiO_2	49.0	48.67	47.74	50.1	47.54	48.58	48.3	46.69	48.47	49.15
TiO_2	0.54	0.11	0.03	0.42	0.41	0.22	0.48	0.11	0.37	0.49
Al_2O_3	9.1	8.87	15.09	7.4	8.83	13.74	7.9	20.89	9.46	9.96
Cr_2O_3	0.78	0.56	0.14	0.72	0.53	0.63	0.63	0.33	0.63	0.56
FeO	16.5	16.04	13.72	17.6	15.94	14.85	18.3	9.97	17.16	18.03
MnO	0.45	0.53	0.51	0.46	0.41	0.50	0.50	0.36	0.53	0.53
MgO	14.8	14.20	12.16	15.0	13.15	11.89	14.6	7.52	12.00	12.40
CaO	7.26	6.77	10.38	6.44	6.65	9.47	6.64	13.09	8.08	8.06
Na_2O	0.22	0.34	0.20	0.17	0.29	0.22	0.20	0.30	0.46	0.42
a	38.4	38.8	38.8	39.7	40.5	41.2	41.3	42.7	44.5	44.9
b	8	12	4	7	10	5	8	5	15	13
c	26	26	42	21	25	38	22	58	28	29
d	7,36	6,36	8,36	7,37	6,38	7,38	7,38	9,39	10,40	9,41
e	69	69	49	74	66	58	70	38	67	67
f	2.0 ol	0.5 ol	8.8 ol	1.9 q	1.1 q	2.4 ol	3.7 ol	2.1 ol	0.4 ol	2.3 ol
g	p	p	m	p	p	u	p	u	p	p

TABLE 1.—Continued.

Constituent	21	22	23	24	25	26	27	28	29	30
SiO_2	47.97	49.00	49.18	47.4	48.16	50.10	49.32	48.97	48.28	49.0
TiO_2	0.73	0.79	0.57	0.38	0.32	0.92	0.72	0.56	0.90	0.78
Al_2O_3	11.31	11.02	10.82	15.7	15.57	6.68	12.12	12.63	11.43	12.6
Cr_2O_3	0.10	0.59	0.56	0.51	0.44	0.18	0.42	0.72	0.40	0.36
FeO	14.61	17.02	17.00	15.0	15.02	18.66	18.31	17.83	18.03	18.1
MnO	0.53	0.58	0.52	0.40	0.31	0.50	0.54	0.58	0.53	0.50
MgO	9.96	11.27	11.24	8.97	8.41	9.40	8.37	7.88	7.58	7.1
CaO	10.76	8.63	8.49	11.0	11.08	10.03	9.97	9.72	9.95	10.9
Na_2O	0.41	0.24	0.35	0.40	0.45	1.28	0.48	0.32	0.51	0.19
a	45.1	45.9	45.9	48.4	50.0	52.7	55.1	56.0	57.2	58.8
b	11	7	10	8	9	48	12	8	14	5
c	32	31	31	44	44	23	35	36	33	35
d	16,38	9,42	9,41	10,44	11,45	21,42	13,48	11,50	14,49	15,50
e	62	64	65	50	54	72	62	58	60	59
f	0.9 q	1.4 q	1.3 q	3.8 ol	0.04 ol	0.2 ol	1.6 q	3.1 q	2.4 q	3.6 q
g	m	p	p	u	u	u	p	p	m ?	u

Constituent	31	31	33	34	35	36	37	38	39	40
SiO_2	50.7	48.29	48.92	50.0	48.80	48.26	49.8	49.32	52.0	48.0
TiO_2	0.98	0.60	0.73	0.78	0.71	0.63	0.67	0.68	0.68	0.55
Al_2O_3	11.7	12.84	12.22	12.5	13.44	12.85	11.9	12.64	12.8	13.1
Cr_2O_3	0.33	0.31	0.39	0.40	0.21	0.32	0.40	0.30	0.33	0.39
FeO	17.6	18.25	17.56	18.5	18.47	19.10	18.7	18.49	18.3	19.0
MnO	0.47	0.53	0.56	0.46	0.63	0.59	0.54	0.53	0.61	0.44
MgO	6.9	7.08	6.74	7.1	6.98	7.14	6.96	6.83	6.76	7.0
CaO	10.4	10.39	9.63	10.0	11.48	10.25	10.0	10.32	10.2	10.3
Na_2O	0.38	0.42	0.43	0.46	0.52	0.51	0.45	0.42	0.36	0.32
a	58.9	59.2	59.4	59.4	59.8	60.1	60.2	60.2	60.3	60.4
b	10	10	11	11	12	12	12	10	9	8
c	33	37	35	36	39	37	34	36	36	37
d	15,50	13,51	13,52	13,52	16,50	13,52	14,52	14,52	13,52	12,53
e	57	59	55	58	61	60	59	58	57	59
f	6.3 q	2.9 q	4.8 q	4.0 q	0.3 q	0.7 q	4.1 q	3.3 q	6.5 q	1.6 q
g	m	m	m?	p	u	m	m	m	m	u

NUMBER 22

TABLE 1.—Continued.

Constituent	41	42	43	44	45	46	47	48	49	50	51
SiO_2	49.5	50.1	48.7	49.32	49.33	48.30	48.59	49.13	52.6	49.46	49.03
TiO_2	0.67	0.78	0.36	0.42	0.96	0.57	0.65	0.70	0.66	0.95	0.85
Al_2O_3	12.8	11.8	12.4	11.24	12.34	11.92	12.70	12.75	12.2	11.78	11.54
Cr_2O_3	0.32	0.39	0.28		0.28	0.33	0.33	0.32	0.36	0.29	0.35
FeO	18.3	19.0	20.4	19.99	17.92	19.95	19.58	19.83	18.5	20.10	22.81
MnO	0.57	0.51	0.63		0.50	0.43	0.56	0.55		0.56	0.60
MgO	6.70	6.91	7.41	7.15	6.36	6.96	6.77	6.80	6.12	5.46	5.87
CaO	10.4	10.3	9.44	10.84	10.58	9.67	10.25	10.48	10.2	10.40	10.27
Na_2O	0.36	0.41	0.31	0.40	0.60	0.37	0.45	0.47	0.51	0.57	0.49
a	60.6	60.7	60.8	61.0	61.3	61.7	61.8	62.C	62.8	67.4	68.6
b	9	11	8	11	15	9	11	11	13	15	13
c	36	34	35	32	39	34	36	37	35	34	33
d	14,52	15,52	10,55	16,51	16,51	12,54	13,54	14,54	15,54	16,57	14,59
e	58	60	62	64	54	61	60	61	57	59	65
f	3.9 q	4.2 q	1.5 q	2.2 q	3.8 q	2.3 q	1.6 q	1.6 q	7.6 q*	4.0 q	1.6 q
g	m	u	m	m	m	m	m	m	m	m	m

compositions; plagioclase Ab 5–17, average 10; one grain of augite, $Wo_{44}Fs_{26}En_{30}$; one grain of olivine, Fa 31; and one grain of a silica polymorph, probably tridymite.

10. LUOTOLAX.—Thin sections show a polymict breccia mostly of individual mineral grains (hypersthene, pigeonite, plagioclase) but with occasional eucrite clasts; one section had an anorthosite clast (~90% plagioclase, 10% pyroxene). Microprobe analyses showed pyroxene compositions ranging Fs 33–52, plagioclase ranging Ab 4–19.

11. YURTUK.—Thin sections show a polymict breccia with large (up to 1 mm) orthopyroxene and smaller pigeonite clasts; lithic fragments are also present, both eucritic and diogenitic; rare grains of olivine were seen. Microprobe analyses show pyroxene ranging in composition from Fs 31 to Fs 50.

12. BUNUNU.—This meteorite was described by Mason (1967a), with an analysis by E. Jarosewich. We have made microprobe analyses of the pyroxenes and the plagioclase. The range of plagioclase composition is Ab 6–17, average 10. Orthopyroxene and pigeonite range is Fs 24–63; one grain of augite, $Wo_{43}Fs_{25}En_{32}$, was analyzed.

13. MEDANITOS.—This meteorite was described by

Symes and Hutchison (1970), who classed it as a howardite because of its high content of Ca-poor pyroxene; however, Hutchison et al. (1977) reclassify it as a eucrite, commenting (page 149): "Further unpublished work . . . indicates that it is a eucrite, mineralogically similar to Moore County and Serra de Magé." The analysis is noteworthy for the very low TiO_2 and Cr_2O_3 and high Al_2O_3.

14. LE TEILLEUL.—Thin sections show this meteorite is a polymict breccia; hypersthene clasts (some with augite exsolution lamellae) predominate, with minor amounts of pigeonite and rare eucrite enclaves; one enclave of coarse plagioclase, reminiscent of an anorthosite, was seen. Microprobe analyses show a range of Fs 24–41 in hypersthene and pigeonite, and Ab 10–24 in plagioclase. Desnoyers and Jérome (1973) analyzed 13 grains of olivine in Le Teilleul, and found a composition range of Fa 28–42.

15. MOLTENO.—This meteorite was described by Frost (1971) as a howardite, with pyroxene ranging from $Wo_2Fs_{22}En_{76}$ to $Wo_4Fs_{58}En_{38}$ and then to $Wo_{41}Fs_{26}En_{33}$, with plagioclase (An 84), and with small quantities of olivine (Fa 12), troilite, nickel-iron, ilmenite and chromite. Desnoyers and Jérome

(1973) analyzed 9 grains of olivine in Molteno, and record a composition range of Fa 11–56.

16. MOAMA.—The analysis of this meteorite shows that it is very similar to Medanitos. Lovering (1975) describes it as an unbrecciated adcumulate of pyroxene and plagioclase, with accessory amounts of chromite, troilite, nickel-iron, and tridymite (the presence of olivine in the norm and free silica as tridymite in the mode is probably due to all Fe being reported as FeO, whereas some is present as troilite and nickel-iron). Lovering's microprobe analyses show plagioclase of uniform composition (Ab 6); the major pyroxene is hypersthene ($Wo_{3.4}Fs_{41.6}En_{55.0}$) with exsolution lamellae of augite ($Wo_{44.9}Fs_{18.4}En_{36.7}$).

17. JODZIE.—Bunch et al. (1976) describe this meteorite as follows:

The Jodzie howardite is a polymict-regolith breccia similar to other howardites with two unique exceptions: 1, large cm size lithic clasts of cumulate ferrogabbros, and 2, fragments of C2 carbonaceous chondrites (8 vol. %). The cumulate ferrogabbros contain large 1 to 5 mm ferrohypersthene or ferropigeonite grains with exsolved ferroaugite lamellae, calcic plagioclase (An 84–89), ilmenite, FeS, and rarely free silica and phosphates. Bulk analyses of these clasts are similar to lithic clast ferrobasalts in other howardites . . . The C2 fragments range in size from 1μ to 6 mm and are similar in bulk composition and mineralogy to C2 inclusions in the Abbott and Plainview chondrites and the Kapoeta and Washougal howardites.

18. SERRA DE MAGÉ.—This meteorite has been described by Prinz et al. (1977) as follows:

The Serra de Magé meteorite is a medium to coarse grained anorthositic norite cumulate (eucrite) with a mosaic texture. . . . Phases present are plag (An_{95}), opx ($En_{55.5}$), augite ($Wo_{45}En_{39}Fs_{16}$), chromite (Cr_2O_3, 50–54%), SiO_2, Ni-Fe (Ni, 0.3–1.5%; Co, 0.8–1.2%), troilite, and a trace of ilmenite; zircon and phosphate are present but were not found in section . . . It is highly equilibrated and the pyroxenes record a complex subsolidus history.

Serra de Magé is unique in having the highest Al_2O_3 content and hence the highest plagioclase content of any meteorite. In its high plagioclase content, and in other compositional and textural features it is clearly related to Medanitos, Moama, Nagaria, and Moore County.

19. KAPOETA.—The polymict character of this meteorite was clearly established by Fredriksson and Keil (1963), in one of the first applications of microprobe analysis to meteorite research; they analyzed 132 pyroxene grains from the light portion and found Fe (weight percent) ranging from 8.3 to 28.4, and 132 grains from the dark portion with an Fe range of 7.5 to 26.3; they also analyzed five olivine grains, with Fa ranging from 8.5 to 37.7 mole percent. Their work has been greatly extended by Dymek et al. (1976), who comment:

Kapoeta is a "regolith" meteorite, and mineral-chemical and petrographic data were obtained for numerous other rock and mineral fragments in order to characterize the surface and near-surface materials on its parent body. Rock clasts can be grouped into two broad lithologic types on the basis of modal mineralogy—basaltic (pyroxene- and plagioclase-bearing) and pyroxenitic (pyroxene-bearing). Variations in the compositions of pyroxenes in rock and mineral clasts are similar to those in terrestrial mafic plutons such as Skaergaard, and indicate the existence of a continuous range in rock compositions from Mg-rich orthopyroxenites to very iron-rich basalts. . . . We interpret these observations to indicate that the Kapoeta meteorite represents the comminuted remains of differentiated igneous complexes together with "primary" undifferentiated basaltic rocks. The presently available isotopic data are compatible with the interpretation that this magmatism is related to primary differentiation of the Kapoeta parent body. In addition our observations preclude the interpretation that the Kapoeta meteorite is a simple mixture of eucrites and diogenites.

20. MALVERN.—This meteorite is extremely similar to Kapoeta in chemical and mineralogical composition, and in texture, having the same prominent contrasted light-dark areas. It has been described by Simpson (1975) and Desnoyers and Jérome (1977), who clearly established its nature as a polymict breccia.

21. POMOZDINO.—Kvasha and Dyakonova (1972) describe this meteorite as a eucrite. A section we have examined shows that the meteorite is a monomict breccia, the breccia fragments consisting of a subophitic intergrowth of plagioclase and pigeonite.

22. BRIENT.—This meteorite is described by Zavaritskii and Kvasha (1952) as a howardite, and their illustrations (page 230) show that it is a polymict breccia. Thus in spite of the close similarity in chemical composition between Brient and Pomozdino they are quite different structurally.

23. PETERSBURG.—Thin sections show that this meteorite is a polymict breccia; the dominant clasts are subequal amounts of orthopyroxene and pigeonite (up to 1 mm across); plagioclase clasts are also present, and occasional olivine clasts (one olivine clast 2 mm across); small ophitic eucrite enclaves are not uncommon. Microprobe analyses show orthopyroxene and pigeonite ranging in composi-

tion from Fs 22 to Fs 55; plagioclase ranges in composition from Ab 8 to Ab 14; two grains of olivine, Fa 38 and Fa 42, were analyzed. Duke and Silver (1967, fig. 15) have published a diagram showing the compositional range of pyroxenes in Petersburg.

24. NAGARIA.—A thin section shows that this meteorite is unbrecciated with a cumulus texture, consisting of approximately equal amounts of plagioclase and pyroxene. It is very similar to Moore County in chemical and mineralogical composition and texture. The minerals are highly equilibrated. Microprobe analyses show plagioclase of uniform composition, Ab 8; the pyroxene evidently crystallized originally as pigeonite, but the individual grains are now hypersthene ($Wo_{1.3}Fs_{50.4}En_{48.3}$) with exsolved augite ($Wo_{43.3}Fs_{18.9}En_{37.8}$).

25. MOORE COUNTY.—A comprehensive description of this meteorite was published by Hess and Henderson (1949). Additional information on the pyroxenes has been provided by Ishii and Takeda (1974); they showed that the primary pigeonite ($Wo_{10.1}Fs_{44.3}En_{45.6}$) has exsolved augite ($Wo_{41.5}Fs_{21.7}En_{36.8}$) and the host pyroxene now has the composition $Wo_{5.8}Fs_{47.5}En_{46.7}$. Plagioclase has uniform composition, Ab 9.

26. SHERGOTTY.—Although it belongs mineralogically with the pyroxene-plagioclase achondrites, Shergotty (and the closely-related Zagami) has several features distinguishing it from other meteorites in this group. It contains much more Na_2O than the other meteorites, and as a result the plagioclase composition is that of labradorite instead of bytownite-anorthite; the plagioclase has been shock-transformed into the isotropic form maskelynite. It also contains magnetite, which indicates a much higher oxygen fugacity in its place of crystallization than for the eucrites and howardites. Duke (1968) has provided a comprehensive description of Shergotty, with analyses of the bulk meteorite, the maskelynite ($Or_2Ab_{49}An_{49}$), and the pyroxene ($Wo_{22}Fs_{41}En_{37}$); the pyroxene is strongly zoned, as shown by Duke's microprobe analyses.

Binns (1967) has shown that Zagami is closely similar to Shergotty both in texture and mineralogical composition; for an analysis of Zagami, see Easton and Elliott (1977). We have compared thin sections of the two meteorites, and find that Zagami differs from Shergotty only in being somewhat finer-grained (feldspar laths average twice as long in Shergotty); it is certainly possible, if not probable,

that both had a common parent body. The chemical composition of Shergotty places it well away from the main trend of the eucrites and howardites (Figure 3). It is significant that Bunch (1975) found no shergottite clasts in the howardites, although he found numerous clasts of eucrites, and less numerous clasts of other meteorite types. All these facts indicate that Shergotty (and Zagami) probably come from a different parent body than the other pyroxene-plagioclase achondrites.

27. MACIBINI.—This meteorite has been described by Reid (1974), as follows:

The Macibini meteorite is a complex polymict breccia with rock and mineral clasts that are extraordinarily diverse in texture and composition . . . . Pyroxenes encompass a range from magnesian orthopyroxene through pigeonite and ferropigeonite to ferroaugite and to hedenbergite. The trend mimics, and extends the pyroxene trend shown by the basaltic achondrite group of meteorites. The more magnesian pyroxenes are coarser grained and tend to occur as mineral clasts; the more iron-rich pyroxenes are commonly present within fine-grained eucritic lithic fragments that have subophitic textures. . . . From the coherence of the mineral data, the parent materials are not a random set of unrelated rocks but appear to be derived predominantly from a suite of related samples, that may have differentiated from a single source The sequence of mineral compositions appears to be continuous and the basaltic achondrites appear to be related by fractional crystallization, involving dominantly pyroxene. There is evidence for the existence of achondrites with compositions intermediate between the hypersthene achondrites and the eucrites; howardites are not simply two-component mixtures.

We have examined sections of Macibini and agree with Dr. Reid's comments. Our microprobe analyses show orthopyroxene and pigeonite with a composition range Fs 19–61, together with occasional grains of ferroaugite; plagioclase composition range is Ab 7–21. Desnoyers and Jérome (1973) analyzed 11 grains of olivine in Macibini, with a composition range Fa 56–83 (unusually iron-rich).

28. BIALYSTOK.—This meteorite resembles Macibini closely in composition and texture. It is a polymict breccia, with mostly pyroxene clasts (pigeonite > orthopyroxene) in a fine-grained groundmass; small ophitic eucrite enclaves are present. Microprobe analyses showed a range in composition of Fs 25–62 for orthopyroxene and pigeonite, and Ab 7–12 for plagioclase; three grains of olivine, Fa 71–73, were analyzed, and rare grains of a silica polymorph, probably tridymite, were seen.

29. YAMATO-74450.—This meteorite, collected by

the Japanese Antarctic Expedition in 1974, has been analyzed by Wänke et al. (1977), who describe it as a eucrite. We have been informed (H. Takeda, pers. comm.) that Yamato-74450 is a monomict breccia, with pyroxene compositions similar to those in Pasamonte.

30. IBITIRA.—This meteorite has been described by Wilkening and Anders (1975) and Steele and Smith (1976). The latter authors describe it as follows:

Ibitira meteorite is interpreted as a strongly metamorphosed, unbrecciated, vesicular eucrite with a primary variolitic and secondary hornfelsic texture dominated by 60% pyroxene (bulk composition $En_{37}Fs_{48}Wo_{15}$ exsolved into lamellae several micrometers wide of augite $En_{32}Fs_{27}Wo_{41}$ and pigeonite $En_{40}Fs_{56}Wo_4$) and 30% plagioclase An_{94} (mosaic extinction and variable structural state). Minor phases are 5% tridymite plates one-quarter occupied by plagioclase (An_{94}) inclusions; several percent intergrowths of ilmenite and Ti-chromite with trace kamacite $Fe_{99}Co_{0.5}Ni_{0.2}$ and narrow olivine (Fa_{83}) rims; one grain of low-Ti-chromite enclosed in tridymite; trace troilite with kamacite $Fe_{98}Co_{1.0}Ni_{0.9}$. Euhedral ilmenite, Ti-chromite, plagioclase and merrillite in vesicles indicate vapor deposition. These properties can be explained by a series of processes including at least the following: (1) igneous crystallization under pressure low enough to allow vesiculation, (2) prolonged metamorphism, perhaps associated with vapor deposition and reduction, to produce the coarse exsolution of the pyroxene and the coarse ilmenite-chromite intergrowths, (3) strong shock which affected the plagioclase and tridymite but not the pyroxene, (4) sufficient annealing to allow recrystallization of the plagioclase and tridymite, and partial conversion to the low structural state of the former.

31. JONZAC.—Thin sections show that this meteorite is strongly brecciated, only a few small areas retaining the igneous subophitic texture of intergrown plagioclase and pyroxene. Our microprobe analyses (Figure 1) show pyroxene ranging in composition from $Wo_2Fs_{65}En_{34}$ to $Wo_{47}Fs_{24}En_{29}$, the En content remaining almost constant while the Wo and Fs contents vary inversely; this pattern is characteristic for most eucrites, as noted by Duke and Silver (1967) for Sioux County, Juvinas, and Nuevo Laredo. Plagioclase composition ranges from Ab 7–17, with an average of Ab 11.

32. SIOUX COUNTY.—Duke and Silver (1967) describe this meteorite as a monomict breccia made up of coarse-grained lithic fragments with equigranular and ophitic textures. They show the range in composition of the pyroxenes in the form of a diagram (their fig. 15); the pyroxenes range continuously from pigeonite through subcalcic augite to

ferroaugite with relatively constant molecular percentage (~30) of $MgSiO_3$.

33. ALLAN HILLS No. 5.—This meteorite was collected in Antarctica in 1977 and described by Olsen et al. (1978). They state: "Thus, in a strict sense, Allan Hills #5 is polymict, however, the exceptional anorthosite clasts are so few, and the bulk composition so close to the average for eucrites, we classify this meteorite as a eucrite" (p. 223). This is clearly a meteorite whose classification as a eucrite or as a howardite depends on a subjective evaluation of the amount of foreign admixture.

34. NOBLEBOROUGH.—Thin sections show this meteorite to be a polymict breccia, with clasts dominantly of pyroxene (mostly pigeonite), minor plagioclase (Ab 7–17, average 9), some tridymite grains, and occasional lithic fragments of eucritic composition and texture; one grain of unusually iron-rich olivine (Fa 88) was found. The polymict character is well illustrated by a plot of pyroxene compositions determined by the microprobe (Figure 1); most of the pyroxene grains are pigeonite, but compositions falling in the fields of hypersthene, augite, subcalcic ferroaugite, ferroaugite, and ferrohedenbergite were recorded, and one grain $(Wo_{14}Fs_{82}En_4)$ is almost certainly pyroxferroite. The extreme contrast in pyroxene compositions between Jonzac (a monomict breccia) and Nobleborough (a polymict breccia), in spite of their almost identical bulk compositions, supports the division of the pyroxene-plagioclase achondrites into eucrites and howardites on the basis of structure rather than composition. Of course, the mere existence in these meteorites of pyroxenes with a wide range of composition is not necessarily evidence for a polymict origin; a similar range of composition for a zoned single crystal has been recorded for many pyroxenes in lunar basalts (e.g., Mason et al., 1972). The wide range of pyroxene compositions in Nobleborough, however, has been recorded on discrete grains, not zoned crystals. This indicates that at least some of the rocks from which these grains were derived were probably not cogenetic.

35. CHERVONY KUT.—This meteorite has been described by Zavaritskii and Kvasha (1952). Their illustration (fig. 252) shows an unbrecciated structure, with pigeonite and plagioclase in an equigranular to subophitic texture.

36. CACHARI.—Cachari is a monomict breccia, extensively crushed, and veined with brown glass;
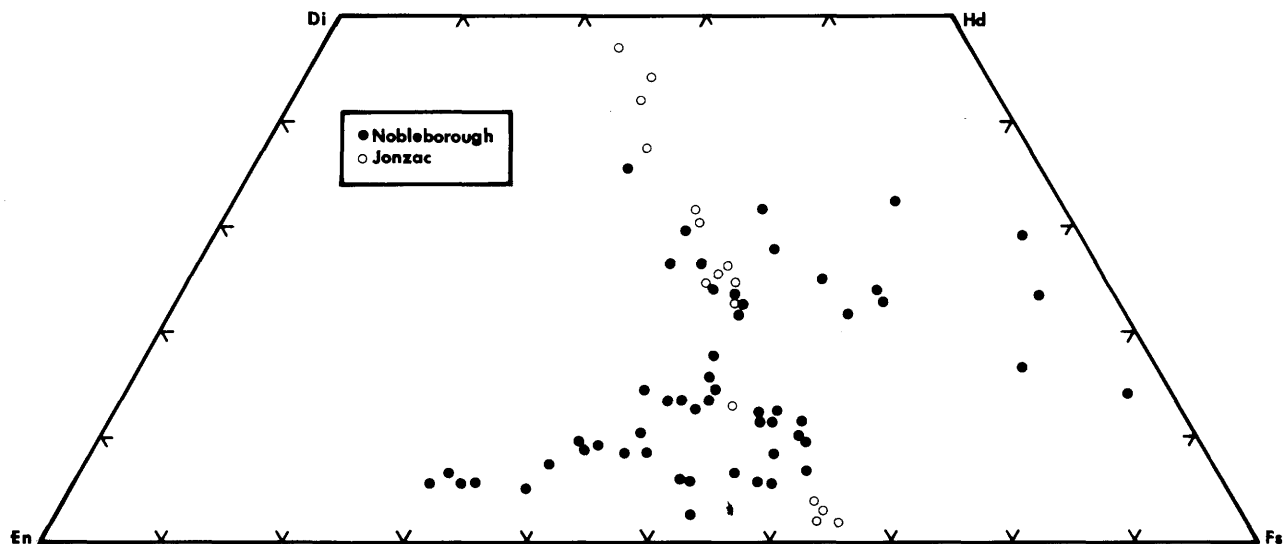
FIGURE 1.—Pyroxene compositions (microprobe analyses) in the Nobleborough howardite and the Jonzac eucrite, two pyroxene-plagioclase achondrites with very similar bulk compositions.

large areas, however, are unbrecciated, and show an equigranular to subophitic association of pigeonite and plagioclase. Cachari has been described by Fredriksson and Kraut (1967) as a rather typical brecciated eucrite, consisting of orthopyroxene ($Wo_2Fs_{59}En_{39}$) and clinopyroxene ($Wo_{42}Fs_{27}En_{31}$), plagioclase (An 88), with minor amounts of chromite, ilmenite, and troilite.

37. KIRBYVILLE.—This meteorite has never been described; a small portion was kindly made available to us by its owner, Mr. Oscar Monnig. It is a monomict breccia; pyroxene compositions, determined by the microprobe, are similar to those in Jonzac, ranging from $Wo_2Fs_{66}En_{32}$ to $Wo_{40}Fs_{29}En_{31}$. A silica polymorph, probably tridymite, was detected with the microprobe.

38. JUVINAS.—This meteorite has been extensively described in the literature, most recently by Duke and Silver (1967). They record it as a monomict breccia, and provide a plot of pyroxene compositions, which show a continuous range from pigeonite through subcalcic ferroaugite to ferroaugite with relatively constant $MgSiO_3$ contents, similar to that of Jonzac and other eucrites.

39. MILLBILLILLIE.—A sawn surface of this meteorite presents a brecciated appearance, with a prominent light-dark structure. The brecciated appearance is not so marked in a thin section, but can be seen as areas of coarser and finer grain. Our microprobe analyses show pryoxene composi-

tions similar to those in Jonzac, ranging from $Wo_2Fs_{66}En_{32}$ to $Wo_{45}Fs_{26}En_{29}$; plagioclase composition range is Ab 9–18, average 12; a silica polymorph was observed.

40. MOUNT PADBURY.—This meteorite is a mesosiderite containing a varied range of achondrite enclaves, which have been described by McCall (1966). We have examined one of these, an unbrecciated hypidiomorphic-granular aggregate of pyroxene and plagioclase. Its bulk composition is essentially identical with many eucrites. Microprobe analyses show pyroxene compositions ranging from $Wo_2Fs_{64}En_{34}$ to $Wo_{20}Fs_{49}En_{32}$, i.e., pigeonite to subcalcic ferroaugite; plagioclase composition is very uniform, Ab 8.

41. PADVARNINKAI.—This meteorite has been classed as a shergottite, because it contains maskelynite; however, Binns (1967) showed that it differs significantly in chemistry and mineralogy from Shergotty, and it still retains some untransformed plagioclase, which has a bytownitic composition quite different from the Shergotty maskelynite. The chemical analysis shows that its composition is essentially identical with other eucrites. Our microprobe analyses show pyroxene compositions ranging from $Wo_2Fs_{67}En_{31}$ to $Wo_{44}Fs_{27}En_{29}$, similar to those in Millbillillie; the plagioclase composition range is Ab 10–23, average 11.

42. ADALIA.—This meteorite is unbrecciated, with an ophitic texture. Our microprobe analyses show

pyroxene ranging from $Wo_2Fs_{63}En_{35}$ to $Wo_{36}Fs_{34}$ En_{30}, closely similar to the preceding meteorites; plagioclase ranges Ab 9–18, average 11; accessory grains of a silica mineral were noted.

43. PALO BLANCO CREEK.—This meteorite is described by Lange and Keil (1976) as a monomict pigeonite-plagioclase achondrite. Their plot of pyroxene compositions show them closely clustered in two areas, one pigeonite and one ferroaugite; our microprobe analyses confirm this, with mean compositions $Wo_2Fs_{65}En_{33}$ and $Wo_{44}Fs_{28}En_{28}$; plagioclase is very uniform in composition, Ab 10.

44. PERAMIHO.—This meteorite was described by Berwerth (1903); it is a typical monomict eucritic breccia. Our microprobe analyses show pyroxene compositions clustered around $Wo_2Fs_{63}En_{35}$ and $Wo_{43}Fs_{27}En_{30}$, similar to those in Palo Blanco Creek; feldspar composition range is Ab 9–14, average 11.

45. STANNERN.—This meteorite has been comprehensively described by von Engelhardt (1963). It is a monomict breccia; some areas retain the original ophitic texture of pigeonite and plagioclase, but much of the meteorite is strongly crushed and brecciated. Our microprobe analyses show pyroxene ranging in composition from $Wo_3Fs_{65}En_{32}$ to $Wo_{26}Fs_{46}En_{28}$, and plagioclase from Ab 12 to Ab 20, average 17.

46. HARAIYA.—This meteorite is a monomict breccia, with areas of original ophitic texture separated by areas of crushed material; some of the crushed material appears to have recrystallized into a granular aggregate of pyroxene and plagioclase. Our microprobe analyses show pyroxene compositions ranging from $Wo_2Fs_{67}En_{31}$ to $Wo_{43}Fs_{29}En_{28}$; plagioclase compositions range Ab 9–18, average 11.

47. PASAMONTE.—This meteorite is a breccia containing clasts dominantly of pigeonite with lesser amounts of plagioclase, and lithic fragments with ophitic texture. It has been classified as a monomict breccia by Duke and Silver (1967) and by Takeda, Miyamoto, and Duke (1976). Takeda et al. have shown that Pasamonte is almost unique among the monomict breccias in having strongly zoned pyroxenes with no visible exsolution lamellae. Our microprobe analyses show pigeonite compositions ranging from $Wo_6Fs_{33}En_{61}$ to $Wo_6Fs_{65}En_{29}$, with some Ca-rich pyroxene ranging up to $Wo_{33}Fs_{39}En_{28}$.

48. BEREBA.—The mineralogy and petrology of this meteorite were comprehensively described by Lacroix (1926). It is a monomict breccia; our mi-

croprobe analyses show pyroxene of composition $Wo_3Fs_{61}En_{36}$ with narrow exsolution lamellae of ferroaugite ($Wo_{36}Fs_{35}En_{29}$), and plagioclase with composition Ab 8–10; a silica polymorph (quartz, according to Lacroix) was detected.

49. EMMAVILLE.—This meteorite was briefly described by Mason (1974). It is a monomict breccia with veinlets of brown glass. It is noteworthy for being the finest-grained of all the eucrites, with a hornfelsic hypidiomorphic-granular texture, the pyroxene grains averaging 0.02-0.03 mm across and set in a plagioclase matrix. Our microprobe analyses show hypersthene ($Wo_2Fs_{66}En_{32}$) coexisting with augite ($Wo_{47}Fs_{25}En_{28}$). Plagioclase compositions range from Ab 9 to Ab 20, and average Ab 13. The pyroxene compositions indicate that Emmaville probably recrystallized and equilibrated at temperatures well below the liquidus.

50. NUEVO LAREDO.—This meteorite has been described by Duke and Silver (1967). It is a monomict breccia in which the lithic clasts are rather fine grained. Our microprobe analyses show pyroxene compositions ranging from $Wo_5Fs_{68}En_{27}$ to $Wo_{41}Fs_{34}$ En_{24}, similar to those reported by Duke and Silver.

51. LAKANGAON.—There is very little published information about this meteorite, except for the analysis by McCarthy et al. (1974). It is a monomict breccia, the individual lithic clasts being coarse-grained granular to subophitic intergrowths of pyroxene and plagioclase. Pyroxene compositions range from $Wo_5Fs_{66}En_{27}$ to $Wo_{43}Fs_{33}En_{24}$; plagioclase from Ab 10 to Ab 19, average Ab 15.

Neither analytical data nor a description are available for Muckera, which is catalogued by Hutchison et al. (1977) as a howardite. Melrose (b), which we have not examined, was briefly described and identified as a howardite by Sibray et al. (1976). We accept the identification by Tschermak (1872) of Constantinople as a mislabelled fragment of Stannern.

Chemical and Mineralogical Relationships

Examination of Table 1 reveals a number of regularities in the composition of the pyroxene-plagioclase achondrites. The SiO_2 content is remarkably uniform at 50±3 percent (Serra de Magé, with 46.69% SiO_2, is exceptional because of its high content of plagioclase). The FeO content is also fairly uniform (Serra de Magé is again exceptional),

and the MgO content shows a fairly regular decrease with increasing $FeO/(FeO+MgO)$ molecular percentage, whereas CaO and Al_2O_3 show the reverse effect. The Na_2O content is low throughout, except in Shergotty (1.28%). Of the minor components, MnO is rather constant (Dymek et al. (1976) demonstrated that the FeO/MnO ratio in Kapoeta pyroxenes is fairly uniform ($\sim$35) and significantly lower than in lunar pyroxenes ($\sim$60), and Marvin (1976) has confirmed this for other pyroxene-plagioclase achondrites); Cr_2O_3 decreases with increasing $FeO/FeO+MgO)$ molecular percentage, whereas TiO_2 increases.

A notable feature of Table 1 is the marked cluster of analyses (analyses 29–49) with $FeO/(FeO+MgO)$ mole percentage of 60±3, i.e., almost half the analyses group together, with very limited internal variation. They are unbrecciated or monomict breccias, except Nobleborough (34), and form what may be called the main-group eucrites.

Additional correlations are revealed by the calculation of normative mineralogy (because the

actual minerals present are essentially identical with those calculated in the norm, normative and modal mineralogy are closely similar). Since practically all the Al_2O_3 is combined in plagioclase, Al_2O_3 and plagioclase contents are directly related; plagioclase content increases with increase in $FeO/(FeO+MgO)$ mole percentage, from 12% in Yamato-7307 to almost 40% in main-group eucrites. A few eucrites (Medanitos, Serra de Magé, Nagaria, Moore County) contains more than 40% plagioclase, and are believed to have a cumulate origin. Normative plagioclase composition is rather uniform at Ab 10±5, except for Shergotty (Ab 48), reflecting the rather uniform Na_2O content; in individual meteorites actual plagioclase composition may vary from grain to grain and within grains but will average close to the normative composition. Normative pyroxene increases in amount and becomes more calcic and iron-rich with increase in $FeO/(FeO+MgO)$ mole percentage. Actual pyroxene compositions vary widely in the howardites, but generally show a limited and systematic range in the eucrites (Figure 1).
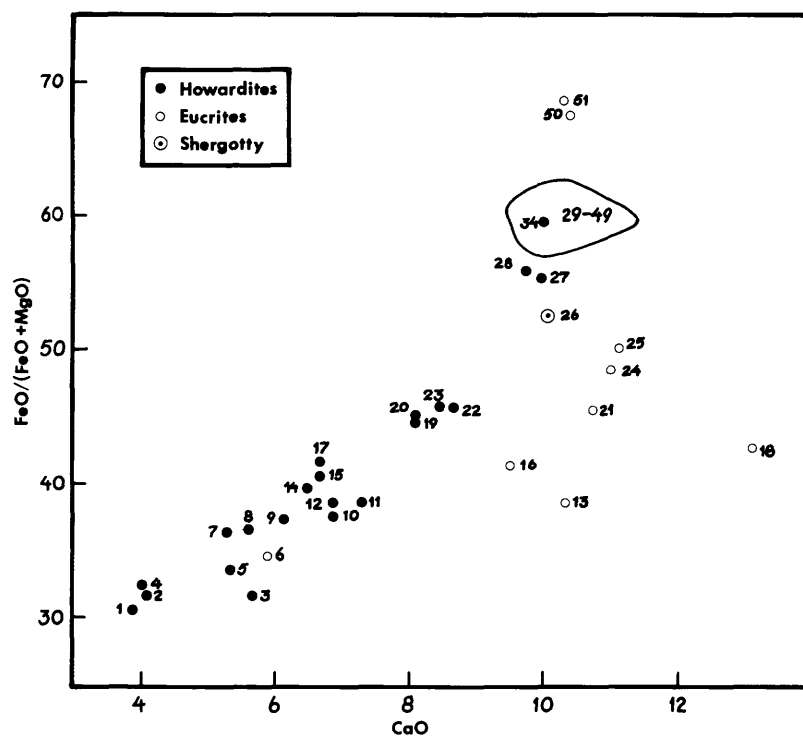
FIGURE 2.—CaO (weight percent) plotted against $FeO/(FeO+MgO)$ (mole percent) from analyses of the pyroxene-plagioclase achondrites (the ellipse encloses values for 20 eucrites and one howardite; numbers are those of analyses in Table 1).

A significant feature that becomes evident from the norm calculation is the close approach to silica-saturation in all the pyroxene-plagioclase achondrites, so close in many instances that a change of less than 1% in SiO₂ percentage would change an analysis from olivine-normative to quartz-normative. The eucrites, however, are consistently quartz-normative (except Binda, Medanitos, Moama, Nagaria, Moore County), whereas most howardites are olivine-normative. Accessory olivine is present in most howardites, but we have not found it in any of the eucrites we have examined. Most eucrites (even the olivine-normative Binda, Moama, and Moore County) contain accessory free silica, usually as tridymite, sometimes as quartz or cristobalite.

Additional relationships are clarified by composition diagrams. Figure 2 plots CaO weight percentage against FeO/(FeO+MgO) mole percentage. The close groupings of analyses 29 through 49 is apparent; there are too many analyses to be shown individually, but the one howardite within this cluster is shown. Nuevo Laredo (50) and Lakangaon (51), although identical to main-group eucrites in CaO content, are clearly differentiated on FeO/(FeO+MgO) mole percentage. Outside the main-group eucrites are Binda (6) and six probable cumulates: Medanitos (13), Moama (16), Serra de Magé (18), Pomozdino (21), Nagaria (24), and Moore County (25). Another intriguing feature is that howardite compositions are fairly continuous in the
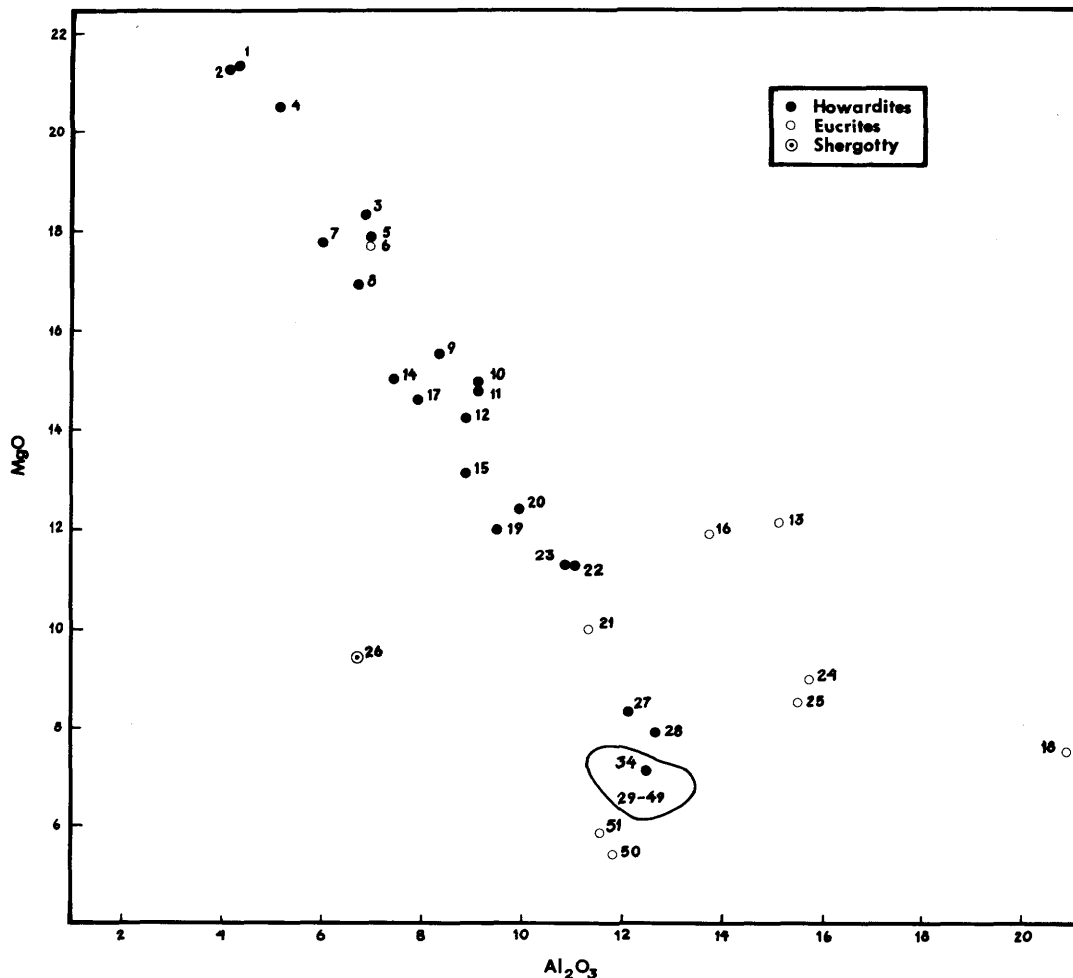
FIGURE 3.—MgO (weight percent) plotted against Al₂O₃ (weight percent) from analyses of the pyroxene-plagioclase achondrites (the ellipse encloses the values for 20 eucrites and one howardite; numbers are those of analyses in Table 1).
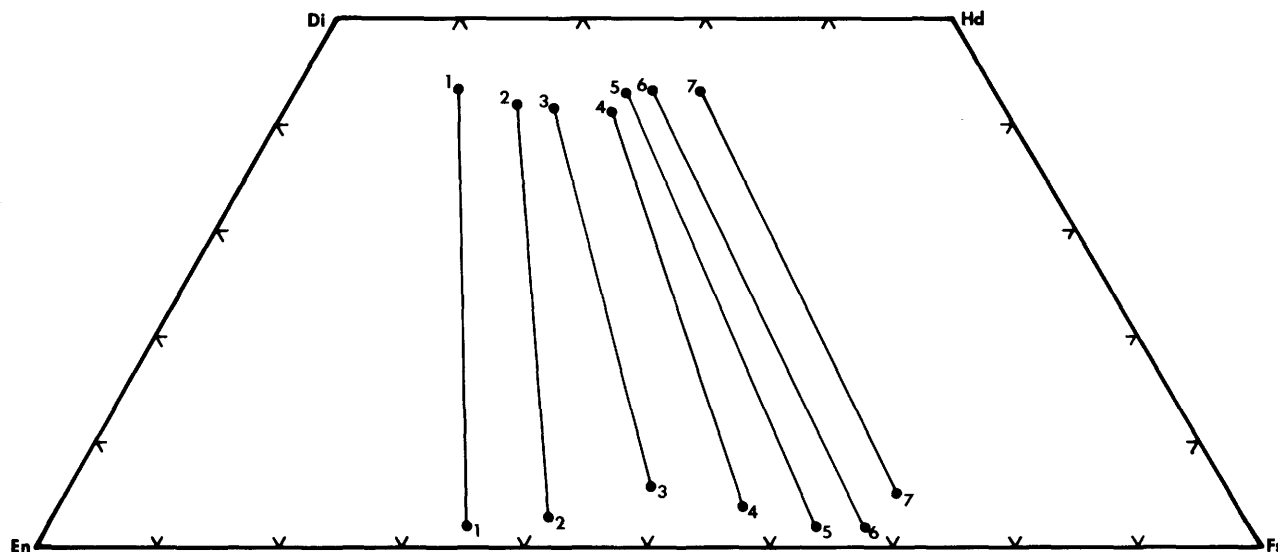
FIGURE 4.—Compositions of coexisting calcium-poor and calcium-rich pyroxenes in selected eucrites (1 = Binda (Takeda, Miyamoto, Ishii and Reid, 1976); 2 = Moama (Takeda, Miyamoto, Ishii, and Reid, 1976); 3 = Moore County (Ishii and Takeda, 1974); 4 = Ibitira (Steele and Smith, 1976); 5 = Peramiho (this paper); 6 = Haraiya (this paper); 7 = Lakangaon (this paper)).

FeO/(FeO+MgO) range 30–46, but there is then a hiatus to FeO/(FeO+MgO) = 55, with only three beyond this—Macibini, Bialystok, and Nobleborough.

The MgO–Al₂O₃ diagram (Figure 3) demonstrates many of the same relationships as Figure 2. It shows even more clearly than Figure 2 the linear relationship between the howardites and the main-group eucrites, i.e., although the howardites are polymict breccias, their bulk composition is clearly constrained. The MgO–Al₂O₃ relationship can be projected to include the diogenites, whose compositions cluster around 26% MgO, 1% Al₂O₃; the relationship between diogenites, howardites, and eucrites will be discussed in a later section. Figure 3 shows how the Shergotty composition falls well away from the eucrites and howardites, and justifies placing it in a special category, as already indicated by its mineralogy. Relative to the eucrites and howardites, Shergotty is enriched in pyroxene and depleted in plagioclase; its texture suggests a pyroxene cumulate.

As demonstrated in Figure 1, howardites are distinguished from eucrites by their great range in pyroxene composition; in eucrites pyroxene compositions may range in Wo content from pigeonite to augite or ferroaugite, but the En content remains practically constant. The extremes in pyroxene com-

position are plotted in Figure 4 for seven eucrites, ranging from the most Mg-rich (Binda) to the most iron-rich (Lakangaon). In most of these meteorites all intermediate compositions between the extremes may be found by microprobe analyses, because of the presence of microscopic to submicroscopic exsolution lamellae of calcium-rich pyroxene in a calcium-poor host.

The Relationship between Diogenites, Howardites, and Eucrites

The fact that the bulk compositions of diogenites, howardites, and eucrites form an almost continuous sequence has long been known and commented on. Mason (1962) suggested that these three classes might be related as successive members of a fractional crystallization sequence from a melt of approximately chondritic composition (the pallasites being the initial member of the sequence). Jérome and Goles (1971) pointed out that howardites are polymict breccias, and therefore are not direct products of magmatic crystallization; from that observation they proceeded to the postulate that howardites are mechanical mixtures of diogenites and eucrites. This postulate has been supported by McCarthy et al. (1972) and later researchers, most recently by Dreibus et al. (1977:211),

who state: "The hypothesis of Jérome and Goles (1971) and McCarthy et al. (1972), according to which howardites are thought to be mechanical mixtures of eucrites and diogenites, is strongly confirmed by mixing computations."

The fatal flaw in this hypothesis is the remarkable uniformity of pyroxene compositions in diogenites (Fs 25–27), as has been demonstrated by Mason (1963) and Fredriksson et al. (1976). Calcium-poor pyroxene compositions in eucrites (Figure 4) range from Fs 33 to Fs 68. Therefore, if howardites are mixtures of diogenites and eucrites, their pyroxenes should comprise a large component with composition Fs 26±1 (the diogenite fraction) and additional calcium-poor pyroxenes possibly ranging from Fs 33 to Fs 68 (the eucrite fraction). That this is not the case was already evident in 1971 from the work of Fredriksson and Keil (1963) on Kapoeta; figures 7 and 8 of their paper show pyroxene compositions extending as low as Fs 14 and no large component at Fs 26. These results on Kapoeta have been confirmed and extended by Dymek et al. (1976). Similar evidence is available from Macibini (Reid, 1974) and Malvern (Simpson, 1975); both Reid and Simpson conclude that these meteorites could not have been produced by the physical mixing of diogenite and eucrite (Desnoyers and Jérome (1977), however, disagree with Simpson in the case of Malvern). Our data on the howardites confirm and extend the conclusions of Reid and Simpson. Not only do the howardites contain calcium-poor pyroxenes much more magnesian than those in diogenites, but some of them (notably Pavlovka and Nobleborough) have pyroxenes more iron-rich than have been found in any eucrite. The presence of accessory olivine in many howardites, with a wide range of composition—Fa 11–83, according to Desnoyers and Jérome (1973)—also argues for a component not represented either in the diogenites or the eucrites. We agree, nevertheless, with Reid's comment (1974:398) on Macibini: "The parent materials [of the howardites] are not a random set of unrelated rocks but appear to be derived predominantly from a suite of related samples, that may have differentiated from a single source."

The Eucrite Parent Body

Discussions of the eucrite parent body usually imply the parent body of what we have called the main-group eucrites, i.e., the compositional cluster around $FeO/(FeO+MgO)$ molecular percentage of 60. Within this group a wide variety of primary (i.e., pre-brecciation) textures are seen, indicating a considerable variety of crystallization conditions in the parent body. Nevertheless, most, if not all, crystallized under low pressure (the common occurrence of tridymite indicates a confining pressure of 3 kbar ôr less).

Although the textures of the clasts in most of the eucrites resemble those of the lunar basalts, the exsolution and inversion features show significant differences. The pyroxenes in lunar basalts are strongly zoned, and can range from orthopyroxene through pigeonite to augite and hedenbergite in a single crystal. In most eucrites the pyroxenes are essentially unzoned, and consist of pigeonite of uniform composition with exsolution lamellae of augite. Possibly the eucrites crystallized originally like the lunar basalts, as thin surface flows, but later were annealed (perhaps by burial under successive flows), whereby originally zoned pyroxenes were homogenized, and then exsolved augite on slow cooling. If true, it is noteworthy that this equilibration occurred without textural change, except for Ibitira and Emmaville, which have a hornfelsic texture. Presumably the absence of water and other volatiles inhibited textural alteration.

Some years ago one of us (Mason, 1967b) proposed that the eucrites were derived from a relatively thin surface crust of a differentiated asteroid consisting of a pallasitic core and a diogenitic mantle. The radius of the hypothetical asteroid was set at 300 km, to be consistent with the measured cooling rates of pallasite meteorites (Buseck and Goldstein, 1967). It had a pallasitic core with radius 207 km, a diogenitic mantle 80 km thick, and a eucritic crust 13 km thick. The overall mineralogical composition of this asteroid was calculated to be (weight percent): nickel-iron, 14; olivine, 25; hypersthene, 46; pigeonite, 9; plagioclase, 6. The bulk composition of this asteroid was then calculated from the average mineral compositions in these meteorites, with the results as given in Table 2. It is gratifying to see that recent deductions as to the composition of the eucrite parent body, based on sophisticated geochemical arguments (e.g., Morgan et al., 1978) are in good agreement with the simple petrological model. The composition derived by Morgan et al. (Table 2, analysis 2) would give a

TABLE 2.—Composition of (1) an asteroid consisting of pallasite core, diogenite mantle, and eucrite crust (Mason, 1967b); and (2) the eucrite parent body (Morgan et al., 1978)

Constituent	1	2
SiO_2	42.7	35.0
Al_2O_3	2.3	2.2
FeO	12.7	23.2
MgO	26.2	24.8
CaO	2.0	1.8
Na_2O	0.1	0.04
Fe	12.5	11.2
Ni	1.5	1.7

parent body with more olivine and less pyroxene than that of Mason, i.e., one with a larger pallasite core and smaller diogenite mantle.

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Fusion of Rock and Mineral Powders for Electron Microprobe Analysis

Peter A. Jezek, John M. Sinton, Eugene Jarosewich, and Charles R. Obermeyer

ABSTRACT

Rock and mineral powders, finer than 100 mesh, were fused in a molybdenum or tungsten boat in a nitrogen atmosphere. The fusion times ranged from 5 to 30 sec at temperatures between 1650° C and 1750° C. The fusion bridge was powered by a 1.5 kVA welding transformer.

This fusion technique in combination with the electron microprobe uses very small amounts of sample and is suitable for very rapid analysis of rock samples ranging in composition from 45 to about 65 weight percent SiO_2. In general, the glasses are sufficiently homogeneous to be suitable for electron microprobe analysis. The electron microprobe results, when compared to analyses obtained by classical chemical methods, have average accuracy better than 5 percent (relative) for all major components except TiO_2, which is better than 13 percent (relative). A major part of the error in the TiO_2 analyses is probably due to the presence of minute residual or quench Fe-Ti oxides in the glass.

The samples investigated suggest that if fusion times of less than 20 sec are used, Na_2O loss is prevented or greatly restricted and homogeneous glasses still result.

Introduction

Brown (1977) summarized techniques used in electron microprobe major elements analysis of whole rock samples. He also described a new technique for fusing rock powders in molybdenum boats in a pressurized (60 psi) argon atmosphere.

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We have investigated direct fusion of rock and mineral powders in molybdenum and tungsten boats in a nitrogen atmosphere (at atmospheric pressure), using a strip furnace which is easily built and inexpensive to operate. These experiments were aimed at developing a rapid, simple, and inexpensive method of fusion of rock powders into representative, homogeneous beads or shards suitable for analysis by electron microprobe, without the need of an argon pressure chamber.

INSTRUMENTATION.—The fusion bridge (Figures 1, 2) is powered by a 1.5 kVA welding transformer. The primary of the transformer is connected through a Variac autotransformer to 115 VAC. The secondary of the transformer, rated at 11.5 V, is connected to a 100 A silicon diode bridge rectifier. The DC output of the rectifier then powers the fusion bridge (Figure 3). To reach a temperature of 1670° C the strip receives 40 A at 4 VDC. Temperatures were measured by an optical pyrometer. The particular welding transformer employed in this instrument was used because of its availability; two parallel-wired filament transformers, 25 A each, could be used instead.

The Mo and W boats used in the fusion are inexpensive and readily available from most SEM suppliers. They are very practical for holding all molten glasses, and are especially useful in restricting the flow of low viscosity basaltic glasses. The size best suited for routine sample fusion is a 1 7/8 in. strip containing a boat 7/16 in. long, 3/16 in. wide and 3/32 in. deep.

TECHNIQUE.—The melting boat, connected between two posts, is covered by a glass bell jar that is continuously flushed by nitrogen (Figure 1). After placing the powder, ground finer than 100 mesh,

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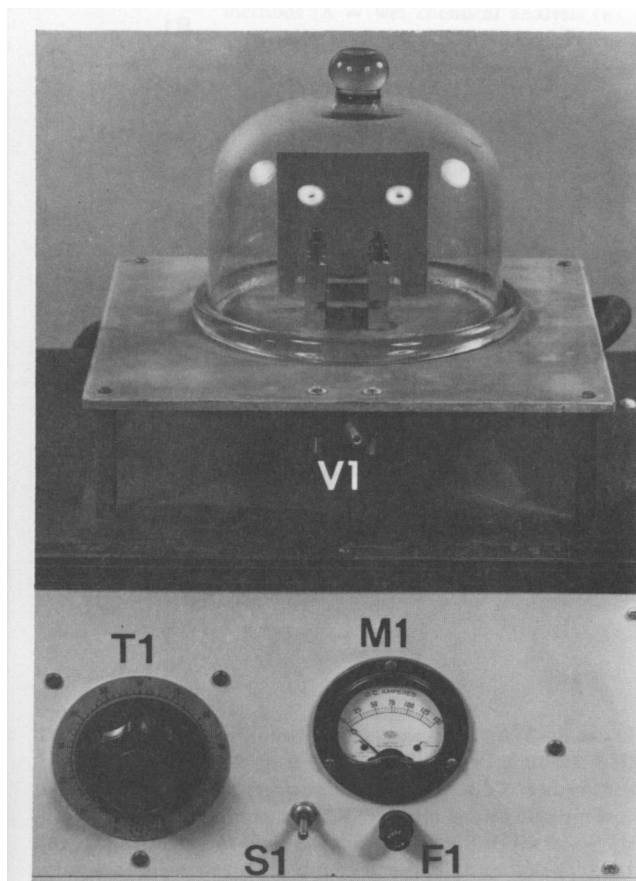
FIGURE 1.—Front view of the fusion furnace: the fusion boat is mounted between the two posts and the whole assembly is covered by a glass bell jar that is continuously flushed by nitrogen (for symbol explanation see Figure 3).

FIGURE 2.—Detail of the fusion bridge (P = positive and negative terminals of the bridge; B = fusion boat; Q = outlet of the nitrogen quench line; O = outlets through which the gas under the glass bell jar is forced out; S = vertical shield behind which is located the outlet for the purge line through which nitrogen enters the glass bell jar during the flushing cycle (see Figure 3).

in the fusion boat and covering the fusion assembly by the bell jar it takes about 1 min to establish an atmosphere of almost pure nitrogen. This is documented by the lack of oxidation of a Mo strip heated in this atmosphere at 1750° C for 25 min.

Two melting procedures were used. (1) Samples were heated for about 10 sec at low temperature (dark red glow of the strip) to drive off adsorbed water and water of hydration if present. The temperature was then rapidly increased to approximately 1700° C. The powders usually melt in 3-5 sec but total heating at the final temperature for about 10-30 sec promotes diffusion and thus formation of more homogeneous glasses. (2) Rapid heating of the cold powder to about 1700° C was also investigated. When subjected to this technique the powders fuse more rapidly probably due to the presence of water, which is driven off when the first technique is used.

There is no apparent difference in the homogeneity of the glasses produced by these two techniques.

Quenching of the melts is accomplished by simultaneously shutting off the power to the fusion bridge and directing a stream of nitrogen onto the bottom of the fusion boat. Cooling is sufficiently fast to prevent crystallite formation in all but the most mafic samples. Quench olivine is common in the more mafic samples.

In order to avoid either strip-contaminated glass, glass possibly depleted by elemental diffusion into the strip (Brown, 1977), or elemental volatilization into the nitrogen atmosphere, only glass in the interior of the bead or shard was analyzed.

The glasses were analyzed by a 9-spectrometer computer-automated ARL-SEMQ electron microprobe. The spectrometers were equipped with the following analyzing crystals. Si-EDDT, Al-EDDT,
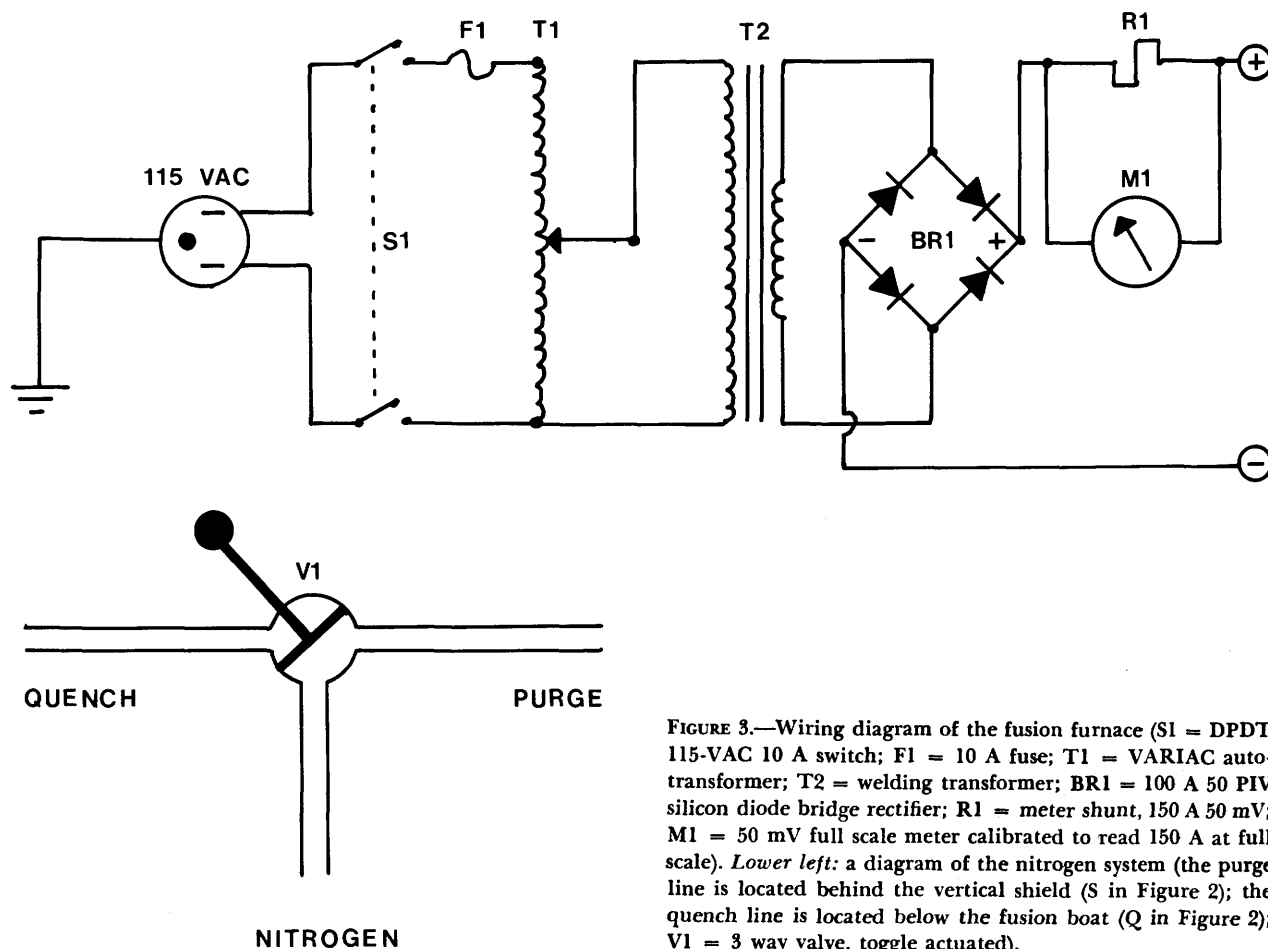
FIGURE 3.—Wiring diagram of the fusion furnace (S1 = DPDT 115-VAC 10 A switch; F1 = 10 A fuse; T1 = VARIAC autotransformer; T2 = welding transformer; BR1 = 100 A 50 PIV silicon diode bridge rectifier; R1 = meter shunt, 150 A 50 mV; M1 = 50 mV full scale meter calibrated to read 150 A at full scale). Lower left: a diagram of the nitrogen system (the purge line is located behind the vertical shield (S in Figure 2); the quench line is located below the fusion boat (Q in Figure 2); V1 = 3 way valve, toggle actuated).

Fe-LiF, Mg-ADP, Ca-LiF, Na-RAP, K-LiF, P-ADP. The data were corrected by an on-line computer using the method of Bence and Albee (1968). During the analysis 15 kV accelerating potential and 0.02 μA sample current were used. A defocused beam, 20-50 μm in diameter, practically eliminates Na volatilization during analysis and also helps to average local, small inhomogeneities which may exist in the glass. It is recommended that 10 sec count times be used and the analysis repeated at least ten times to accumulate a statistically significant body of data. The repeated measurements also help to average possible larger scale inhomogeneities.

Results

Eleven rock powders and three mineral samples were fused by the described technique. The rocks were selected to cover as wide a compositional range as possible. Analytical data for the eleven rock samples are presented in Table 1. The electron microprobe data show good agreement with the wet chemical values, which were recalculated volatile free in order to facilitate direct comparison with the electron microprobe analyses. The CV values (CV = standard deviation x 100/mean) reflect significantly the homogeneity of the glasses but also include a component of variation due to instrumental instability. The standards used in the glass analyses were analyzed by wet chemical techniques at the Department of Mineral Sciences, Smithsonian Institution. Their compositions are given in Jarosewich, Nelen, and Norberg (this volume).

The average differences between the wet chemical analyses and the electron microprobe analyses are shown in Table 2. The average accuracy in weight percent is better than 0.2 for all major components except SiO_2 which is accurate to better than 0.3. In

TABLE 1.—Analyses of 11 fused rock powder samples by wet chemical and electron microprobe methods (A = wet chemical analysis (wt %); B = electron microprobe analysis (wt %), numbers in parentheses are the numbers of point analyses averaged; CV (approximate measure of glass homogeneity) = (SD × 100)/x̄; ND = no data; Std (standard or reference sample) 1 = VG–568 (glass), 2 = VG–A99 (glass), 3 = tektite glass (synthetic), 4 = VG–2 (glass), 5 = Kakanui hornblende; wet chemical analyses of W-1, BCR-1, and AGV-1 from Flanagan, 1973; remaining wet chemical analyses by E. Jarosewich and J. Norberg, Department of Mineral Sciences, Smithsonian Institution; all wet chemical analyses recalculated as volatile free to facilitate direct comparison with microprobe analyses; standard analyses given in Table 1, Jarosewich, Nelen, and Norberg, this volume)

Constituent	113180/B159(b)				D-14-53				MI-8				W-1			
	A	B(14)	CV	Std	A	B(26)	CV	Std	A	B(46)	CV	Std	A	B(29)	CV	Std
SiO_2	47.32	47.41	1.07	4	51.09	51.19	0.42	3	50.99	51.23	1.30	4	53.00	53.14	1.29	4
TiO_2	2.87	2.67	3.19	5	0.92	0.98	3.95	5	1.87	2.06	4.54	5	1.08	1.05	5.33	5
Al_2O_3	16.99	16.85	1.99	4	18.92	19.14	1.77	5	19.27	19.02	2.96	4	15.10	15.44	1.90	4
FeO	11.12	10.97	1.43	4	11.26	11.11	1.93	2	9.60	9.81	2.21	4	10.05	9.85	2.56	4
MnO	0.19	ND			0.15	0.14			0.16	ND			0.17	ND		
MgO	7.60	7.65	2.40	5	3.16	3.34	4.99	2	4.05	4.01	3.99	4	6.67	6.51	2.51	5
CaO	10.26	10.13	1.55	4	10.17	10.11	1.14	2	9.35	9.33	2.73	4	11.04	11.15	1.46	4
Na_2O	2.79	2.96	2.42	3	2.49	2.30	3.51	1	3.50	3.58	2.40	4	2.16	2.14	2.92	4
K_2O	0.69	0.63	10.17	3	1.42	1.30	4.73	3	0.57	0.57	9.13	3	0.65	0.62	7.77	3
P_2O_5	0.28	ND			0.14	ND			0.23	ND			0.14	ND		
Total	100.11	99.27			99.72	99.61			99.59	99.61			100.06	99.90		

FUSION CONDITIONS

	113180/B159(b)	D-14-53	MI-8	W-1
Temp. (°C)	1700	1750	1650	1670
Time (sec)	30	30	20	15, 20

Constituent	113419				BCR-1				SH-384-2				AGV-1			
	A	B(16)	CV	Std	A	B(29)	CV	Std	A	B(25)	CV	Std	A	B(22)	CV	Std
SiO_2	54.50	54.51	1.63	3	55.37	55.21	0.78	4	56.64	57.86	1.99	3	60.14	60.46	0.27	4
TiO_2	0.64	0.60	6.32	5	2.24	2.09	4.06	5	0.95	0.80	9.29	5	1.06	0.92	6.48	5
Al_2O_3	19.49	19.75	2.20	5	13.83	13.79	2.42	4	19.80	18.77	3.65	5	17.58	17.59	1.56	4
FeO	7.28	7.04	3.05	2	12.30	12.26	2.35	4	6.33	5.88	3.81	2	6.23	6.20	3.24	4
MnO	0.16	0.17			0.18	ND			0.11	0.11			0.10	ND		
MgO	4.87	4.84	4.07	2	3.52	3.48	4.33	5	3.48	3.73	3.84	2	1.56	1.55	4.35	5
CaO	9.46	9.30	1.35	2	7.03	7.06	1.79	4	6.92	6.78	1.34	2	4.99	5.09	1.72	4
Na_2O	2.90	3.17	3.03	1	3.32	3.26	2.25	4	4.58	4.46	2.92	1	4.34	4.05	2.49	4
K_2O	0.62	0.60	8.27	3	1.73	1.66	2.75	3	1.18	1.20	6.75	3	2.95	2.84	2.21	3
P_2O_5	0.16	ND			0.36	ND			0.15	ND			0.50	ND		
Total	100.08	99.88			99.88	98.81			100.14	99.59			99.45	98.70		

FUSION CONDITIONS

	113419	BCR-1	SH-384-2	AGV-1
Temp. (°C)	1670	1670	1670	1670
Time (sec)	30	10, 20	21	15

TABLE 1.—Continued.

Constituent	SH-281				111108				VG-568			
	A	B(24)	CV	Std	A	B(16)	CV	Std	A	B(21)	CV	Std
SiO_2	63.76	63.67	1.01	3	64.01	63.37	1.65	3	76.70	76.48	1.19	1
TiO_2	0.66	0.60	5.30	2	0.32	0.36	7.99	2	0.12	0.18	15.58	1
Al_2O_3	17.69	17.78	1.23	5	12.95	13.06	2.72	5	12.42	12.33	1.65	1
FeO	4.48	4.33	2.16	3	6.79	6.65	2.35	3	1.23	1.24	2.49	1
MnO	0.08	0.08			0.13	0.13			0.03	ND		
MgO	1.91	1.87	4.71	3	5.47	5.84	2.73	3	<0.1	ND		
CaO	5.12	5.05	1.09	3	7.51	7.34	1.92	3	0.50	0.54	12.15	1
Na_2O	4.85	4.95	2.10	1	1.83	2.01	3.16	1	3.74	3.71	3.11	1
K_2O	1.40	1.33	2.82	1	0.95	0.86	7.04	1	4.88	4.89	4.36	1
P_2O_5	0.13	ND			0.06	ND			<0.01	ND		
Total	100.08	99.66			99.96	99.62			99.73	99.37		

FUSION CONDITIONS

	SH-281	111108	VG-568
Temp. (°C)	1670	1700	1750
Time (sec)	10	15	10

TABLE 2.—Absolute differences and relative differences (percents of the amounts present) between the wet chemical and electron microprobe analyses presented in Table 1

Constituent	Range of Analyzed Samples (wt %)	Average Absolute Difference (wt %)	Range Absolute Difference (wt %)	Average Relative Difference (%)	Range Relative Difference (%)
SiO_2	47.32 - 76.70	0.21	0.09 - 0.64	0.4	0.1 - 1.0
TiO_2	0.12 - 2.87	0.10	0.04 - 0.20	12.7	2.8 - 50.0
Al_2O_3	12.42 - 18.92	0.14	0.01 - 0.34	0.9	0.1 - 2.3
FeO	1.23 - 12.30	0.16	0.01 - 0.45	2.2	0.3 - 7.1
MgO	<0.01 - 7.60	0.12	0.01 - 0.37	2.8	0.6 - 7.2
CaO	0.50 - 10.26	0.09	0.02 - 0.17	1.9	0.2 - 8.0
Na_2O	1.83 - 4.85	0.13	0.02 - 0.18	4.5	0.8 - 9.8
K_2O	0.57 - 4.89	0.05	0.00 - 0.12	4.5	0.0 - 9.5

relative percent the average accuracy is better than 5 for all major components except TiO_2 which is better than 13. The somewhat poorer accuracy in measuring TiO_2 is due in part to some very low measured concentrations. In such cases a small error (e.g., 0.06 wt % of TiO_2 in sample VG-568) represents as much as 50% relative error. However, the major part of the error is probably due to the presence of residual or quench Fe-Ti oxides observed in the form of opaque spots in some glasses. Due to their very small size a positive identification is difficult.

Attempts to fuse granitic samples and MgO-rich, low-silica samples to homogeneous glasses were unsuccessful. USGS samples G-2, GSP-1, and G-1 produced very inhomogeneous glasses when less than 100 mesh powders were used. Subsequent testing showed that if very fine powders are used more

homogeneous glasses result. The required preparation of very fine powders and the increased possibility of Na_2O loss on fusion make routine fusion of high-silica samples impractical. The MgO-rich, low-silica samples could not be prevented from growing skeletal olivine crystals during quenching.

Three mineral samples (Table 3) and a sample of natural rhyolite glass (VG-568, Table 1) were fused to evaluate: (1) Na_2O loss, (2) the behavior of hydrous minerals during fusion, and (3) the impact of rapid dehydration on the composition of the resulting glass.

It is clear that prolonged fusion of the samples results in Na_2O loss. But fusion times ranging up to 20 sec produce good glasses with minimal Na_2O loss. The three fusion times used in the fusion of the Lake County plagioclase sample (Table 3) did not produce significantly large differences in the Na_2O

TABLE 3.—Comparison of analyses of crystalline minerals with analyses of the same minerals fused for various times (A = electron microprobe analyses of the unfused minerals; B = electron microprobe analyses of fused minerals; numbers in parentheses are the numbers of point analyses averaged; C = wet chemical analyses of crystalline mineral recalculated water free, based on data in Table 1, Jarosewich, Nelen, and Norberg, this volume)

Constituent	Lake Co. Plagioclase USNM 115900				Omphacite USNM 110607			Arenal Hornblende USNM 111356	
	A	B			A	B		C	B
	(13)	(17)	(13)	(21)	(14)	(18)	(12)		(16)
SiO_2	51.29	51.27	51.04	51.30	55.36	55.01	55.48	42.36	42.18
TiO_2	---	---	---	---	0.37	0.37	0.37	1.44	1.22
Al_2O_3	31.07	30.78	30.78	31.01	8.81	8.69	8.60	15.81	15.56
FeO	0.50	0.50	0.50	0.49	4.58	4.56	4.63	11.72	11.79
MgO	---	---	---	---	11.69	12.01	12.03	14.55	14.97
CaO	13.79	13.70	13.64	13.77	13.86	13.64	13.67	11.80	11.63
Na_2O	3.33	3.38	3.45	3.30	4.95	5.10	4.20	1.95	2.12
K_2O	---	---	---	---	0.15	0.17	0.15	0.21	0.21
Total	99.98	99.63	99.41	99.87	99.77	99.55	99.13	99.84	99.68

FUSION CONDITIONS

Temp. (°C)		1670	1670	1730		1700	1730		1670
Time (sec)		5		25		10	30		5

concentration. However, the 25 sec fusion probably records a small Na_2O loss, and the 30 sec fusion of omphacite has clearly resulted in a significant Na_2O loss.

Arenal hornblende frothed extensively during fusion due to the escape of structural water (1.21 wt % H_2O). The composition of the resulting glass is very close to the crystalline mineral composition recalculated water free. Although it was anticipated that Na_2O may be volatilized more rapidly during H_2O release from hydrous minerals, no Na_2O loss was observed in three separate glasses, each produced by 5 sec fusion. The hornblende sample was not fused longer than 5 sec because the water present in the mineral facilitates rapid fusion.

No Na_2O was lost during the 10 sec fusion of VG-568. This sample is a natural glass and therefore provides information only on Na_2O stability during fusion.

Summary and Conclusions

The described fusion technique uses very small amounts of sample and is rapid. The furnace can be built and operated inexpensively. When used in conjunction with an electron microprobe, major element concentrations can be measured rapidly and quite accurately for rock samples ranging in composition from basalts to high-silica andesites. More mafic samples have a tendency to crystallize olivine on cooling. Granites and other high-silica, high-alkali samples produce glasses of high viscosity preventing homogenization during the short fusion

times necessary to prevent Na_2O loss. Fusion of extremely fine powders may decrease the inhomogeneity of the resulting glass and improve the resulting analysis.

In general the fused glasses are sufficiently homogeneous and the electron microprobe is suitably accurate to allow routine use of the technique. The average accuracy of better than 5% relative for all major components except TiO_2 (better than 13%) is quite acceptable.

The rapidity and convenience with which the samples can be prepared and analyzed allowed major element reconnaissance analyses of rock suites previously not analyzed due to time and cost factors involved. The rock powders and the three mineral samples investigated suggest that if fusion times of less than 20 sec are used Na_2O loss is prevented or greatly restricted and glasses result that are sufficiently homogeneous to be suitable for microprobe analysis.

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Microprobe Analyses of Four Natural Glasses and One Mineral: An Interlaboratory Study of Precision and Accuracy

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ABSTRACT

An interlaboratory study for precision and accuracy of electron microprobe analyses of four natural glasses and one mineral is reported in this compilation. The results obtained by the three participating laboratories are in good agreement with chemical analysis values (where available) for SiO_2, Al_2O_3, FeO, CaO, and K_2O ($\geq$ 2 wt %). One laboratory shows a considerable bias for Na_2O and a slight bias for MgO. Some results for MnO, K_2O ($\sim$0.2 wt %), and P_2O_5, considering their low concentrations, are in reasonably good agreement; others show scatter. In general, considering that different reference samples and operating parameters were used to obtain these analyses, the correlation of results is encouraging. On the basis of the available data, however, it is evident that the precision and accuracy of these results cannot be improved much without more elaborate data acquisition techniques.

Introduction

The need for accurate microprobe analyses of natural glasses is of great importance in the study of volcanic and deep sea rocks. Melson et al. (1977) briefly summarized this need, referring specifically to the analyses of glasses from the Deep Sea Drilling Project. Since a standardized method for analysis of such glasses is not available, each laboratory has developed its own techniques and has been using its

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own preferred reference samples for these analyses. It is rather remarkable that many of the results obtained on the same or similar samples, using different techniques and reference samples, are generally in good agreement. Occasionally, however, some of these results exceed accepted analytical errors. Since more than one institution may participate in the study of volcanic or deep sea rocks and the analytical data may be used interchangeably for petrologic studies, it is of utmost importance that the precision and accuracy of these analyses be determined. As a start in obtaining this type of data, a set of the same samples has been analyzed by three laboratories, each using its own standard operating parameters; these results are compared for precision and accuracy. The participating laboratories were: Massachusetts Institute of Technology (MIT), Smithsonian Institution (SI), and U.S. Geological Survey (USGS).

The data presented in this paper are meant to serve primarily as a general guide for the expected accuracy and precision of microprobe analyses of glasses; however, they can serve as a guide for such analyses of minerals as well.

Experimental Procedure

One disc was prepared containing only one grain of Kakanui hornblende and only one grain of each

of the following natural glasses:

VG–2 (USNM 111240–52), Basalt with a few rare micro-phenocrysts of olivine and plagioclase in section, less than 1%. Chemical analysis, Table 4.

VG–A99 (USNM 113498–1). Basalt from Makaopuhi Lava Lake, Hawaii (Wright and Okamura, 1977). Micropheno-crysts of plagioclase in section, about 1% or less. Chem-ical analysis, Table 4.

VG–999 (USNM 113155–614). High-titanium ferro-basalt from DeSteiguer dredge D6, Galapagos Spreading Center (Byerly et al., 1976). Phenocrysts of plagioclase, augite, and olivine. Microphenocrysts of plagioclase and augite, about 10%–15% in section.

VG–D08 (USNM 113154–557). Basalt from DeSteiguer dredge D5, Galapagos Spreading Center (Byerly et al., 1976). Phenocrysts of olivine, plagioclase, and minor spinel. No microphenocrysts in section.

This disc was carbon coated and sent to the three laboratories for microprobe analysis.

These four glasses were selected because they represent the approximate elemental ranges encountered in the study of natural basaltic glasses. Classical chemical analyses are available for Kakanui hornblende, VG-2, and VG-A99 for comparison with the microprobe results (see Table 1, Jarosewich, Nelen, and Norberg, this volume). Although no chemical analyses are available for VG-999 and VG-D08, these two samples were included in this study to obtain additional data on the precision among the microprobe analyses themselves. The same grain was analyzed by each laboratory to elimi-nate the variable of possible inhomogeneities be-tween different grains of the same sample.

Since the primary purpose of this work was to obtain analytical values for the samples as they are

obtained under the laboratories' normal operating conditions, the operating parameters (kv, μA, beam size, etc.) were not specified. The samples were analyzed employing the standard operating param-eters and reference samples used in each laboratory (Tables 1, 2).

The precision was obtained by analyzing all sam-ples using Kakanui hornblende as the reference sample. In this manner discrepancies due to the use of different reference samples were eliminated and any deviations could be ascribed to the instrumen-tal parameters. Since Kakanui hornblende is not an ideal reference sample for obtaining accurate anal-yses of these glasses, the accuracy was determined by analyzing these samples using each laboratory's pre-ferred reference samples and comparing results with the chemical analyses of these glasses. The analytical results were compiled in the following manner. (1) Each sample was analyzed several times using Kakanui hornblende as the reference sample; the number of individual analyses and the averages are given in Tables 5–7. (2) The samples were analyzed several times using each laboratory's preferred ref-erence samples; the number of individual analyses, the averages, and the type of reference samples used in these analyses are also given in Table 5–7. (3) The uncorrected averages obtained using Kakanui hornblende as the reference sample are summarized in Table 3 for comparisons of precision; these re-sults indicate the variation of the data due only to the instrumental variation. (4) Table 4 summarizes the corrected results obtained using each labora-tory's preferred reference samples; comparisons of

TABLE 1.—Instrumental parameters used by participating laboratories

Laboratory	Instrument	Accelerating Potential (kV)	Sample Current (μA)	Beam Size (μm)	Counting Time
MIT	ETEC MAC 5	15	0.03	4	30 sec or 60,000 counts
SI	ARL-SEMQ 9 spectrometers	15	0.05	2, 30	Seven 10 sec counts for each analysis
USGS	ARL-EXM-SM	15	0.05	20	20 sec or 20,000 counts for each element

Table 2.—Analyses of reference samples used by participating laboratories

Reference sample	SiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO
					MIT					
DJ35	56.88	8.82		12.10	16.83	5.36				
P-140	40.86		7.23	51.63						
AN-60	53.05	30.01			12.38	4.56				
MAC AP	0.05		0.03	0.01	38.82	0.18			17.86	
Orthoclase	64.39	18.58				1.14	14.92			
Di2Ti	54.36			18.26	25.38			2.00		
MnIlm			45.41	0.25				51.61		1.50
Coss	40.93		40.99				6.93	8.71		
					SI					
Kak hornblende	40.37	14.90	10.92	12.80	10.30	2.60	2.05	4.36		0.09
VG-2	50.81	14.06	11.83	6.71	11.12	2.62	0.19	1.85	0.20	0.22
Apatite	0.34	0.07	0.05		54.02	0.23			40.78	
Fayalite	29.22		67.54					0.04		2.14
					USGS					
Rhodonite	46.76	0.96	12.49	˙0.42	5.62					33.34
Garnet-Pyrope	41.45	23.50	10.76	18.80	5.09			0.51		0.33
Orthoclase	63.42	19.24	0.10		0.08	0.36	15.34		0.49	
Di2Ti	54.39			18.26	25.38			2.00		
Diopside-Jadeite	56.10	3.78		15.84	22.02	2.31				

these results with the chemical values indicate the accuracy of the microprobe results.

Discussion

Comparisons for precision of the results obtained using Kakanui hornblende as the reference sample (Table 3) indicate that careful microprobe analyses for all major elements, titanium, and high potassium (≥ 2 wt %) produce relatively precise results. The results also indicate that minor elements and sodium vary considerably and more careful work must be done if the results for these elements are to be used for exacting petrological work. There is no pronounced bias in the results by any of the three laboratories for the major elements except for a slight bias in the magnesium results. There is a bias in the results for sodium, low potassium ($\sim$0.2 wt %), and phosphorus. The sodium and phosphorus results analyzed by laboratory 1 run consistently high. The potassium results by laboratory 2 run slightly high and by laboratory 3, low. The discrepancy for these three elements is significant because all elements were determined using the same reference sample, indicating that the techniques for acquiring the data should be examined.

Comparisons for precision of the results of microprobe analyses in which each laboratory's preferred reference samples were used (Table 4) also check favorably for the major elements, titanium, and potassium (≥ 2 wt %); more important, these results are in excellent agreement with the values for the three samples analyzed by classical chemical methods, thus showing a high level of accuracy. The results for sodium show a much larger discrepancy than those given in Table 3; only the lowest values of the microprobe analyses check well with the chemically analyzed sodium values. Sodium frequently presents a problem in microprobe analysis and to demonstrate this problem, laboratory 2 analyzed sodium using a 2 μm beam and a 30 μm beam; the former gives somewhat lower values for some samples (Table 6, results in brackets), the latter gives acceptable values. Kakanui hornblende sodium results are not affected by the beam size. One of the possible explanations for the higher results of laboratory 1 and lower results of laboratory 2 with the small beam is the unique behavior of sodium in the electron beam for both the reference samples and the unknown samples. If for example a reference sample in which sodium is easily "volatilized" (accepted description of decreasing inten-

TABLE 3.—Summary of uncorrected data from microprobe analyses of the 5 samples, using Kakanui hornblende as the reference sample, for interlaboratory comparison of precision (figure in parentheses indicates number of analyses averaged; each analysis represents up to 10 individual point analyses; laboratory 1 = MIT, 2 = SI, 3 = USGS; data based on Tables 5–7)

Constituent	Lab	KH	VG-2	VG-A99	VG-999	VG-D08
SiO_2	1	40.45 (2)	51.07 (2)	52.49 (1)	52.27 (2)	50.17 (1)
	2	40.58 (4)	51.62 (4)	52.45 (4)	52.21 (4)	50.56 (4)
	3	40.31 (3)	51.05 (4)	52.54 (2)	51.88 (1)	50.36 (2)
Al_2O_3	1	14.88 (2)	14.69 (2)	13.23 (1)	13.61 (2)	16.60 (1)
	2	14.97 (4)	15.06 (4)	13.54 (4)	14.12 (4)	17.27 (4)
	3	14.98 (3)	14.85 (4)	13.13 (2)	14.41 (1)	16.71 (2)
FeO	1	10.85 (2)	11.96 (2)	13.57 (1)	13.79 (2)	9.00 (1)
	2	10.91 (4)	11.84 (4)	13.60 (4)	13.71 (4)	8.97 (4)
	3	10.81 (3)	11.78 (4)	13.46 (2)	13.66 (1)	8.88 (2)
MgO	1	12.83 (2)	7.02 (2)	5.29 (1)	5.98 (2)	9.36 (1)
	2	12.67 (4)	6.90 (4)	4.98 (4)	5.81 (4)	8.71 (4)
	3	12.92 (3)	6.87 (4)	4.99 (2)	5.57 (1)	8.70 (2)
CaO	1	10.20 (2)	11.12 (2)	9.38 (1)	10.39 (2)	12.48 (1)
	2	10.39 (4)	11.16 (4)	9.29 (4)	10.40 (4)	12.39 (4)
	3	10.24 (3)	11.01 (4)	8.80 (2)	10.26 (1)	12.13 (2)
Na_2O	1	2.74 (2)	2.90 (2)	2.91 (1)	2.89 (2)	2.77 (1)
	2	2.59 (2)	2.65 (2)	2.71 (2)	2.60 (2)	2.38 (2)
	3	2.67 (3)	2.78 (4)	2.71 (2)	2.66 (1)	2.40 (2)
K_2O	1	2.02 (2)	0.18 (2)	0.77 (1)	0.14 (2)	0.06 (1)
	2	2.05 (4)	0.20 (4)	0.83 (4)	0.17 (4)	0.08 (4)
	3	1.96 (3)	0.06 (4)	0.72 (2)	0.03 (1)	0.00 (2)
TiO_2	1	4.36 (2)	1.66 (2)	3.65 (1)	1.72 (2)	0.98 (1)
	2	4.38 (4)	1.67 (4)	3.70 (4)	1.74 (4)	1.01 (4)
	3	4.27 (3)	1.64 (4)	3.77 (2)	1.66 (1)	0.92 (2)
P_2O_5	1	0.09 (2)	0.24 (2)	0.44 (1)	0.22 (2)	0.16 (1)
	2	0.06 (2)	0.20 (2)	0.39 (2)	0.19 (2)	0.12 (2)
	3	0.08 (3)	0.20 (4)	0.42 (2)	0.17 (1)	0.12 (2)
MnO	1	0.07 (2)	0.16 (2)	0.16 (1)	0.17 (2)	0.16 (1)
	2	0.09 (2)	0.18 (2)	0.18 (2)	0.20 (2)	0.14 (2)
	3	0.19 (3)	0.25 (4)	0.22 (2)	0.13 (1)	0.16 (2)

sity) is used for standardization to analyze an unknown sample which does not show this volatilization effect, the sodium results for the unknown sample will be high. If on the other hand the sodium in the reference sample is "stable" and sodium in the unknown sample is easily volatilized, low results will be obtained. The use of a larger beam size may diminish this discrepancy.

Low potassium, manganese, and phosphorus results vary just as much as those in Table 3. It

should be noted that phosphorus corrects up by 15%–20% in most cases, giving much higher values than those of the chemical analyses. These higher phosphorus corrections are evident with both the up-dated Bence-Albee (Albee and Ray, 1970) and Magic IV correction procedures. Both correction procedures performed by one of us (A. P.) give excellent agreement with each other for all elements (Table 5).

Since for this study some grains were analyzed up

TABLE 4.—Summary of corrected data from microprobe analyses of the 5 samples using each laboratory's preferred reference samples, along with chemical analyses of 3 of the samples, for interlaboratory comparison of precision and accuracy (figures in parentheses indicates number of analyses averaged; each analysis represents up to 10 individual point analyses; laboratory 1 = MIT, 2 = SI, 3 = USGS; Chem. = chemical analysis from Table 1, Jarosewich, Nelen, and Norberg, this volume; microprobe data based on Tables 5–7)

Constituent	Lab	KH	VG-2	VG-A99	VG-999	VG-D08
SiO_2	1	40.65 (5)	50.85 (1)	51.05 (4)	51.16 (1)	50.29 (1)
	2	40.72 (4)	50.72 (4)	51.22 (4)	51.41 (4)	50.18 (4)
	3	40.42 (2)	50.75 (1)	50.80 (1)	50.70 (1)	49.77 (1)
	(Chem.)	40.37	50.81	50.90		
Al_2O_3	1	14.61 (5)	13.81 (1)	12.59 (4)	13.06 (1)	15.80 (1)
	2	14.95 (4)	14.15 (4)	12.66 (4)	13.36 (4)	16.17 (4)
	3	14.76 (2)	13.98 (1)	12.80 (1)	13.54 (1)	15.44 (1)
	(Chem.)	14.90	14.06	12.97		
FeO	1	10.45 (5)	11.26 (1)	13.24 (4)	12.94 (1)	8.67 (1)
	2	10.93 (4)	11.79 (4)	13.47 (4)	13.68 (4)	8.96 (4)
	3	10.54 (2)	11.79 (1)	13.41 (1)	13.30 (1)	8.78 (1)
	(Chem.)	10.92	11.83	13.18		
MgO	1	12.95 (5)	7.01 (1)	5.24 (4)	5.99 (1)	8.88 (1)
	2	12.70 (4)	6.78 (4)	4.95 (4)	5.77 (4)	8.46 (4)
	3	13.03 (2)	7.02 (1)	5.16 (1)	6.13 (1)	8.78 (1)
	(Chem.)	12.80	6.71	5.18		
CaO	1	9.99 (5)	10.85 (1)	9.08 (4)	10.12 (1)	12.23 (1)
	2	10.47 (4)	11.14 (4)	9.28 (4)	10.36 (4)	12.41 (4)
	3	10.12 (2)	10.72 (1)	8.97 (1)	10.18 (1)	12.05 (1)
	(Chem.)	10.30	11.12	9.38		
Na_2O	1	2.80 (5)	3.17 (1)	2.81 (4)	3.06 (1)	2.79 (1)
	2	2.60 (2)	2.66 (2)	2.70 (2)	2.61 (2)	2.25 (2)
	3	2.72 (2)	2.75 (1)	2.73 (1)	2.57 (1)	2.39 (1)
	(Chem.)	2.60	2.62	2.73		
K_2O	1	2.10 (5)	0.20 (1)	0.82 (4)	0.14 (1)	0.07 (1)
	2	2.06 (4)	0.21 (4)	0.90 (4)	0.19 (4)	0.09 (4)
	3	1.94 (2)	0.18 (1)	0.76 (1)	0.04 (1)	0.09 (1)
	(Chem.)	2.05	0.19	0.80		
TiO_2	1	4.87 (5)	1.86 (1)	4.04 (4)	1.93 (1)	1.09 (1)
	2	4.40 (4)	1.91 (4)	4.05 (4)	1.96 (4)	1.14 (4)
	3	4.65 (2)	1.86 (1)	3.77 (1)	1.80 (1)	1.03 (1)
	(Chem.)	4.36	1.85	4.06		
P_2O_5	1	0.14 (5)	0.32 (1)	0.54 (4)	0.29 (1)	0.23 (1)
	2	0.07 (2)	0.23 (2)	0.46 (2)	0.22 (2)	0.15 (2)
	3	0.04 (2)	0.19 (1)	0.31 (1)	0.15 (1)	0.08 (1)
	(Chem.)	0.00	0.20	0.41		
MnO	1	0.10 (5)	0.22 (1)	0.19 (4)	0.29 (1)	0.18 (1)
	2	0.11 (2)	0.22 (2)	0.22 (2)	0.25 (2)	0.17 (2)
	3	0.06 (2)	0.23 (1)	0.19 (1)	0.20 (1)	0.13 (1)
	(Chem.)	0.09	0.22	0.19		

TABLE 5.—MIT laboratory individual analyses of Kakanui hornblende and 4 natural glasses using Kakanui hornblende as reference sample and also the laboratory's preferred reference samples

Run No.	Conditions	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
					Kakanui hornblende						
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	40.39	14.69	10.99	12.57	10.13	2.71	2.03	4.34	0.10	0.04
	B-A Corr.	40.35	14.68	10.99	12.59	10.13	2.71	2.03	4.34	0.12	0.04
	Magic IV Corr.	40.35	14.68	10.99	12.59	10.13	2.71	2.04	4.35	0.12	0.05
	σ (5)	0.17	0.11	0.15	0.13	0.15	0.12	0.02	0.03	0.00	0.01
2	Uncorrected	40.51	15.07	10.70	13.09	10.27	2.77	2.00	4.37	0.08	0.10
	B-A Corr.	40.55	15.07	10.71	13.08	10.28	2.76	2.00	4.38	0.10	0.10
	Magic IV Corr.	40.56	15.08	10.70	13.07	10.28	2.75	2.00	4.37	0.12	0.10
	σ (6)	0.53	0.08	0.22	0.22	0.07	0.12	0.04	0.03	0.00	0.03
	Standards	DJ35	AN-60	P-140	P-140	DJ35	DJ35	Ortho	Di2Ti	MAC AP	MnIlm
4	Uncorrected	38.21	12.61	10.48	11.68	10.11	2.55	2.10	5.13	0.10	0.10
	B-A Corr.	40.29	14.45	10.37	12.98	9.92	2.87	2.05	4.94	0.12	0.11
	Magic IV Corr.	40.36	14.54	10.43	13.04	9.96	2.90	2.05	4.94	0.12	0.11
	σ (10)	0.34	0.08	0.27	0.26	0.14	0.09	0.02	0.08	0.00	0.03
5a	Uncorrected	38.92	12.66	10.34	11.58	10.20	2.55	2.16	5.05	0.11	0.12
	B-A Corr.	40.97	14.48	10.23	12.86	10.02	2.86	2.11	4.87	0.13	0.13
	Magic IV Corr.	41.07	14.57	10.29	12.88	10.05	2.89	2.10	4.87	0.15	0.12
	σ (5)	0.21	0.08	0.12	0.13	0.18	0.11	0.04	0.05	0.00	0.01
5b	Uncorrected	38.71	12.68	10.29	11.51	10.18	2.59	2.15	5.11	0.11	0.11
	B-A Corr.	40.75	14.50	10.18	12.78	9.99	2.91	2.10	4.92	0.15	0.12
	Magic IV Corr.	40.85	14.59	10.24	12.82	10.03	2.93	2.09	4.93	0.15	0.12
	σ (5)	0.32	0.08	0.13	0.17	0.13	0.08	0.04	0.05	0.00	0.03
	Standards	DJ35	AN-60	Coss.	DJ35	DJ35	DJ35	Ortho	Di2Ti	MAC AP	MnIlm
6	Uncorrected	38.32	12.83	10.26	12.38	10.18	2.49	2.16	5.03	0.11	0.04
	B-A Corr.	40.43	14.71	10.68	13.10	9.98	2.80	2.11	4.84	0.15	0.04
	Magic IV Corr.	40.52	14.80	10.60	13.18	10.02	2.83	2.10	4.85	0.15	0.04
	σ (10)	0.30	0.09	0.12	0.10	0.07	0.11	0.05	0.05	0.02	0.04
	Standards	DJ35	AN-60	Coss.	DJ35	DJ35	DJ35	Ortho	MnIlm	MAC AP	MnIlm
8	Uncorrected	38.71	13.00	10.35	12.34	10.23	2.29	2.16	4.20	0.13	0.11
	B-A Corr.	40.82	14.89	10.77	13.05	10.04	2.57	2.11	4.79	0.16	0.11
	Magic IV Corr.	40.92	14.97	10.70	13.14	10.09	2.60	2.10	4.73	0.15	0.11
	σ (10)	0.19	0.09	0.18	0.15	0.10	0.07	0.05	0.05	0.00	0.03
					VG-2						
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	51.36	14.51	12.15	6.83	11.03	2.82	0.19	1.67	0.23	0.14
	B-A Corr.	49.98	14.03	12.15	6.89	11.03	2.84	0.20	1.67	0.30	0.14
	Magic IV Corr.	50.08	14.03	12.15	6.88	11.04	2.84	0.19	1.67	0.30	0.14
	σ (10)	0.51	0.13	0.14	0.08	0.08	0.11	0.00	0.02	0.02	0.04

Table 5.—Continued

Run No.	Conditions	SiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO
2	Uncorrected	50.77	14.87	11.76	7.21	11.20	2.97	0.17	1.65	0.24	0.18
	B-A Corr.	49.52	14.39	11.77	7.26	11.20	2.99	0.17	1.66	0.31	0.18
	Magic IV Corr.	49.61	14.39	11.76	7.25	11.21	2.99	0.17	1.65	0.33	0.18
	σ (10)	0.41	0.19	0.18	0.10	0.07	0.12	0.01	0.03	0.00	0.04
	Standards	DJ35	AN-60	P-140	P-140	DJ35	DJ35	Ortho	Di2Ti	MAC AP	MnIlm
5	Uncorrected	49.61	12.49	11.39	6.27	11.05	2.80	0.20	1.93	0.25	0.20
	B-A Corr.	50.85	13.81	11.26	7.01	10.85	3.17	0.20	1.86	0.32	0.22
	Magic IV Corr.	51.05	13.88	11.33	7.02	10.91	3.19	0.20	1.86	0.33	0.22
	σ (6)	0.83	0.13	0.14	0.06	0.08	0.11	0.00	0.07	0.02	0.03

VG-A99

Run No.	Conditions	SiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
2	Uncorrected	52.49	13.23	13.57	5.29	9.38	2.91	0.77	3.65	0.44	0.16
	B-A Corr.	50.68	12.78	13.53	5.42	9.36	2.99	0.77	3.64	0.56	0.16
	Magic IV Corr.	50.84	12.78	13.55	5.41	9.37	2.99	0.77	3.64	0.56	0.15
	σ (10)	0.43	0.15	0.09	0.08	0.10	0.08	0.02	0.03	0.02	0.03
	Standards	DJ35	AN-60	P-140	P-140	DJ35	DJ35	Ortho	Di2Ti	MAC AP	MnIlm
4	Uncorrected	50.22	11.18	13.25	4.61	9.11	2.63	0.84	4.30	0.42	0.19
	B-A Corr.	51.03	12.36	13.06	5.24	8.91	3.05	0.82	4.12	0.54	0.20
	Magic IV Corr.	51.30	12.44	13.16	5.26	8.96	3.08	0.82	4.12	0.53	0.20
	σ (10)	0.28	0.09	0.19	0.10	0.06	0.08	0.01	0.05	0.02	0.03
5	Uncorrected	50.25	11.20	12.85	4.54	9.24	2.55	0.84	4.28	0.41	0.17
	B-A Corr.	51.00	12.34	12.68	5.16	9.04	2.95	0.83	4.10	0.53	0.18
	Magic IV Corr.	51.42	12.44	12.77	5.17	9.10	2.98	0.82	4.11	0.53	0.18
	σ (10)	0.49	0.08	0.18	0.07	0.08	0.15	0.02	0.05	0.02	0.03
	Standards	DJ35	AN-60	Coss.	DJ35	DJ35	DJ35	Ortho	Di2Ti	MAC AP	MnIlm
6	Uncorrected	50.32	11.50	13.11	4.88	9.29	2.24	0.83	4.27	0.43	0.18
	B-A Corr.	51.17	12.71	13.61	5.27	9.08	2.61	0.81	4.08	0.55	0.20
	Magic IV Corr.	51.43	12.78	13.53	5.31	9.14	2.63	0.81	4.09	0.56	0.19
	σ (5)	0.32	0.06	0.19	0.03	0.01	0.11	0.02	0.05	0.00	0.01
	Standards	DJ35	AN-60	Coss.	DJ35	DJ35	DJ35	Ortho	MnIlm	MAC AP	MnIlm
8	Uncorrected	50.09	11.73	13.09	4.88	9.51	2.24	0.85	3.41	0.42	0.16
	B-A Corr.	50.99	12.95	13.59	5.27	9.30	2.61	0.83	3.87	0.54	0.18
	Magic IV Corr.	51.26	13.03	13.50	5.30	9.36	2.63	0.83	3.83	0.53	0.18
	σ (10)	0.53	0.11	0.14	0.10	0.11	0.12	0.02	0.07	0.02	0.03

Table 5.—Continued

Run No.	Conditions	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
						VG-999					
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	52.20	13.66	14.03	5.85	10.23	2.75	0.15	1.70	0.21	0.13
	B-A Corr.	50.64	13.24	13.99	5.97	10.21	2.82	0.15	1.69	0.27	0.13
	Magic IV Corr.	50.79	13.24	14.01	5.98	10.24	2.82	0.16	1.70	0.27	0.13
	σ (5)	0.34	0.17	0.20	0.05	0.07	0.09	0.00	0.03	0.02	0.01
2	Uncorrected	52.34	13.56	13.55	6.11	10.54	3.02	0.13	1.73	0.23	0.20
	B-A Corr.	50.77	13.15	13.52	6.24	10.52	3.09	0.13	1.73	0.30	0.20
	Magic IV Corr.	50.91	13.16	13.53	6.24	10.54	3.08	0.13	1.73	0.30	0.21
	σ (10)	0.68	0.42	0.17	0.07	0.08	0.09	0.00	0.03	0.00	0.03
	Standards	DJ35	AN-60	P-140	P-140	DJ35	DJ35	Ortho	Di2Ti	MAC AP	MnIlm
5	Uncorrected	50.07	11.80	13.11	5.30	10.33	2.66	0.14	2.01	0.22	0.27
	B-A Corr.	51.16	13.06	12.94	5.99	10.12	3.06	0.14	1.93	0.29	0.29
	Magic IV Corr.	51.42	13.16	13.03	6.02	10.17	3.09	0.14	1.94	0.30	0.29
	σ (10)	0.45	0.08	0.17	0.07	0.06	0.20	0.01	0.03	0.02	0.03
						VG-D08					
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
2	Uncorrected	50.17	16.60	9.00	9.36	12.48	2.77	0.06	0.98	0.16	0.16
	B-A Corr.	49.25	16.02	9.04	9.20	12.53	2.70	0.07	0.99	0.21	0.16
	Magic IV Corr.	49.30	16.06	9.04	9.20	12.54	2.70	0.06	0.99	0.21	0.17
	σ (10)	0.43	0.55	0.09	0.18	0.08	0.09	0.01	0.03	0.00	0.03
	Standards	DJ35	AN-60	P-140	P-140	DJ35	DJ35	Ortho	Di2Ti	MAC AP	MnIlm
5	Uncorrected	48.68	14.35	8.73	8.13	12.41	2.55	0.07	1.12	0.18	0.17
	B-A Corr.	50.29	15.80	8.67	8.88	12.23	2.79	0.07	1.09	0.23	0.18
	Magic IV Corr.	50.43	15.86	8.72	8.88	12.29	2.81	0.07	1.08	0.24	0.18
	σ (10)	0.60	0.06	0.10	0.12	0.06	0.12	0.00	0.03	0.02	0.03

to 40 times to obtain good precision, it is reasonable to assume that, on the basis of the data in Table 3, the precision of microprobe analyses of basaltic glasses cannot be much improved without more elaborate data acquisition techniques. The standard deviations for various elements given in Tables 5–7 are of similar magnitudes for the three laboratories and they realistically indicate the expected scatter of analytical results. It is obvious that longer counts would not improve the precision very much and, indeed, extended counting times are impractical in day-to-day operation.

The accuracy, on the other hand, can be in some cases improved by the selection of suitable reference samples for a given unknown sample. From the data in Tables 5–7 it is evident that the microprobe results for some elements are in better agreement with the chemical results when reference samples other than Kakanui hornblende are used. The standard deviation here again is similar to that of the precision and thus could also be used as an indication of the expected scatter of the results. Analysis of elements below 0.1 wt % should be done with extra care and accepted with caution.

TABLE 6.—SI laboratory individual analyses of Kakanui hornblende and 4 natural glasses using Kakanui hornblende as reference sample and also the laboratory's preferred reference samples

Run No.	Conditions	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
					Kakanui hornblende						
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	41.09	15.05	10.87	12.78	10.70	2.58	*1.98	4.33	0.05	
	B-A Corr.	41.09	15.02	10.88	12.75	10.72	2.58	1.98	4.34	0.07	
	σ (7)	0.49	0.23	0.26	0.43	0.26	0.08	0.08	0.12	0.02	
2	Uncorrected	40.45	14.83	11.11	12.60	10.22	2.60	2.13	4.45	0.06	
	B-A Corr.	40.46	14.82	11.11	12.60	10.24	2.59	2.13	4.45	0.07	
	σ (7)	0.28	0.24	0.27	0.38	0.04	0.07	0.07	0.11	0.02	
3	Uncorrected	40.03	14.95	10.88	12.79	10.22	2.60	2.04	4.43		0.09
	B-A Corr.	40.13	14.98	10.88	12.83	10.23	2.60	2.04	4.43		0.09
	σ (7)	0.38	0.21	0.12	0.26	0.07	0.02	0.05	0.04		0.01
4	Uncorrected	40.76	15.06	10.76	12.51	10.40	2.58	2.05	4.29		0.09
	B-A Corr.	40.76	15.02	10.77	12.49	10.42	2.58	2.05	4.30		0.09
	σ (7)	0.23	0.28	0.08	0.21	0.14	0.01	0.06	0.07		0.01
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	Fay
1	Uncorrected	41.09	15.05	10.87	12.78	10.70	2.58	1.98	4.33	0.05	
	B-A Corr.	41.09	15.02	10.88	12.75	10.72	2.58	1.98	4.34	0.07	
	σ (7)	0.49	0.23	0.26	0.43	0.26	0.08	0.08	0.12	0.02	
2	Uncorrected	40.45	14.83	11.11	12.60	10.22	2.60	2.13	4.45	0.06	
	B-A Corr.	40.46	14.82	11.11	12.60	10.24	2.59	2.13	4.45	0.07	
	σ (7)	0.28	0.24	0.27	0.38	0.09	0.07	0.07	0.11	0.02	
3	Uncorrected	40.44	15.00	10.95	12.77	10.28	2.62	2.03	4.51		0.11
	B-A Corr.	40.51	15.02	10.96	12.82	10.30	2.62	2.03	4.51		0.12
	σ (7)	0.17	0.20	0.14	0.17	0.11	0.04	0.04	0.09		0.03
4	Uncorrected	40.83	14.95	10.76	12.63	10.57	2.58	2.08	4.30		0.10
	B-A Corr.	40.83	14.92	10.76	12.61	10.60	2.57	2.08	4.30		0.10
	σ (7)	0.37	0.22	0.07	0.25	0.14	0.03	0.06	0.06		0.02
					VG-2						
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	52.04	15.10	12.01	6.85	11.22	2.53	0.19	1.67	0.20	
	B-A Corr.	51.18	14.55	12.03	6.87	11.32	2.53	0.19	1.68	0.25	
	σ (7)	0.42	0.18	0.10	0.19	0.13	0.11	0.02	0.07	0.03	
2	Uncorrected	51.32	14.90	12.01	7.00	11.19	2.53	0.20	1.71	0.19	
	B-A Corr.	50.49	14.38	12.03	7.03	11.29	2.53	0.20	1.72	0.24	
	σ (7)	0.73	0.16	0.07	0.09	0.14	0.06	0.02	0.01	0.03	
3	Uncorrected	50.89	15.12	11.82	6.91	10.96	2.69	0.21	1.69		0.17
	B-A Corr.	50.19	14.64	11.83	6.98	11.06	2.69	0.21	1.70		0.17
	σ (7)	0.48	0.19	0.11	0.21	0.17	0.03	0.02	0.03		0.02

Table 6.—Continued

Run No.	Conditions	SiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO
4	Uncorrected	52.21	15.11	11.53	6.83	11.28	2.60	0.20	1.62		0.18
	B-A Corr.	51.32	14.55	11.55	6.85	11.39	2.59	0.20	1.63		0.18
	σ (7)	0.43	0.19	0.09	0.12	0.14	0.03	0.03	0.05		0.02
	Standards	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	AP	Fay
1	Uncorrected	50.56	14.14	11.72	6.57	11.10	2.62	0.22	1.94	0.19	
	B-A Corr.	50.57	14.13	11.73	6.57	11.11	2.62	0.21	1.94	0.24	
	σ (7)	0.48	0.25	0.15	0.11	0.09	0.11	0.02	0.06	0.02	
2	Uncorrected	50.69	14.08	11.54	7.01	11.18	2.47	0.22	1.92	0.18	
	B-A Corr.	50.71	14.08	11.56	6.99	11.19	2.46	0.21	1.93	0.22	
	σ (7)	0.51	0.26	0.09	0.15	0.13	0.21	0.02	0.05	0.03	
3	Uncorrected	50.93	14.15	11.87	6.69	11.13	2.64	0.23	1.92		0.20
	B-A Corr.	50.99	14.16	11.88	6.70	11.13	2.65	0.22	1.92		0.22
	σ (7)	0.59	0.19	0.19	0.11	0.16	0.06	0.07	0.03		0.02
4	Uncorrected	50.52	14.21	11.99	6.83	11.13	2.66	0.22	1.85		0.19
	B-A Corr.	50.60	14.23	12.00	6.84	11.13	2.66	0.21	1.85		0.22
	σ (7)	0.61	0.24	0.11	0.08	0.18	0.05	0.03	0.07		0.02

VG-A99

Run No.	Conditions	SiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	52.56	13.72	13.90	4.89	9.30	2.33	0.84	3.66	0.37	
	B-A Corr.	51.39	13.19	13.88	4.97	9.36	2.37	0.84	3.66	0.45	
	σ (7)	0.45	0.12	0.08	0.20	0.08	0.10	0.12	0.06	0.04	
2	Uncorrected	52.76	13.51	13.59	4.98	9.34	2.22	0.82	3.68	0.41	
	B-A Corr.	51.53	12.99	13.57	5.06	9.38	2.26	0.83	3.68	0.51	
	σ (7)	0.29	0.22	0.06	0.11	0.18	0.11	0.04	0.03	0.04	
3	Uncorrected	51.65	13.47	13.62	5.07	9.07	2.72	0.80	3.81		0.18
	B-A Corr.	50.63	13.03	13.59	5.19	9.10	2.75	0.81	3.81		0.18
	σ (7)	0.66	0.27	0.12	0.13	0.17	0.03	0.02	0.10		0.02
4	Uncorrected	52.82	13.46	13.30	4.98	9.46	2.70	0.84	3.65		0.18
	B-A Corr.	51.63	12.96	13.29	5.06	9.50	2.75	0.85	3.66		0.18
	σ (7)	0.58	0.24	0.17	0.10	0.08	0.03	0.02	0.06		0.02
	Standards	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	AP	Fay
1	Uncorrected	51.08	12.68	13.48	4.78	9.18	2.42	0.93	4.05	0.38	
	B-A Corr.	50.78	12.65	13.45	4.83	9.13	2.47	0.90	4.02	0.47	
	σ (7)	0.75	0.23	0.08	0.06	0.04	0.17	0.06	0.09	0.04	
2	Uncorrected	51.71	12.65	13.42	4.95	9.36	2.27	0.91	4.12	0.37	
	B-A Corr.	51.38	12.62	13.39	5.00	9.32	2.32	0.88	4.09	0.45	
	σ (7)	0.28	0.20	0.26	0.44	0.45	0.10	0.04	0.11	0.01	

Table 6.—Continued

Run No.	Conditions	SiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO
3	Uncorrected	51.77	12.74	13.39	4.83	9.38	2.64	0.94	4.05		0.19
	B-A Corr.	51.51	12.72	13.36	4.89	9.31	2.70	0.91	4.03		0.21
	σ (7)	0.90	0.22	0.11	0.11	0.12	0.03	0.04	0.17		0.02
4	Uncorrected	51.46	12.64	13.73	5.00	9.41	2.63	0.92	4.08		0.20
	B-A Corr.	51.21	12.65	13.69	5.07	9.35	2.69	0.89	4.05		0.22
	σ (7)	0.62	0.13	0.14	0.14	0.14	0.06	0.04	0.14		0.01
	VG-999										
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	52.46	14.22	13.91	5.71	10.59	2.31	0.16	1.71	0.19	
	B-A Corr.	51.47	13.69	13.89	5.77	10.66	2.35	0.16	1.71	0.23	
	σ (7)	0.70	0.29	0.11	0.11	0.19	0.11	0.03	0.06	0.00	
2	Uncorrected	52.17	14.04	13.76	5.96	10.43	2.32	0.17	1.75	0.18	
	B-A Corr.	51.20	13.54	13.75	6.03	10.50	2.36	0.17	1.75	0.22	
	σ (7)	0.77	0.18	0.13	0.06	0.03	0.07	0.02	0.08	0.02	
3	Uncorrected	51.89	14.01	13.59	5.83	10.10	2.60	0.18	1.75		0.19
	B-A Corr.	51.02	13.55	13.58	5.93	10.17	2.63	0.18	1.76		0.19
	σ (7)	0.61	0.07	0.03	0.15	0.13	0.01	0.03	0.07		0.02
4	Uncorrected	52.31	14.20	13.56	5.72	10.47	2.60	0.16	1.73		0.20
	B-A Corr.	51.35	13.69	13.55	5.80	10.54	2.63	0.16	1.73		0.20
	σ (7)	0.44	0.17	0.13	0.11	0.07	0.05	0.00	0.03		0.02
	Standards	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	AP	Fay
1	Uncorrected	51.64	13.32	13.53	5.57	10.30	2.48	0.21	1.93	0.18	
	B-A Corr.	51.52	13.30	13.51	5.62	10.28	2.52	0.20	1.93	0.22	
	σ (7)	0.58	0.13	0.17	0.10	0.11	0.11	0.02	0.06	0.03	
2	Uncorrected	51.77	13.35	13.59	5.85	10.43	2.38	0.16	2.00	0.18	
	B-A Corr.	51.67	13.34	13.56	5.89	10.42	2.41	0.16	1.99	0.22	
	σ (7)	0.64	0.22	0.20	0.16	0.10	0.17	0.02	0.04	0.03	
3	Uncorrected	51.46	13.37	13.75	5.66	10.33	2.54	0.20	1.97		0.21
	B-A Corr.	51.42	13.37	13.73	5.72	10.29	2.57	0.20	1.96		0.24
	σ (7)	0.38	0.10	0.07	0.17	0.15	0.09	0.03	0.09		0.02
4	Uncorrected	51.06	13.39	13.95	5.80	10.46	2.60	0.18	1.95		0.22
	B-A Corr.	51.04	13.42	13.92	5.86	10.43	2.65	0.18	1.94		0.25
	σ (7)	0.41	0.03	0.09	0.20	0.22	0.06	0.03	0.03		0.02

The data in Tables 5–7 contain a wealth of information for statistical evaluation that is beyond the scope of this paper. One point, however, should be emphasized: there is a general apprehension on the part of the staff responsible for the microprobe analyses regarding use of the observed standard deviation of a single day's analyses, based on one standardization, as a measure of precision. Since most microprobe users complete the analysis of a particular mineral within one day, this is often the

Table 6.—Continued

Run No.	Conditions	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
					VG-D08						
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	50.61	17.37	9.06	8.34	12.46	2.34	0.07	0.96	0.11	
	B-A Corr.	50.02	16.69	9.11	8.22	12.64	2.28	0.07	0.97	0.14	
	σ (7)	0.58	0.19	0.11	0.21	0.15	0.06	0.02	0.05	0.02	
2	Uncorrected	50.39	17.25	8.97	8.95	12.45	2.31	0.09	1.01	0.12	
	B-A Corr.	49.84	16.62	9.02	8.80	12.63	2.24	0.09	1.02	0.15	
	σ (7)	0.73	0.19	0.06	0.11	0.13	0.03	0.02	0.05	0.02	
3	Uncorrected	50.42	17.10	8.89	8.79	12.21	2.32	0.08	1.05		0.13
	B-A Corr.	49.90	16.51	8.94	8.68	12.39	2.25	0.08	1.06		0.14
	σ (7)	0.20	0.20	0.23	0.30	0.18	0.09	0.07	0.07		0.02
4	Uncorrected	50.83	17.36	8.97	8.77	12.45	2.44	0.07	1.00		0.15
	B-A Corr.	50.26	16.71	9.02	8.63	12.64	2.37	0.07	1.01		0.15
	σ (7)	0.31	0.13	0.06	0.24	0.04	0.06	0.02	0.03		0.03
	Standards	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	VG-2	AP	Fay
1	Uncorrected	49.37	16.09	8.85	8.36	12.25	2.38	0.09	1.13	0.11	
	B-A Corr.	49.63	16.06	8.89	8.20	12.33	2.31	0.09	1.14	0.14	
	σ (7)	0.46	0.13	0.12	0.12	0.05	0.03	0.02	0.06	0.03	
2	Uncorrected	50.22	16.05	8.89	8.99	12.24	2.37	0.09	1.11	0.12	
	B-A Corr.	50.49	16.04	8.93	8.81	12.33	2.30	0.09	1.12	0.15	
	σ (7)	0.37	0.20	0.26	0.44	0.45	0.16	0.01	0.02	0.01	
3	Uncorrected	50.08	16.30	8.91	8.45	12.39	2.30	0.09	1.14		0.16
	B-A Corr.	50.37	16.25	8.96	8.28	12.46	2.23	0.09	1.15		0.18
	σ (7)	0.56	0.21	0.20	0.11	0.17	0.04	0.02	0.05		0.01
4	Uncorrected	49.93	16.33	9.01	8.73	12.44	2.33	0.10	1.12		0.14
	B-A Corr.	50.22	16.31	9.05	8.56	12.51	2.26	0.09	1.13		0.16
	σ (7)	0.24	0.12	0.05	0.25	0.16	0.01	0.02	0.06		0.01

*Na_2O results in brackets, obtained using a $2\mu m$ beam, are not included in compilations of Tables 3 and 4. See explanation in text.

only measure of precision that can be observed. It is clear, however, that the average values of analyses made on two separate days, with separate standardizations, may occasionally be different. For example, in the analysis of Kakanui hornblende, one of us (A. P.) performed a Student's t-test for runs 1 and 2 (Table 5). Run 1 gives a mean for MgO of 12.57 with a standard deviation of 0.13 and run 2 gives a mean of 13.09 with a standard deviation of 0.22. The Student's t-test indicates that the difference be-

tween the two means (i.e., the error) is significant at the 99% confidence level. Of course, this is to be expected occasionally, given the limited stability of the instruments and the vagaries of data acquisition in general. For microprobe users, however, it is difficult to realize, and frequently even more difficult to accept, the fact that their data might not be as good as it appears. Concern about the precision and accuracy of microprobe analyses is ever-present with the discriminating worker. One way to monitor the

Table 7.—USGS laboratory individual analyses of Kakanui hornblende and 4 natural glasses using Kakanui hornblende as reference sample and also the laboratory's preferred reference samples

Run No.	Conditions	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
						Kakanui hornblende					
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	40.43	14.93	10.50	13.02	10.66	2.68	1.89	4.31	0.09	0.08
	B-A Corr.	40.42	14.93	10.51	12.99	10.66	2.68	1.89	4.32	0.11	0.09
	σ (10)	0.28	0.40	0.14	0.28	0.49	0.13	0.12	0.18	0.02	0.12
2	Uncorrected	40.35	15.09	10.86	12.89	9.71	2.76	1.98	4.30	0.09	0.11
	B-A Corr.	40.39	15.10	10.86	12.89	9.72	2.76	1.98	4.30	0.11	0.11
	σ (10)	0.56	0.26	0.03	0.35	0.63	0.12	0.02	0.08	0.02	0.10
3	Uncorrected	40.14	14.91	11.06	12.84	10.34	2.58	2.02	4.20	0.06	0.37
	B-A Corr.	40.15	14.93	11.05	12.86	10.34	2.58	2.02	4.20	0.07	0.37
	σ (10)	0.64	0.45	0.19	0.17	0.08	0.07	0.05	0.13	0.05	0.41
	Standards	Di85	Ortho	Garnet	Di2Ti	Di2Ti	Di85	Ortho	Di2Ti	Ortho	Rhod
4a	Uncorrected	38.61	12.71	10.53	12.34	10.57	2.47	1.95	4.90	0.02	0.07
	B-A Corr.	40.73	14.48	10.50	13.13	10.20	2.68	1.91	4.74	0.02	0.07
	σ (5)	0.24	0.43	0.44	0.58	0.32	0.12	0.04	0.15	0.07	0.04
4b	Uncorrected	37.94	13.21	10.59	12.15	10.40	2.54	2.01	4.70	0.05	0.04
	B-A Corr.	40.11	15.04	10.57	12.93	10.04	2.76	1.97	4.55	0.05	0.04
	σ (10)	0.24	0.42	0.19	0.17	0.11	0.05	0.02	0.10	0.05	0.01
						VG-2					
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	50.63	14.87	11.94	6.93	10.90	2.77	0.02	1.63	0.22	0.23
	B-A Corr.	49.58	14.46	11.95	6.98	10.91	2.79	0.02	1.63	0.27	0.23
	σ (10)	0.68	0.21	0.26	0.10	0.20	0.11	0.06	0.03	0.05	0.06
2a	Uncorrected	51.38	14.71	11.82	6.94	10.97	2.75	0.05	1.65	0.17	0.36
	B-A Corr.	50.25	14.30	11.83	6.98	10.98	.77	0.05	1.66	0.22	0.36
	σ (4)	0.77	0.43	0.30	0.10	0.28	0.09	0.07	0.08	0.05	0.03
2b	Uncorrected	51.00	14.75	11.77	6.88	10.94	2.85	0.05	1.66	0.22	0.32
	B-A Corr.	49.91	14.34	11.77	6.91	10.95	2.86	0.05	1.66	0.28	0.32
	σ (10)	0.48	0.40	0.19	0.18	0.21	0.15	0.05	0.07	0.05	0.05
3	Uncorrected	51.18	15.07	11.60	6.71	11.22	2.75	0.10	1.63	0.18	0.08
	B-A Corr.	50.05	14.61	11.61	6.73	11.24	2.75	0.10	1.63	0.21	0.08
	σ (5)	0.28	0.30	0.13	0.03	0.08	0.05	0.06	0.03	0.07	0.10
	Standards	Di85	Ortho	Garnet	Di2Ti	Di2Ti	Di85	Ortho	Di2Ti	Ortho	Rhod
	Uncorrected	49.19	12.65	11.82	6.55	11.11	2.55	0.19	1.92	0.20	0.21
	B-A Corr.	50.75	13.98	11.79	7.02	10.72	2.75	0.18	1.86	0.19	0.23
	σ (10)	0.42	0.19	0.14	0.05	0.06	0.12	0.06	0.08	0.05	0.05

Table 7.—Continued

Run No.	Conditions	SiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO
						VG-A99					
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	52.39	13.25	13.39	4.89	8.44	2.80	0.77	3.81	0.40	0.27
	B-A Corr.	50.80	12.84	13.36	.4.99	8.42	2.88	0.78	3.79	0.49	0.27
	σ (10)	0.51	0.30	0.15	0.10	0.48	0.20	0.11	0.10	0.04	0.05
2	Uncorrected	52.69	13.00	13.53	5.08	9.16	2.62	0.67	3.73	0.44	0.16
	B-A Corr.	50.69	12.62	13.50	5.18	9.13	2.69	0.67	3.71	0.54	0.16
	σ (6)	0.28	0.08	0.27	0.08	0.18	0.07	0.08	0.10	0.02	0.04
	Standards	Di85	Ortho	Garnet	Di2Ti	Di2Ti	Di85	Ortho	Di2Ti	Ortho	Rhod
	Uncorrected	49.58	11.61	13.48	4.76	9.33	2.44	0.77	3.91	0.32	0.18
	B-A Corr.	50.80	12.80	13.41	5.16	8.97	2.73	0.76	3.77	0.31	0.19
	σ (10)	0.60	0.26	0.23	0.10	0.17	0.08	0.07	0.12	0.04	0.06
						VG-999					
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
3	Uncorrected	51.88	14.41	13.66	5.57	10.26	2.66	0.03	1.66	0.17	0.13
	B-A Corr.	50.62	13.98	13.63	5.65	10.25	2.72	0.03	1.66	0.21	0.13
	σ (10)	0.32	0.40	0.36	0.08	0.14	0.11	0.04	0.08	0.01	0.30
	Standards	Di85	Ortho	Garnet	Di2Ti	Di2Ti	Di85	Ortho	Di2Ti	Ortho	Rhod
	Uncorrected	49.37	14.24	12.75	5.67	10.57	2.30	0.04	1.87	0.15	0.20
	B-A Corr.	50.70	13.54	13.30	6.13	10.18	2.57	0.04	1.80	0.15	0.20
	σ (10)	0.09	0.04	0.21	0.10	0.03	0.03	0.00	0.17	0.11	0.04
						VG-D08					
	Standards	KH	KH	KH	KH	KH	KH	KH	KH	AP	KH
1	Uncorrected	50.30	16.38	8.75	8.86	12.03	2.44	0.00	0.88	0.13	0.18
	B-A Corr.	49.47	15.86	8.79	8.71	12.10	2.39	0.00	0.89	0.16	0.19
	σ (10)	0.73	0.47	0.22	0.18	0.66	0.04	0.00	0.03	0.01	0.01
3	Uncorrected	50.41	17.04	9.01	8.54	12.22	2.36	0.00	0.96	0.10	0.14
	B-A Corr.	49.60	16.46	9.05	8.40	12.29	2.30	0.00	0.97	0.12	0.15
	σ (5)	0.66	0.34	0.19	0.12	0.15	0.08	0.11	0.07	0.02	0.21
	Standards	Di85	Ortho	Garnet	Di2Ti	Di2Ti	Di85	Ortho	Di2Ti	Ortho	Rhod
	Uncorrected	47.97	14.02	8.76	8.36	12.42	2.23	0.09	1.05	0.08	0.12
	B-A Corr.	49.77	15.44	8.78	8.78	12.05	2.39	0.09	1.03	0.08	0.13
	σ (10)	0.24	0.17	0.18	0.07	0.03	0.07	0.06	0.05	0.02	0.01

precision and accuracy is to present data of samples with known composition together with the microprobe analyses of the unknown samples. This suggestion has been made frequently and is followed by many, but it would serve the scientific community much better if practiced even more extensively.

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Electron Microprobe Reference Samples for Mineral Analyses

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ABSTRACT

A table is presented containing compositional data for 25 minerals, four natural glasses, and one synthetic glass prepared and analyzed for use as microprobe reference samples at the Smithsonian Institution. The table includes new chemical analyses of minerals and some updated analyses of minerals published previously.
Detailed descriptions of sample preparation and evaluation of homogeneity are given.

Introduction

Microprobe analyses are an essential part of present-day mineralogical and petrological studies. It can be said that the application of the microprobe to mineral studies and material sciences in general is one of the most significant advances since the first use of the petrographic microscope in the middle of the last century. The technique is now well established, widely used, and capable of high-quality analyses. As with all comparative instrumental techniques, however, it requires well-characterized reference samples. Prime prerequisites for microprobe reference samples are homogeneity at the micrometer level and availability in reasonable quantities for standard chemical analyses. Either prerequisite is usually easily satisfied by itself but together are difficult to achieve.

One of the problems with some minerals used as microprobe reference samples is a lack of proper documentation. Even if well-described minerals are from the same locality and/or are obtained from a reliable source, they may vary in chemical com-

position. Therefore, a mineral sample intended as a reference sample should be carefully selected and used only when analytical data on this particular specimen are available. Since natural materials fulfilling all the above requirements are not always available, synthetic minerals and glasses have occasionally been prepared as substitutes. Again, homogeneity of these materials should be checked and chemical analyses performed. The assumption that the precalculated composition is correct is certainly not always valid.

In general, the most reliable microprobe analyses are obtained when a reference sample of composition and structure close to that of the unknown is used because the matrix and possible wavelength shift effects are minimized, and only small corrections are needed. It is generally accepted that, regardless of the type of correction used, results corrected by more than 10 percent should be viewed with caution. Difficulties with correction procedures in the Si-Al-Mg system have been pointed out by Bence and Holzwarth (1977). Similar discrepancies have been observed by other probe users.

All minerals and glasses described here, except one, are of natural origin. Most have been obtained from the Smithsonian collections and were selected either in conjunction with specific projects or for use in silicate analyses in general.

Preparation of Reference Samples

When a sufficient quantity (at least 2 g) of a mineral or glass is available for use as a microprobe

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reference sample, a thin section is prepared for microscopic examination. Next, a microprobe analysis for composition and homogeneity is performed. If preliminary results are favorable, the material is gently crushed, sized usually between 20 and 80 mesh, and further purified using either a heavy liquid separation or a Franz magnetic separator or both. In some instances cleaning with a suitable acid is also useful. As a final step, the material is examined under a low-powered microscope and most remaining foreign grains are removed by hand. The purified grains are again checked by microprobe for homogeneity (sigma ratios) within and among grains (Table 2). Finally, a chemical analysis using classical methods (Peck, 1964; Hillebrand et al., 1953) is performed on the same separate that is to be used as the reference sample.

Discussion

In Table 1 are presented the data for newly analyzed minerals, earlier published analyses, and updated analyses for several minerals that have been in use for some time. Johnstown meteorite hypersthene and Springwater meteorite olivine have been re-analyzed using what we believe to be much cleaner separates. Kakanui hornblende has been re-analyzed for TiO_2.

Even after the most careful preparation of the reference sample, a grain of accessory mineral or matrix may remain in the sample, which, in the course of preparation of the standard discs, could be included with the reference sample. Occasional grains of the standard itself will be "off composition," due to inhomogeneity. These problems can never be totally eliminated. The user should be aware of the possible presence of such "impurities" and make a thorough check for them. For example, occasional grains are found that are lower in sodium and higher in potassium than usual in the reference sample microcline, lower in manganese than usual in Rockport fayalite, and lower in sodium than usual in Lake County plagioclase. Infrequent inclusions in the glasses 72854, 111240/52, 113498/1, and 113716 are also found.

The overall homogeneity of each sample was determined using the criteria given by Boyd et al. (1967) whereby the sample is considered to be homogeneous if the sigma ratio (homogeneity index) of observed standard deviation (sigma) to the standard

deviation predicted from counting statistics alone does not exceed 3. The sigma ratios were calculated with reference to ten ten-second counts on each of ten randomly selected grains. Table 2 gives sigma ratios for the ten grains of each reference sample for major and some minor elements. The values in parentheses indicate the worst sigma ratio observed for an element in a single grain. This does not, however, imply a single worst grain, as different grains may exhibit differing degrees of homogeneity for each element present. When the criterion of sigma ratios is used as a measure of homogeneity, all the reference samples prove to be very homogeneous provided a reasonably large number of counts are taken on a reasonably large number of grains. In practice, however, fewer counts and grains are normally used for standardization, and under these circumstances a grain having a slightly different composition may influence the microprobe results adversely. For this reason, grains showing some discrepancy in composition should be avoided. The percentages of these "impurities" in the whole samples are minimal and the effects on the bulk analyses of the samples are negligible.

These samples were prepared in only small quantities, but they can be judiciously made available to microprobe users interested in the analysis of geologic materials. Potential users should remember that the purified samples differ in bulk chemistry from the specimens from which they were separated and should be very specific in their requests— i.e., the requests should be made for *microprobe standard* USNM no. *n* rather than simply material from specimen USNM no. *n*.

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Key to Table 1
Analysts, Sources, References

Analysts:

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5. B. Wiik, Geological Survey, Finland
6. U.S. Geological Survey, Geochemistry and Petrology Branch
7. D. Mills, X-Ray Assay Laboratories, Ontario, Canada; J. Nelen; J. Norberg
8. E. Kiss, Dept. of Geophysics and Geochemistry, Australian National University
9. J. J. Fahey and L. C. Peck, U.S. Geological Survey

Sources:

1. P. Desautels, J. S. White, Jr., and P. J. Dunn, Dept. of Mineral Sciences, Smithsonian Institution
2. B. Mason, Dept. of Mineral Sciences, Smithsonian Institution
3. G. Switzer, Dept. of Mineral Sciences, Smithsonian Institution
4. W. G. Melson, Dept. of Mineral Sciences, Smithsonian Institution
5. T. L. Wright, U.S. Geological Survey
6. H. Staudigel, Massachusetts Institute of Technology
7. R. S. Clarke, Jr., Dept. of Mineral Sciences, Smithsonian Institution
8. J. H. Berg, Northern Illinois University

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TABLE 1.—Chemical analyses of electron microprobe reference samples; analysts, sources, and references identified in "Key to Table 1" on facing page; these purified samples all differ, to greater or lesser degree, from the bulk chemistry of the USNM specimens from which they were separated (see text).

Mineral	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3	H_2O	Total	Analyst	Source	Reference
Anorthite, Great Sitkin Island, AL USNM 137041	44.00	36.03		0.62	<0.02	19.09	0.53	0.03	0.03					100.33	1	1	
Anorthoclase, Kakanui, New Zealand USNM 133868	66.44	20.12		0.20		0.87	9.31	2.35					<0.05	99.29	3	2	
Apatite (Fluorapatite), Durango, Mexico[1] USNM 104021	0.34	0.07	0.06	0.00	0.01	54.02	0.23	0.01		40.78	0.01		0.01	99.94	4	1	2
Augite, Kakanui, New Zealand USNM 122142	50.73	7.86	3.69	3.45	16.65	15.82	1.27	0.00	0.74		0.13		0.04	100.38	5	2	3
Benitoite, San Benito County, CA[2] USNM 86539	43.75								19.35					100.15	2	1	
Chromite, Tiebaghi Mine, New Caledonia[3] USNM 117075		9.92		13.04	15.20	0.12					0.11	60.5		98.89	2	1	
Corundum, synthetic[4] USNM 657S		99.99												99.99	1	1	
Diopside, Natural Bridge, NY USNM 117733	54.87	0.11		0.24	18.30	25.63	0.34				0.04			99.53	2	1	
Fayalite, Rockport, MA USNM 85276	29.22		1.32	66.36					0.04		2.14		0.1	99.18	2	1	
Garnet, Roberts Victor Mine, South Africa USNM 87375	39.47	22.27	2.77	13.76	6.55	14.39			0.39		0.59		<0.01	100.19	1	3	4
Garnet, Roberts Victor Mine, South Africa USNM 110752	40.16	22.70	2.17	9.36	7.17	18.12			0.35		0.19		<0.01	100.22	1	3	4
Glass, Basaltic, Juan de Fuca Ridge USNM 111240/52 VG-2	50.81	14.06	2.23	9.83	6.71	11.12	2.62	0.19	1.85	0.20	0.22		0.02	99.86	1	4	5
Glass, Basaltic, Makaopuhi Lava Lake, HI USNM 113498/1 VG-A99	50.94	12.49	1.87	11.62	5.08	9.30	2.66	0.82	4.06	0.38	0.15		0.02	99.39	3	5	
Glass, Basaltic, Indian Ocean[5] USNM 113716	51.52	15.39	1.12	8.12	8.21	11.31	2.48	0.09	1.30	0.12	0.17		0.18	100.07	3	6	
Glass, Rhyolitic, Yellowstone Nat. Pk., WY[6] USNM 72854 VG-568	76.71	12.06	0.48	0.80	<0.1	0.50	3.75	4.89	0.12	<0.01	0.03		0.12	99.56	3	4	
Glass, Tektite, synthetic[7] USNM 2213	75.75	11.34	0.64	4.32	1.51	2.66	1.06	1.88	0.50	0.00	0.11		0.10	99.88	6	7	
Hornblende, Arenal Volcano, Costa Rica USNM 111356	41.46	15.47	5.60	6.43	14.24	11.55	1.91	0.21	1.41	<0.01	0.15		1.21	99.64	1	4	5
Hornblende, Kakanui, New Zealand[8] USNM 143965	40.37	14.90	3.30	7.95	12.80	10.30	2.60	2.05	4.72	0.00	0.09		0.94	100.02	1	2	4
Hypersthene, Johnstown meteorite USNM 746	54.09	1.23		15.22	26.79	1.52	<0.05	<0.05	0.16		0.49	0.75	0.00	100.25	3	7	
Ilmenite, Ilmen Mtns., Miask, USSR[9] USNM 96189			11.6	36.1	0.31				45.7		4.77			99.40	7	1	
Magnetite, Minas Gerais, Brazil[10] USNM 114887			67.5	30.2										98.16	3	1	
Microcline, location unknown USNM 143966	64.24	18.30	0.00	0.04	0.03	0.02	1.30	15.14	0.01		0.04			99.12	8	3	
Olivine (Fo_{90}), San Carlos, Gila Co., AZ[11] USNM 111312/444	40.81			9.55	49.42	<0.05			0.00		0.14			100.29	1	2	
Olivine (Fo_{83}), Springwater meteorite USNM 2566	38.95			16.62	43.58						0.30	0.02	<0.05	99.47	3	7	
Omphacite, Roberts Victor Mine, So. Africa USNM 110607	55.42	8.89	1.35	3.41	11.57	13.75	5.00	0.15	0.37		0.10		0.02	100.03	1	3	4
Osumilite, Nain, Labrador USNM 143967	60.20	22.60		6.38	5.83	<0.03	0.39	4.00	0.18				0.02	99.60	1	8	
Plagioclase (Labradorite), Lake County, OR USNM 115900	51.25	30.91	0.34	0.15	0.14	13.64	3.45	0.18	0.05		0.01		0.05	100.17	9	1	1
Pyrope, Kakanui, New Zealand USNM 143968	41.46	23.73		10.68	18.51	5.17			0.47		0.28		<0.01	100.30	1	2	4
Quartz, Hot Springs, AR[12] USNM R17701	99.99													99.99	1	1	
Scapolite (Meionite), Brazil[13] USNM R6600-1	49.78	25.05		0.17		13.58	5.20	0.94					0.21	99.86	2	1	

[1] SrO 0.07; RE_2O_3 1.43; ThO_2 0.02; As_2O_3 0.09; V_2O_5 0.01; CO_2 0.05; SO_3 0.37; F 3.53; Cl 0.41; sub-total: 101.52; O equivalent to Cl, F = 1.58; final total: 99.94.

[2] BaO 37.05.

[3] Total Fe reported as FeO.

[4] Emission spectrometric analysis: Si 0.03; Fe 0.003; Mg 0.007; Ca 0.003; Na 0.005; K 0.005.

[5] S 0.12; sub-total: 100.13; O equivalent to S = 0.06; final total: 100.07.

[6] Cl 0.13; sub-total: 99.59; O equivalent to Cl = 0.03; final total: 99.56.

[7] CO_2 not determined (insufficient sample); Cl 0.00; F 0.01. Synthetic glass prepared by Corning Glass Company.

[8] New TiO_2 value: 4.72.

[9] Nb_2O_5 0.92.

[10] Preliminary values: MgO 0.05; TiO_2 0.16; MnO <0.01; Cr_2O_3 0.25.

[11] NiO 0.37.

[12] Emission spectrometric analysis: Al 0.0005; Fe 0.01; Mg 0.005; Ca 0.001; Na 0.001; K 0.0003.

[13] CO_2 2.5; SO_3 1.32; Cl 1.43; sub-total: 100.18; O equivalent to Cl = 0.32; final total: 99.86.

TABLE 2.—Sigma ratios (homogeneity indices) for all analyzed grains of each reference sample

$$\text{(sigma ratio for } n \text{ grains } = \frac{\text{observed sigma for } n \text{ grains}}{\text{sigma predicted from counting statistics}} \text{; least homogeneous grain in}$$

parentheses; dashes = not evaluated)

Mineral	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
Anorthite	0.96 (1.51)	0.81 (1.26)			0.92 (1.23)						
Anorthoclase	1.09 (1.60)	0.79 (1.38)				1.11 (1.57)					
Apatite (Fluorapatite)					1.02 (1.51)				0.97 (1.51)		
Augite	0.99 (1.37)	0.97 (1.66)	0.84 (1.26)	0.94 (1.23)	1.00 (1.25)						
Benitoite	----------										
Chromite		1.00 (1.47)	1.01 (1.66)	1.11 (1.50)							**1.12 (1.49)**
Corundum	----------										
Diopside	1.07 (1.37)			0.97 (1.50)	0.95 (1.50)						
Fayalite	0.95 (1.46)		1.14 (2.32)							1.03 (1.58)	
Garnet, 87375	0.89 (1.26)	1.01 (1.42)	1.06 (1.41)	1.01 (1.49)	0.86 (1.11)						
Garnet, 110752	0.88 (1.32)	0.94 (1.28)	0.90 (1.20)	1.00 (1.34)	0.87 (1.47)						
Glass, 111240/52 VG-2	0.94 (1.10)	0.89 (1.11)	0.86 (1.13)	0.96 (1.61)	1.00 (1.27)	1.05 (1.31)					
Glass, 113498/1 VG-A99	0.94 (1.32)	1.10 (1.46)	1.07 (1.38)	0.92 (1.38)	0.93 (1.34)	1.15 (2.10)		0.97 (1.44)			
Glass, 113716	1.12 (1.42)	1.00 (1.30)	0.94 (1.34)	1.01 (1.36)	0.83 (1.19)	1.25 (2.59)					
Glass, 72854 VG-568	0.97 (1.61)	1.00 (1.47)				2.31 (3.45)	0.98 (1.36)				
Glass, 2213	1.05 (1.72)	0.87 (1.24)	1.01 (1.34)		1.05 (1.61)						
Hornblende, Arenal	1.07 (1.67)	0.97 (1.66)	1.12 (1.36)	1.11 (1.67)	1.01 (1.27)	0.98 (1.32)					
Hornblende, Kakanui	1.01 (1.38)	1.00 (1.24)	1.30 (1.67)	1.16 (2.38)	1.10 (1.73)	1.15 (2.15)	0.90 (1.29)	1.01 (1.49)			
Hypersthene	1.07 (1.55)		1.10 (1.37)	0.93 (1.27)							
Ilmenite			1.72 (3.60)					1.34 (1.98)		1.21 (1.53)	
Magnetite			0.84 (1.16)								
Microcline	0.94 (1.13)	1.04 (1.52)					1.09 (1.59)				
Olivine (Fo_{90}), San Carlos	0.81 (1.13)		0.90 (1.29)	1.00 (1.64)							
Olivine (Fo_{83}), Springwater	0.96 (1.42)		1.06 (1.51)	0.99 (1.12)							
Omphacite	0.89 (1.23)	0.95 (1.64)	0.96 (1.87)	0.91 (1.30)	1.02 (1.51)	0.99 (1.31)					
Osumilite	0.96 (1.90)	1.27 (1.89)	1.20 (2.19)	1.00 (1.70)			1.13 (1.64)				
Plagioclase (Labradorite)	1.09 (1.49)	0.95 (1.40)			1.04 (1.65)	0.91 (1.33)					
Pyrope	1.08 (1.46)	0.95 (1.20)	1.09 (1.59)	0.98 (1.21)	0.97 (1.18)						
Quartz	----------										
Scapolite (Meionite)	0.99 (1.29)	0.95 (1.41)			0.91 (1.16)	0.96 (1.41)					

$$\text{Sigma ratio for 10 grains } = \frac{\text{observed sigma for all grains}}{\text{sigma predicted from counting statistics}}$$

$$\text{Sigma ratio for least homogeneous grain } = \frac{\text{observed sigma for this particular grain}}{\text{sigma predicted from counting statistics}}$$
$$\text{(in parentheses)}$$

Smithsonian Contributions to the Earth Sciences