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MINERALOGY OF THE ASUKA 87 AND 88 EUCRITES AND CRUSTAL EVOLUTION OF THE HED PARENT BODY

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Abstract: Mineralogical study of three apparently crystalline eucrites, Asuka (A)-87272, A-881388 and A-881394 revealed that their textures are not primary crystallization products from a magma. A-87272 is a monomict breccia, but the fine-grained matrix is recrystallized to a granulitic texture with fine, rounded pyroxene crystals set in a plagioclase matrix. Large fragments of pyroxene are inverted to orthopyroxene with coarse exsolution lamellae on (001) and fine ones on (100). A-881388 contains a large, rounded opaque grain with a tail, and with an ilmenite-chromite-troilite-metal assemblage in fine-grained granulitic silicates, suggesting recrystallization. A-881394 is coarser grained than A-881388 and contains more magnesian pyroxene as in cumulate eucrites, but the plagioclase composition is extremely calcic (An 98) and the grains are composed with a few rounded grains. The A-881394 chromite, showing a pokilitic texture with rounded plagioclase and minor pyroxene, suggests a metamorphic texture. Our present interpretation for a common formation process among these eucrites is that despite their crystalline texture, they might have experienced extensive metamorphism after the initial crystallization in the early history of the crustal evolution.

1. Introduction

Eucrites have been known as the earliest basalts extruded on a planetary surface. Their textures are commonly brecciated (DUKE and SILVER, 1967) and Fe/Mg distribution of pyroxenes is homogenized (TAKEDA and GRAHAM, 1991). Such monomict eucrites are often called "ordinary eucrites", because of the similarity to ordinary chondrites. Combined chronological and mineralogical studies of ordinary eucrites revealed that they experienced extensive metamorphic events in the early history of the crustal evolution (*e.g.*, NYQUIST *et al.*, 1986; BOGARD *et al.*, 1993; YAMAGUCHI *et al.*, 1994). However, such events were overprinted by other features such as impacts (BOGARD, 1995). Thus, it has been difficult to decipher metamorphic records from the petrological and isotopic studies. Crystalline eucrites may give us more definitive answers, because their mineralogical records were not disturbed by the impact cratering events. Ibitira is a rare unbrecciated eucrite but experienced an extensive thermal event (BOGARD and GARRISON, 1995). In the new Catalog of the Antarctic Meteorites (YANAI and KOJIMA, 1995), some crystalline eucrites and nearly crystalline eucrites have been described. Preliminary examination of some typical and unique specimens in the Asuka 87 and Asuka 88 collections have been reported by YANAI (1993). We report mineralogical examination of such eucrites in connection with recent works on the crustal evolution of eucrites (YAMAGUCHI *et al.*, 1996; NYQUIST *et al.*, 1996, 1997).

A-87272 (5706 g) is the largest achondrite in the Asuka collections and shows coarse-grained, moderately brecciated texture (YANAI, 1993), but its matrix is recrystallized on a finer scale. A-881388 (16.92 g) shows a fine-grained crystalline texture. A-881394 (70.92 g) shows a coarse-grained granular texture and is classified as a cumulate eucrite. We studied these three eucrites by mineralogical techniques to find whether the apparent crystalline textures of these eucrites represent direct crystallization from a magma.

2. Samples and Experimental Techniques

Polished thin sections (PTS) of three Asuka eucrites, A-87272,51-2, A-881388,54-1 and A-881394,52-2, were supplied by the National Institute of Polar Research. The original masses and their preliminary descriptions are given in the Catalog (YANAI and KOJIMA, 1995). The PTSs were studied with an optical microscope, and electron probe microanalyzer (EPMA) JEOL 733 at Ocean Research Institute of the University of Tokyo. The method is the same as that described previously (YAMAGUCHI and TAKEDA, 1995). Elemental distribution maps of a large opaque grain in A-881388 were obtained with a JEOL 8900 at the Geological Institute, University of Tokyo.

3. Results

3.1. Asuka-87272

A brief description was previously given by YANAI (1993) and TAKEDA *et al.* (1996). Microscopic examination of PTS, 51-2 shows that it consists of remnant coarse pyroxene and plagioclase crystals set in much finer, rounded grains of pyroxene (0.01–0.14 mm in diameter) which, in turn, are set in matrices of white plagioclase (Fig. 1a). This texture of the matrix gives the rock a granulitic appearance (Fig. 2a), as was described in some eucrites (YAMAGUCHI and TAKEDA, 1995), suggestive of recrystallization on a finer scale. The original crystalline texture is disturbed, presumably by a brecciation event, but on a large scale, the remnant of the original large pyroxene and plagioclase crystals can be recognized (Fig. 1a). A noteworthy feature is that the pyroxene crystals (up to 1 mm long) reveal coarse herring-bone exsolution textures with thick (up to 35 μm) exsolution lamellae of augite on (001) (Fig. 2b, c). Much thinner lamellae on (001) or (100) or both are often observed in the low-Ca host phase between the coarse (001) augite lamellae. This texture with (100) lamellae suggests that pigeonite is inverted to orthopyroxene. In the adjacent area, high-Ca pyroxenes with fine, closely spaced exsolution on (001) (up to 0.8×0.5 mm in size), are often found (Fig. 2d), which may be a calcic rim of an originally zoned pyroxene with variable Ca-Mg-Fe contents (Fig. 3, fine exsolution). Large ilmenite crystals (0.25×0.12 mm) are rarely found. In the fine-grained granulitic regions, where rounded

(a) *A-78272 eucrite, showing an over all texture. Note brecciated monomict-eucrite-like texture with remnants of large pyroxene and plagioclase crystals, but in a finer scale, fine pyroxene grains have rounded shapes and entire parts are recrystallized.*

(b) *A-881388 eucrite.*

(c) *A-881394 eucrite.*

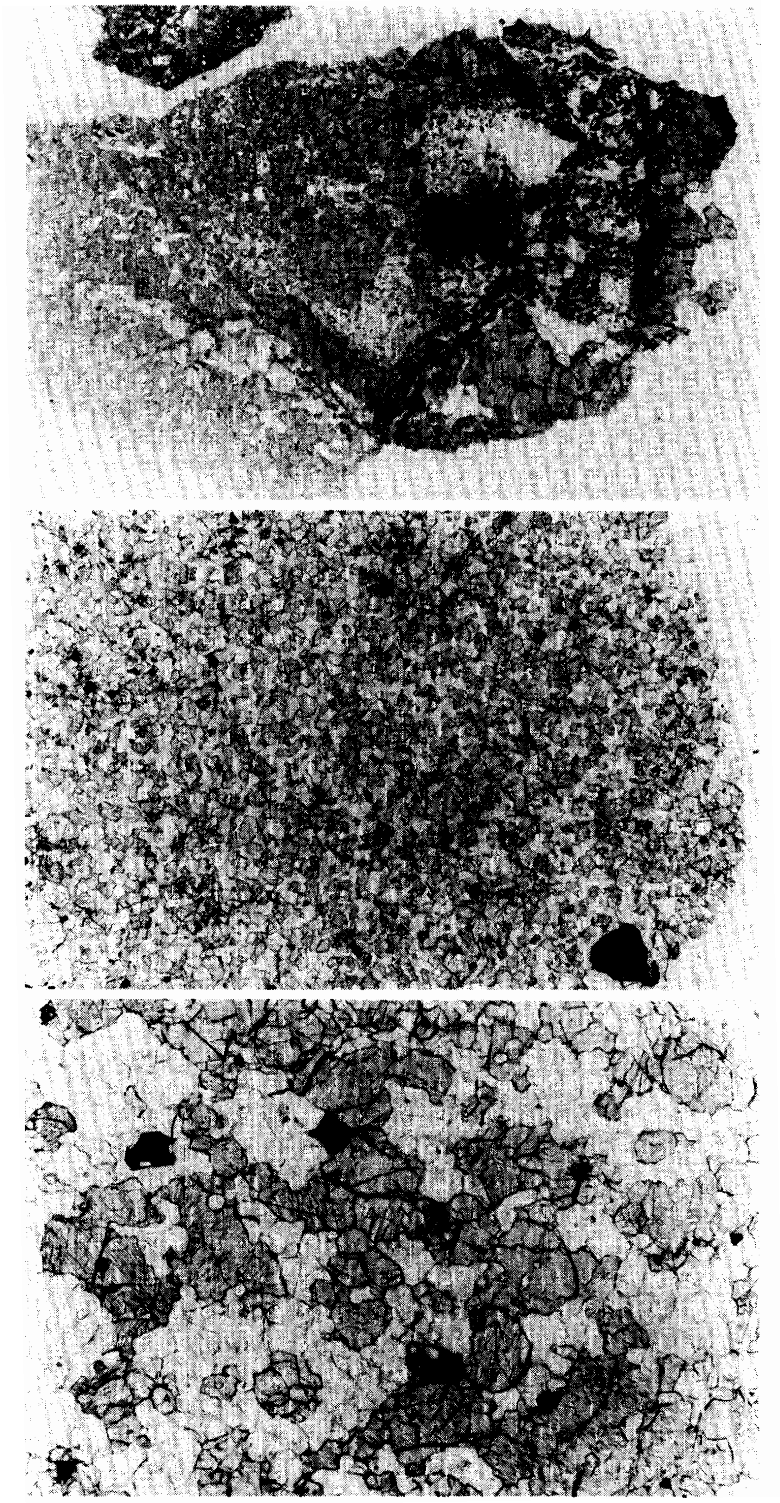
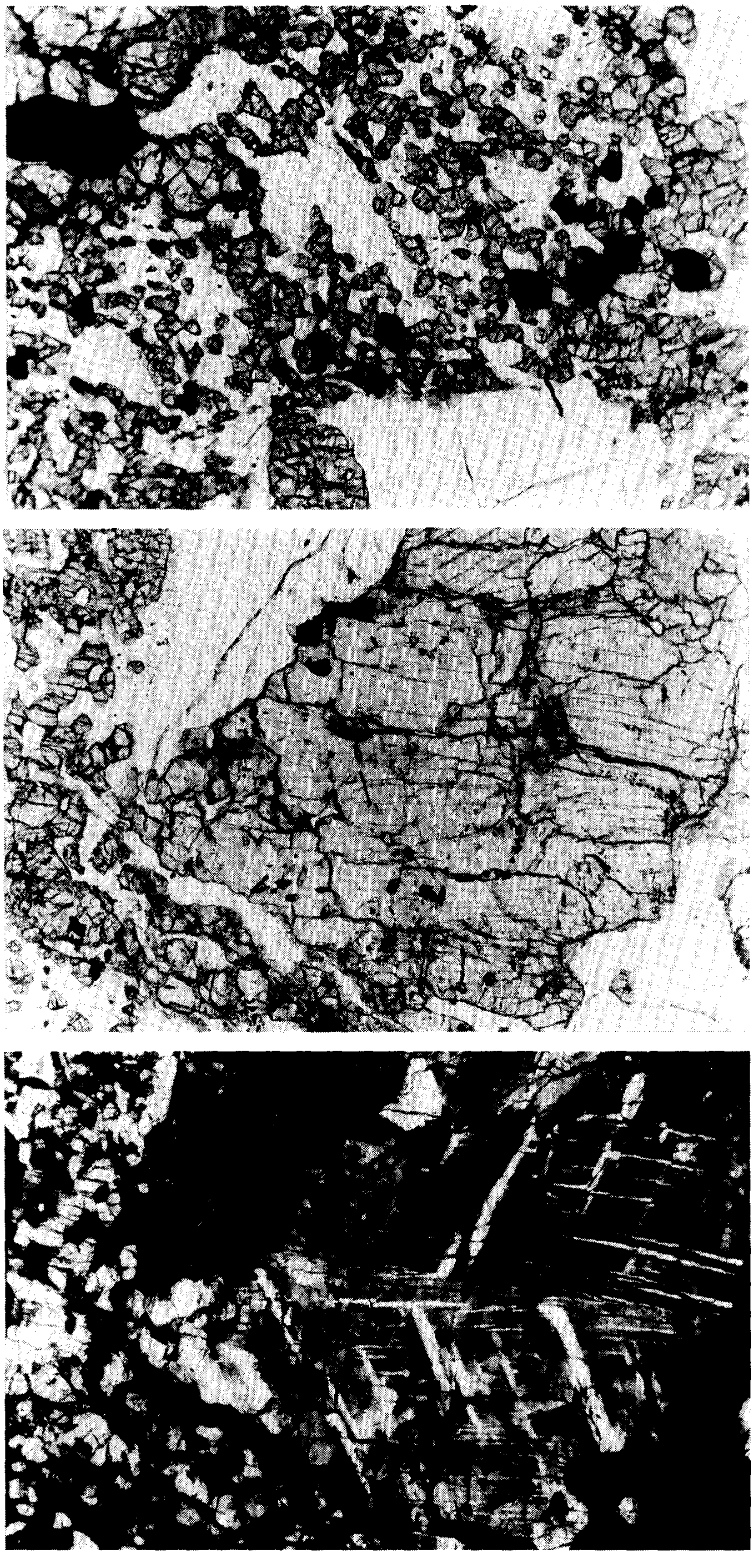


Fig. 1. Photomicrographs showing overall textures of three Asuka eucrites. Width is 6.6 mm. Plane polarized light.

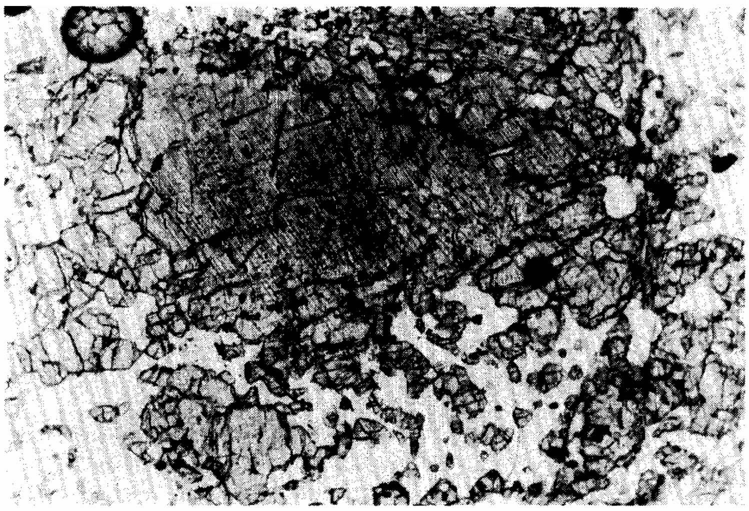


(a) Enlarged view of the fine-grained granulitic portions of A-87272. Fine grained pyroxenes show rounded shapes, indicating recrystallization. They are presumably fragments in the breccia matrix.

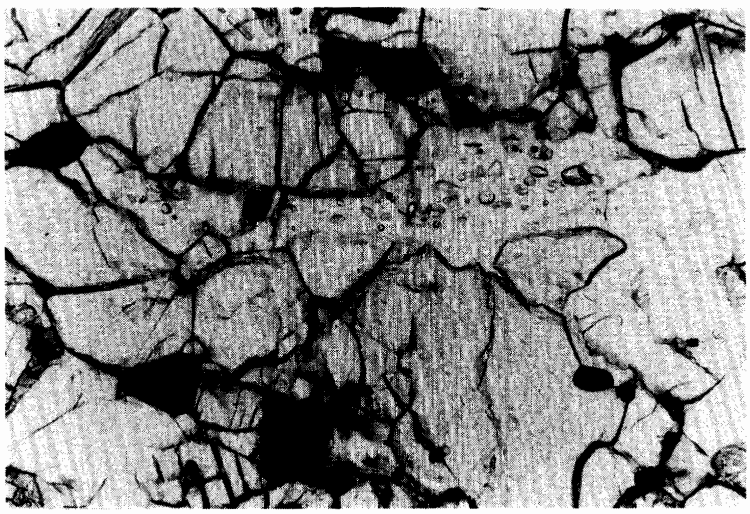
(b) An enlarged view of the remnant crystal of exsolved pyroxene. Finer pyroxene fragments have rounded outer shapes. The pyroxene is not dusty.

(c) Cross polarized light photo of the same view. Note that exsolution textures of large pyroxene grains. Twinned pyroxene shows herring-bone exsolution texture of the inverted pigeonite. (001) exsolution lamellae are thicker than the (100) lamellae developed in the orthopyroxene inverted form the pigeonite.

Fig. 2. Photomicrographs of a specific features observed in three Asuka eucrites. Plane polarized light and width is 1.3 mm if otherwise stated.



(d) Photomicrograph of a pyroxene crystal with finer exsolution lamellae, which might have been originally augitic rims of a zoned pyroxene.



(e) Lath-shaped plagioclase crystal with tiny rounded inclusions in A-881388.

(f) Exsolution texture of pyroxenes in A-881388. Cross polarized view.

Fig. 2 (Continued).

(g) Large opaque grain in A-881388. Width is 3.3 mm.

(h) Twinned exsolved pyroxenes in A-881394. Note a herring-bone texture.

(i) Chromite crystal poikilitically including rounded plagioclase and rare pyroxene. Width is 3.3 mm.

Fig. 2 (Continued).

grains of low-Ca pyroxene and rare augite are coexisting, several small rounded graines (0.01–0.14 mm) of ilmenite and chromite are found together, often along a line (Fig. 2a).

The chemical compositions of all pyroxenes in the PTS fall on a tie line between $Ca_2Mg_{37}Fe_{61}$ and $Ca_{44}Mg_{29}Fe_{27}$ in the pyroxene quadrilateral (Fig. 3a). Because of their coarse textures, the bulk composition is difficult to obtain. This trend is the same as that of the ordinary eucrites (YAMAGUCHI and TAKEDA, 1995), despite the coarse exsolution texture. 'Clouding' of pyroxenes common in the ordinary eucrites (HARLOW and KLIMENTIDIS, 1980) is not noticeable. Plagioclases are chemically zoned from An_{87} to An_{90} (Fig. 4), preserving the initial crystallization trend. The difference in composition between the large remnant crystals and the ones in the matrices of the granulitic

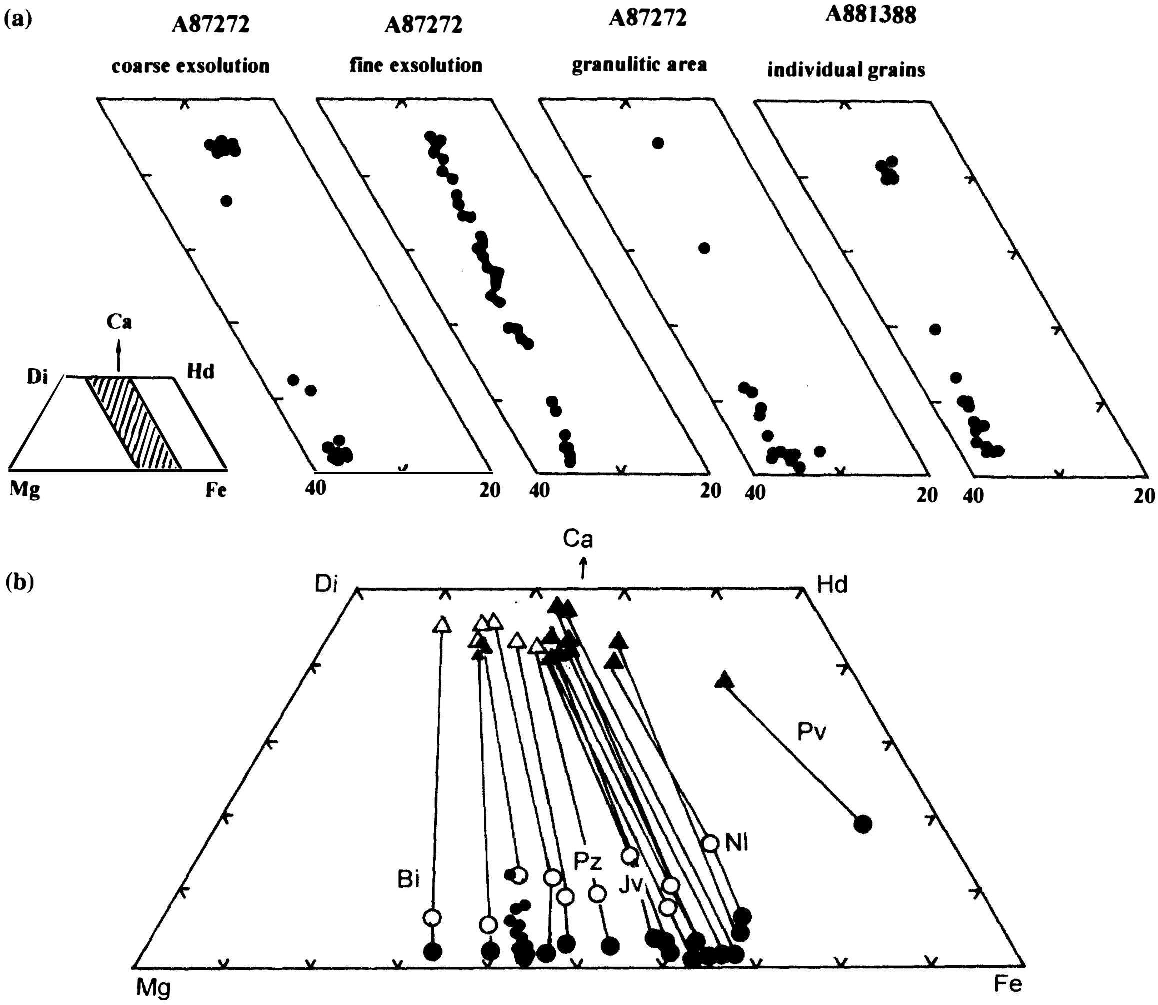


Fig. 3. (a) Parts of the pyroxene quadrilaterals of A-87272 and A-881388, which have the same pyroxene compositions as ordinary eucrites such as Juvinas of degree of pyroxene homogenization types 5 and 6. (b) The pyroxene quadrilateral of A-881394 (small solid circles) and non-Antarctic eucrites (MASON et al., 1979). Mg: enstatite, Fe: ferrosilite, Di: diopside, and Hd: hedenbergite. Open circles: bulk compositions, large solid circles: host phases, triangles: exsolved augite, and tie line connects the exsolved pair. Cumulate eucrites from Bi to Pz and ordinary eucrites from Jv to Nl.

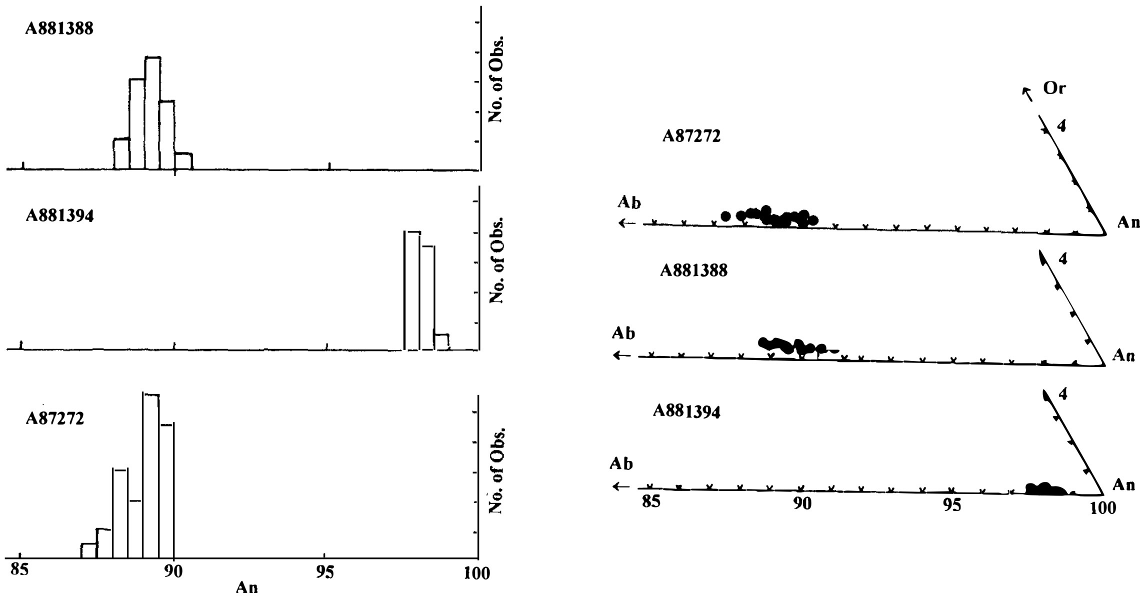


Fig. 4. The An contents of plagioclase in A-87272, A-881388 and A-881394. Except for A-881394, they represent original zoning during crystal growth. An: anorthite, Or: orthoclase, and Ab: albite.

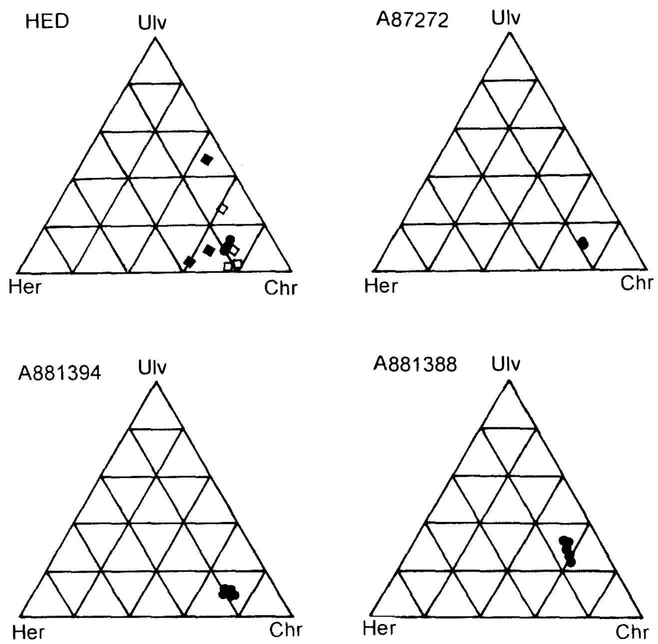


Fig. 5. Chemical compositions of chromites of Asuka eucrites (A-87272, A-881394, A-881388) and HED plotted in the chromite (Chr)-Ulvöspinel (Ulv)-Hercinite (Her) diagrams. The A-87272 and A-881388 chromites are coexisting with ilmenite. □ : diogenites, ◇ : cumulate eucrites, ● : ordinary eucrites (types 5 and 6), ◆ : other eucrites such as in types 1–4.

areas is not significant. The compositions of chromite $Chr_{71}Ulv_{11}Her_{18}$ (Fig. 5) are within the ranges of known ordinary eucrites (BUNCH and KEIL, 1971; NYQUIST *et al.*, 1997).

3.2. Asuka-881388

Fine-grained pyroxene crystals 0.03–0.35 mm in diameter are connected to form complex chains and set in a continuous matrix of white plagioclase (Fig. 1b) consisting of polygonal smaller grains (0.05–0.18 mm in diameter). This texture resembles some granulitic eucrites described by YAMAGUCHI and TAKEDA (1995). Some lath-shaped plagioclase crystals (up to 0.62×0.12 mm in size) with tiny rounded transparent inclusions can be recognized (Fig. 2e). Largest pyroxene crystals reach up to 0.5 mm along the longest dimension. Augite grains up to 0.24×0.19 mm are present. Exsolution lamellae in pyroxenes are very fine (less than 1 μm) and appear like striations with 4 to 11 μm intervals (Fig. 2f). Subrounded opaque grains 0.01–0.09 mm in diameter are scattered throughout the PTS. Most of them are ilmenite (up to 0.13× 0.08 mm), but rare chromite and troilite are present.

At one corner of the PTS, there is an unusually large opaque grain 0.54×0.61 mm in size with rounded triangular shape and a small tail at one corner (Fig. 2g). The size is unusually large in comparison with the silicate grains. It consists mostly of ilmenite with 1.0–1.6 wt% of MgO and 0.04–0.6 wt% of Cr_2O_3. Chromites with compositions $Chr_{57}Ulv_{31}Her_{13}$–$Chr_{66}Ulv_{17}Her_{16}$ (Fig. 5) were found at the tail and near the rims. Troilite was found along the rims and two rounded low-Ni Fe metal grains were found in the interior (Fig. 6). EPMA studies of pyroxenes show that the host phase is homogeneous ($Ca_4Mg_{29}Fe_{67}$) and thin augite lamellae are detected. Individual grains of pigeonite (bulk composition: $Ca_8Mg_{36}Fe_{56}$) and minor augite ($Ca_{41}Mg_{30}Fe_{29}$) coexist (Fig. 3a). The An contents of plagioclase range from 87 to 91 (Fig. 4).

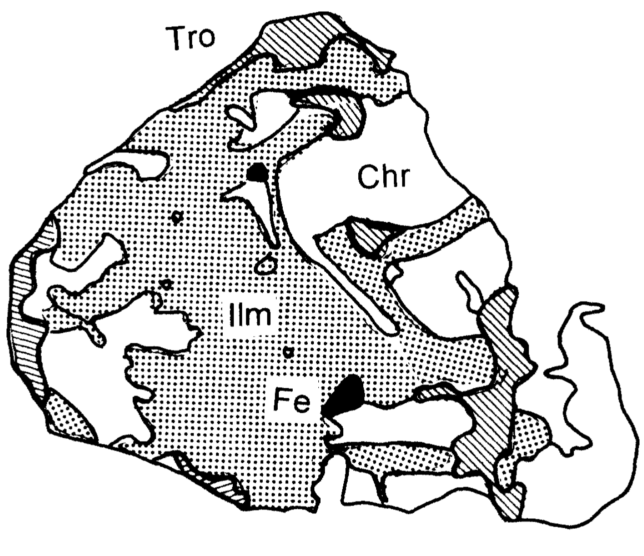


Fig. 6. Mineral distribution in a rounded opaque grain in A-881388. Dotted area (Ilm): ilmenite, white (Chr): chromite, shaded area (Tro): troilite, black (Fe): Fe metal. The longest dimension of the grain is 0.61 mm.

3.3. Asuka-881394

Pale brown pyroxene crystals 0.4 to 1.5 mm in diameter are connected to form a granular texture and white plagioclase fills their interstices (Fig. 1c). The pyroxene crystals show well-developed exsolution textures such as a herring-bone texture (Fig. 2h), and between the thick lamellae a few thinner (001), but no (100) lamellae were found. The thickness of the (001) augite lamellae is about 10 μm. The plagioclase regions are more than 2 mm along the longest dimension and consist of rounded smaller crystals 0.1–0.4 mm in diameter (up to 1×0.5 mm). A silica mineral is common in the section. Opaque grains are mostly chromite, but rare troilite is present. Three grains of chromite partly bound by crystal faces, up to 0.55×0.30 mm in size are present in plagioclase attached on one side to pyroxene. These chromites poikilitically enclose plagioclase and rare pyroxene (Fig. 2i).

Chemical compositions of the exsolved pyroxene analyzed by EPMA show that the host $Ca_2Mg_{54}Fe_{44}$ and the lamella augite $Ca_{42}Mg_{39}Fe_{19}$ are well separated (Fig. 3b). The bulk compositions obtained by a line analysis and broad beam analyses are $Ca_{13}Mg_{50}Fe_{37}$. The An contents of plagioclase are unusually calcic (97–98) for eucrites (Fig. 4). Chromite contains 1.6–2.5 wt% of MgO and the composition $Chr_{72}Ulv_{10}Her_{18}$ (Fig. 5) suggests formation below 800°C (SACK and GHIORSO, 1991), which is the same as those deduced from the bulk compositions of the coexisting pyroxene pair by using the pyroxene geothermometer (LINDSLEY, 1983).

4. Discussion

Ibitira has been known as an unbrecciated eucrite, but it experienced extensive thermal metamorphism in the early history of the HED parent body (BOGARD and GARRISON, 1995). The only pristine basalts that preserve the original crystallization record have been found as a clast in polymict eucrites (DELANEY *et al.*, 1984; TAKEDA *et al.*, 1994). The texture and mineral chemistry of three essentially crystalline eucrites described in this paper are not those of subophitic basalts, which formed by simple crystallization of a eucritic liquid. A-87272 was classified as a monomict eucrite, but the texture does not look like that of a monomict breccia of ordinary eucrites nor polymict eucrites (DELANEY *et al.*, 1984). The fact that the degree of pyroxene homogenization on the TAKEDA and GRAHAM (1991) scale is over type 6, suggests extensive thermal metamorphism. The recrystallized texture with secondary augite of the fine-grained portion of A-87272 resembles that of granulitic eucrites described by YAMAGUCHI and TAKEDA (1995). They proposed that these granulitic eucrites are comparable to those of lunar highland granulites. The entire texture of A-881388 is similar to these granulites. If we extend this idea one step further, the texture of A-881394 can be interpreted as a coarse-grained version of A-881388, although A-881394 has been classified as a cumulate eucrite. We interprete these textures in the light of other mineralogical records and recent models of the origin of ordinary eucrites (YAMAGUCHI *et al.*, 1996).

The texture of A-881388 can be interpreted as granulitic and is similar to the hypidiomorphic-granular texture of Emmavile (MASON *et al.*, 1979), but the crystallinity of Emmavile is not as pronouncd as that of A-881388. Caldera is another newly reported crystalline eucrite and shows hypidiomorphic-granular texture and relatively coarse grain size and the exsolution microtextures in pyroxene are suggestive of slow annealing at subsolidus temperature (BOCTOR *et al.*, 1995). The presence of coexisting low-Ca pyroxene and augite is a common mineral assemblage of the three eucrites. The discovery of an unusually large rounded grain of ilmenite-chromite-metal-troilite with a tail in comparison with fine-grained dust-free pyroxene and plagioclase indicates that this granulitic texture is not a product of primary crystallization. Formation of chromite-ilmenite in the dust-free granoblastic pyroxene areas in Y-792510, which also include minor secondary augite, has been interpreted as induced by a shock event at high temperature and subsequent thermal metamorphism (NYQUIST *et al.*, 1997). The detection of fossil ^{53}Mn in the Y-792510 eucrite suggests that the metamorphic event took place in the early history of the HED parent body (NYQUIST *et al.*, 1997). Rounded inclusions in plagioclase known in Y-792510 were also found in a lath-shaped plagioclase crystal of A-881388, which can be interpreted as a relict crystal. The absence of clouding in pyroxene grains in A-881388 is also noticed in the clear glanoblastic regions in Y-792510 (NYQUIST *et al.*, 1997). Because augite and chromite have not been found in a pristine eucrite (TAKEDA *et al.*, 1994), the presence of coexisting low-Ca pyroxene-augite and ilmenite-chromite assemblages can be taken as an indicator of the recrystallization products.

The presence of inverted pigeonite with coarse exsolution lamellae in A-87272 close to that of the Moore County cumulate eucrite (MIYAMOTO and TAKEDA, 1994), casts some doubts on the assertion that A-87272 may be a cumulate eucrite, but the chemical composition of the low-Ca-pyroxene-augite pair is similar to those of the ordinary eucrites (Fig. 3a). The presence of (100) exsolution lamellae and the straight extinction of the host phase suggest that the host is inverted to orthopyroxene. This kind of inversion is possible only in the plutonic environment in a layered intrusion. The metamorphic grade of the pyroxene can be higher than that of type 6 pyroxene (TAKEDA and GRAHAM, 1991) , and the grade can be designated as type 7 as was proposed by YAMAGUCHI *et al.* (1996). All these facts indicate that the metamorphism of the eucritic crust is comparable to the cooling environment of cumulate eucrites in the HED parent body or Vesta (BINZEL and XU, 1993).

The exsolution texture of A-881394 is not like that of a typical cumulate eucrite such as Serrà de Mage (MIYAMOTO and TAKEDA, 1994), although it is classified as a cumulate eucrite. The texture of A-87272 is more like a cumulate eucrite than A-881394. There is no evidence of inversion to orthopyroxene. The fact that the thickness of exsolution lamellae of A-881394 is thinner than that of A-87272, assuming a bulk composition of A-87272 pyroxene as $Ca_{12}Mg_{50}Fe_{38}$, indicates faster cooling for A-881394. The *mg* number [$=Mg\times100/(Mg+Fe)$ mol%] of A-881394 is identical to that of cumulate eucrites (Fig. 3b). The poikilitic texture of chromite in A-881394 suggests rather a metamorphic event. A domain of plagioclase is composed of finer-grained rounded crystals as in some granulitic eucrites (YAMAGUCHI and TAKEDA, 1995). The rounded texture of pyroxene and granoblastic texture of plagioclase are in favor of the granulitic origin. A possible thermal history of A-881394 is that the recrystallization process was as extensive as that of cumulate eucrites but the subsequent cooling was faster than that of cumulate eucrites.

The most important and unusual feature of A-881394 is the very calcic nature of plagioclase, which suggests affinity to angrites. However, trace element data of this interesting achondrite are still within the range of cumulate eucrites (WARREN *et al.*, 1996). They pointed out that volatile trace elements are depleted in A-881394. A-881394 might have experienced an extensive thermal event during which the valatile elements and Na had been lost. An early formed scarf-like crust (TAKEDA and MORI, 1985), may experience more heating from the magma beneath, especially if an additional heating is generated by an impact. We need more data before we further discuss their relationship to other meteorite classes. Our present interpretation is that despite their crystalline texture, they might have experienced extensive metamorphism after the initial crystallization in the early history of the crustal evolution.

In summary, (1) The texture and mineral chemistry of three essentially crystalline eucrites described in this paper are not simple products of normal crystallization. (2) The entire texture of A-881388 and a part of A-87272 and the presence of coexisting low-Ca pyroxene-augite and ilmenite-chromite are similar to those of granulitic eucrites. (3) The discovery of an unusually large rounded grain of ilmenite-chromite-metal-troilite with a tail and the poikilitic texture of chromite in A-881394 suggests rather a metamorphic event. (4) The presence of inverted pigeonite with coarse exsolution lamellae in A-87272 close to those of the Moore County cumulate eucrite indicates that the metamorphism of the eucritic crust is comparable to the cooling environment of cumulate eucrites on the HED parent body. (5) Our present interpretation is that despite their crystalline texture, they might have experienced extensive metamorphism after the initial crystallization in the early history of the crustal evolution.

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References

BINZEL, R. P. and XU, S. (1993): Chips off of asteroid 4 Vesta: evidence for the parent body of basaltic achondrite meteorites. Science, **260**, 186–191.

BOCTOR, N. Z., PALME, H., SPETTEL, B., EL GORESY, A. and MCPHERSON, G. J. (1995): Caldera: A second unbrecciated noncumulate eucrite. Meteoritics, **30**, 445.

BOGARD, D. D. (1995): Impact ages of meteorites: a synthesis. Meteoritics, **30**, 244–268.

BOGARD, D. D. and GARRISON, D. H. (1995): ^{39}Ar-^{40}Ar age of the Ibitira and constraints on the time of pyroxene equilibration. Geochim. Cosmochim. Acta, **59**, 4317–4322.

BOGARD, D. D., NYQUIST, L., TAKEDA, H., MORI, H., AOYAMA, T., BANSAL, B., WIESMAN, H. and SHIH, C.-Y. (1993): Antarctic polymict eucrite Yamato 792769 and the cratering record on the HED parent body. Geochim. Cosmochim. Acta, **57**, 2111–2121.

BUNCH, T. T. and KEIL, K. (1971): Chromite and ilmenite in non-chondritic meteorites. Am. Mineral., **56**, 146–157.

DELANEY, J. S., PRINZ, M. and TAKEDA, H. (1984): The polymict eucrites. Proc. Lunar Planet. Sci. Conf., 15th, Pt. 1, C251–C288 (J. Geophys. Res., **89**, Suppl.).

DUKE, M. B. and SILVER, L. T. (1967): Petrology of eucrites, howardites, and mesosiderites. Geochim. Cosmochim. Acta, **31**, 1637–1665.

HARLOW, G. E. and KLIMENTIDIS, R. (1980): Clouding of pyroxene and plagioclase in eucrites: Implications, for post-crystallization processing. Proc. Lunar. Sci. Conf., 11th, 1131–1143.

LINDSLEY, D. H. (1983): Pyroxene thermometry. Am. Mineral., **68**, 477–493.

MASON, B., JAROSEWICH, E. and NELEN, J. A. (1979): The pyroxene-plagioclase achondrites. Smithson. Contrib. Earth Sci., **22**, 27–45.

MIYAMOTO, M. and TAKEDA, H. (1994): Evidence for excavation of deep crustal material of a Vesta-like body from Ca compositional gradients in pyroxene. Earth Planet. Sci. Lett., **122**, 343–349.

NYQUIST, L. E., TAKEDA, H., BANSAL, B. M., SHIH, C.-Y., WIESMANN, H. and WOODEN, J. L. (1986): Rb-Sr and Sm-Nd internal isochron ages of a subophitic basalt clast and a matrix sample from the Y75011 eucrite. J. Geophys. Res., **91**, 8137–8150.

NYQUIST, L. E., TAKEDA, H., BOGARD, D. D., SHIH, C.-Y. and WIESMANN, H. (1996): Crystallization, recrystallization, and impact-metamorphic ages of monomict eucrite Y792510. Lunar and Planetary Science XXVII. Houston, Lunar Planet. Inst., 969–970.

NYQUIST, L., BOGARD, D., TAKEDA, H., BANSAL, B., WIESMANN, H. and SHIH, C.-Y. (1997): Crystallization, recrystallization, and impact-metamorphic ages of eucrites Y792510 and Y791186. Geochim. Cosmochim. Acta, **61**, 2119–2138.

SACK, R. O. and GHIORSO, M. S. (1991): Chromian spinels as petrogenetic indicators: Thermodynamics and petrological applications. Am. Mineral., **76**, 827–847.

TAKEDA, H. and GRAHAM, A. L. (1991): Degree of equilibration of eucritic pyroxenes and thermal metamorphism of the earliest planetary crust. Meteoritics, **26**, 129–134.

TAKEDA, H. and Mori, H. (1985): The diogenite-eucrite links and the crystallization history of a crust of their parent body. Proc. Lunar Planet. Sci. Conf., 15th, Pt. 2, C636–C648 (J. Geophys. Res., **90** Suppl.).

TAKEDA, H., MORI, H. and BOGARD, D. D. (1994): Mineralogy and ^{39}Ar-^{40}Ar age of an old pristine basalt: Thermal history of the HED parent body. Earth Planet. Sci. Lett., **122**, 183–194.

TAKEDA, H., ISHII,T. and MIYAMOTO, M. (1996): Coarsely exsolved pyroxenes in a eucrite from Antarctica and the highest degree of crustal metamorphism. Meteorit. Planet. Sci., **31**, Suppl., A138–139.

WARREN, P. H., KALLEMEYN, G. W., ARAI, T. and KANEDA, K. (1996): Compositional-petrologic investigation of eucrites and the QUE94201 shergottite. Antarctic Meteorites XXI. Tokyo, Natl Inst. Polar Res., 195–197.

YAMAGUCHI, A. and TAKEDA, H. (1995): Mineralogical study of some Antarctic eucrites including Yamato 74356–A unique rock containing recrystallized clastic matrix. Proc. NIPR Symp. Antarct. Meteorites, **8**, 167–184.

YAMAGUCHI, A., TAKEDA, H., BOGARD, D. D. and GARRISON, D (1994): Textural variation and impact history of the Millbillillie eucrite. Meteoritics, **29**, 237–245.

YAMAGUCHI, A., TAYLOR, G. J. and KEIL, K. (1996): Global crustal metamorphism of the eucrite parent body. Icarus, **124**, 97–112.

YANAI, K. (1993): The Asuka-87 and Asuka-88 collections of Antarctic meteorites: Preliminary examination with brief descriptions of some typical and unique-unusual specimens. Proc. NIPR Symp. Antarct. Meteorites, **6**, 148–170.

YANAI, K. and KOJIMA, H. comp. (1995): Catalog of Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 230 p.

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