MODAL COMPARISON OF YAMATO AND ALLAN HILLS POLYMICT EUCRITES

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Abstract: Comparison of modal analyses of seven Yamato and six Allan Hills polymict eucrite specimens reveals differences of plagioclase and pyroxene content between the two groups. The Yamato suite has more "pigeonitic" pyroxene and less plagioclase and low calcium pyroxene than the Allan Hills suite. Variations within each suite are small and three sections of Allan Hills A78040 are more variable than the Allan Hills suite considered as a group. Modal data provides a basis for pairing polymict eucrite specimens when used together with mineralogical and petrographic criteria. The Yamato suite is tentatively considered to sample three meteorites although further work may reduce this number to two. The Allan Hills suite presently samples two meteorites. Modal data also provides constraints on the petrography of the rock types sampled by these polymict eucrites, and in addition to confirming the presence of several rock types previously identified using pyroxene crystallography, hints at the presence of an augite-rich component.

1. Introduction

Many polymict eucrite specimens have been recovered from Yamato Mountains and Allan Hills, Antarctica. Suites of both Yamato and Allan Hills specimens were made available as part of a United States-Japanese cooperative agreement. Specimens from both localities have been examined in thin section using optical and electron microprobe techniques. Modal analysis was used to determine: (a) the differences and similarities between the two suites; (b) the variability within each suite; (c) the variability within an individual specimen; (d) the modal composition of the lithic components that were mixed to form polymict eucrites and (e) the relative abundances of these components in the polymict eucrites.

2. Samples Studied and Analytical Procedure

2.1. Samples

Polished thin sections were prepared from specimens provided by the National Institute of Polar Research (NIPR), Japan for the specimens Yamato-74159, -74450, -75011, -75015, -790007, -790020, -790260, and Allan Hills-765, -78158, -78165. These were studied in conjunction with thin sections provided by the curatorial facility at

Johnson Space Center (NASA) for Allan Hills A77302, A78006 and A78040. The two suites of thin sections together provide comprehensive sampling of both the Yamato and Allan Hills polymict eucrites.

2.2. Modal analysis

Modes of these thin sections were obtained using an ARL-SEMQ microprobe. The technique used is described in PRINZ et al. (1980). The microprobe standardization used was chosen to minimize ZAF effects since mineral identification is based on uncorrected intensity data to permit rapid (8 points/min) analysis. Computer assignments were later checked manually for consistency. Particular attention was paid to those points identified as ortho- and clinopyroxene by the modal program. Since pyroxene in the polymict eucrites is dominated by pigeonitic compositions, all pyroxene analyses in the modal data were reassigned to one of three groups on the basis of the wollastonite (Wo) content. Orthopyroxene, "pigeonite" and augite were assigned as pyroxene with $Wo < 5$, $5 < Wo < 20$, $Wo > 20\%$ (mol) respectively (DEER et al., 1978). The assignment of the modal data does *not* represent identification of three crystallographic polymorphs and at least part of the "pigeonite" fraction must represent overlap of low-Ca hosts with high-Ca lamellae within exsolved pyroxene crystals. The relative abundance of true pigeonite compositions and lamellae overlap artifacts varies from specimen to specimen and can only be assessed using optical or X-ray diffraction techniques. The data presented are, however, consistent with qualitative optical estimates of the relative abundance of the three polymorphs in the Yamato and Allan Hills specimens.

Errors in the modal analysis of these polymict breccias can arise in two main ways. (a) The sample size may be too small relative to the general fabric and grain size of the source rock. (b) The spacing of points on the analytical grid may be inappropriate for the grain size. (An orthogonal sampling grid is employed instead of truely random points, but this should have no influence as the samples are unbanded.) These errors may be assessed in two ways.

(a) Statistical formalism may be applied to the modal data to assess the precision of the data. Several methods for assessing various errors have been published (*e.g.* CHAYES, 1956; NEILSON and BROCKMANN, 1977; SOLOMON, 1963). Using a number of techniques the precision of major mineral modes are generally within 5%. For minor components this precision deteriorates rapidly. Using purely statistical techniques few conclusions could be drawn from the minor mineral modes presented. The most severe problem, however, is one of sample heterogeneity (Table 3). Since only limited samples are available the problems of sample heterogeneity cannot be assessed quantitatively, but the data for ALHA78040 suggest that errors of this type may well camouflage all other types of errors taken together.

(b) The precision of the modal data may also assessed independently by comparison with published bulk chemical analysis of the specimens. Almost all the samples studied have been analyzed either by wet chemical or instrumental techniques. Using normative calculations, these chemical compositions may be compared directly with the modal data presented. All the modal trends and variations discussed are detectable in the bulk compositional data and indicate that with an error bar of approximately

10% the major mineral modal data are consistent with bulk compositional data. The modal data are, therefore, believed to provide a good approximation of variations within the polymict eucrites.

3. Modal Results

3.1. Yamato polymict eucrites

The modal composition of seven Yamato polymict eucrites is given in Table 1. Typically up to 1000 points were analyzed for a representative thin section from each specimen. For Y-790260 the quoted mode is the area weighted average of two large thin sections.

Table 1. Modes of Yamato polymict eucrites.

	74159 PB	74450 ,63Cl	75011 ,87	75015 ,2	Yamato- 790007 ,91	790020 ,81	790260 ,71	X̄	sd
Olivine	0.4	0.1	1.4	1.0	1.1	1.0	tr	0.7	0.5
Orthopyroxene	6.7	5.4	6.1	9.5	13.8	6.9	9.3	8.2	2.9
"Pigeonite"	40.2	29.8	37.1	29.2	35.5	36.9	31.9	34.4	4.1
Augite	10.8	16.3	13.5	10.0	10.1	11.9	14.4	12.4	2.4
Feldspar	37.6	39.2	36.5	43.3	35.7	39.2	40.1	38.8	2.5
Silica	3.5	5.8	3.6	4.3	2.1	2.7	2.8	3.5	1.2
Ilmenite	0.7	0.7	1.1	1.0	1.1	0.8	0.9	0.8	0.3
Chromite	<0.1	0.1	0.2	0.3	0.3	0.3	0.2	0.2	0.1
Phosphate	<0.1	0.1	0.3	0.2	nd	0.4	0.1	0.2	0.1
Troilite	<0.1	1.8	0.2?	0.2	0.5	0.2?	0.3	0.5	0.6
Metal	nd	nd	nd	nd	nd	nd	nd	—	—
Gypsum	nd	nd	nd	0.1	nd	nd	<0.1	tr	—
Area, mm²	33.0	45.3	41.1	39.6	58.8	54.4	328		
Points	925	960	963	957	897	830	3707		

nd = not detected; tr = trace.

The thin sections studied have similar modes but some variation of the two main components, pyroxene and feldspar is noticeable. The variation of modal pyroxene and feldspar is compared with the monomict eucrites, howardites and other polymict eucrites in Fig. 1. The Yamato polymict eucrites (except Y-74450 and Y-75015) cluster tightly with pyroxene-plagioclase ratios intermediate between the monomict eucrites and howardites. Modally, these meteorites do not overlap the field of monomict eucrites despite bulk compositional similarities.

The modes of Y-74450 and Y-75015 are more feldspathic than the others and overlap the field of monomict eucrites. Y-74450 contains several large basaltic clasts (TAKEDA et al., 1980) so that the feldspar content observed in this thin section may be higher than the average for the bulk meteorite. High modal feldspar content should be reflected by high Al_2O_3 in a bulk chemical analysis. Y-74450 does not, however, show significantly higher Al_2O_3 than the other Yamato polymict eucrites (TAKEDA et al., 1978; WÄNKE et al., 1977; JOCHUM et al., 1980) suggesting that the present mode may contain more basaltic clast material than the bulk specimen. In Y-75015 the high mo-
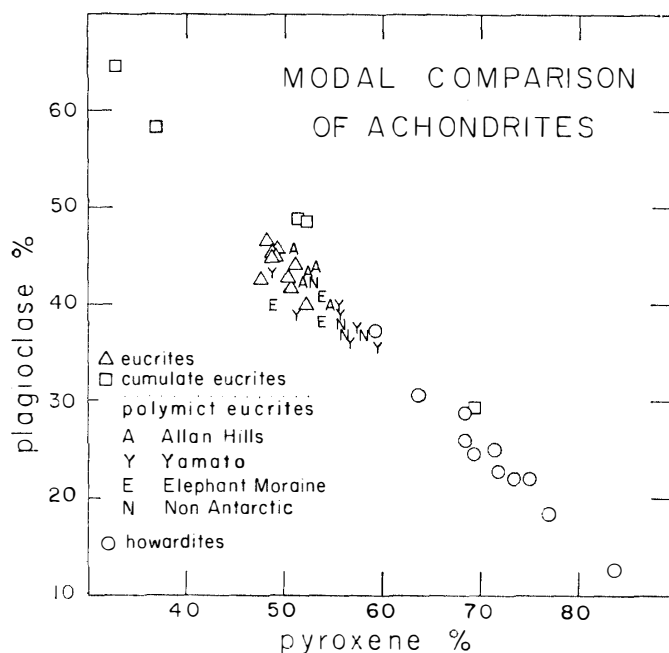
Fig. 1. Modal plagioclase vs. total pyroxene content of Yamato and Allan Hills polymict eucrite specimens compared with howardites, eucrites and cumulate eucrites. Data for Elephant Moraine and non-Antarctic polymict eucrites are also shown.

dal feldspar abundance is consistent with the high Al_2O_3 content of the bulk analysis (TAKEDA *et al.*, 1979). The Y-75015 samples studied so far are, therefore, significantly more feldspathic than most Yamato specimens. Whether this is caused by sample heterogeneity or some more fundamental difference between Y-75015 and the other Yamato specimens is unclear.

Olivine is not usually found in eucritic meteorites. Its presence in most Yamato specimens is, therefore, significant. The olivine present is not, however, the magnesian to intermediate composition olivine (Fo_{90}–Fo_{40}) commonly found in howardites and mesosiderites (DELANEY *et al.*, 1980; DESNOYERS, 1982). The olivine of the Yamato polymict eucrites is invariably iron-rich with compositions ranging from Fo_{20} to Fo_{13}. The olivine is typically found filling cracks in large pyroxene crystals in basaltic clasts and probably represents late, interstitial material that crystallized in preference to iron-rich pyroxene (TAKEDA and YANAI, 1982). The abundances quoted in Table 1, however, represent the maximum amounts of olivine identified because overlaps of low calcium pyroxene with troilite, below the microprobe electron beam, may produce results that resemble iron-rich olivine (the present program does not analyze sulfur). Only those analyses that appeared to show good olivine stoichiometry were accepted but some points are probably pyroxene-troilite overlaps and the present data should be treated as maximum olivine contents.

The low-calcium pyroxene (Wo$<$5; orthopyroxene in Table 1) content of the Yamato polymict eucrites is generally low. Only Y-790007 contains more than 10%. The abundance of orthopyroxene in Y-790007 is consistent with mineralogical observation of TAKEDA and YANAI (1982) that this specimen contains more of the Binda-type

of pyroxene than most Yamato specimens (TAKEDA et al., 1978). As with the feld-spar content of Y-75015, it is not clear if this abundance of Binda-type pyroxene results from sample heterogeneity or from some distinct difference between Y-790007 and the majority of Yamato polymict eucrite specimens.

In general, the modes of the Yamato polymict eucrite specimens are similar and reflect their apparently similar mineralogy and chemistry. Of the specimens examined, only Y-790260 seems petrographically distinct from the others.

3.2. Allan Hills polymict eucrites

Modes of six Allan Hills polymict eucrite specimens are given in Table 2. The Allan Hills A78006 meteorite is included in this table but is distinct from the others both modally and petrographically. The mean ($\bar{X}$) and standard deviation (sd) quoted

Table 2. Modes of Allan Hills polymict eucrites.

| | | | | Allan Hills (ALHA) | | | | |
	76005	77302 ,33	78040 3 pts	78158	78165	$\bar{X}$	sd	78006 ,9
Olivine	nd	nd	tr	nd	nd	tr	—	0.5
Orthopyroxene	15.1	14.9	9.0	13.6	7.7	12.1	3.5	33.8
"Pigeonite"	25.4	29.7	31.6	21.1	29.1	27.4	4.1	10.1
Augite	11.9	10.1	11.5	15.9	16.2	13.1	2.8	9.6
Feldspar	42.9	39.9	42.6	45.9	43.5	43.0	2.1	40.9
Silica	4.3	4.2	4.2	2.3	3.0	3.6	0.9	3.5
Ilmenite	0.1	0.6	0.6	0.4	1.0	0.5	0.3	0.6
Chromite	0.3	0.1	0.1	0.1	0.3	0.2	0.1	0.3
Phosphate	nd	0.2	0.2	nd	0.1	0.1	0.1	0.1
Troilite	nd	tr	0.3	nd	nd	0.1	0.1	0.5
Metal	nd	tr	0.1	0.3	nd	0.1	0.1	nd
Gypsum	nd	nd	nd	nd	nd	—	—	nd
Area mm^2	21.8	132.4	357.4	23.8	37.5	—	—	57.0
Points	788	1175	2769	953	925	—	—	1308

refer only to the other five specimens. ALHA78006 is not discussed in this section. The Allan Hills specimens differ from the Yamato specimens. (i) The feldspar content is higher. Whereas the Yamato polymict eucrites have feldspar contents intermediate between eucrites and howardites, the Allan Hills specimens have essentially identical feldspar contents to the monomict eucrites (Fig. 1). (ii) The low calcium pyroxene content of the Allan Hills specimens is significantly higher than the Yamato specimens. (iii) Almost no olivine was found, although a few microscopic grains (Fo_{18}) were found in ALHA78040. (ALHA78006 contains both magnesian and iron rich olivine.)

Three large area thin sections of ALHA78040 were selected as representative of the diversity within a single specimen. Modes of these sections are given in Table 3. Comparison of the ALHA78040 data with the entire Allan Hills suite reveals several significant features. (i) Despite the generally larger areas of the ALHA78040 sec-tions, this meteorite has modal pyroxene and plagioclase variations that are comparable with or greater than the variations in the entire suite. (ii) The mean composition of ALHA78040 is close to the mean of the main Allan Hills suite and both sets of means

Table 3. *Modes of three polished thin sections of ALHA78040.*

	19	20	61	Mean
Olivine	nd	nd	nd	nd
Orthopyroxene	9.8	9.1	7.2	9.0
"Pigeonite"	32.1	27.7	36.7	31.6
Augite	11.4	10.6	13.2	11.5
Feldspar	41.2	47.1	38.4	42.6
Silica	4.2	4.5	3.5	4.2
Ilmenite	0.6	0.6	0.5	0.6
Chromite	nd	tr	0.3	0.1
Phosphate	0.3	tr	0.2	0.2
Troilite	0.4	0.3	0.2	0.3
Metal	nd	0.1	nd	<0.1
Gypsum	nd	nd	nd	nd
Area mm^2	160	119.3	78.1	357.4
Points	873	982	914	2769

generally lie within one standard deviation of each other. (iii) Because of the large modal variability within ALHA78040 and the general similarities between the average modes of all the specimens studied, it is possible to suggest that all the Allan Hills specimens are in fact derived from a single statistical population. (iv) The variability within ALHA78040 may, therefore, be considered to represent the minimum extent of modal variation within the Allan Hills suite.

4. Pairing of Polymict Eucrite Specimens

4.1. Criteria for pairing

Noble gas data for polymict eucrites are presently sparse so that pairing on the basis of cosmic ray exposure ages, terrestrial residence ages and isotopic ratios cannot yet be done. In both the Allan Hills and Yamato suites of polymict eucrite specimens general modal similarities are clear (Tables 1–3). These similarities suggest that the specimens known, and presumably others yet to be recovered from the Antarctic ice, may be samples of a small number of meteorites or meteorite showers. Modal data alone are insufficient to provide clear pairing of meteorite specimens. They do, however, provide a guide for further examination of the specimens with the aim of pairing them.

Table 4. *Some mineralogical-petrological criteria for pairing polymict eucrite specimens.*

1.	Modal similarities.
2.	Bulk compositional similarities.
3a.	Textures of bulk samples.
b.	Textures of lithic fragments.
c.	The presence or absence of distinctive clast types.
4.	Mineral compositions.
5.	Metamorphic grade.
6.	Field criteria.

In addition to the modal data, several other types of information are useful for suggesting which specimens should be paired. These are summarized in Table 4.

4.2. Modal and bulk compositional pairing

The data for ALHA78040 (Table 3) indicate that a single specimen can show significant heterogeneities. Using these three modes to define the variability to be expected within the Allan Hills suite (except for ALHA78006), the other Allan Hills modes may be examined to detect variability in excess of that within ALHA78040. The close correspondence of the means and standard deviations of the two Allan Hills data sets suggests that they sample the same population. The ALHA78006 meteorite is excluded from this group as it is petrographically as well as modally unlike the others.

The Yamato specimens have similar modes and if they are individually as heterogeneous as ALHA78040, then they might be considered samples of a single meteorite using modal data alone.

Bulk chemical compositions are available for most of the meteorites discussed, but the variations of Al_2O_3, CaO, and alkalies are directly comparable to modal variations described. Bulk chemical data, therefore, provide no new constraints on the pairing within these suites.

4.3. Distinctive variations within polymict eucrite suites

The textures of thin sections from potentially paired specimens often show distinctive features. A feature that appears in one suite of specimens but not in another can, therefore, be used to support pairing arguments. For example, in the Allan Hills suite (except ALHA78006) matrix silica grains often show rims of low-calcium pyroxene (FUHRMAN and PAPIKE, 1981). This feature has not been observed in the Yamato meteorites, but is common in the Allan Hills specimens.

Similarly clasts of Binda-type pyroxene are present in most Yamato samples but are absent in the Allan Hills suite. The presence of distinctive textural features in each suite of meteorites, and their absence in other suites, provides good evidence of closely related origins for the members of each suite. These textural results may, therefore, be used as supporting evidence for pairing and may also be used to exclude modally similar specimens from the paired suites.

4.4. Mineral chemistry

Because all the polymict eucrites have generally similar modal mineralogy, the chemical composition of the major minerals provides a further constraint on pairing arguments. For example, diogenitic pyroxene ($En_{>70}$ Wo_{1-4}) is present in some polymict eucrite specimens but absent in others. It is, therefore, unreasonable to pair two specimens if one contains abundant pyroxene of this composition while the other does not. This constraint is particularly important when comparison is made of the very common zoned pyroxene in the Yamato and Allan Hills specimens. Reconnaisance work (TAKEDA et al., 1983) shows that pyroxene zoning patterns seem to vary from one suite to the other, but further work is necessary to substantiate and document these results.

4.5. "Metamorphic grade"

The features discussed (textures, mineral chemistry) are often influenced by the amount of thermal annealing and metamorphism of the breccias. Collation of these features suggests that different suites of polymict eucrites show varying degrees of metamorphism. If all specimens within a suite show the same metamorphic phenomena, then they may reasonably be paired. If, however, there is reason to believe that different specimens have been metamorphosed differently, then they should not be paired.

4.6. Field criteria

Supporting evidence for pairing polymict eucrite specimens may also be provided by the clustering of specimens on the Antarctic ice. The pairing of 29 Yamato diogenite specimens was supported by their proximity to one another within the Yamato Mountains area. Another diogenite (Y-75032), which is quite distinct from the others, was recovered from a different spot in the Yamato Mountains region (TAKEDA et al., 1981). Field maps of the meteorite distribution (e.g. YANAI, 1982) may, therefore, be useful guides to the pairing of specimens when used in conjunction with other criteria.

4.7. Proposed grouping of polymict eucrite specimens

On the basis of all the criteria discussed above, the polymict eucrites from Yamato Mountains, Allan Hills and Elephant Moraine have been paired as shown in Table 5. The total number of specimens is over thirty including ALHA-81 specimens, but they are believed to represent only seven meteorites. In addition, Table 5 lists five non-Antarctic basaltic achondrites that have been reclassified as polymict eucrites (DELANEY et al., 1983).

The Yamato specimen suite is believed to sample either two or three meteorites.

Table 5. Pairing of polymict eucrite specimens.

Meteorite	Specimen numbers
	Antarctic
1. Yamato I	74159, 74450, 75011, 75015, 75295?, 79296?, 75307?, 790006?, 790020, 790113?, 790114?, 790122?, 790266
2. Yamato II	790260
3. Yamato III?	790007 (provisional—see text)
4. Allan Hills I	76005, 77302, 78040, 78132?, 78158, 78165, 79017, 80102?, 81006?, 81007?, 81008? 81010?
5. Allan Hills II	78006
6. Elephant Moraine I	79004, 79011
7. Elephant Moraine II	79005, 79006

Non Antarctic

8. Macibini; 9. Bialystok; 10. Nobleborough; 11. Petersburg; 12. Jodzie.

Note: Specimens with question marks (?) have not been examined modally and are provisionally paired on the basis of published data.

All these specimens have very similar modal compositions. Y-790260, however, has a very distinctive texture suggesting that the fine-grained matrix has been partially melted. This specimen, therefore, is unlikely to be a sample of the same meterorite as the Yamato-74, 75 and many 79 specimens (Yamato I) and is, therefore, called Yamato II. Y-79007 is also distinct as it has abundant Binda-type pyroxene (TAKEDA and YANAI, 1982) but it does not otherwise differ from most Yamato samples. Because of this mineralogical distinction, Y-790007 is *provisionally* considered to be a sample of a third Yamato meteorite (Yamato III?) but it is possible that it is a slightly atypical sample of Yamato I in the same way that Y-75015 is considered to be part of Yamato I.

The Allan Hills specimens, except ALHA78006, have very similar modes, mineralogy, textures and mineral chemistry and are, therefore, thought to be samples of a single meteorite (Allan Hills I). ALHA78006 is distinct from the others modally (Table 2), mineralogically as it contains both magnesian olivine and orthopyroxene and texturally. This specimen, therefore, represents the Allan Hills II polymict eucrite.

The Elephant Moraine polymict eucrites, although modally similar may be divided into two groups. Elephant Moriane A79004 and A79011 are both significantly metamorphosed and their mineral chemistry shows evidence for homogenization reactions. These two are paired as Elephant Moraine I. Elephant Moraine A79005 and A79006 are petrographically similar (DELANEY *et al.*, 1981, unpublished data; SIMON *et al.*, 1982) and are paried provisionally. The non-Antarctic specimens are unpaired.

5. Modal Variation in Polymict Achondrites

5.1. Variations within the polymict eucrites

The major mineral phases of the polymict eucrites and related howardites are pyroxene and plagioclase. In Fig. 1, the variation of modal feldspar with total pyroxene content in the polymict eucrites is compared with the eucrites and howardites.

The Allan Hills polymict eucrites essentially overlap the compositional field of the monomict eucrites. This modal similarity between the Allan Hills polymict eucrites and the eucrites is reinforced by the available bulk chemical analyses of these meteorites. The range of Al_2O_3 in monomict eucrites is from 11.2% to 13.4% (MASON *et al.*, 1979). Since Al_2O_3 in eucrites is dominantly in feldspar with only minor amounts in pyroxene and spinel, the observed variation reflects modal feldspar variation in the eucrites. The Allan Hills polymict eucrites have a range of Al_2O_3 from 12.0% to 13.1% (WOODEN *et al.*, 1981).

The Yamato polymict eucrites, however, have modal feldspar contents between the eucrites and the howardites and hence have lower bulk Al_2O_3 contents from 10.4% to 13.7% with most specimens lying between 10.4% and 12.0% (TAKEDA and YANAI, 1982; TAKEDA *et al.*, 1978). (Polymict eucrites from Elephant Moraine (PALME *et al.*, 1983; DELANEY *et al.*, 1982) also plot between the eucrites and howardites.) Several polymict achondrites that have been classified as both howardites and eucrites by different authors plot in the fields of both the Allan Hills and Yamato polymict eucrites. These meteorites have been reclassified as polymict eucrites (DELANEY *et al.*, 1983).

Although the polymict eucrites are modally intermediate between howardites and eucrites with respect to total pyroxene and feldspar content, further insight may be

gained by examining the types of pyroxene present in these meteorites. The Yamato and Allan Hills specimens have variable contents of low calcium and high calcium pyroxene. In general, the Allan Hills specimens contain more low Ca pyroxene than the Yamato specimens which have abundant "pigeonite". Because eucrites are dominated by pigeonitic pyroxene and howardites by orthopyroxene, the greater similarity between the Allan Hills specimens and the eucrites (Fig. 1) suggest that they may contain more pigeonite than the Yamato specimens.

The modal variations of pyroxene types in polymict eucrites are shown in Figs. 2a and 2b. Because modal analysis by automated electron microprobe does not distinguish between true pigeonitic clinopyroxene and compositions produced by orthopyroxene-augite overlap, two versions of this figure are shown. Both versions represent the same data but the pigeonitic component is treated differently to illustrate the differences between the two possible assignments. In Fig. 2a the "pigeonite" of the modes (Tables 1 and 2) is treated as true pigeonitic pyroxene. The polymict eucrites may be seen optically to contain abundant pigeonite but the amount of clinopyroxene in Fig. 2a includes an overestimate of the pigeonite content caused by host-lamella overlaps in exsolved pyroxene. All clinopyroxene ("pigeonite"+augite) is assigned to one vertex. The polymict eucrites from Allan Hills, Yamato Mountains and Elephant Moraine show considerable diversity of orthopyroxene/clinopyroxene ratios (Fig. 2). The two largest suites, Allan Hills and Yamato, generally, define distinct compositional fields with only atypical specimens such as Y-75015 showing overlap. For clarity, data points for individual eucrites, howardites, diogenites and cumulate eucrites are omitted from Fig. 2a. Note, that making the assumption that all "pigeonite" in Tables 1 and 2 is true pigeonitic clinopyroxene, the polymict eucrites as a group become
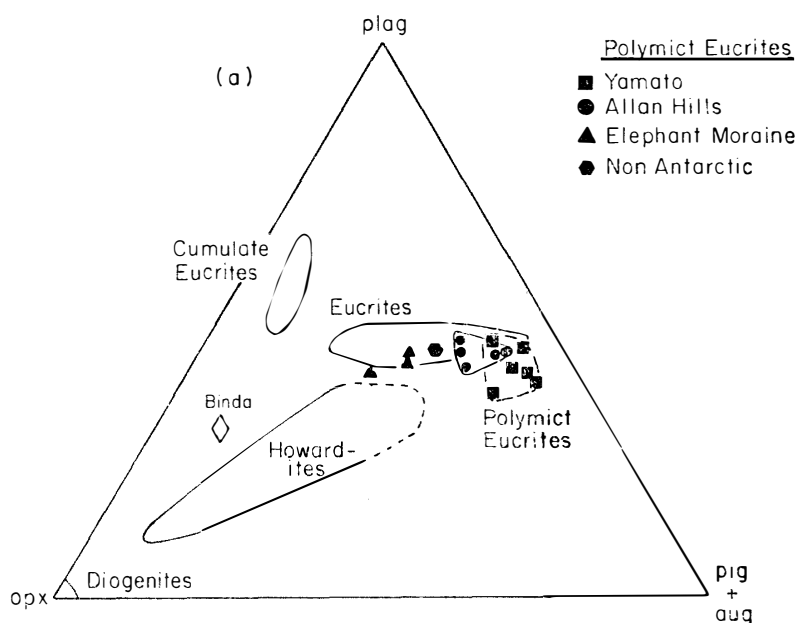

Fig. 2a. Modal orthopyroxene—"clinopyroxene"—plagioclase ternary diagram for Yamato and Allan Hills polymict eucrites compared with other basaltic achondrites. In this figure all modal "pigeonite" is assumed to be true pigeonite clinopyroxene.
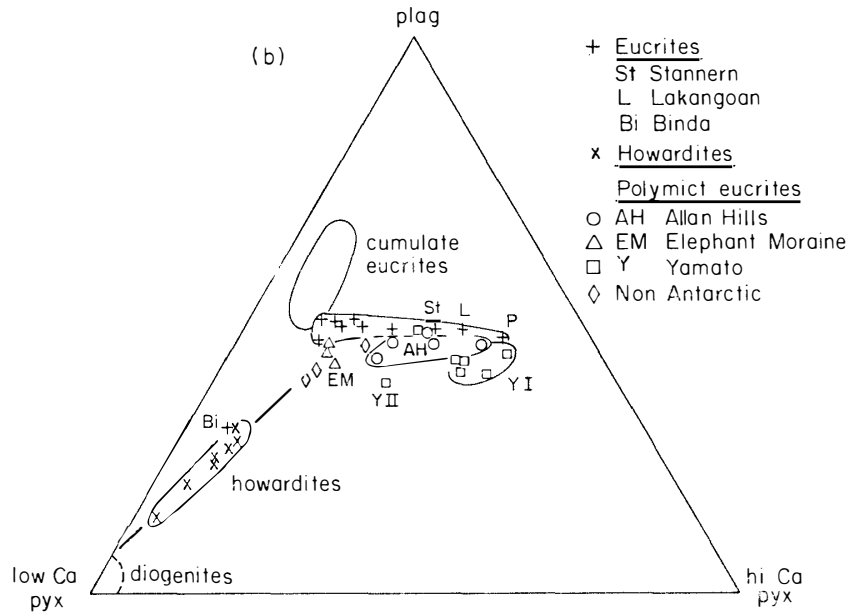
Fig. 2b. Modal low-Ca pyroxene—high-Ca pyroxene—plagioclase ternary
derived from data for Fig. 2a. In this figure all modal "pigeo-
nite" is assumed to be an artifact caused by the overlap of
orthopyroxene and augite hosts and lamellae.

the feldspar enriched continuation of the trend displayed by the howardites. As the
feldspar content of the polymict achondrites increases, the ratio of clinopyroxene/or-
thopyroxene also tends to increase. However, the cpx/opx ratio of these breccias not
only increases but also shows increased variability as the amount of feldspar increases.

In Fig. 2b, the same data used in Fig. 2a have been plotted treating all the
"pigeonite" from the modes as an artifact caused by the overlap, beneath the electron
beam, of orthopyroxene and augite. In this figure, the amount of true pigeonitic clino-
pyroxene is systematically underestimated but the figure provides a clearer impression
of the variation of Ca distribution between coexisting pyroxene than is given by Fig.
2a. As in Fig. 2a, the polymict eucrites show a great range of cpx/opx ratios but the
different suites of specimens show little overlap.

Despite the different assumptions made in constructing Figs. 2a and 2b, the poly-
mict eucrites show the same trends in each, and they also show the same general rela-
tionships to the basaltic achondrites. The true modal compositions of the polymict
eucrites lie between the extremes illustrated.

5.2. Modal comparison of the polymict eucrites with other basaltic achondrites

In Fig. 2 fields for the eucrites, cumulate eucrites, diogenites (orthopyroxenite)
and howardites are presented. The feldspar cumulate eucrites (Serra de Magé, Moore
County, Moama, Medanitos were examined) plot as a distinct feldspar-rich field. Bin-
da, the pyroxene cumulate eucrite (GARCIA and PRINZ, 1978), plots on a feldspar de-
pleted extrapolation of this field near the howardites and has a similar cpx/opx ratio
to the cumulate eucrites. Most monomict eucrites plot in a small cluster near this field
(Fig. 2b) and have slightly higher cpx/opx ratios than the cumulate eucrites, in part be-

cause they contain more pigeonite, but more significantly, because the bulk composition of their pyroxene is more calcic than the cumulate eucrites. In comparison with the polymict eucrites, however, most monomict eucrites have low cpx/opx ratios implying that the polymict eucrites have more abundant calcic pyroxene. Three monomict eucrites deviate significantly from the main group. These are Stannern, Lakangoan and Pasamonte. Stannern and Lakangoan contain significantly more calcic pyroxene than most eucrites and as shown by DELANEY *et al.* (1981) also have more sodic plagioclase compositions than most eucrites. Both Stannern and Lakangoan have high cpx/opx ratios but neither has a ratio as high as the Yamato polymict eucrites. Pasamonte, which has mainly pigeonitic pyroxene, is similar to polymict eucrites. Comparable high cpx/opx ratios have also been found in a few mafic clasts from the howardites Kapoeta (DELANEY, unpublished data) and Yamato-7308 (NEHRU *et al.*, 1983). No monomict basaltic achondrite is presently known that contains so much augitic pyroxene as these clasts from the howardites.

The howardites are the most diverse group of basaltic achondrites, containing both orthopyroxenitic and mafic clast components in varying proportions. In Fig. 2a, the howardites fall in a field that radiates from a point on the plagioclase-orthopyroxene join that is equivalent to a diogenite with about 5% modal feldspar. The feldspar-rich limit of the howardite field is the transition to the polymict eucrites. In common with the polymict eucrites, the howardites contain a significant calcic pyroxene component in addition to the typical eucrites, though this component is less abundant than in polymict eucrites.

In Fig. 2b, the howardite field is more restricted. This is caused by the lesser abundance of calcic pyroxene component in howardites. Note, however, that the modal composition of the howardites *cannot* be approximated by a simple eucrite-diogenite mixing model using the observed modal compositions of the typical eucrites (Fig. 2b). Although mixing models using bulk chemical data for eucrites and diogenites provide good approximations of the bulk compositions of the howardites (*e.g.* DREIBUS and WÄNKE, 1980), the mixing components needed to represent the modal composition of the howardites differ. The "diogenite" component is not represented by pure diogenitic orthopyroxene but requires, in addition, a significant feldspar fraction. The "eucrite" end member may be treated in two ways. If a eucrite similar to the main cluster in Fig. 2b is used as a mixing component, then a third calcic pyroxene-rich or pigeonite-rich component is needed to define the howardite trend. The presence of augite-rich clasts in howardites suggests that this may be reasonable. On the other hand if the eucrites are assumed to be like the average mode of *all* the eucrites including Stannern and Lakangoan, then it may be possible to approximate the howardites by a two component mixture.

Modally, the polymict eucrites and howardites form a continuum and similar clast types are observed in both groups. Only the abundances of the clast types differ. It is impossible to represent the polymict eucrites as mixtures of known eucritic types and a calcic pyroxene-rich component is needed. The howardites may also be represented using the same components, and a minimum of three components is necessary to approximate their modes. These components are an ultramafic pyroxenite and two mafic rock types.

6. Components in Polymict Eucrites

6.1. Modal composition of components

Early descriptions of the Yamato and Allan Hills polymict eucrites recognized the diversity of clast types present. Takeda et al. (1978) studied pyroxene crystallography and demonstrated that the observed clasts must have crystallized in a variety of environments ranging from plutonic (Binda-type) to volcanic (Pasamonte-type). They also recognized that diogenite-like orthopyroxene was absent or very rare. Olsen et al. (1978) noted the presence of lithic clasts unlike monomict eucrites in Allan Hills A76005. Polymict eucrites of different types may be approximated by mixing together varying proportions of the mineralogically identifiable components.

Several mineralogically identified components have been discussed (Takeda et al., 1978; Takeda, 1979; Miyamoto et al., 1978). These include: (a) Diogenite material; (b) Binda-type pyroxene; (c) Moore County/Nagaria-type pyroxene; (d) Juvinas-type; (e) Pasamonte-type. These components all have distinctive pyroxene crystallography and their mineralogy will be discussed elsewhere (Takeda et al., 1983). Modally these components are also associated with rock types that plot in various parts of Fig. 2.

(a) *Diogenitic* material is absent (or rare) in Yamato and most of Allan Hills specimens but is present in ALHA78006, Elephant Moraine II and non-Antarctic polymict eucrites. Diogenitic (orthopyroxene more magnesian than En_{65}) is not seen as lithic fragments in most polymict breccias except as polygranular pyroxene aggregates and rarely as pyroxene-olivine assemblages. Modally this component may be approximated by the field labelled orthopyroxenites in Fig. 3.

(b) *Cumulate Eucrite* fragments have been identified using the style of pyroxene exsolution. Two types have been distinguished. Type I, the Binda-like pyroxene is ubiquitous in the Yamato specimens but is not present in Allan Hills specimens. This type is generally found as mineral fragments. Lithic fragments are rare and are not sufficiently large to provide representative modal data. Takeda and Yanai (1982) described one small lithic clast from Y-790007 but the modal pyroxene and plagioclase contents of the source rock cannot be estimated. Pyroxene from Serra de Magé and Moama is similar in some respects to that in Binda but these meteorites are very feldspathic, plotting near the top of the "cumulate eucrite" field (Fig. 3). It is, therefore, possible that the Binda-type clasts in polymict eucrites, sampled cumulates with modal pyroxene/plagioclase ratios covering the entire range between the "melanorite" and the "cumulate eucrite" fields of Fig. 3. Because the Yamato specimens contain Binda-type pyroxene and are modally more pyroxenitic than the Allan Hills specimens which contain none, and because definitive samples are not yet available, it is assumed that this component has a modal composition similar to Binda and plots in the pyroxene rich "melanorite" field.

(c) *Cumulate Eucrite II:* The second type of cumulate eucrite—derived pyroxene is the Nagaria/Moore County type of clast. Lithic fragments are uncommon so that the modal composition of this component is merely inferred to fall in the "cumulate eucrite" field of Fig. 3 so that it resembles the known cumulate eucrites.

In both groups of cumulate eucrite-type pyroxene, the cpx/opx ratio is low and, therefore, does not seem to account for the clinopyroxene-rich nature of the Yamato
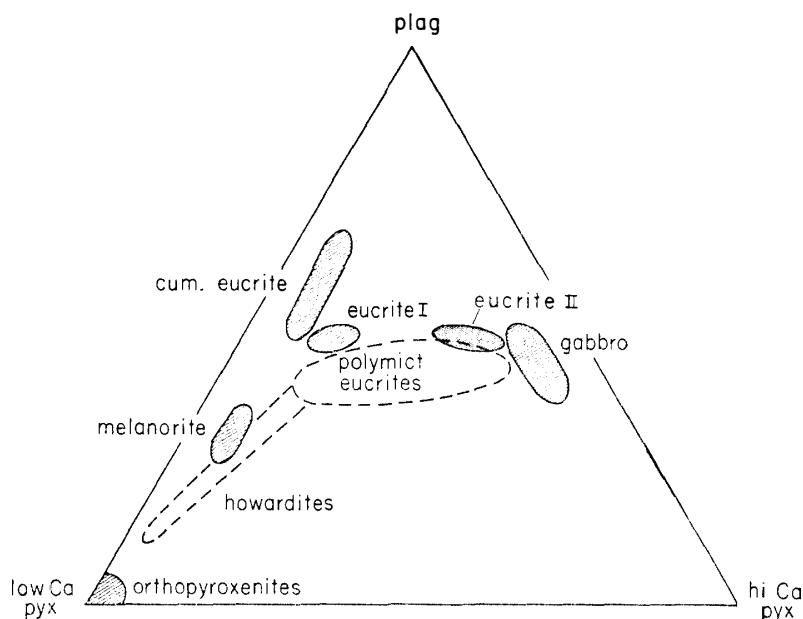
Fig. 3.   Modal orthopyroxene—"clinopyroxene"—plagioclase ternary similar to Fig. 2b with compositional fields marked for the components that are mixed to form polymict eucrites. Fields for polymict achondrites are shown for comparison.

polymict eucrites.

(d) *Eucrites I:*   A common type of pyroxene in polymict eucrites has been described as Juvinas-type. This is compositionally homogeneous, finely exsolved pyroxene. Modes of lithic clasts in ALHA78040 with this type of pyroxene have been determined and have low cpx/opx ratios comparable with the majority of the eucrites (Fig. 2b). This component is, therefore, considered to be represented by the "Eucrite I" field of Fig. 3.

(e) *Eucrites II:*   The most characteristic lithic clast type, in both the Yamato and Allan Hills polymict eucrites, are those containing Pasamonte-type pyroxene. Modally Pasamonte is extremely enriched in pigeonite. Pasamonte therefore plots close to, but on the feldspar-rich side of, the Yamato polymict eucrites. Mixing various amounts of both the "eucrite" components can account for much of the observed cpx/opx variation observed in the polymict eucrites.

(f) *Gabbro:*   Figure 3 contains an additional area labelled "gabbro". This represents a component that appears to be necessary to explain the modal composition of the polymict eucrites. This component has not, however, been described mineralogically and is uncommon. It differs from the known eucritic meteorites as it is dominated by augitic pyroxene rather than orthopyroxene and pigeonite. The existence of a component dominated by augite is necessary to explain the observed orthopyroxene-clinopyroxene-plagioclase distribution in the polymict eucrites, especially those from Yamato Mountains.

Of the known eucrites Stannern is most like this component. In Stannern the cpx/opx ratio is too low for this meteorite be to used as a modal end member in mixing models. In addition, the known eucrites are too feldspathic to account for the low

feldspar content of the Yamato achondrites. This "gabbro" component is, therefore, considered to be an augite-rich mafic rock of a type uncommon in basaltic achondrites. Alternately, the high augite content may represent a clinopyroxene cumulate comparable with the Binda orthopyroxene-rich cumulate. No direct evidence for such a component has yet been observed. In either case, this component could be recognized as clasts of augitic pyroxene in the matrices of the polymict eucrites.

Further modal studies on individual clasts may lead to recognition of this gabbroic component (and perhaps even a melagabbro, rich in pyroxene). The small size of most clasts, especially the coarse grained clasts, makes such study difficult since many are clearly unrepresentative of the rocks from which they are derived.

6.2. Componental composition of the Yamato and Allan Hills polymict eucrites

The modal data summarized in Fig. 3 may be used to model the polymict eucrites as mixtures of the six recognized components. All polymict eucrites lie in a band with feldspar abundances between 35% and 45% vol. The Yamato I suite has systematically lower feldspar abundances than the Allan Hills suite (Fig. 2) and both have lower feldspar abundances than the monomict eucrites and feldspar cumulate eucrites.

(a) *Eucritic components*: Both the Allan Hills I suite and the Yamato I suite have a wide range of cpx/opx ratios. Most monomict eucrites have low cpx/opx ratios unlike the typical polymict eucrites (Fig. 2b). The unique eucrite Pasamonte has a high cpx/opx ratio because rapid cooling resulted in the crystallization of abundant pigeonite. Most of the cpx/opx variation of the polymict eucrites may, therefore, be accounted for by mixing variable amounts of typical eucrite (Juvinas-type) with Pasamonte-type pyroxene. The high cpx/opx ratios of many specimens, especially from the Yamato suite confirms the mineralogical observation that Pasamonte-type pyroxene is abundant in these meteorites.

The presence of an augite-rich component in the polymict eucrites could also explain the variation of the cpx/opx ratio, but is not seen in sufficient abundance to account for all of the observed variation.

(b) *Cumulate components*: Although a mixture of Eucrite I (Juvinas-type) and Eucrite II (Pasamonte-type) components can partially explain the variable cpx/opx of the polymict eucrites, such a mixture would produce breccias containing more feldspar than is presently observed. If a cumulate eucrite component (such as Moore County) is mixed in, then this imbalance of feldspar abundances becomes more severe. The observed relationship between the monomict and polymict eucrites requires that a pyroxene-rich component be added in addition to the two eucrite components.

In the howardites, this pyroxene-rich component is the prominent diogenite, or orthopyroxenite, component. In the Yamato I and Allan Hills I suites, however, no diogenitic component has been identified. The observation of Binda-type pyroxene in Yamato I suite, however, is consistent with the lower feldspar abundance in this suite. This component is described as a melanorite in Fig. 3. The Allan Hills I suite does not contain a recognizable Binda-type component but it contains less feldspar than the monomict eucrites. Several possible explanations exist but none can be demonstrated unequivocally. (a) Allan Hills I contains a small diogenitic component that has not been recognized. The intensive, but unsuccessful search for this component by

several researchers makes this unlikely.   (b) Allan Hills I contained a pyroxenite com-
ponent like the diogenites, but localized heating of these breccias caused Fe-Mg homog-
enization in the matrix which has modified their Fe/Mg ratios so that they are not
recognized as being originally diogenitic.   Some evidence for this type of homogenization
in the fine-grained matrix of ALHA76005 is presented by FUHRMAN and PAPIKE (1981)
and the Elephant Moraine I suite has seen similar modification.   (c) Allan Hills I
contains a pyroxene-rich component in its matrix that is more iron-rich than diogenites
but is texturally unlike the Binda-type component of the Yamato I suite.   Brecciation
of such a component would produce mineral clasts that are difficult to associate with
any particular component.   The Allan Hills I suite contains small pyroxene mineral
clasts of composition between En_{80} and En_{45} that are uncommon in the lithic clasts
but criteria to distinguish between options (b) and (c) are not yet known.   (d) Allan
Hills I is in fact a mixture of two feldspar poor eucritic components that have not been
recognized as discrete meteorites.   (The Allan Hills II–78006–specimen contains diog-
enitic pyroxene and hence, presents no comparable problem.)

(c) *Augite-rich components:*   The modal data for the Yamato I suite are not entirely
explained by mixing the three components described above.   Several modes lie outside
the area defined by these three components (Eucrite I, Eucrite II and Melanorite) in
Fig. 3. All these modes lie to the clinopyroxene-rich side of this area.   These modes
require the presence in the Yamato I suite (and probably in the Allan Hills I suite also)
of an augite-rich component.   This component may be similar to the Pasamonte-type
of material but with significantly higher CaO or may be a clinopyroxene-rich basaltic
rock such as those observed in Yamato-7308 (NEHRU *et al.*, 1983).   In either case, this
component is rare and further careful work is needed to document it adequately.

7. Conclusions

(1)   The polymict eucrites from Allan Hills and Yamato Mountains differ mod-
ally and are not samples of the same fall.

(2)   The modal results in combination with mineralogical and petrographic data
provide guidelines for pairing the many polymict eucrite specimens.   The presently
known 32 specimens from Antarctica are believed to be samples of six or seven meteor-
ites.   Most specimens from Allan Hills and Yamato Mountains sample only two me-
teorites (Allan Hills I and Yamato I).

(3)   Modal variations within both suites are consistent with bulk compositional
variations but highlight the role of the petrographic components that were mixed to
form the polymict eucrites.

(4)   The Yamato I suite is dominated by a mixture of three modally recognizable
components that are equated with the mineralogically recognizable components. These
are two eucritic components and a melanorite component (Juvinas, Pasamonte and
Binda-types).   The modes of some Yamato specimens seem to require a fourth augite-
rich component in addition to these three.

(5)   The Allan Hills I suite is dominated by the same two eucritic components as
Yamato I.   The presence of the melanorite component is eliminated by petrographic
evidence, but a third pyroxene-rich component is needed.   The augite-rich component

may also be present.

Acknowledgments

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