1.2.8 THE BASALTIC METEORITES

1.2.8.1 Introduction

The known range of basaltic volcanism in the solar system is considerably extended in space and time by studies of basaltic material in meteorites. This material occurs in various types of meteorites: eucrites and shergottites consist entirely of basaltic material, whereas howardites and mesosiderites contain basaltic material variously mixed and metamorphosed with other types of materials. The eucrites, most of which are monomict breccias, are the most abundant of the basaltic meteorites. The eucrites crystallized 4.54 ± 0.02 b.y. ago (see Chapter 7) in magmatic events that occurred largely within 30 ± 20 m.y. after the earliest (dated) event in our solar system, which was the formation of the refractory particles now included in the Allende carbonaceous chondrite. Thus, the eucrites are the oldest known basalts and are basalts which may have formed by partial melting of primitive (i.e., little differentiated) condensed solar material. Investigations of the eucrites can lead to an understanding of very early magmatic processes and can be used to constrain hypotheses on the nature of their source material, and thereby the processes of condensation and accretion in the early solar system. Only small samples of a limited number of eucrites are available to us on Earth. We lack any direct information on their geologic setting, except that we can infer that most of them crystallized close to a planetary surface. The parent body or bodies from which the eucrites are derived have not been identified, although a strong argument can be made in favor of their derivation from asteroids. A specific asteroid, 4 Vesta, has been cited as a possible source for the eucrites (Consolmagno and Drake, 1977), based upon infrared spectrophotometric observations of its surface (McCord et al., 1970; Larson and Fink, 1975).

Most eucrites are pyroxene-plagioclase rocks with the textures of rapidly cooled melts. They occur as unbrecciated basalts or, more commonly, as monomict breccias. A few eucrites have coarser, cumulate-like textures. Basalt fragments occur also as clasts in howardites and in mesosiderites. Howardites contain a variety of clast types from fine-grained basalts to coarse, monomineralic fragments of pyroxene and plagioclase with rare exotic fragments, including carbonaceous debris (Wilkening, 1976). Howardites have been interpreted as polymict regolith breccias, of which eucrite and diogenite fragments are prominent components. Diogenites are orthopyroxenites, most of which are monomict breccias, that may have formed initially as cumulates or as residua from partial melting events. Mesosiderites are stony-iron meteorites, half metallic iron and half silicate. The silicate portion is complex, but commonly contains a high proportion of eucritic material. Most investigators believe that eucrites, howardites, diogenites and the silicate portions of the mesosiderites are genetically related, but opinions differ as to the nature of the relationship.

The meteorites Shergotty and Zagami constitute a compositionally-distinct group of basaltic meteorites, the shergottites. These are unbrecciated, pyroxene-feldspar rocks, which differ from the eucrites in bulk composition, in mineral composition, and in having crystallized under more oxidizing (Earth-like) conditions. The shergottites are believed to be derived from a parent body which is distinct from that of the eucrites, and which has produced basaltic melts with a crystallization age of 0.65 b.y. (Nyquist et al., 1979b), which would be younger than any other extraterrestrial basalt yet sampled. A possibly related meteorite, ALHA 77005, contains substantial amounts of olivine, but otherwise is mineralogically similar to Shergotty and apparently has a young crystallization age (Nyquist et al., 1979a).

Other achondrites, mostly unique occurrences such as the nakhlites, angrites, and chassignites (Mason, 1962), apparently have been formed by igneous processes. These are ultrabasic materials which have not been shown to have close genetic relationships to either eucrites or shergottites, although Stolper et al. (1979)

Note: Eu = eucrite; Ho = howardite; Di = diogenite; Sh = shergottite. [a] Classification according to Mason et al. (1979) or from description for meteorites discovered since 1962. [b] Bp = polymict breccia; Bm = monomict breccia; NB = not brecciated. [c] E = equilibrated; U = unequilibrated; C = cumulate; R = recrystallized. [d] Reference to descriptive classification only (petrography or chemistry): (a) Mason et al. (1979); (b) Lomena et al. (1976); (c) Takeda et al. (1978a); (d) Olsen et al. (1978); (e) Antarctic Meteorite Newsletter V. 2 No. 3, 1979. (g) LaCroix (1926); (h) Duke and Silver (1967); (i) Zavaritskii and Kvasha (1952); (j) Mason (1967); (k) Wahl (1952); (l) Mason and Wiik (1966); (m) Steele and Smith (1976); (n) Bunch et al. (1976); (o) Fredriksson and Keil (1963); (p) Stolper (1977); (q) Reid (1974); (r) Jérome and Christopher Michel-Levy (1971); (s) Hutchison et al. (1977); (t) Lovering (1975); (u) Frost (1971); (v) Hess and Henderson (1949); (w) Binns (1967); (x) Lange and Keil (1976); (y) Foshag (1938); (z) Stolper and McSween (1979); (aa) Smith and Hering (1979); (bb) Engelhardt (1963); (cc) Takeda et al. (1978b); (dd) Takeda (1979).

Table 1.2.8.1 Basaltic material in meteorites.

Meteorite	Class[a]	Structure[b]	Eucrite[c] Type	Reference[d]
Adalia	Eu	NB	E	(a)
Aioun El Atrouss	Eu/Di	Bp	E	(b) (c)
Allan Hills-76005	Eu	Bm	U	(d)
Allan Hills-77302	Eu	Bm	U	(e)
Allan Hills-77005	Sh	NB	C	(e)
Allan Hills-78006	Ho	Bp	—	(f)
Allan Hills-78132	Eu	Bm	E	(f)
Allan Hills-78158	Eu	Bm	E	(f)
Allan Hills-78165	Eu	Bm	E	(f)
Béréba	Eu	Bm	E	(g)
Bholghati	Ho	Bp	—	(a)
Bialystok	Ho	Bp	—	(a)
Binda	Eu	Bm	C	(h)
Brient	Ho	Bp	—	(i)
Bununu	Ho	Bp	—	(j)
Cachari	Eu	Bm	E	(k)
Chaves	Ho	Bp	—	(h) (a)
Chervony Kut	Eu	NB	E	(k)
Emmaville	Eu	Bm	E	(a)
Frankfort	Ho	Bp	—	(l)
Haraiya	Eu	Bm	E	(h)
Ibitira	Eu	NB	R	(m)
Jodzie	Ho	Bp	—	(n)
Jonzac	Eu	Bm	E	(k)
Juvinas	Eu	Bm	E	(k)
Kapoeta	Ho	Bp	—	(o)
Kirbyville	Eu	Bm	E	(a)
Lakangaon	Eu	Bm	E	(p)
LeTeilleul	Ho	Bp	—	(k)
Luotolax	Ho	Bp	—	(k)
Macibini	Ho	Bp	—	(q)
Malvern	Ho	Bp	—	(r)
Mässing	Ho	Bp	—	(a)
Medanitos	Eu	NB?	C?	(s)
Millbillillie	Eu	Bm	E	(a)
Moama	Eu	NB	C	(t)
Molteno	Ho	Bp	—	(u)
Moore County	Eu	NB	C	(v)
Nagaria	Eu	Bm	E	this work
Nobleborough	Ho	Bp	—	(a)
Nuevo Laredo	Eu	Bm	E	(h)
Padvarninkai	Eu	Bm	E	(w)
Palo Blanco Creek	Eu	Bm	E	(x)
Pasamonte	Eu	Bm	U	(y)
Pavlovka	Ho	Bp	—	(h)
Peramiho	Eu	Bm	—	(k)
Petersburg	Ho	Bp	—	(h)
Pomozdino	Eu	Bm	?	(a)
Serra de Magé	Eu	NB	C	(l)
Shergotty	Sh	NB	C	(z) (aa)
Sioux County	Eu	Bm	E	(h)
Stannern	Eu	Bm	E	(bb)
Washougal	Ho	Bp	—	(h)
Yamato-7307(e)	Ho	Bp	—	(a)
Yamato-74159	Eu	Bp	U	(cc)
Yamato-74356	Eu	Nb	E	(dd)
Yamato-74450	Eu	Bm	U	(cc)
Yamato-75011	Eu	Bp	U	(cc)
Yamato-75015	Eu	Bp	U	(cc)
Yurtuk	Ho	Bp	—	(a)
Zagami	Sh	NB	C	(w)
Zmenj	Ho	Bp	—	(a)

discussed possible genetic relationships among the hypothetical parental materials for this range of meteorites.

1.2.8.2 Reference Suite

A current list of eucrites, howardites and shergottites (Table 1.2.8.1) contains 62 meteorites.* The sample suite assembled for this study has been chosen to exhibit the range of basaltic compositional and textural types among eucrites and shergottites. Selection was also constrained by sample availability; therefore, the suite is biased towards the larger falls, which are also those for which the most data already exist. Howardites have been excluded because of the small size of most of their clasts, and their polymict character. Six basaltic meteorites were selected: Juvinas, Pasamonte, Stannern, Nuevo Laredo, Aioun el Atrouss and Shergotty. Detailed descriptions and new analytical data for these meteorites are given in Appendix A-8.

In any plot of bulk eucrite compositions, there is a clustering of points around an apparent preferred composition (e.g., see Fig. 1.2.8.7). Eucrites with compositions close to this preferred composition are referred to here as **main group** eucrites. Juvinas is an example of the most common eucrite composition. The bulk composition of Pasamonte is close to the main group, though with a slightly lower $Mg/(Mg + Fe)$ ratio. Most main group eucrites contain an equilibrated pyroxene assemblage consisting of pigeonite and augite with near constant $Mg/(Mg + Fe)$ ratios. In contrast, Pasamonte has strongly-zoned, unequilibrated pyroxenes. Stannern is one of the most studied eucrites and is of particular interest because of its relatively high content of incompatible trace elements. Compared with the main group eucrites, Stannern has a similar $Mg/(Mg + Fe)$ ratio but higher contents of large-ion-lithophile trace elements and of alkalies. For example, Stannern has higher REE contents than Juvinas and has a negative europium anomaly. Nuevo Laredo was selected because it also has higher incompatible element concentrations than the main group eucrites, but this occurs in conjunction with a substantially lower $Mg/(Mg + Fe)$ ratio. Nuevo Laredo contains quench textures, and may be the most rapidly cooled of the eucrite melts. The inclusion of Aioun el Atrouss in the sample suite was governed by availability and by the virtual lack of any data on this unique meteorite. Aioun el Atrouss is a mixture dominantly of diogenite with distinct clasts of eucrite, which are evidence for a complex history following primary crystallization. Data are presented here only for the eucrite portion of Aioun el

Atrouss. The Shergotty meteorite was included as a representative of the shergottite class of meteoritic basalts and as a sample apparently derived from a different parent body.

For Juvinas, Pasamonte, Stannern and Nuevo Laredo, studies were made of individual clasts in the breccias in order to assess the amount of interclast variability. Where possible, large clasts with igneous textures were identified and were separated to provide subsamples of unequivocal melt fragments with no adhering matrix. These subsamples were analyzed by instrumental neutron activation. Portions were cut from the clasts and polished thin sections were made for petrographic and mineral chemical studies by electron microprobe. About 90 mg to 1 g of material remains from each of the analyzed clasts and is available for further study.

1.2.8.3 Petrography of meteoritic basalts

The meteoritic basalts contain calcic plagioclase and clinopyroxene with minor amounts of accessory phases that include orthopyroxene, silica (cristobalite, tridymite, quartz), phosphate, oxides (chromite, ilmenite, magnetite), sulfide (troilite), and metallic iron. Fayalitic olivine occurs in Ibitira and Shergotty. Forsteritic olivine is present in ALHA 77005 and occurs as mineral fragments in some howardites, where it may represent a related cumulus or residual mineral. The eucrites and shergottites represent distinct basalt types and will be described separately below.

Eucrite basalts

The dominant minerals are calcic plagioclase (~35%), pigeonite and augite (~60%), with about 5% of accessory phases (cristobalite, tridymite, quartz, chromite, ilmenite, troilite, metal). Hydrous phases have not been observed. Grain size ranges from amorphous or cryptocrystalline to coarse, and textures include a variety of subophitic, variolitic (fan-spherulitic) and intersertal textures. Related rocks of possible cumulate origin have medium to coarse-grained equigranular textures. For the most part, the following descriptions are based on individual rock fragments from brecciated meteorites. Some rock fragments are modified by shock processes; no modification of textures by weathering is observed.

Vitric texture.   Rare fragments of dark amorphous "glass" occur in the Nuevo Laredo meteorite, in which the fragments generally exhibit the finest-grained igneous textures found in the eucrites. Duke and Silver

---

*Mesosiderites and diogenites are excluded from Table 1.2.8.1.

(1967) show an example of such a glass containing a phenocryst of clinopyroxene. Other examples of this vitric material in eucrites contain small cavities, possibly vesicles (Fig. 1.2.8.1a). This material is apparently structureless and is distinct from other vitric material apparently formed by shock processes, such as the irregular glass pods and veins in Stannern (Duke and Silver, 1967), Cachari (Fredriksson and Kraut, 1967), and Bereba, which also contain highly strained mineral fragments.

Intersertal texture.   This texture occurs in fine-grained fragments, principally in Nuevo Laredo, where grain sizes of 0.02–0.2 mm are typical (Fig. 1.2.8.1a). Pyroxene grains typically lie between plagioclase laths in this texture, rather than being penetrated by plagioclase. Vesicles are not present.

Subophitic texture.   Varieties of subophitic texture are the most abundant texture, and are found in all brecciated eucrites. Subophitic textures range from fine-grained to medium-grained varieties (Fig. 1.2.8.1b,c). In these textures, plagioclase occurs primarily as laths or plates, growing into and partially surrounded by clinopyroxene. Accessory phases are concentrated in interstitial areas, where they commonly form a fine-grained mesostasis-like intergrowth with plagioclase. The textures are nonporphyritic.

Two varieties of pyroxene crystallization are observed. In Pasamonte, pyroxenes have pigeonite cores, which are zoned outward toward either pigeonite or augite rims. Augite is texturally late. The pyroxenes do not contain exsolution lamellae which are visible optically, but are exsolved on a submicroscopic scale (Takeda *et al.*, 1976). In Juvinas, Nuevo Laredo, and Stannern, pigeonite is the predominant clinopyroxene (Nuevo Laredo has a small amount of primary augite) and does not show significant zonation. In these textures, pyroxenes show exsolution lamellae ranging in size from barely visible in the microscope to several microns in width.

"Vesicles" have been reported in the Juvinas meteorite (LaCroix, 1926) but have not been observed by the authors in fragments with subophitic texture, which are dominant in that meteorite.

Variolitic texture.   A wide range of variolitic textures (also called fan-spherulitic, see Table 1.3.3.1) are present. Pasamonte, Y-74159, Y-74450 and Stannern show particularly good examples. In the finest-grained variolitic textures, sheaves of pyroxene and plagioclase are closely intergrown into a felted mass. Patches of this sheaf-like texture are intergrown with coarser-grained

material in Y-74450. Coarser varieties occur with radiating plagioclase and pyroxene (Fig. 1.2.8.1d); unfortunately, these have not been seen in fragments large enough to observe the intervariole texture. The variolitic textures are not reported to be vesicular, except that the recrystallized meteorite Ibitira contains both cavities and a relict variolitic texture. Vesicles have been described in Ibitira by Wilkening and Anders (1975) and by Steele and Smith (1976).

Porphyritic texture.   Only one eucrite, Y-74450, contains basalt with distinctly porphyritic textures (Takeda *et al.*, 1978a). In this texture, clinopyroxene cores, commonly equant in shape, are surrounded by a finer-grained, somewhat variolitic texture (Fig. 1.2.8.1e). Although the fragments are small and modal statistics are poor, the porphyritic basalt appears to be richer in pyroxene than basalts with subophitic textures.

Other textures.   Rocks which appear to be cumulates have medium- to coarse-grained equigranular textures (Fig. 1.2.8.1f). Evidence for preferred orientation of pyroxene grains has been reported by Hess and Henderson (1949) and by Duke and Silver (1967). Exsolution lamellae are prominent in the pyroxenes, and the original pigeonite has partially or completely inverted to orthopyroxene (Hess and Henderson, 1949; Duke and Silver, 1967). The Sioux County meteorite contains some very coarse-grained rock fragments (grain size up to 1 cm). These have not been studied petrographically, but appear to fall between the subophitic and equigranular cumulate-like textures macroscopically.

In the Aioun el Atrouss meteorite, irregular patches of granoblastic material are closely intergrown with subophitic basalt (Fig. 1.2.8.1g). This texture has been interpreted to represent recrystallized basalt breccia, in which the granoblastic material corresponds with recrystallized breccia matrix (Duke, 1978). Small rock fragments with granoblastic textures, which occur commonly in howardites, may represent similar recrystallized material.

Shergottites

The textures of Shergotty and Zagami, the two examples of the shergottite class, consist of 75% prismatic clinopyroxene grains with strong planar orientation (Duke, 1968) and 25% interstitial tabular plagioclase and accessory phases (Fig. 1.2.8.1h). Both Ca-rich and Ca-poor pyroxenes are strongly zoned (Duke, 1968; Stolper and McSween, 1979). The accessory phases are silica, titano-magnetite, whitlockite, ilmenite and pyrrhotite (Smith and Hervig, 1979; Stolper and McSween, 1979). These meteorites are not brecciated but have
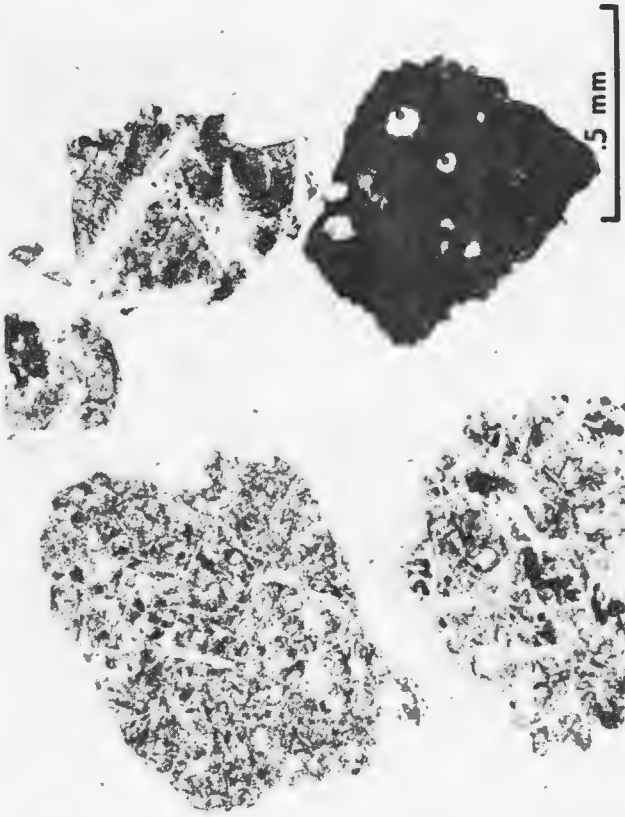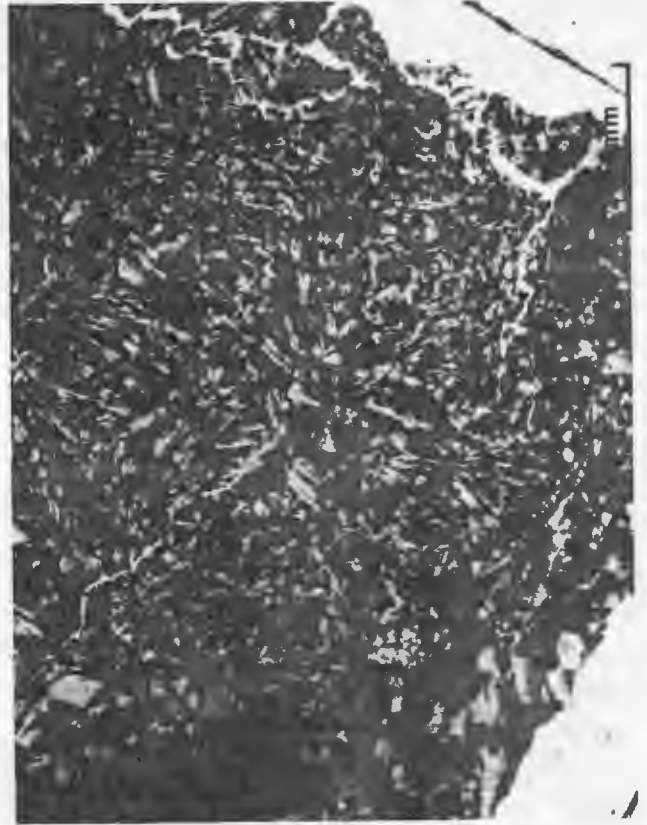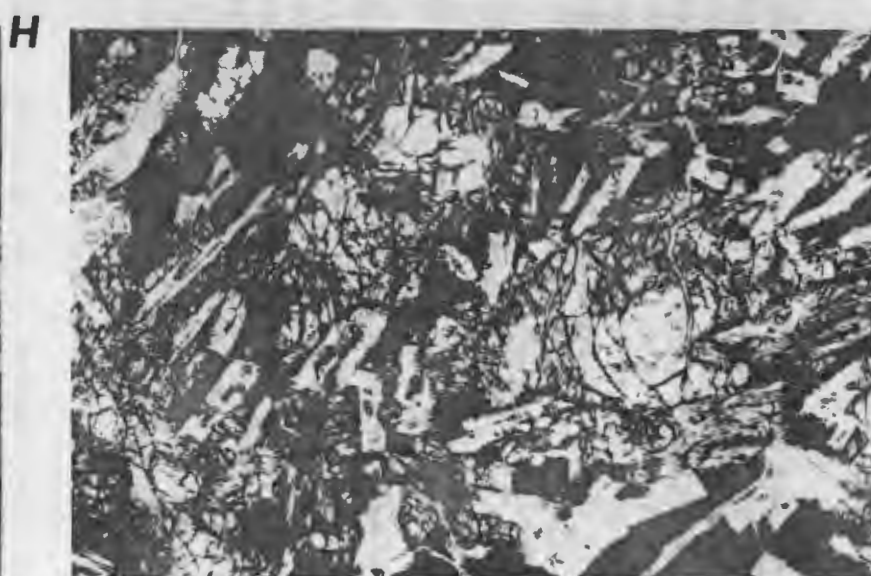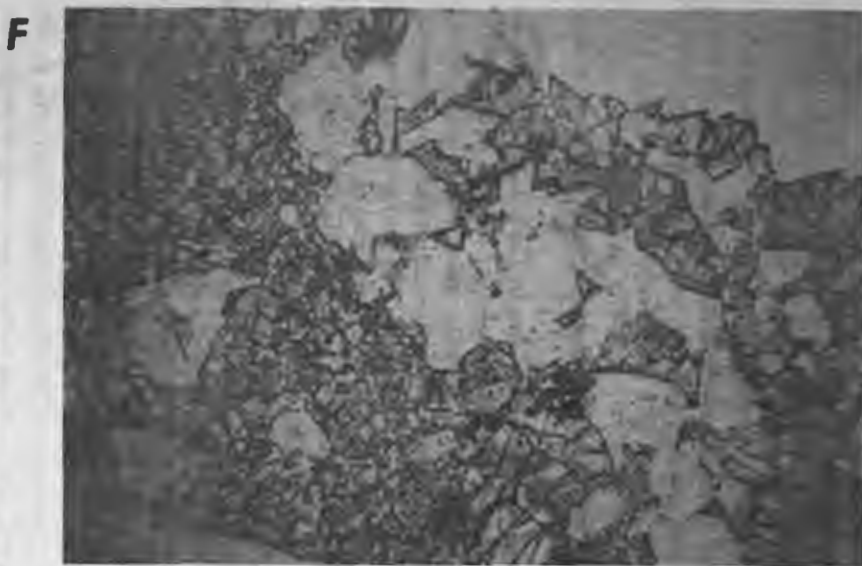
1.2.8.1 Photomicrographs of basaltic meteorite textures: **a.** Nuevo Laredo; vitric, vesicular breccia fragment on right, intersertal fine-grained fragment on left. **b.** Nuevo Laredo, varieties of subophitic texture. **c.** Pasamonte, subophitic texture. **d.** Stannern, variolitic texture. **e.** Yamato 74450, pigeonite phenocrysts. Cores are uniform magnesian pigeonite, grading to more iron-rich at rims. Tabular plagioclase apparently nucleated on pyroxene phenocrysts. **f.** Moore County, cumulate texture. Note complex exsolution in pyroxenes. **g.** Aioun el Atrouss; fine recrystallized breccia in contact with recrystallized subophitic basalt. **h.** Shergotty; preferred orientation of clinopyroxene and maskelynite (width of field is 8 mm.).

been strongly shocked, with all of the plagioclase transformed to a vitreous glass (maskelynite) and the silica transformed to cryptocrystalline cristobalite, without modification of the original texture. The origin of the texture is uncertain, but Stolper and McSween (1979) believe it to be cumulate. ALHA 77005 consists of olivine, Ca-rich and Ca-poor pyroxene, maskelynite and chromite with minor ilmenite, troilite and whitlockite in a hypidiomorphic granular to medium-grained texture (McSween *et al.*,1979b). This meteorite may represent a more basic differentiate related to the shergottites.

Range of textures in individual eucrites

Most brecciated eucrites show a prominent textural type among their clasts, in most cases a subophitic texture. Characteristic combinations of igneous texture, subsolidus inversion of pyroxenes, shock effects and brecciation tend to render each meteorite distinctive and recognizable to an experienced observer. However, there are minor variations of textural type observed in the clasts of each meteorite, which probably would be extended if larger samples were to be studied. For example, in Nuevo Laredo, a few vitric fragments and a few subophitic fragments containing pyroxene grains as large as 1 mm are found mixed with more common intersertal and subophitic fragments containing 0.1–0.3 mm pyroxene grains. The predominant fragments in Pasamonte are subophitic; however, a few variolitic clasts occur. In Y-74450, most fragments appear to be variolitic/porphyritic, with the exception of some that are more typically subophitic. Such variations are consistent with the environment of mechanical mixing that must have existed during breccia formation. However, to our knowledge, the varieties observed in any brecciated eucrite are consistent with derivations from closely associated igneous bodies. Mixing has been limited and can be interpreted as having been confined to a single lava flow or intrusion, or to very closely related bodies. This conclusion is supported by mineralogical data and by crystallographic study of the pyroxenes (Takeda, 1979).

1.2.8.4   Chemical composition

Major elements

Selected major element analyses for meteoritic basalts are given in Table 1.2.8.2. The quality of available analytical data on eucrites is variable and several older analyses that give extreme values should be repeated using modern techniques. The majority of modern analyses derive from the papers by Duke and

Silver (1967) and by McCarthy *et al.* (1972, 1973, 1974). Much of our understanding of the bulk composition of meteoritic basalts and much of the discussion of their formation depend upon the data base from those papers. This data base has recently been expanded by Mason *et al.* (1979) and should be extended to include all meteoritic basalts where adequate material is available.

The analyses and norms in Table 1.2.8.2 represent the compositional range of eucrites and shergottites. For a eucrite, there is a close relationship between the CIPW norm derived from the major element composition and the modal analysis. The major element variations are principally related to two parameters: the pyroxene/plagioclase ratio and the $Mg/(Mg + Fe)$ ratio in pyroxenes. Most eucrite compositions cluster near the compositions of Juvinas, Sioux County and Pasamonte. Nuevo Laredo is distinguished by a lower $Mg/(Mg + Fe)$ ratio and by a slightly lower pyroxene/plagioclase ratio than the main group. The Yamato meteorites Y-74450 and Y-74159 have more modal pyroxene, with a higher $Mg/(Mg + Fe)$ ratio than the main group. The meteorites Moore County, Serra de Magé, Moama and Binda have higher $Mg/(Mg + Fe)$ ratios and show a range of pyroxene/plagioclase ratios. The alkali contents of eucrites generally are low, although Nuevo Laredo and Stannern are noticeably richer than the main group. The normative plagioclase contents of cumulate eucrites are slightly more calcic than those of the basaltic members. The eucrites, like lunar basalts, are free of ferric iron and water. A FeO/MnO ratio of about 33 (by weight) is characteristic of the eucrites.

The shergottites also have iron-rich basaltic compositions, but are much lower in Al_2O_3 than eucrites, reflecting their lower feldspar contents. On textural grounds, the shergottites are believed to be cumulates, so their compositions cannot be considered to represent basalt liquid compositions. The Ca/Al ratios are higher than those of the eucrites due to a greater abundance of Ca-rich pyroxene, which is approximately equal in abundance to Ca-poor pyroxene. The shergottites also are distinct from the eucrites in their higher alkali contents ($Na_2O \sim 1.3$, $K_2O \sim 0.2$ wt.%, i.e., more than twice eucritic abundances), in containing significant Fe^{3+}, and in their high phosphorus contents ($P_2O_5 \sim 0.5$ wt.%). The unique meteorite, ALHA 77005, differs in bulk composition from the shergottites, reflecting its substantial content of olivine, but bears a chemical signature that ties it closely to the shergottites, particularly with respect to trace element abundances, volatile/involatile element ratios and oxidation state.

Table 1.2.8.2 Chemical compositions of eucrites.

	Sioux County *(2)*	Pasamonte *(2)*	Juvinas *(2)*	Béréba *(2)*	Cachari *(2)*	Haraiya *(2)*	Macibini *(2)*	Nuevo Laredo *(1)*
SiO_2	49.03	48.07	49.34	49.13	48.26	48.69	49.32	49.46
TiO_2	0.62	0.72	0.64	0.70	0.63	0.56	0.72	0.95
Al_2O_3	12.84	12.25	13.00	12.75	12.85	12.49	12.12	11.78
Cr_2O_3	0.35	0.31	0.34	0.32	0.32	0.32	0.42	0.29
FeO	18.58	19.10	18.82	19.83	19.10	19.25	18.31	20.10
MnO	0.56	0.56	0.56	0.55	0.59	0.59	0.54	0.56
MgO	7.11	6.53	7.27	6.80	7.14	7.11	8.37	5.46
CaO	10.35	10.24	10.38	10.48	10.25	10.26	9.97	10.40
Na_2O	0.45	0.51	0.47	0.47	0.51	0.50	0.48	0.57
K_2O	0.04	0.04	0.04	0.04	0.05	0.03	0.05	0.05
P_2O_5	0.09	0.11	0.09	0.10	0.08	0.10	0.11	0.11
TOTAL	100.02	98.44	100.95	101.95	99.78	99.90	100.41	99.73
Qz	2.17	1.90	1.83	1.58	0.66	1.30	1.61	4.00
Or	0.24	0.24	0.24	0.24	0.30	0.18	0.30	0.30
Ab	3.81	4.32	3.98	3.98	4.32	4.23	4.06	4.82
An	32.90	31.02	33.25	32.56	32.63	31.75	30.77	29.44
Di	15.15	16.24	14.98	15.99	15.03	15.72	15.17	18.38
Hy	43.87	42.68	44.77	44.82	45.02	44.98	46.29	40.33
Ol	—	—	—	—	—	—	—	—
Cm	0.52	0.46	0.50	0.47	0.47	0.47	0.62	0.43
Ilm	1.18	1.37	1.22	1.33	1.20	1.06	1.37	1.80
Ap	0.20	0.24	0.20	0.22	0.17	0.22	0.24	0.24
Mg'	0.44	0.40	0.43	0.40	0.43	0.42	0.48	0.35

Table 1.2.8.2 *(Continued)*

	Stannern *(1)*	Yamato 74159	Yamato 74450 *(3)*	Moore County *(2)*	Serra de Magé *(2)*	Moama *(4)*	Binda *(2)*	Shergotty *(5)*
SiO_2	49.33	49.04	49.36	48.32	48.42	48.58	50.41	50.1
TiO_2	0.96	1.09	1.04	0.44	0.17	0.22	0.23	0.92
Al_2O_3	12.34	10.35	10.82	12.65	12.69	13.74	6.94	6.68
Cr_2O_3	0.28	0.44	0.33	0.44	0.54	0.61	0.75	0.18
FeO	17.92	19.23	18.26	17.24	16.18	14.85	16.83	18.66
MnO	0.50	0.53	0.51	0.52	0.55	0.50	0.54	0.50
MgO	6.36	8.29	8.06	9.41	11.35	11.89	17.75	9.40
CaO	10.58	9.48	9.52	9.37	9.08	9.47	5.82	10.03
Na_2O	0.60	0.58	0.51	n.d.	n.d.	0.22	0.20	1.28
K_2O	0.08	0.07	0.06	0.02	0.007	0.01	<.01	0.16
P_2O_5	0.13	0.07	0.10	0.04	0.06	—	0.04	0.71
TOTAL	99.08	99.17	98.57	98.45	99.05	100.09	99.52	100.11 [†]
Qz	3.67	1.94	3.44	2.43	0.68	—	—	0.89
Or	0.47	0.41	0.35	0.12	0.06	0.06	0.06	0.95
Ab	5.08	4.91	4.32	—	—	1.86	1.69	10.83
An	30.74	25.43	27.06	34.46	34.60	36.48	18.04	12.01
Di	17.77	17.83	16.47	9.85	8.37	8.67	8.67	28.09
Hy	38.83	45.78	44.26	50.02	54.10	49.16	65.69	41.63
Ol	—	—	—	—	—	2.55	3.76	2.16
Cm	0.41	0.65	0.49	0.65	0.80	1.27	1.10	0.27
Ilm	1.82	2.07	1.98	0.84	0.32	0.90	0.44	1.75
Ap	0.28	0.15	0.22	0.09	0.13	0.42	0.09	1.55
Mg'	0.41	0.46	0.47	0.52	0.58	0.61	0.68	0.48

References: *(1)* Duke and Silver (1967); *(2)* McCarthy *et al.* (1973); *(3)* Takeda *et al.* (1978a); *(4)* Lovering (1975); *(5)* Duke (1968).
[†] 1.49% Fe_2O_3 included in total.

Trace elements

Trace element data for selected eucrites are given in Table 1.2.8.3. Ahrens and Danchin (1971) summarized the available eucrite data, but a substantial number of additional analyses are now available (e.g., Schmitt *et al.*, 1972; Laul *et al.*, 1972; McCarthy *et al.*, 1972, 1973; Wänke *et al.*, 1977; Morgan *et al.*, 1978). Figures 1.2.8.2a and b show trace element data for eucrites, two of which are cumulate eucrites, normalized to type 1 carbonaceous chondrite abundances. Refractory lithophile trace elements are enriched over C1 chondrite values ($\sim$ 13 times C1 chondrites) but are essentially unfractionated except for Sc, which is depleted relative to elements of similar volatility by about a factor of 2. The main group eucrites have REE patterns which are unfractionated relative to chondritic abundances at levels about 6–10 times chondritic (Fig. 1.2.8.3). Stannern and Nuevo Laredo have higher REE abundances and negative europium anomalies. The more magnesian (cumulate) eucrites have lower absolute REE abundances (1–5 times chondritic) and Moore County, Serra de Magé and Moama have positive europium anomalies (see summary in Consolmagno and Drake, 1977). In contrast, the more volatile lithophile trace elements are depleted, with Rb, Cs, Br and Bi present at approximately 6×10^{-2} times C1 chondrites.

Siderophile trace elements are strongly depleted in eucrites relative to chondritic abundances (Fig. 1.2.8.2b). There is no simple correlation between relative abundance and condensation temperature. Morgan *et al.* (1978) have suggested that siderophile abundances may be controlled by metal/silicate partitioning. These data suggest derivation of the eucritic liquids from sources that retained a metallic iron phase in the residuum or from sources that had lost metallic iron and the associated siderophile elements prior to formation of the eucrite basalts. Siderophile trace element abundances may also have been affected by meteoritic contamination subsequent to basalt crystallization, particularly if some eucrites are regolith breccias, so the observed values may represent only upper limits on original values. Figure 1.2.8.2b also shows relative abundances of chalcophile trace elements, which are depleted relative to C1 chondrites.

The shergottites are not characterized by the volatile element depletion that is so evident in the eucrite basalts. Laul *et al.* (1972), Stolper (1979) and Stolper and McSween (1979) have stressed similarities between trace element abundances in shergottites and in terrestrial basalts. This similarity extends to the volatile, refractory and siderophile trace elements as well, and contrasts strongly with the trace element abundance patterns in eucrites. The chondrite-normalized REE pattern of Shergotty is slightly heavy REE-enriched at about 6–8 times chondritic levels with no europium anomaly.

1.2.8.5 Mineral chemistry

Mineral assemblages in meteoritic basalts are simple, consisting of clinopyroxene (dominantly pigeonite with augite subordinate except in shergottites), and calcic plagioclase with minor free silica, ilmenite, chromite, troilite and metallic iron. Orthopyroxene and augite are present as products of the exsolution and inversion of pigeonite. Magnesian olivine is not present in rocks with basaltic textures, but ultramafic, apparently cumulate, material found in howardites contains minor olivine, and ALHA 77005, a cumulate which seems to be related to the shergottites, contains magnesian olivine as a major phase. Fayalite occurs in Ibitira and Sher-

Table 1.2.8.3 Selected trace element abundances in eucrites and Shergotty, *ppm.*

	Stannern	Nuevo Laredo	Pasamonte	Juvinas	Aioun el Atrouss	Moore County	Binda	Shergotty
K	550(1)	400(4)	355(1)	340(1)	308(14)	180(1)	85(1)	—
Rb	0.827(3)	0.380(3)	0.242(3)	0.202(3)	—	0.061(3)	—	6.1(13)
Ba	50(1)	44(8)	33(1)	31(1)	—	19(1)	11(1)	90(8)
Sr	92(1)	84(9)	80(1)	78(1)	80(14)	64(1)	33(1)	65(8)
Sm	3.17(6)	2.19(5)	1.90(6)	1.70(6)	2.6(14)	0.94(7)	—	1.25(8)
Eu	0.83(6)	0.75(5)	0.68(6)	0.62(6)	0.59(14)	0.59(7)	—	0.49(8)
Y	26(1)	—	17(1)	16(1)	—	—	4.4(1)	—
Sc	32(9)	38(10)	26(10)	29(10)	33.5(14)	24(10)	—	52.4(8)
Th	0.50(11)	0.47(11)	0.52(2)	0.60(11)	—	0.06(12)	0.06(12)	0.3(8)
Zr	87(1)	67(6)	53(1)	46(1)	—	—	15(1)	—

References: (1) McCarthy *et al.* (1973); (2) Morgan *et al.* (1978); (3) Papanastassiou and Wasserburg (1969); (4) Duke and Silver (1967); (5) Schmitt *et al.* (1963); (6) Schmitt *et al.* (1964); (7) Schnetzler and Philpotts (1969); (8) Gast (1965); (9) Gast (1962); (10) Schmitt *et. al.* (1972); (11) Rowe *et al.* (1963); (12) Morgan and Lovering (1964); (13) Laul *et al.* (1972); (14) D. Blanchard, analyst.
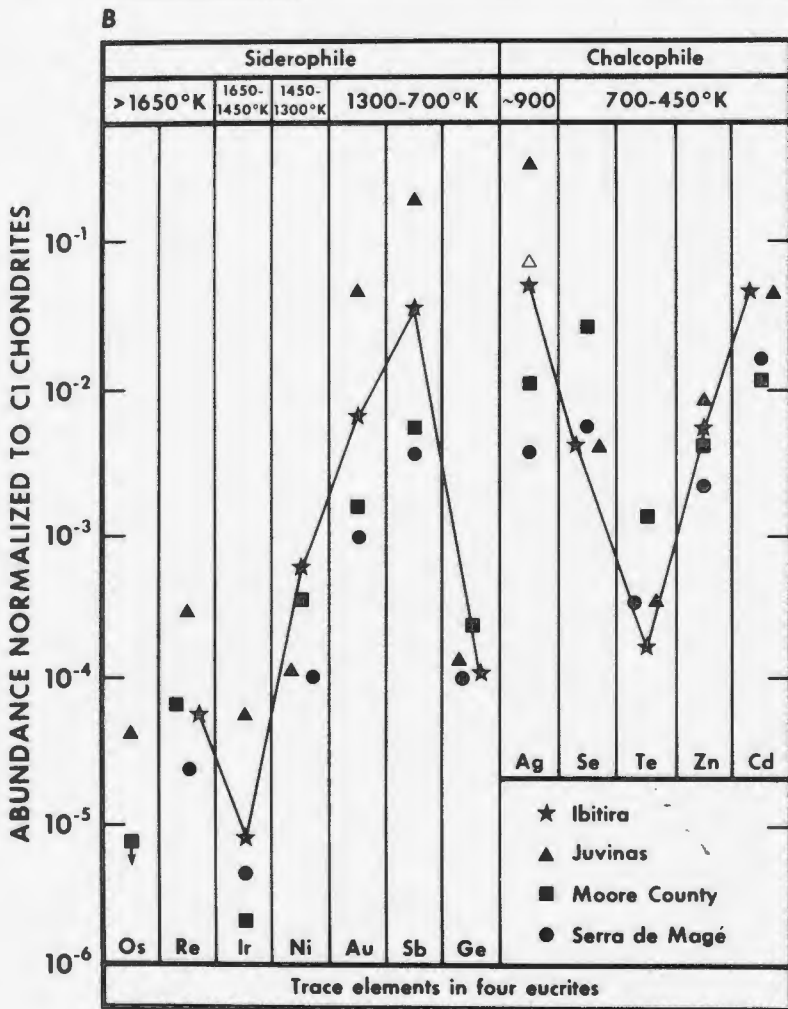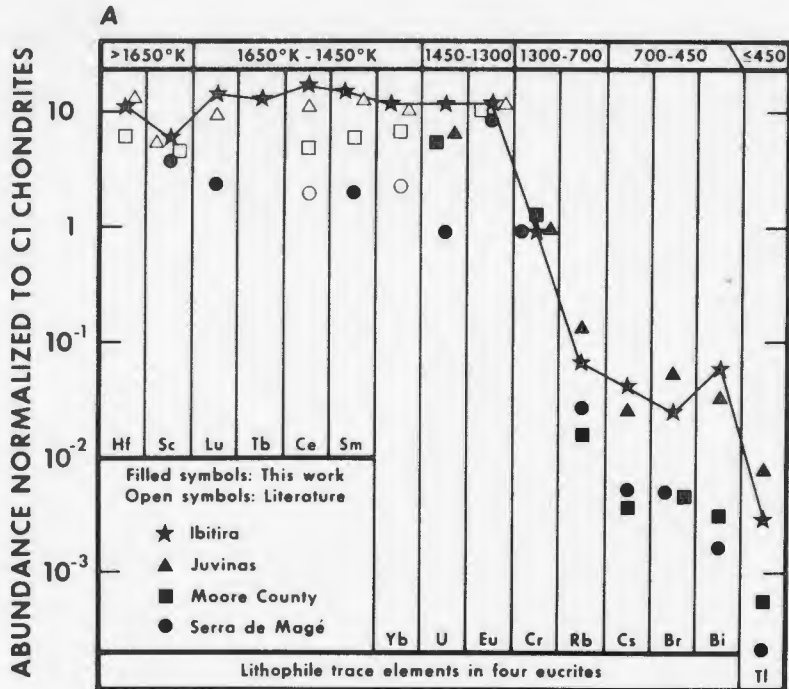
1.2.8.2 Trace elements in eucrites. **a**. Abundances relative to C1 chondrites of large-ion-lithophile trace elements, arranged in approximate order of condensation temperature, in four eucrites. **b**. Similar figure for siderophile and chalcophile trace elements in four eucrites. After Morgan et al. (1978).
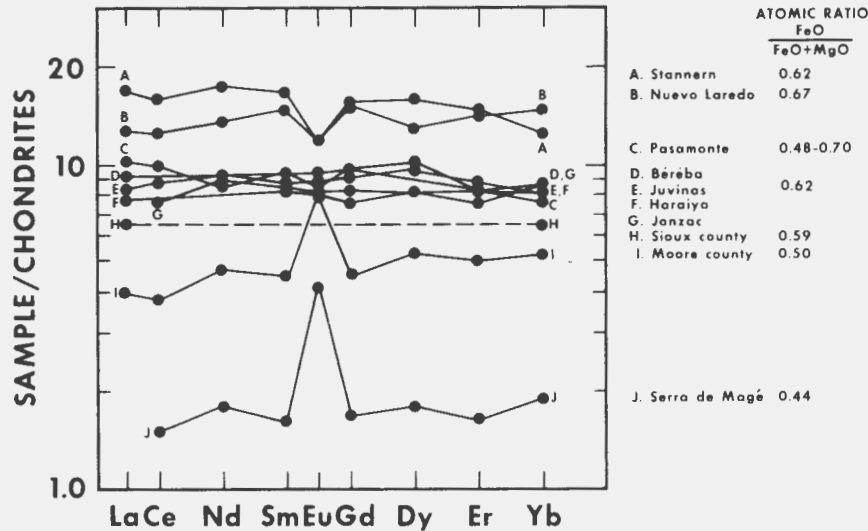
1.2.8.3 Chondrite-normalized rare-earth element abundances of eucrites. After Consolmagno and Drake (1977).

gotty. A complex, fine-grained mesostasis is present in some samples but has not been studied in detail. The shergottites also contain magnetite and whitlockite but lack metallic iron. Mineral compositional data are reported in Appendix A-8.

Pyroxene

The dominant primary pyroxene in all eucrites is pigeonite. Two specific types of pigeonite occurrences have been recognized. *Unequilibrated* eucrites are characterized by the presence of pigeonites with a wide range of $Mg/(Mg + Fe)$ values expressed largely as normal zoning. These pyroxenes do not exhibit microscopic exsolution. *Equilibrated* eucrites have pigeonite with only a narrow range of $Mg/(Mg + Fe)$ values; however, individual grains show a range of $Ca/(Ca + Fe)$ values, due to the presence of microscopic exsolution lamellae. Table 1.2.8.1 classifies eucrites according to this characteristic. The classification has been made petrographically for meteorites which have not been studied with the electron microprobe, based upon the presence or absence of exsolution lamellae and visible compositional zoning.

The pyroxenes of the Pasamonte meteorite are typical of the unequilibrated eucrites (Fig. 1.2.8.4a). The full range of compositions is shown in individual subcentimeter-size basalt clasts. Cores of pigeonites are magnesium-rich, with normal zoning toward Ca-rich or Fe-rich rims and small interstitial grains. Takeda *et al.* (1978a) found Ca-enrichment toward contacts with mesostasis areas and Fe-enrichment toward plagioclase crystal contacts. Some of the scatter in values for calcium contents of the Fe-rich pyroxenes may be due to incipient exsolution, which can be observed in X-ray patterns but not optically (Takeda *et al.*, 1976). The

bulk meteorite $Mg/(Mg + Fe)$ ratio is 0.38. The most magnesian pigeonite has a $Mg/(Mg + Fe)$ ratio of 0.69, which is consistent with Stolper's (1977) experimental determination of the composition of the first pyroxene to crystallize from a liquid of eucrite composition.

Minor element contents of the pyroxenes reflect their crystallization history. Al_2O_3 content is about 0.13% and shows little variation with fractionation. This is consistent with petrographic and experimental evidence that pigeonite and plagioclase crystallized simultaneously from the beginning of crystallization. Titanium contents in the high magnesium cores are low and increase with decreasing $Mg/(Mg + Fe)$, particularly in the latest-formed Ca-rich pyroxenes, which is consistent with the late and minor role of ilmenite. Chromium diminishes in pyroxenes with decreasing $Mg/(Mg + Fe)$, with a greater decrease in pigeonite less magnesian than $Mg/(Mg + Fe) = 0.65$ that may be related to the late crystallization of chromite, which also is a minor interstitial phase (Bunch and Keil, 1971).

Unequilibrated eucrites are uncommon. Y-74450 and Y-74159 are the only other unequilibrated eucrites that have been studied in any detail (Takeda *et al.*, 1978a, b). In Y-74450, a magnesian pigeonite [$Mg/(Mg + Fe) = 0.72$] crystallized first, followed by pigeonites, which were richer in iron and calcium. The early pigeonites of Y-74450 are Al-rich, consistent with some crystallization of pyroxene prior to initiation of plagioclase crystallization.

Stannern is an example of an equilibrated eucrite (Fig. 1.2.8.4b). The bulk composition of Stannern is similar to that of Pasamonte, but the pyroxene compositional variation is distinctively different. The pyroxenes in Stannern exhibit a narrow range of $Mg/(Mg + Fe)$ values which define a trend approximately

measure lamellae
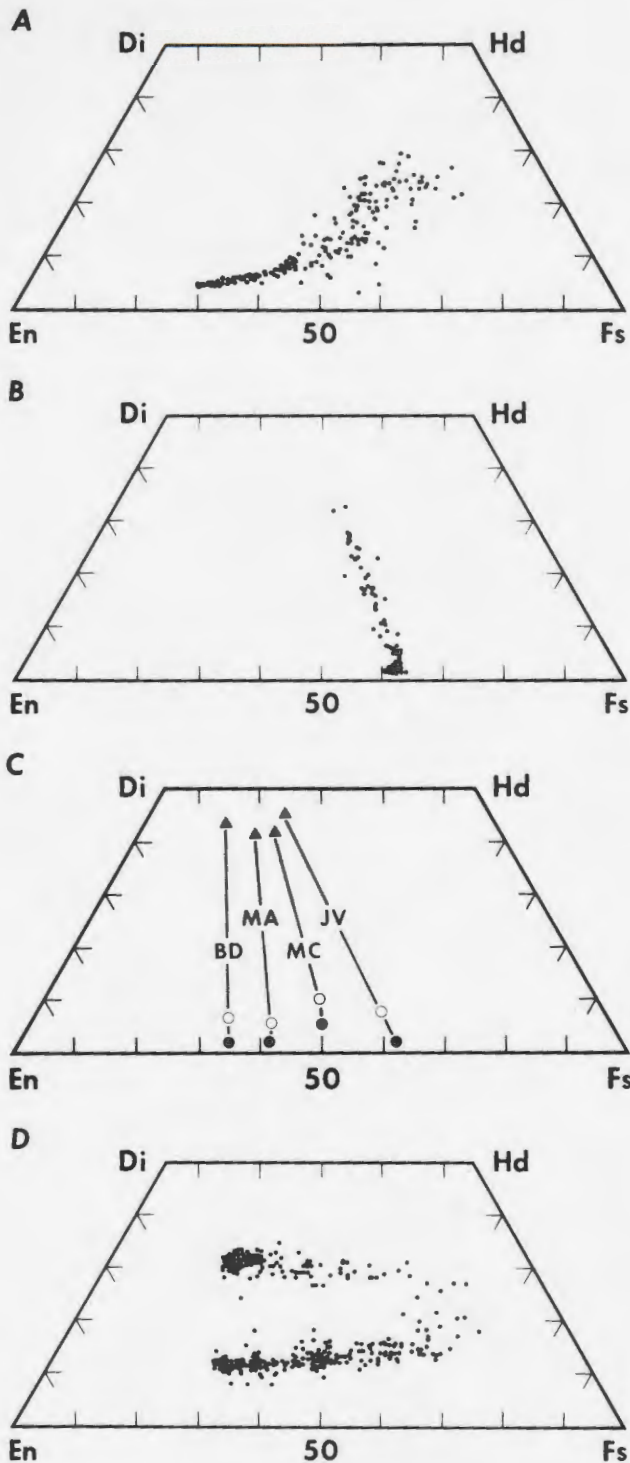
1.2.8.4 Pyroxene compositions in basaltic meteorites. **a**. Pasamonte, an unequilibrated eucrite. **b**. Stannern, an equilibrated eucrite. **c**. Three cumulate eucrites (BD-Binda, MA-Moama, MC-Moore County) plus one main group eucrite (JV-Juvinas). Open circles represent bulk compositions of pyroxenes; filled circles represent exsolution lamellae. **d**. Shergotty.

parallel to the Hd-Fs boundary of the quadrilateral. This trend in part or in whole reflects the presence of numerous thin lamellae of ferroaugite, which cannot be completely resolved by the microprobe, within the low Ca-pyroxene host. Within most equilibrated pyroxenes, a concentration of analyses at low-Ca values ($\sim$Wo$_2$) may indicate the composition of the host phase (clinohypersthene in Juvinas; Takeda *et al.*, 1976). The narrow ferroaugite lamellae mostly are too narrow for standard electron microprobe analysis; however, some analyses are as calcic as Wo$_{30}$. Average compositions are difficult to determine for pyroxenes, due to the complexity of exsolution and inversion features. Despite the obvious heterogeneity, the pyroxene analyses all plot along the same narrow trend. The constraint on Mg/(Mg + Fe) values suggests that the general subsolidus equilibration between high and low-Ca phases occurred within a limited temperature range.

Stannern pyroxenes have low TiO$_2$ and Al$_2$O$_3$ contents (average TiO$_2$ $\sim$0.25 wt.%). Ti and Al do not vary sympathetically with Fe or Ca content but there is a weak positive correlation between Ti and Al. Chromium is high and uniform (average 0.73 wt.%). Similar pyroxene relationships are found in the other equilibrated eucrites, Juvinas, Nuevo Laredo and Aioun el Atrouss. In Nuevo Laredo, texturally primary ferroaugite and pigeonite coexist in basaltic fragments (Takeda *et al.*, 1978a).

The fine-grained textures of the eucrites, such as Juvinas and Pasamonte, indicate that they crystallized from the magma rapidly. Under such crystallization conditions in the laboratory, pyroxenes grow with strong Fe/Mg zonation. Furthermore, exsolution of pigeonite does not occur in such rapid crystallization environments. These two characteristics, lack of exsolution and strongly-zoned pyroxenes are characteristic of the unequilibrated eucrites, such as Pasamonte. The equilibration observed in meteorites such as Juvinas implies that subsequent recrystallization has occurred either as a transformation during the initial crystallization and cooling episode, or through subsequent reheating and metamorphism.

The occurrence of two primary clinopyroxenes, augite and pigeonite, in Nuevo Laredo suggests that two pyroxenes would be stable near the solidus in the main group eucrites. However, in those meteorites, the primary pyroxene phase was pigeonite alone. Recrystallization to two discrete pyroxenes would be expected if the pyroxene zonation was homogenized much below the solidus. Exsolution in the main group eucrites has produced lamellae of relatively uniform dimensions and composition throughout the host pigeonite. This implies

that exsolution occurred subsequent to homogenization. Since exsolution appears to have developed in homogeneous pigeonite grains, the homogenization must have occurred at near-solidus temperatures. Takeda *et al.* (1976) have concluded that the exsolution in Juvinas occurred at high temperature (~900°C). Liquidus temperatures are approximately 1160°C for Stannern and 1180°C for Juvinas and pyroxene, plagioclase and silica would all have begun to crystallize by 1090°C (Stolper, 1977). If homogenization took place slightly above solidus temperatures, the presence of residual liquid could have facilitated the process.

The pyroxenes of the cumulate eucrites, Moore County, Serra de Magé, Moama and Binda, show similarities to those of equilibrated eucrites (Fig. 1.2.8.4c). They typically have coarser exsolution lamellae and partial to complete inversion of primary pigeonite to orthopyroxene, as was shown for Moore County by Hess and Henderson (1949), who suggested its origin in a buried intrusive body. In howardites, such as Kapoeta, a wide range of pigeonite compositions is present (Fredriksson and Keil, 1963; Dymek *et al.*, 1976). It is probable that the brecciated pyroxene fragments include representatives of unequilibrated, equilibrated and cumulate eucrites; however, detailed studies of the total range of pyroxene types in howardites have yet to be made.

The shergottites contain two primary pyroxenes, pigeonite and augite (Stolper and McSween, 1979; Smith and Hervig, 1979), both of which are highly zoned (Fig. 1.2.8.4d). Our data show that the most magnesian pigeonite is $Wo_{12}En_{61}Fs_{27}$ and the most magnesian augite is $Wo_{33}En_{49}Fs_{18}$. Both have relatively homogeneous cores with highly-zoned outer margins. The two pyroxene trends are subparallel except for high Fe compositions where the two trends merge at approximately $Wo_{22}En_{16}Fs_{62}$. There is a natural break in compositions between high-Ca and low-Ca pyroxenes at approximately Wo_{24}, but many pigeonites have ferroaugite rims with Wo > 24. Exsolution lamellae with contrasting Ca contents, which are present in both types of pyroxene, record a lower temperature subsolidus history. The lamellae are very narrow (< 2 microns) and their presence contributes to the scatter of electron microprobe analytical values seen in Fig. 1.2.8.4d.

The shergottites apparently are cumulates. A well-defined planar orientation of prismatic pyroxene grains is present (Duke, 1968). The initiation of plagioclase crystallization probably was responsible for an abrupt decrease in aluminum content of the pyroxenes for compositions less magnesian than (augite) $Wo_{32}En_{41}Fs_{28}$ and (pigeonite) $Wo_{13}En_{48}Fs_{39}$.

Plagioclase

Eucrites contain plagioclase with high-Ca contents, generally in the range An_{80} to An_{90} with some interstitial grains as sodic as An_{65} (Duke and Silver, 1967). In unequilibrated eucrites such as Pasamonte, the range is from $Or_{0.06}Ab_5An_{95}$ to $Or_{1.2}Ab_{19}An_{80}$ and there are small differences, though with considerable overlap, from clast to clast. The feldspars have low but detectable contents of Ti, Fe and Mg. Pasamonte feldspars show apparent departures from stoichiometry (Si-Na-K averages 2.03, Al-Fe-Ca averages 0.93) and in this respect resemble the feldspars in lunar mare basalts.

Feldspars in equilibrated eucrites, such as Juvinas, show a comparable range in compositions from $Or_{0.5}Ab_6An_{93}$ to $Or_{1.7}Ab_{18}An_{80}$. Stannern, also equilibrated, has more sodic plagioclases, ranging from $Or_{0.4}Ab_{11}An_{89}$ to $Or_2Ab_{26}An_{72}$. The departures from stoichiometry in the equilibrated eucrites are less than in the unequilibrated. Stannern feldspars analyzed in this study average Si-Na-K of 2.004 and Al-Fe-Ca of 0.96. This close approach to stoichiometry is consistent with the occurrence of a thermal annealing event subsequent to primary crystallization. Relatively little work has been done on optical properties of eucrite plagioclase. Game (1957) reported varied optical properties in Juvinas plagioclase and Duke (1963) reported high but varied structural states from X-ray studies of the same meteorite. The persistence of evidence for disequilibrium in plagioclases contrasts with the equilibrated characters of the pyroxenes.

Plagioclase feldspar in the Shergotty meteorite has been converted by high shock pressures ($\geqslant 250$ kb) to maskelynite (Schaal and Hörz, 1977). The maskelynite preserves the original feldspar crystal forms and apparently preserves original compositions as well, including normal zoning. The range of compositions in Shergotty is from $Or_1Ab_{42}An_{56}$ to $Or_{4.5}Ab_{60}An_{39}$, reflecting the higher alkali contents of shergottites. The maskelynites contain around 0.6 wt.% FeO and low but detectable amounts of Ti and Mg. Departures from stoichiometry, assuming that maskelynites retain feldspar compositions, are greater than in the unequilibrated eucrites (Si-Na-K averages 2.04, Al-Fe-Ca averages 0.91).* Stolper and McSween (1979) have presented evidence that a potassium-rich phase present in the mesostasis is glass.

---

*Errors in electron microprobe analysis make it very difficult to assess whether the apparent departures from strict stoichiometry in meteorite plagioclases are real. We believe that it is significant that the plagioclases in "unequilibrated" eucrites consistently show larger departures from stoichiometry than the plagioclases in "equilibrated" eucrites.

Other phases

Free silica is present in all of the basalts. A summary of occurrences is found in Duke and Silver (1967). In cases where cristobalite or tridymite is the primary phase, some quartz typically is present, apparently as a late-stage crystallization product in interstices, rather than as an inversion product from the higher temperature polymorph. In Shergotty, the silica is a glassy form, devitrified to cristobalite (Duke, 1968).

Ilmenite and chromite are principal oxide phases, typically making up less than 0.5% by weight of the basalts. Their compositions in eucrites have been studied by Bunch and Keil (1971), who found that chromites contain 9–12% Al_2O_3, 3–4% TiO_2, and smaller amounts of V_2O_3, MgO, MnO and ZnO.

Ilmenite is rather pure $FeTiO_3$, containing less than 1% of Cr_2O_3, MnO, MgO, CaO and Al_2O_3. Titanomagnetite ($Mt_{37}Usp_{63}$) coexists with ilmenite ($Ilm_{95}Hm_5$) in Shergotty, defining an equilibration temperature of 860° C and log f_{O_2} of –4 (Stolper and McSween, 1979).

Sulfide (troilite) is found primarily in interstitial areas where it occurs with silica, plagioclase and minor metallic iron. Some rock fragments in the breccias are highly fractured, possibly by impact processes. Some of the fractures show localized grains of sulfide and appear bleached, apparently with loss of iron to the sulfide phase and, in some cases, crystallization of silica. In Shergotty, the sulfide is pyrrhotite, consistent with a more oxidized state for that meteorite (Smith and Hervig, 1979).

Metallic iron exists in the eucrite basalts in two forms (Duke, 1965): as a primary phase generally in the mesostasis, and as metal formed by reduction of pyroxene. The metal in the basalts is quite low in nickel (Lovering, 1964; Duke, 1965); the Co/Ni ratio is variable (Hewins and Klein, 1978).

Phosphate (whitlockite) occurs in abundances of 1–2% in Shergotty, but has not been observed in eucrites, except as grains on the interior of vesicles in Ibitira (R. Fruland, pers. comm., 1979).

Mineral proportions

Modal proportions of minerals are difficult to determine in most eucrites, due to the small size of breccia clasts and the difficulty of determining minerals in the breccia matrix. Because eucrite mineral compositions typically are simple, with little Al in pyroxenes, the modal and normative mineralogies are closely comparable. By weight, the proportions are typically 35–37% plagioclase, 59–60% pyroxene, 1–3% silica and 2% opaques. The modal silica content is less than that of the norm, but silica can be found petrographically in all of the eucrites. Nuevo Laredo is slightly poorer in plagio-

clase and richer in silica, which is consistent with the expected trend of cotectic compositions with decreasing $Mg/(Mg + Fe)$ (see next section). Y-74159 and Y-74450 have slightly lower feldspar and higher pyroxene contents, which is consistent with the porphyritic nature of some of the lithic fragments. The equilibrated eucrites contain relatively small amounts of mesostasis. The cumulate eucrites, Moore County, Serra de Magé, Moama and Binda, show a range of feldspar-pyroxene proportions, with Binda being lowest in feldspar. Shergotty also is relatively depleted in feldspar, and apparently does not represent a basaltic liquid.

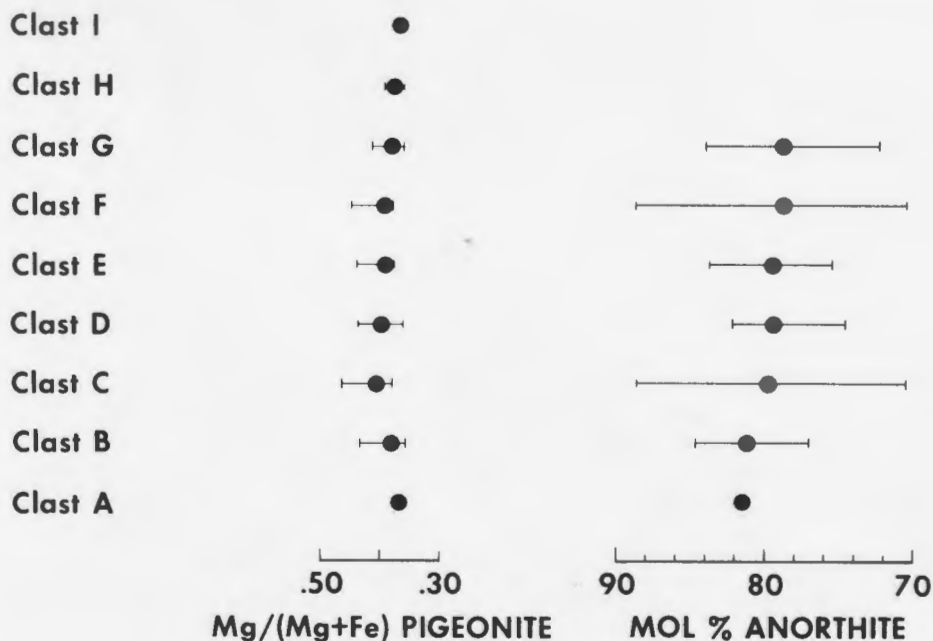## Variations within eucrite breccias

Most eucrites are breccias; therefore, before bulk analyses can be used to formulate and to test petrologic models, we must address the question of whether eucrite bulk analyses represent the compositions of individual rocks or are merely averages on a range of clast and matrix compositions. Most workers have treated the eucrites as monomict breccias because of the overall similarities observed among clasts in terms of petrography and mineral chemistry and because different samples of a eucrite have yielded the same bulk compositions. Other kinds of evidence that support this interpretation include the observation that unbrecciated eucrites (e.g., Ibitira; Wilkening and Anders, 1975) have compositions similar to the brecciated eucrites, and experimental studies (Stolper, 1977), which show that most eucrite compositions are multiply-saturated at one atmosphere liquidus temperatures.

Petrographic studies of eucrites reveal a range of textural types in clasts from a single meteorite, indicating a variety of thermal histories. Despite this range, the similarities in mineral assemblage and in mineral chemistry from clast to clast indicate that, even if the eucrites are polymict breccias, the individual fragments must be closely related and interclast differences must be minor.

We have studied several clasts from two eucrites, Stannern and Pasamonte, in order to determine whether clast-to-clast differences are significant (Reid and Barnard, 1979). The pyroxene compositions in Stannern are uniform within individual clasts (Fig. 1.2.8.5a), whereas strongly-zoned pyroxenes occur in most clasts in Pasamonte (Fig. 1.2.8.5b; see also the section on mineral chemistry and Appendix A-8).

The pyroxene and feldspar compositions in Stannern show little variation from clast to clast and INAA of three clasts show essentially identical REE patterns (Fig. 1.2.8.6a). The pyroxene and plagioclase compositions are more complex in Pasamonte clasts. Each clast shows a range of compositions with small differences from clast to clast. Within the clasts investigated,

A

Clast I

Clast H

Clast G

Clast F

Clast E

Clast D

Clast C

Clast B

Clast A

.50 .30   90 80 70

Mg/(Mg+Fe) PIGEONITE   **MOL % ANORTHITE**

B

Clast I

Clast H

Clast G

Clast F

Clast E

Clast D

Clast C

Clast B

Clast A

.80 .60 .40 .20   100 90 80 84

Mg/(Mg+Fe) PIGEONITE   **MOL % ANORTHITE**

1.2.8.5 Ranges of compositions of pyroxene and plagioclase in clasts from: **a**. Stannern, an equilibrated eucrite; **b**. Pasamonte, an unequilibrated eucrite.
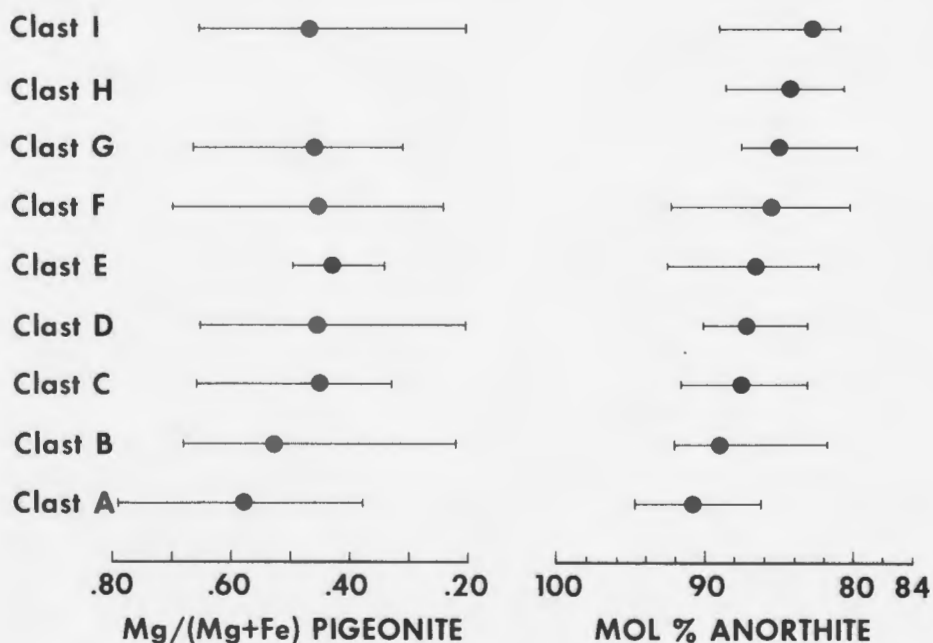
increases in albite content of plagioclases can be correlated with decreasing $Mg/(Mg + Fe)$ ratios in pyroxene and with increases in the proportion of fine-grained, complex mesostasis. Large-ion-lithophile element abundances are also correlated with increasing amounts of mesostasis in the three analyzed clasts (Fig. 1.2.8.6b, also see Appendix A-8). Among three clasts

analyzed, one had a small positive Eu anomaly, two had small negative anomalies. These variations observed in Pasamonte appear to have been due either to local inhomogeneities in the crystallizing magma or to sampling problems related to the small size of the clasts, rather than to the mixing of rocks of different composition.
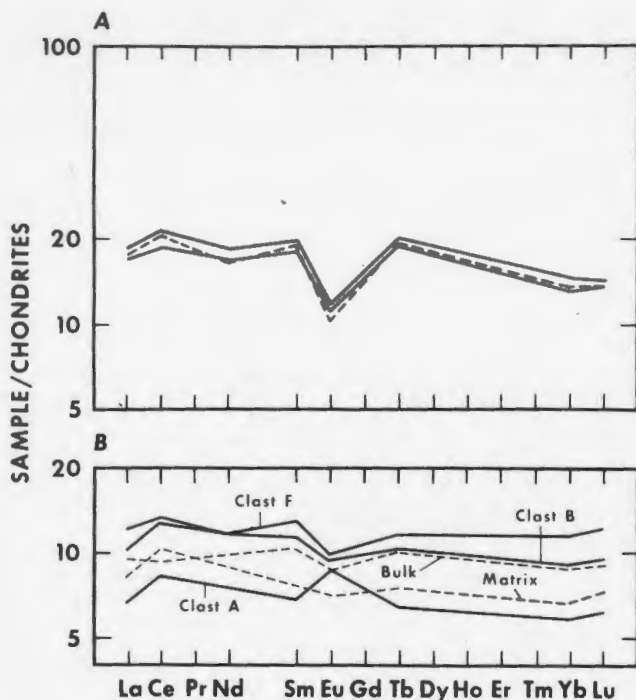
1.2.8.6 Chondrite-normalized rare-earth element abundances in separated clasts from: **a.** Stannern, an equilibrated eucrite; **b.** Pasamonte, an unequilibrated eucrite.

We have not encountered any "exotic" clasts in our sample suite study, i.e., clasts that are not eucrites or eucrite fragments. The possibility that such clasts exist cannot be excluded, but they certainly are not abundant.

We conclude that eucrites are monomict breccias wherefrom exotic clasts are rare or absent, and wherein interclast variations are minor and are consistent with limited crystal-liquid fractionation. Bulk eucrite analyses can thus be used to indicate original rock compositions despite the brecciation events.

## 1.2.8.6 Petrogenesis of meteoritic basalts

Eucrite compositional types

Figure 1.2.8.7 shows TiO_2 variation as a function of $Mg/(Mg + Fe)$, which is one of several two-component diagrams that can be used to depict major element variations among the eucrites. The data, which come from a variety of sources, define several distinctive groups with some apparent anomalies:

(1) **Main group eucrites**: On binary plots of eucrite bulk compositions, there is a grouping of data points among the eucrites that have basaltic textures. This cluster of compositions defines what are here called the *main group* eucrites. Sioux County, Juvinas, Cachari and Haraiya are main group eucrites and Jonzac, Chervony Kut and Bereba have similar compositions. The bulk compositions of these main group eucrites represent the most common meteoritic basalt in our limited sample collection.

(2) **The Stannern trend**: A second group of eucrites defines a trend from the main group eucrites to Stannern and includes Chervony Kut, ALHA 76005 and Ibitira. Along this trend there are only minor differences in major element compositions and in $Mg/(Mg + Fe)$ ratios. There are, however, changes in minor and trace element compositions from the main group eucrites to Stannern, which has substantially higher concentrations of alkalies, TiO_2 and large-ion-lithophile trace elements. The Stannern trend is extended further if we include a basaltic clast (KV-04) from the Nobleborough howardite, which was analyzed by Mittlefehldt (1979a).

(3) **The Nuevo Laredo trend**: The compositional trend from the main group eucrites to Nuevo Laredo includes Pasamonte, Lakangaon and Nuevo Laredo. Compositional changes along this trend encompass increases, relative to the main group eucrite values, in alkalies, TiO_2 and large-ion-lithophile trace elements.
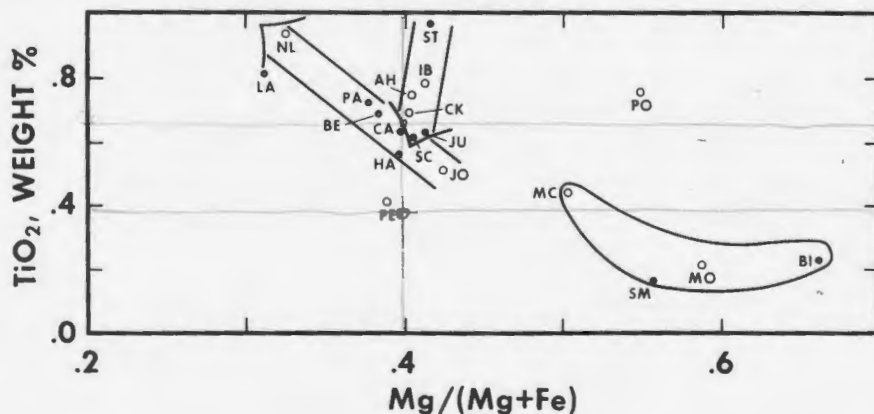
1.2.8.7 Bulk composition of eucrites expressed as a plot of wt.% TiO_2 vs. molar $Mg/(Mg + Fe)$. AH-ALHA 76005; BE-Béréba; BI-Binda; CA-Cachari; CK-Chervony Kut; IB-Ibitira; JO-Jonzac; JU-Juvinas; LA-Lakangaon; MO-Moama; MC-Moore County; NL-Nuevo Laredo; PA-Pasamonte; PE-Peramiho; PO-Pomozdino; SC-Sioux County; SM-Serra de Magé; ST-Stannern. Filled circles are University of Cape Town analyses.

In contrast to the Stannern trend, the minor and trace element differences are coupled to systematic changes in major element composition and particularly to decreases in $Mg/(Mg + Fe)$ ratios.

(4) **Cumulate eucrites**: The high-Mg eucrites plotted in Fig. 1.2.8.7 are those with $Mg/(Mg + Fe)$ ratios substantially higher than the main group eucrites and with lower TiO_2 contents. They include Moore County, Serra de Magé, Moama and Binda. Unlike other eucrites they do not have basaltic textures, but are coarser-grained and show evidence of extensive subsolidus reequilibration of pyroxenes. Some members of this group have cumulate textures.

(5) **Anomalies**: Some eucrites, such as Pomozdino and Peramiho, do not fit into any of the above groups. These eucrites may represent products of separate source regions or of different fractionation processes, or of both. Further analytical work is needed on eucrites from this group, including comparative analyses from the laboratories responsible for the bulk of the eucrite data, so that their apparently anomalous positions can be evaluated properly.

Crystallization history models

The experimental petrologic data of Stolper (1977) have laid a framework for interpreting the history of these basalts. He demonstrated that the main group eucrites can be understood as near-peritectic compositions in the pseudoternary system $Ol-SiO_2-An$ (see Fig. 3.5.1 and related discussion in Chapter 3). Stolper (1977) argues that the eucrite compositions are concentrated near this pseudoperitectic because the eucrites are partial melts of a source region which contained olivine (Fo_{65}), pigeonite (Wo_5En_{65}), plagioclase (An_{94}), Cr-rich spinel and metal. Magmas which were evolving by fractional crystallization would not be constrained to pause at the pseudoperitectic, so no concentration of compositions would be likely to result at that point. Additional modelling, directed at understanding the nature of the differences in eucrite compositions, has been performed largely within the framework defined by the experimental data.

Broadly, there are three processes which may contribute to compositional variations within the eucrites: (1) different degrees of partial melting of a common source material; (2) fractional crystallization of a common parent material; and (3) partial melting of slightly different source compositions. Models that relate all eucrites to processes (1) and (2), operating on a common source material, have been investigated by Schnetzler and Philpotts (1969), McCarthy *et al.* (1973), Consolmagno and Drake (1977), and Reid *et al.* (1979).

The abundances of the rare-earth elements are of particular value in attempts to refine the petrological models. Consolmagno and Drake (1977) accepted the general model proposed by Stolper and attempted to model the proposed fractionation process quantitatively to account for the rare-earth element abundances in eucrites. Fixing the mineral compositions of the source region according to Stolper's model, and assuming the derived liquid composition to be defined by the peritectic, Consolmagno and Drake were able to construct consistent models for: (1) derivation of the main group eucrites (Juvinas, Sioux County) by 10–15% equilibrium partial melting of a source with the relative and absolute REE abundances of chondrites, (2) derivation of the Stannern composition by about 4% partial melting of the same source, (3) derivation of the eucrites Moore County and Serra de Magé as cumulates from a Juvinas-like melt. They also suggested that Nuevo Laredo could be a residual liquid from such fractional crystallization.

Additional modelling of the type performed by Consolmagno and Drake, but also including the elements Sc, Ba, Sr, Zr, and Y, plus major element modelling to derive the Nuevo Laredo trend have been reported by Reid *et al.* (1979). Adding the other refractory trace elements and utilizing the Stolper model, the Juvinas composition can be generated by 12–13% equilibrium partial melting of a source with chondritic abundances. Sioux County can be modelled as a 14% equilibrium partial melt of the same source. The main group eucrites have flat chondrite-normalized REE patterns consistent with exhaustion of plagioclase from the source region, which occurs in these models at 12–13% melting. With smaller degrees of melting the liquid would have a negative Eu anomaly, as in Stannern, which can be derived as a 6% equilibrium partial melt of the same source. If trace elements are considered alone, this model suggests that Stannern, Ibitira, ALHA 76005, and main group eucrites (Juvinas, Sioux County) represent increasing degrees of partial melting of the same source region (the Stannern trend).

A possible problem with this model is that small but significant variations in $Mg/(Mg + Fe)$ should accompany the different degrees of partial melting of the source. Thus, Stannern should be slightly less magnesian than the common eucrites. This difference, if present, is small.

Small differences in alkali contents of the source region can have significant effects on the compositions of partial melts. Such variations in source composition offer an alternative explanation for the differences between Stannern and Juvinas, but are difficult, if not

impossible, to test. Stolper *et al.* (1979) have suggested a model relating eucrites and shergottites which is based on alkali variations in otherwise similar source regions.

The magnesium-rich eucrites, Moore County, Moama, Serra de Magé and Binda, have textures and compositions which are consistent with cumulate origins, being enriched to various degrees in pyroxene with respect to cotectic liquid compositions. Moore County and Serra de Magé cannot be cumulates directly from main group eucrite magmas, because the pyroxenes are too iron-rich to be in equilibrium with the eucrite melts (Stolper, 1977). However, fractional crystallization of main group eucrite melts produces liquids with lower Mg/ Fe ratios (such as Nuevo Laredo) which could be parental to these cumulates. The Nuevo Laredo trend, including Bereba and Pasamonte, can be modelled by removal of pyroxene and plagioclase from a liquid of Sioux County composition. Cachari and Lakangaon lie close to the Nuevo Laredo trend but cannot be successfully modelled as derivatives from a main group eucrite liquid (Reid *et al.*, 1979).

Thermal history of eucrites

Walker *et al.* (1978) have investigated crystallization behavior in melts having the composition of the Stannern eucrite. They found that feldspar crystal size varies as a function of cooling rate approximately according to the relationship $\ln D = (-0.6)\ln R - 2.2$, where D is the size of feldspar grains in millimeters and R is the cooling rate in °C per hour. For Stannern, the observed textures are consistent with cooling rates of 0.1–100°C/hr. Extrapolating to Juvinas, which has some coarser-grained textures, cooling rates as slow as 0.01°C/hr can be inferred. For Sioux County, with plagioclase grains up to 1 cm in size, cooling rates on the order of 0.001°C/hr are inferred. It appears that all of the eucrite basalts cooled from liquidus to solidus ($\sim 100°$C) in times which ranged from hours to a few tens of years. The coarser-grained magnesium-rich eucrites with cumulate textures may have cooled more slowly.

The unequilibrated eucrites have pyroxene compositional variations similar to those observed in the experiments of Walker *et al.* (1978). Early pyroxenes are magnesium-rich pigeonites, with a general iron-enrichment trend as crystallization proceeds. In unequilibrated eucrites, pigeonite grains show only submicroscopic exsolution lamellae, which is consistent with rapid cooling at subsolidus temperatures.

The equilibrated eucrites are characterized by a pigeonite-augite exsolution host-lamella relationship, with limited variability of pigeonite and augite compo-

sitions. In the eucrite basalts, exsolution lamellae range in thickness from less than 1 μm in some fragments in Nuevo Laredo to approximately 7 μm in some grains in Juvinas and Sioux County. Miyamoto and Takeda (1977) developed a model for the development of exsolution lamellae in several achondrites. They assumed a cooling rate defined by the cooling of a spherical asteroid. Under their assumptions, cooling rates of $4°/10^3$ years were required to form the exsolution lamellae of Juvinas at temperatures between 1200° and 850°C. These probably are relatively high temperature estimates, because exsolution of pigeonite must have begun at a temperature well below the Stannern liquidus at 1160°C (Stolper, 1977), and longer times (slower cooling rates) would be necessary if the lamellae actually formed over a smaller temperature range than assumed.

Although further work is required to improve the diffusional model of pyroxene exsolution, it is clear that the subsolidus cooling rates are much slower than the cooling rates through the crystallization interval. Pyroxene homogenization occurred prior to exsolution and at temperatures near the solidus, possibly above the solidus. This suggests that the onset of slower cooling rates may have occurred prior to complete solidification of the basalts. Various physical situations are consistent with a rapid slowing of cooling rates, such as extrusion of a basalt which then was buried in a layer of hot impact ejecta or was covered by additional flows. Alternatively, the eucrite basalts may have been emplaced in an environment whose ambient temperature was close to the eucrite solidus. The distinction among alternative models for eucrite thermal history will require much further detailed study of these meteorites, but can provide significant boundary conditions for the origins and evolution of their parent bodies.

The existence of brecciated eucrites, such as Juvinas, which show 4.5 b.y. internal isochron ages indicates either that brecciation occurred at an early stage of parent body formation or that brecciation was not accompanied by chemical fractionation. Most eucrite breccias, although they are somewhat indurated, do not have a crystalline matrix and cannot have been strongly heated after brecciation. In contrast, the Aioun el Atrouss meteorite contains evidence for thermal annealing of the eucrite breccia at high subsolidus temperatures. The recrystallization of Aioun el Atrouss indicates that, at least in some cases, substantial heating occurred after the brecciation event.

Younger disturbances, perhaps associated with brecciation events, are recorded in some meteorites. The howardite breccias, which contain eucrite basalt fragments, are more akin to regolith breccias. Some of the eucrite fragments in howardites give young ages,

which are believed to represent disturbances rather than initial crystallization (Dymek *et al.*, 1976). These ages could have been produced by impact reheating, and imply that regolith formation continued at least through the period indicated by the youngest ages of 3.6 b.y.

The eucrite parent body

Eucrite basalts are partial melts from a source region that was chemically primitive in the sense that the relative abundances and probably the absolute abundances of the large-ion-lithophile trace elements were chondritic or near-chondritic. Abundances of the moderately volatile elements, such as K, Na and Rb, in the eucritic source are, in contrast, much lower than the chondritic values. Stolper (1977) has concluded that primary eucrite liquids could be generated by partial melting of a source composed of olivine ($\sim Fo_{65}$) + low-Ca pyroxene + plagioclase + Cr-spinel + metal; however, his model constrains only some aspects of the bulk composition of the source. Several authors (e.g., Dreibus *et al.*, 1976, 1977; Consolmagno and Drake, 1977; Morgan *et al.*, 1978) have made estimates of the bulk composition of the eucrite parent body based on the types of evidence outlined above. These estimates are presented and discussed in detail in Chapter 4 (section 4.5.6). The estimates are all to some extent model-dependent and dependent also on the authors' conceptions of the "primitive" composition of the solar system and of the differentiation processes that have contributed to the diversity of compositions within bodies in the solar system. The agreement among the various models is encouraging. All require a parent body which was chondritic or near-chondritic in terms of involatile trace element abundances but which was relatively depleted in alkalies and other volatile elements. Major element abundances are not well constrained but appear to be consistent with chondritic compositions, except for the volatile and the metallic components. The chemical characteristics of the source probably were established during accretion (rather than in a later planetary differentiation process) and therefore provide clues to the types of element fractionation processes which governed differences among solar bodies during or before the accretion event.

The source region for eucrites was one of low pressure (Stolper, 1977). The quartz-normative nature of the eucrite melts requires that source region pressures probably were less than ~2 kb; at higher pressures olivine is no longer in reaction relationship with liquid, and partial melts would be silica-undersaturated. If the parent body was similar in size to the Moon, then the source must have been within 7km of the surface.

Eucrites must be derived from small bodies or from the very near-surface regions of larger bodies. This conclusion is consistent with other lines of evidence that meteorites in general are derived from small planetary (asteroidal) bodies. The asteroid 4 Vesta is the only candidate for a specific source for the eucrites which has been proposed seriously. Infrared spectrophometric observations by McCord *et al.* (1970) and Larson and Fink (1975) indicate that iron-rich pigeonite probably is a major mineral phase on the surface of Vesta. This consideration, plus the density estimate of 3.4 gm cm^{-3} by Morrison (1976), led Consolmagno and Drake (1977) to advocate 4 Vesta as the eucrite parent body. Pressures at the center of Vesta would not reach 2kb (see Fig. 3.5.2).

The relationship between eucrites and shergottites

Petrography, mineral chemistry and the experimental studies by Stolper and McSween (1979) indicate that Shergotty and Zagami do not represent basaltic liquid compositions. The bulk compositions are probably cumulus crystal-enriched, particularly with pyroxene, relative to the parent basaltic liquid. Because we can place only limited constraints on the parental basalt liquid composition, we find it even more difficult to constrain the shergottite source composition.

Differences in alkalies, volatile elements, oxygen fugacity and oxygen isotopes between shergottites and eucrites make it difficult to model them as derivatives from a single source. Stolper *et al.* (1979) have discussed the possibility that eucrites and shergottites are derived by partial melting (followed by some crystal-liquid fractionation) of source regions that are distinct but that could be related to one another rather simply. According to their arguments, eucrites, howardites, shergottites, nakhlites and chassignites all could be derived ultimately by partial melting of plagioclase peridotites that are compositionally distinct but which may form a simple compositional sequence. The putative source regions can be understood in terms of two-component mixtures generated by the increasing addition of a volatile-rich component to the volatile-poor peridotite source of the eucrites. Stolper *et al.* argue that this sequence of peridotites might be present on a single, heterogenous parent body, but more probably would require a series of related parent bodies.

The isotopic data of Nyquist *et al.* (1979b) indicate that Shergotty is the product of at least a two-stage process. The first stage, which occurred early in the history of the parent body, fractionated the rare-earth elements and rubidium. This may have been a planetary

differentiation episode. Later, material was remelted to form the Shergotty parent liquid. This is in contrast with the eucrites, which apparently were essentially primary melts of primordial material, which melted shortly after the origin of the solar system. Thus, Shergotty is derived from a relatively evolved parent, the eucrites from a primitive parent(s). Stolper (1979), Stolper and McSween (1979) and McSween *et al.* (1979a) have emphasized the similarity between shergottites and terrestrial basalts.

The later history of the Shergotty parent body is currently under intense scrutiny. Nyquist *et al.* (1979b) have shown that the shergottites have very young crystallization ages for meteoritic material. Their best estimate of crystallization age for this complex disturbed system is 650 m.y., far younger than any other meteorite (the closest is Nakhla at 1.3 b.y.). The shergottites thus raise major problems in understanding how basaltic liquids can form on small planetary bodies 4 b.y. after formation of the solar system. This problem is compounded by the discovery of an Antarctic meteorite (ALHA 77005) which is an olivine-rich cumulate apparently related to the shergottites by igneous processes (McSween *et al.*, 1979a; 1979b).

The 650 m.y. melting of Shergotty could have been a magmatic event or could have been impact remelting of older basaltic material. If the shergottites and ALHA 77005 are related (and if shergottites and nakhlites are related), then it is difficult to envisage these different meteorites as having been generated by discrete impact events, rather than through normal igneous processes. On the other hand, it is very difficult to postulate a source of thermal energy sufficient to cause magmatism on a small planetary object so long after its initial accretion. If these were 600 m.y. internally-generated magmatic events, then either the thermal constraints on melting in smaller planetary bodies must be reevaluated or the possible parent bodies of shergottites must be reexamined (see Mittlefehldt, 1979b; Walker *et al.*, 1979).

Some conclusions

Meteoritic basalts fall very clearly into two groups, eucrites and shergottites, which derive from at least two different parent bodies. Eucrites, which formed in a small asteroidal-size body (or bodies), date from the first 50 m.y. of solar system history. The material from which they formed as partial melts was primitive in that it had chondritic or near-chondritic abundances for many elements. Alkalies and other volatile element abundances were depleted relative to chondrites. The chemical characteristics of the eucrite source probably were representative of the whole parent body, because

basalt generation is likely to have been a one-stage process in an undifferentiated (hot?) body which had attained its compositional characteristics during accretion.

The shergottites are derived from a parent body that had more nearly chondritic alkali and volatile element abundances and which may have undergone an early planetary differentiation. These basalts have young ages compared with eucrites and the Moon. If they are not impact remelts then they represent extraterrestrial volcanism at a very late stage, when smaller bodies would lack obvious heat sources adequate to support magmatic events.

1.2.8.7 References

Ahrens L. H. and Danchin R. B. (1971) The chemical composition of the basaltic achondrites. *Phys. Chem. Earth* **8**, 267–303.
Antarctic Meteorite Newsletter (1978) vol. 1, no. 2. Johnson Space Center, Houston.
Antarctic Meteorite Newsletter (1979) vol. 2, no. 3. Johnson Space Center, Houston.
Binns R. A. (1967) Stony meteorites bearing maskelynite. *Nature* **213**, 1111–1112.
Bunch T. E. and Keil K. (1971) Chromite and ilmenite in non-chondritic meteorites. *Amer. Mineral.* **56**, 146–157.
Bunch T. E., Chang S., Neil J. M. and Burlingame A. (1976) Unique characteristics of the Jodzie howardite (abstract). *Meteoritics* **11**, 260–261.
Consolmagno G. J. and Drake M. J. (1977) Composition and evolution of the eucrite parent body. *Geochim. Cosmochim. Acta* **41**, 1271–1282.
Dreibus G., Kruse H., Spettel B. and Wänke H. (1977) The bulk composition of the Moon and the eucrite parent body. *Proc. Lunar Sci. Conf. 8th*, p. 211–227.
Dreibus G., Spettel B. and Wänke H. (1976) Lithium as a correlated element, its condensation behavior, and its use to estimate the bulk composition of the Moon and the eucrite parent body. *Proc. Lunar Sci. Conf. 7th*, p. 3383–3396.
Duke M. B. (1963) Petrology of basaltic achondrites. Unpublished Ph.D. thesis, Calif. Inst. of Technology, Pasadena, Calif.
Duke M. B. (1965) Metallic iron in basaltic achondrites. *J. Geophys. Res.* **70**, 1523–1527.
Duke M. B. (1968) The Shergotty meteorite: magmatic and shock metamorphic features. In *Shock Metamorphism of Natural Materials* (B. M. French and N. M. Short, eds.), p. 613–621. Mono Book Corp., Baltimore.
Duke M. B. (1978) Aioun el Atrouss: evidence for thermal recrystallization of a eucrite breccia. *Meteoritics* **13**, 443–448.
Duke M. B. and Silver L. T. (1967) Petrology of eucrites, howardites and mesosiderites. *Geochim. Cosmochim. Acta* **31**, p. 1637–1665.
Dymek F. R., Albee A. L., Chodos A. A. and Wasserburg G. J. (1976) Petrography of isotopically-dated clasts in the Kapoeta howardite and petrologic constraints on the evolution of its parent body. *Geochim. Cosmochim. Acta* **40**, 1115–1130.
Engelhardt W. von (1963) De eukrite von Stannern. *Beit. Mineral Petrog.* **9**, 65–94.
Foshag W. F. (1938) Petrology of the Pasamonte, New Mexico meteorite. *Amer. J. Sci.* **35**, 374–382.
Fredriksson K. and Keil K. (1963) The light-dark structure in the Pantar and Kapoeta stone meteorites. *Geochim. Cosmochim. Acta* **27**, 719–739.
Fredriksson K. and Kraut F. (1967) Impact glass in the Cachari eucrite. *Geochim. Cosmochim. Acta* **31**, 1701–1704.
Frost M. J. (1971) The Molteno meteorite. *Mineral. Mag.* **38**, 89–93.
Game P. (1957) Plagioclases from Juvinas meteorite and from allivalite from the Isle of Rhum. *Mineral. Mag.* **31**, 656–671.

Gast P. W. (1962) The isotopic composition of strontium and the age of stone meteorites. *Geochim. Cosmochim. Acta* **26**, 927–943.

Gast P. W. (1965) Terrestrial ratio of potassium to rubidium and the composition of the Earth's mantle. *Science* **147**, 858–860.

Hess H. H. and Henderson E. P. (1949) The Moore County meteorite: a further study with comment on its primordial environment. *Amer. Mineral.* **34**, 494–507.

Hewins R. H. and Klein L. C. (1978) Provenance of metal and melt rock textures in the Malvern howardite. *Proc. Lunar Planet. Sci. Conf. 9th*, p. 1137–1156.

Hutchison R., Bevan A. W. R. and Hall J. M. (1977) Appendix to the catalogue of meteorites with special reference to those represented in the collection of the British Museum (Natural History). British Museum (Natural History), London. 297 pp.

Jérome D. Y. and Christophe Michel-Lévy M. (1971) Quelques aspects remarquables de la météorite achondritique de Malvern (Afrique du Sud). *Bull. Soc. fr. Minéral. Cristallogr* **94**, 156–161.

LaCroix A. (1926) L'eucrite de Bereba (Haute-Volta) et les Meteorites feldspathiques en general. *Arch. Museum Hist. Nat. Paris Ser.* **6**, 1, 15–58.

Lange D. E. and Keil K. (1976) Meteorites of northeastern New Mexico. *New Mexico Geol. Soc. Guidebook, 27th Field Conference*, p. 293–299.

Larson H. P. and Fink U. (1975) Infrared spectral observations of asteroids 4 Vesta. *Icarus* **26**, 420–427.

Laul J. C., Keays R. R., Ganapathy R., Anders E. and Morgan J. W. (1972) Chemical fractionation in meteorites-V. Volatile and siderophile elements in achondrites and ocean ridge basalts. *Geochim. Cosmochim. Acta* **36**, 329–345.

Lomena I. S. M., Toure F., Gibson E. K., Jr., Clanton U. S. and Reid A. M. (1976) Aioun el Atrouss: a new hypersthene achondrite with eucritic inclusions. *Meteoritics* **11**, 51–57.

Lovering J. F. (1964) Electron microprobe analysis of the metallic phase in basic achondrites. *Nature* **203**, 70.

Lovering J. F. (1975) The Moama eucrite—a pyroxene-plagioclase adcumulate. *Meteoritics* **10**, 101–114.

Mason B. (1962) *Meteorites.* John Wiley and Sons, N.Y. 274 pp.

Mason B. (1967) The Bununu meteorite and a discussion of the pyroxene plagioclase achondrites. *Geochim. Cosmochim. Acta* **31**, 107–115.

Mason B. and Wiik H. B. (1966) The composition of the Bath, Frankfort, Kakangari, Rose City and Tadjera Meteorites. *Amer. Mus. Novitates No. 2272.*

Mason B., Jarosewich E. and Nelen J. A. (1979) The pyroxene-plagioclase achondrites. *Smithsonian Contrib. Earth Sci.* **22**, 27–45.

McCarthy T. S., Ahrens L. H. and Erlank A. J. (1972) Further evidence for the mixing model for howardite origin. *Earth Planet. Sci. Lett.* **15**, 86–93.

McCarthy T. S., Erlank A. J. and Willis J. P. (1973) On the origin of eucrites and diogenites. *Earth Planet. Sci. Lett.* **18**, 442–443.

McCarthy T. S., Erlank A. J., Willis J. P. and Ahrens L. H. (1974) New chemical analyses of six achondrites and one chondrite. *Meteoritics* **9**, 215–221.

McCord T. B., Adams J. B. and Johnson T. V. (1970) Asteroid Vesta: spectral reflectivity and compositional implications. *Science* **168**, 1445–1447.

McSween H. Y. Jr., Stolper E. M., Taylor L. A., Muntean R. A., O'Kelley G. D., Eldridge J. S., Biswas S., Ngo H. T. and Lipschutz M. E. (1979a) Petrogenetic relationship between Allan Hills 77005 and other achondrites. *Earth Planet. Sci. Lett.* **45**, 275–284.

McSween H. Y. Jr., Taylor L. A. and Stolper E. M. (1979b) Allan Hills 77005: a new meteorite type found in Antartica. *Science* **204**, 1201–1202.

Mittlefehldt D. W. (1979a) Petrographic and chemical characterization of igneous lithic clasts from mesosiderites and howardites and comparison with eucrites and diogenites. *Geochim. Cosmochim. Acta* **43**, 1917–1935.

Mittlefehldt D. W. (1979b) The nature of asteroidal differentiation processes: implications for primordial heat sources. *Proc. Lunar Planet. Sci. Conf. 10th*, p. 1975–1993.

Miyamoto M. and Takeda H. (1977) Evaluation of a crust model of eucrites from the width of exsolution lamellae. *Geochem. J.* **11**, 161–169.

Morgan J. W. and Lovering J. F. (1964) Uranium and thorium abundances in stony meteorites II. The achondritic meteorites. *J. Geophys. Res.* **69**, 1989–1994.

Morgan J. W., Higuchi H., Takahashi H. and Hertogen J. (1978) A "chondritic" eucrite parent body: inference from trace elements. *Geochim. Cosmochim. Acta* **42**, 27–38.

Morrison D. (1976) The densities and bulk compositions of Ceres and Vesta. *Geophys. Res. Lett.* **3**, 701–704.

Nyquist L. E., Bogard D. D., Wooden J. L., Wiesmann H., Shih C. -Y., Bansal B. M. and McKay G. (1979a) Early differentiation, late magmatism and recent bombardment of the Shergottite parent planet (abstract). *Meteoritics* **14**, 502.

Nyquist L. E., Wooden J., Bansal B., Wiesmann H., McKay G. and Bogard D. D. (1979b) Rb-Sr age of the Shergotty achondrites and implications for metamorphic resetting of isochron ages. *Geochim. Cosmochim. Acta* **43**, 1057–1074.

Olsen E. J., Noonan A., Fredriksson K., Jarosewich E. and Moreland G. (1978) Eleven new meteorites from Antarctica, 1976–1977. *Meteoritics* **13**, 209–225.

Papanastassiou D. A. and Wasserburg G. J. (1969) Initial strontium isotopic abundances and the resolution of small time differences in the formation of planetary objects. *Earth Planet. Sci. Lett.* **5**, 361–376.

Reid A. M. (1974) The Macibini meteorite and some thoughts on the origin of basaltic achondrites (abstract). *Meteoritics* **9**, 398–399.

Reid A. M. and Barnard B. M. (1979) Unequilibrated and equilibrated eucrites (abstract). In *Lunar and Planetary Science X*, p. 1019–1021. Lunar and Planetary Institute, Houston.

Reid A. M., Duncan A. R. and LeRoex A. (1979) Petrogenetic models for eucrite genesis (abstract). In *Lunar and Planetary Science X*, p. 1022–1024. Lunar and Planetary Institute, Houston.

Rowe M. W., van Dilla M. A. and Anderson E. C. (1963) On the radioactivity of stone meteorites. *Geochim. Cosmochim. Acta* **27**, 983–1001.

Schaal R. B. and Hörz F. (1977) Shock metamorphism of lunar and terrestrial basalts. *Proc. Lunar Sci. Conf. 8th*, p. 1697–1729.

Schmitt R. A., Goles G. G., Smith R. H. and Osborn T. W. (1972) Elemental abundances in stone meteorites. *Meteoritics* **2**, 131–214.

Schmitt R. A., Smith R. H., Lasch J. E., Mosen A. W., Olehy D. A. and Vasilevskis J. (1963) Abundances of the fourteen rare-earth elements, scandium and yttrium in meteoritic and terrestrial matter. *Geochim. Cosmochim. Acta* **27**, 577–622.

Schmitt R. A., Smith R. H. and Olehy D. A. (1964) Rare earth, yttrium and scandium abundances in meteorite and terrestrial matter-II. *Geochim. Cosmochim. Acta* **28**, 67–86.

Schnetzler C. C. and Philpotts J. A. (1969) Genesis of the calcium-rich achondrites in the light of rare earth and barium concentrations. In *Meteorite Research* (P.M. Millman, ed.), p. 207–216. Springer-Verlag, N.Y.

Smith J. V. and Hervig R. L. (1979) Shergotty Meteorite: mineralogy, petrography and minor elements. *Meteoritics* **14**, 121–142.

Steele I. M. and Smith J. V. (1976) Ibitira eucrite: mineralogy and comparison with lunar samples and other eucrites (abstract). In *Lunar Science VII*, p. 833–835. The Lunar Science Institute, Houston.

Stolper E. (1977) Experimental petrology of eucritic meteorites. *Geochim. Cosmochim. Acta* **41**, 587–611.

Stolper E. (1979) Trace elements in shergottite meteorites: implications for the origins of planets. *Earth Planet. Sci. Lett.* **42**, 239–242.

Stolper E. and McSween H. Y. (1979) Petrology and origin of the shergottite meteorites. *Geochim. Cosmochim. Acta* **43**, 1475–1498.

Stolper E., McSween H. Y., Jr. and Hays J. F. (1979) A petrogenetic model of the relationships among achondritic meteorites. *Geochim. Cosmochim. Acta* **43**, 589–602.

Takeda H. (1979) A layered-crust model of a howardite parent body. *Icarus* **40**, 455–470.

Takeda H., Miyamoto M., Ishii T. and Reid A. M. (1976) Characterization of crust formation on a parent body of achondrites and the moon by pyroxene crystallography and chemistry. *Proc. Lunar Sci. Conf. 7th*, p. 3535–3548.

Takeda H., Miyamoto M., Duke M. B. and Ishii T. (1978a) Crystallization of pyroxenes in lunar KREEP basalt 15386 and meteoritic basalts. *Proc. Lunar Planet. Sci. Conf. 9th*, p. 1157–1171.

Takeda H., Miyamoto M., Yanai K. and Haramura H. (1978b) A preliminary mineralogical examination of the Yamato-74 achondrites. *Memoirs of the National Institute of Polar Research, Special Issue No. 8* (T. Nagata, ed.), p. 170–184. Nat'l. Inst. Polar Res., Tokyo.

Wahl W. (1952) The brecciated stony meteorites and meteorites containing foreign fragments. *Geochim. Cosmochim. Acta* **2**, 91–117.

Walker D., Powell M. A. and Hays J. F. (1978) Dynamic crystallization of a eucritic basalt. *Proc. Lunar Planet. Sci. Conf. 9th*, p. 1369–1391.

Walker D., Stolper E. M. and Hays J. F. (1979) Basaltic volcanism: the importance of planet size. *Proc. Lunar Planet. Sci. Conf. 10th*, p. 1995-2105.

Wänke H., Palme H., Braddenhausen H., Dreibus G., Kruse H. and Spettel B. (1977) Element correlations and the bulk compositions of the Moon. *Phil. Trans. Roy. Soc. Lond.* **A285**, 41-48.

Wilkening L. L. (1976) Foreign inclusions in stony meteorites-I. Chondritic inclusions in the Kapoeta howardite. *Geochim. Cosmochim. Acta* **37**, 1985-1989.

Wilkening L. L. and Anders E. (1975) Some studies of an unusual eucrite. *Geochim. Cosmochim. Acta* **39**, 1205-1210.

Zavaritskii A. N. and Kvasha L. G. (1952) *Meteorites of the U.S.S.R.* Academy of Sciences of the U.S.S.R., Moscow. 245 pp.