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VARIETIES OF LUNAR METEORITES RECOVERED FROM ANTARCTICA

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Abstract: By the 1988–1989 field season, more than 10 specimens of lunar meteorites have been recovered in Antarctica by the U. S. and Japanese Expeditions. The specimens from the Yamato Mountains, Allan Hills and MacAlpine Hills (Y-791197, Y-82192/193, Y-86032 [1], ALHA81005 [2], MAC88104/105) are all plagioclase (anorthite)-rich breccias from the lunar highlands. Y-793274 is a pyroxene- and plagioclase-rich breccia, and EET87521 [5] is basaltic clast-rich breccia: Both contain abundant components from the basaltic provinces (the maria) of the lunar crust. Asuka-31 and Y-793169 are unbrecciated, coarse-grained rocks consisting mainly of pyroxene and plagioclase (maskelynitized), together with ilmenite and troilite. The bulk compositions of Asuka-31 and Y-793169 are very similar to low-titanium and very low-titanium (VLT) lunar mare basalts.

Oxygen isotope data strongly support the lunar origin of all the Antarctic lunar meteorites. The FeO/MnO ratios are consistent with the range of those of lunar pyroxenes, which are markedly different from those of basaltic achondrites. However, they contain a wide range of pyroxene compositions. The lunar meteorites have originated from several different places on the Moon surface, comprising single rock facies or monomict-polymict breccia facies.

On the basis of lithology, texture, petrography, chemistry and mineral compositions, the lunar meteorites can be divided into 4 or more different types: namely anorthositic breccias (including 3–4 different facies), basaltic-anorthositic breccias, basaltic breccias, and unbrecciated diabase and gabbro. These types indicate that the samples might have originate from at least 7 different sites on the near- and far-side sites of the Moon. The different types of lunar meteorites strongly suggest that there are other unknown rock type(s) on the Moon, and that new meteorite types are to be expected in Antarctica.

1. Introduction

Lunar meteorites recovered in Antarctica are the first meteorites from the Earth's Moon. Up till now, 11 individual specimens, identified as of lunar origin, have been recovered from several places in Antarctica by the U. S. and Japanese Expeditions. These specimens, named "lunar meteorites" because of their apparent derivation from the lunar surface, have seen classified into several types on the basis of lithological and compositional differences.

Ten Antarctic lunar meteorites were recovered from the Yamato Mountains, Allan Hills, and MacAlpine Hills: Y-791197 (YANAI and KOJIMA, 1984a, b), Y-793169 (YANAI and KOJIMA, 1987b), Y-793274 (YANAI *et al.*, 1984; YANAI and KOJIMA, 1985a, b; YANAI *et al.*, 1986), ALHA81005 (MASON, 1982; MARVIN, 1983), Y-82192/193 (YANAI *et al.*, 1984; YANAI and KOJIMA, 1985a, b; TAKEDA *et al.*, 1986; YANAI *et al.*, 1986; BISCHOFF *et al.*, 1987), Y-86032 (NISHIO *et al.*, 1987; YANAI and KOJIMA, 1987a; TAKEDA *et al.*, 1988, 1989), EET87521 (DELANEY, 1989; WARREN and KALLEMEYN, 1989) and MAC88104/105 (DELANEY, 1990; WARREN and KALLEMEYN, 1990). All except Y-793169 have been classified as an anorthositic polymict breccia, basaltic-anorthositic breccia or basaltic breccias. However, Y-793169 and Asuka-31 (YANAI, 1991) are different from the other known lunar meteorites in that they retained their original diabase-gabbro textures, in spite of the well-known intense bombardment of the early Moon's surface. Lunar meteorites recovered by the Japanese expeditions include Yamato-791197 (hereafter Y-791197), Y-793169, Y-793274, Y-82192/193, Y-86032 and Asuka-31 (tentative), and those by the U. S. expeditions include Allan Hills 81005 (ALHA81005), Elephant Moraine 87521 (EET87521) and MacAlpine Hills 88104/105 (MAC88104/105) (Table 1). The 11 specimens were collected as individual meteorite samples in the field. However, some of them might be paired, because they are very similar to each other and were collected within very limited areas of the bare ice fields.

This paper describes and compares the varieties of lunar meteorites, and discusses their recovery, petrography, mineral and bulk compositions.

2. General Descriptions of the Lunar Meteorites

The known lunar meteorites are listed in Table 1, with their name, weight, date

Table 1. Lunar meteorites from Antarctica.

	Name	wt (g)	Date of find	Lithology and type	Source
1	Y-791197	52.40	Nov. 20, 1979	Anorthositic regolith breccia, A	Highland
2	Y-793169	6.07	Dec. 8, 1979	Unbrecciated diabase	Mare
3	Y-793274	8.66	Jan. 3, 1980	Basaltic-anorthositic breccia (VLT)	Maria-Highland
4	ALHA81005	31.4	Jan. 18, 1982	Anorthositic regolith breccia, B	Highland
5	Y-82192	36.67	Jan. 13, 1983	Anorthositic fragmental breccia	Highland
6	Y-82193	27.04	Jan. 13, 1983	Anorthositic fragmental breccia	Highland
7	Y-86032	648.43	Dec. 10, 1986	Anorthositic fragmental breccia	Highland
8	EET87521	30.7	Dec. 20, 1987	Basaltic breccia (VLT)	Mare-(Highland)
9	Asuka-31 (tentative)	442.12	Dec. 20, 1988	Unbrecciated gabbro	Mare
10	MAC88104	61.2	Jan. 13, 1989	Anorthositic regolith breccia, C	Highland
11	MAC88105	662.5	Jan. 13, 1989	Anorthositic regolith breccia, C	Highland

Japanese collection: 1, 2, 3, 5, 6, 7 and 9; US collection: 4, 8, 10 and 11; Y: Yamato Mountains; Asuka: Asuka (Sør Rondane Mountains); ALH: Allan Hills; EET: Elephant Moraine; MAC: MacAlpine Hills; VLT: very low-titanium mare basalt.

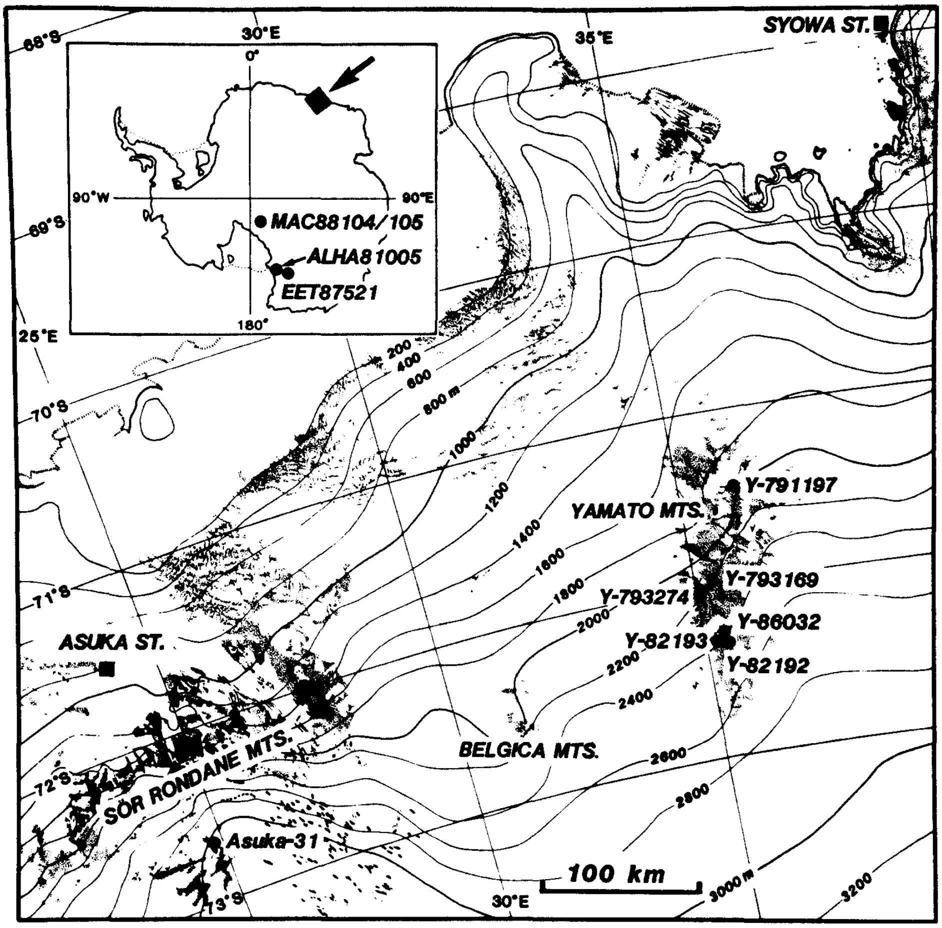

Fig. 1. The discovery sites of the lunar meteorites in Antarctica.

of find, lithology and type, source and collection. Known localities of the lunar meteorite are limited to the Yamato Mountains, Sør Rondane Mountains and Transantarctic Mountains (Fig. 1).

2. 1. *Yamato-791197*

The Y-791197 meteorite was collected on November 20, 1979 on the bare ice at the northeastern end of the Yamato Mountains, Antarctica, and was thought to be somewhat carbonaceous meteorite. It was found by a search party of the 20th Japanese Antarctic Research Expedition (JARE-20), 1979–1980. Y-791197 is 4.5$\times$4.2$\times$2.8 cm in size and originally weighs 52.40 g. The original volume of the specimen was 18.45 cubic centimeters and the specific gravity is 2.84 (g/cm^3). This stone was identified, together with Y-793169 and Y-793274, as one of the unique specimens among over 3500 meteorites of the Yamato-79 collection.

Y-791197 is an almost complete round stone with a very smooth, rounded surface (possibly the original surface), and irregular surface (nearly half) covered by a thick, dusty-gray fusion crust. The interior consists mainly of angular clasts, dark gray to white in color, set in a black to dark brown, glassy matrix. The size of most of the clasts is smaller than 1 mm, but some clasts up to 4 mm in diameter are observed.

A polished thin section was made from a small chip, 0.225 g, at NIPR. The

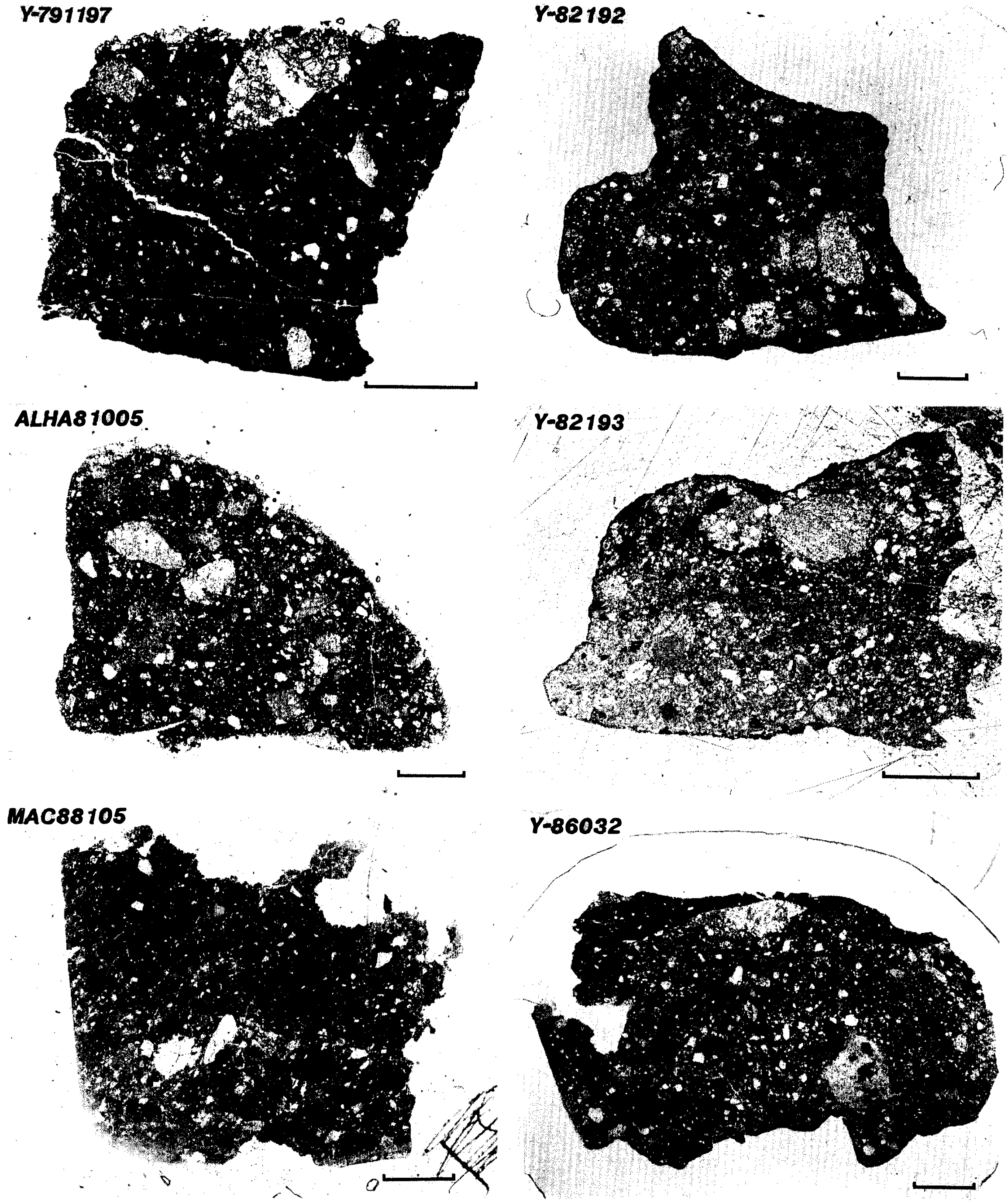

Fig. 2a.

Figs. 2a, b. Photomicrographs of thin sections of each lunar meteorite (plane-polarized light), except Y-793169(b) and Asuka-31(b) which is in cross-polars, showing the maskelynitized plagioclase. Scale bars are 0.2 mm.

specimen differs from all carbonaceous chondrites, including the Allende (CV3) chondrite, and from known polymict eucrites. After examining the whole sample and the thin section, the authors preliminarily classified the specimen as an anorthositic breccia, because it shows a brecciated texture containing many feldspathic

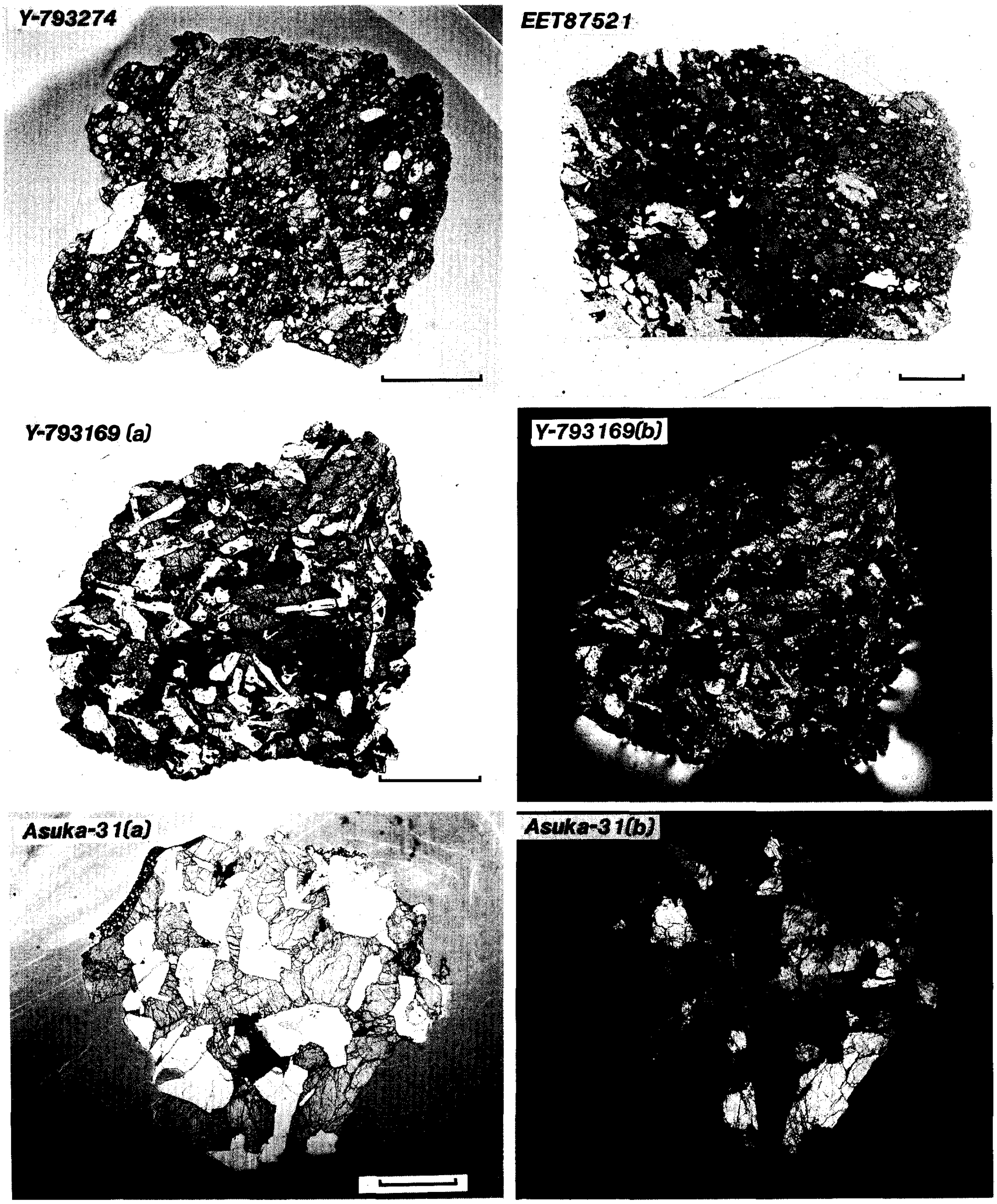

Fig. 2b.

clasts (YANAI and KOJIMA, 1984b).

Petrographically Y-791197 is a polymict microbreccia containing abundant clasts in a dark-brown, glassy matrix (Fig. 2). Two or more types of clasts are observed in this section, including polymineralic, monomineralic and melt clasts. Most of larger clasts are polymineralic, commonly composed of calcic plagioclase, olivine, and pyroxene, less commonly of plagioclase and pyroxene, or plagioclase alone. Smaller clasts are mineral fragments, dominantly plagioclase, with some pyroxene and olivine, and melt rock fragments. The clasts also show a variety of textures, including troctolitic, gabbroic, diabasic, basaltic and also shock-melted glassy clasts. Some clasts are similar to those of eucrites and howardites, but most are more feldspathic. Y-791197 appears to be a regolith breccia with glass spherules and an abundance of clasts, especially feldspathic clasts, set in a dark brown glassy matrix. In texture, Y-791197 resembles lunar regolith breccias.

Microprobe analyses indicate feldspar compositions ranging from $An_{92.0}$ to $An_{98.2}$, but mostly between $An_{95.5}$ and $An_{97.5}$. Pyroxenes and olivines are also varied in composition. The compositional range of pyroxenes is $En_{18.0}$ to $En_{83.1}$, $Fs_{9.0}$ to $Fs_{58.9}$, $Wo_{1.7}$ to $Wo_{44.1}$. Most olivines are Fo_{55} to Fo_{80}, but several grains with $Fo_{92.1}$ and $Fo_{13.3}$ were found.

2.2. *Yamato-793169*

The Y-793169 was located on the bare ice near the Minami-Yamato Nunataks, about 70 km south of Y-791197, and was collected by the meteorite search party of JARE-20 on December 8, 1979. This meteorite is $1.8\times1.7\times1.1$ cm in size with a weight of 6.09 g, and is the smallest known lunar meteorite. Y-793169 is an almost complete stone, with a smoothly rounded surface covered by black fusion crust, and with white laths of plagioclase on the surface. The interior is dark and resembles that of an unbrecciated rock without any clasts. Y-793169 was originally identified as an unbrecciated eucrite based on its constituent minerals, but current petrographic evidence from a more representative thin section (Fig. 2) indicates that it is the first unbrecciated lunar diabase from a lunar mare site.

In thin section, Y-793169 shows an unbrecciated texture, consisting of medium- to coarse-grained pyroxene and plagioclase with ilmenite, spinel and little glass, and very rare olivine (Fig. 2). The feather-like appearance of plagioclase suggests recrystallization after maskelynitization due to shock effects. Microprobe analysis indicates that feldspar is very Ca-rich, ranging from An_{88} to $An_{97.5}$, but mostly between An_{92} to An_{94}. Pyroxenes are varied in composition, ranging from $En_{1.9}$ to $En_{53.5}$, $Fs_{22.2}$ to $Fs_{84.3}$, $Wo_{9.7}$ to $Wo_{40.7}$. Olivine has a high iron content, $Fa_{98.5}$, but only one grain was found in the section. In a plot of the MnO *vs.* FeO, pyroxene compositions of Y-793169 indicate a lunar origin. The meteorite's oxygen isotope signature is also consistent with a lunar origin ($\delta^{18}O=5.35$, $\delta^{17}O=2.79$, R. N. CLAYTON, personal communication).

2.3. *Yamato-793274*

The Y-793274 meteorite has been identified and classified as the fifth lunar meteorite. Y-793274 was found on the bare ice near the Minami-Yamato Nunataks of the Yamato Mountains, Antarctica on January 3, 1980 by the meteorite search party of JARE-20, 1979–1980. The locality of Y-793274 is 10 km southwest from the Y-793169 locality. In the field, Y-793274 was collected as a unique specimen just like the Y-791197, the lunar meteorite.

Y-793274 is a nearly complete and angular, small stone with some smooth surface (possibly original surface) and covered by a thin fusion crust which is a brownish to grayish-dusty in color. Abundant clasts ranging from a few to several millimeters

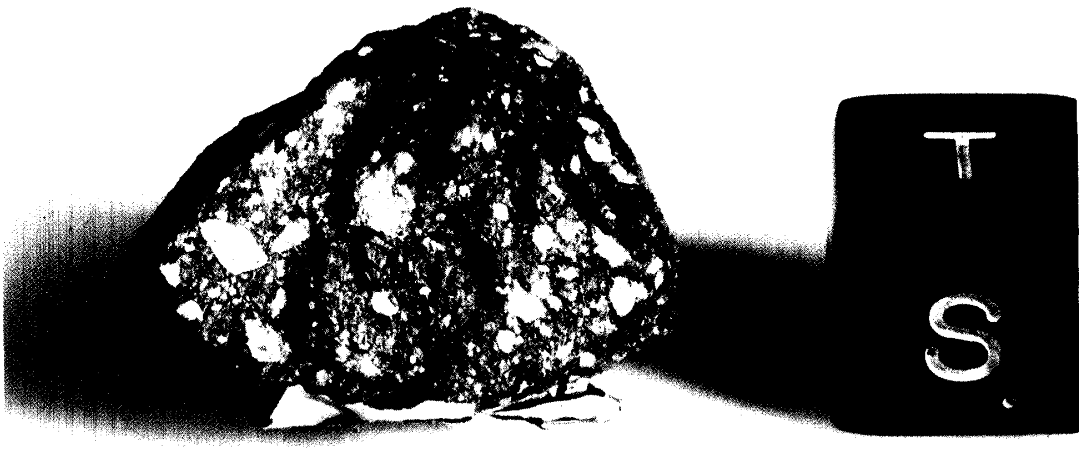

Fig. 3. Photograph of the main mass of Yamato-793274, after chipping, which weighs only 8.8 g and is covered by a dusty-gray fusion crust. Many clasts of white (anorthosite) and yellowish-brown (pyroxene), lithic and mineral fragments occur in the gray to dark gray matrix. Scale cube is 1 cm.

across are distinguished in a dark gray to black matrix (Fig. 3). The clasts are mostly angular in shape, and white and black in color, and set into a matrix. This specimen is $2.6 \times 1.8 \times 1.2$ cm in size and weighs only 8.66 g. The original volume of the specimen was 2.82 cubic cm and the specific gravity is 3.07 (g/cm^3).

Thin section study of Y-793274 shows that it is a polymict microbreccia, containing numerous clasts and mineral fragments set in a brown matrix. The fusion crust is green in color and contains many fine vesicles (Fig. 2). Clasts in the section show a variety of textures, including anorthositic, troctolitic, gabbroic, and melt rock fragments with greenish glass, as well as recrystallized rock fragments and small spherules. Numerous single mineral fragments are present in the section, such as pyroxene (abundant), olivine (intermediate), and calcic plagioclase (comparatively scarce) and glass spherules (rare).

Microprobe analyses show that feldspar ranges from $An_{88.3}$ to $An_{97.4}$. Pyroxene and olivine are varied in composition, pyroxene with $En_{4.2}$ to $En_{67.5}$, $Fs_{16.4}$ to $Fs_{64.3}$, $Wo_{2.8}$ to $Wo_{40.1}$, and olivine with $Fo_{2.7}$ to $Fo_{82.2}$. The MnO contents of both pyroxene and olivine are remarkably lower than those of all basaltic achondrites, but are very similar to those of lunar rocks. Y-793274 was classified as an anorthositic regolith breccia (YANAI and KOJIMA, 1987a) based on the abundant anorthositic clasts, but current studies indicate that it is a basaltic-anorthositic breccia based on the abundance of pyroxene fragments, which suggests a mare origin, and minor highland components.

2.4. *Allan Hills A81005*

The ALHA81005 meteorite was collected on January 18, 1982, on the middle western ice field of the Allan Hills region of Victoria Land, Antarctica by the United States search party. A preliminary description was given by SCORE and MASON (1982), and MARVIN (1983). This meteorite is $3 \times 2.5 \times 3$ cm in size, weighs 31.4 g, and is a small rounded breccia with conspicuous white clasts covered by a pitted, glassy, greenish-tan colored fusion crust. The interior consists of abundant angular clasts ranging from gray to white in color, set in a black matrix. The clasts are as small as submillimeter and as large as 8 mm in diameter.

In thin section, the specimen is a heterogeneous mixture of rock, mineral and glass fragments with colorless glass spherules in a dark-brown, glassy matrix showing a flow structure in places (Fig. 2). Most large clasts are polymineralic, but relatively small fragments may be monomineralic clasts. The clasts consist of abundant plagioclase and lesser amounts of olivine together with pyroxene, and traces of metal. The clasts show granulitic, gabbroic, diabasic and basaltic textures, with many partly-shocked granulated fragments.

Microprobe analyses show that the plagioclase is very Ca-rich, averaging $An_{96.5}$ (range An_{92} to An_{99}); most olivines range between Fo_{70} to Fo_{90}, but several grains were more magnesian than Fo_{90} and also Fo_{44} to Fo_{66}. Pyroxene is varied in composition, $En_{34.9}$ to $En_{82.3}$, $Fs_{6.9}$ to $Fs_{47.9}$, $Wo_{2.0}$ to $Wo_{44.8}$.

The MnO/FeO values measured in the pyroxenes and olivines are equivalent to those previously determined for the ratio in lunar pyroxenes; they plot below the field determined for achondritic pyroxenes. Within ALHA81005 the pyroxenes and olivines fall (as expected) above and below the trend established for lunar bulk rocks.

The meteorite's oxygen isotope signature is also consistent with a lunar origin ($\delta^{18}O=5.48$, 5.86, $\delta^{17}O=2.92$, 3.03; MAYEDA and CLAYTON, 1983).

2.5. *Yamato-82192*

The Y-82192 has been identified as an anorthositic regolith breccia (YANAI *et al.*, 1984). The specimen was collected on the southern bare ice of the Minami-Yamato Nunataks, Yamato Mountains, Antarctica by Mr. T. KATSUSHIMA (University of Hokkaido, geologist), by JARE-23 in the 1982–1983 field season. This specimen comprises nearly half of a whole stone, weighs 36.67 g, and measures $4.3 \times 3.3 \times 2.3$ cm. It is partly covered by relatively meager fusion crust. It has some smooth surface which is coated with a yellowish-tan colored crust. The fresh surface and the interior are light gray to pale violet in color. The specimen consists of abundant clasts which range from one mm to one cm size, and they are dark to black and white in color and are embedded in a light gray matrix.

The thin section of the specimen shows numerous clasts consisting of melt rock, crystalline, and brecciated lithic fragments, embedded in a matrix (Fig. 2). There are two types of clasts in the section, namely polymineralic and monomineralic. They consist of pyroxene and olivine, and plagioclase-pyroxene. The smaller clasts are individual mineral fragments, mostly plagioclase with some pyroxene and minor olivine. Most of the melt rock fragments are brown in color, are devitrified, and contain fine plagioclase and minor pyroxene. Small glass spherules are rare. The clasts of the crystalline rock fragments show a variety of textures including diabasic, basaltic and granulitic: most of them show some degree of shock. The matrix of the specimen consists of two areas, one brown in color, the other light, which shows a devitrified and recrystallized texture. Petrographic evidence from a more representative thin section indicates that Y-82192 is an anorthositic fragmental breccia.

Microprobe analysis shows that feldspar ranges from $An_{83.0}$ to $An_{98.2}$, with most analyses between An_{93} and An_{98}, with a maximum of 1.3% Or. Pyroxene and olivine are varied in composition, pyroxene with $Wo_{1.3}$ to $Wo_{43.2}$, $En_{13.8}$ to $En_{79.4}$, $Fs_{8.1}$ to $Fs_{57.6}$, and olivine with $Fo_{6.8}$ to $Fo_{89.1}$. The MnO contents of both pyroxene and olivine are lower than those of all achondrites, but are very similar to those of lunar rocks.

This specimen shows a brecciated texture with numerous lithic fragments, as is the case with most polymict eucrites and howardites, but it differs from eucrites and howardites in mineralogy, chemistry and FeO *vs.* MnO in pyroxenes.

2.6. *Yamato-82193*

The Y-82193 is identified as a new specimen of lunar meteorite. This specimen can be classified as an anorthositic fragmental breccia. It was collected from an area close to that of the Yamato-82192, on January 13, 1983. The specimen probably represents an individual meteorite, $3.4\times3.0\times2.2$ cm and weighing 37.04 g. The original volume of the specimen is 9.47 cubic cm and the specific gravity is 2.85 g/cm^3. The meteorite is coated with pale ylleowish-tan color. A very thin fusion crust is present on the original surface but most of fusion crust had been already abraded. Fresh surfaces and the interior are of light gray to pale violet color. The interior consists of many angular clasts which range from one mm to several mm across. These clasts are dark gray to white in color, set in a pale light gray to grayish-brown matrix.

Petrographically Y-82193 is a polymict microbreccia containing variety of clasts (Fig. 2). Several types of clasts were observed in thin section; these include polymineralic, monomineralic and 'melt clasts. Most larger clasts are polymineralic and are composed of calcic plagioclase (anorthite), olivine and pyroxene. The small clasts are single mineral fragments, consisting mostly of calcic plagioclase (anorthite), olivine and pyroxene. Abundant melt rock clasts were observed in thin section; and the clasts show a variety of textures including troctolitic, gabbroic, basaltic and shock-melted glassy clasts. The texture of the specimen is similar to those of eucrites and howardites, but the specimen is much more feldspathic.

The Y-82193 meteorite appears to be a polymict breccia with an abundance of feldspathic clasts, set in a light-grayish brown matrix. From its texture and the types of clasts, the Y-82193 resembles the lunar highland breccias of Apollo 16, but the meteorite does not contain any swirly brown glass. Therefore, the specimen may be classified as an anorthositic fragmental breccia. Feldspar compositions range from $An_{88.3}$ to $An_{97.8}$, with most compositions ranging from 93.3 to 97.8. Pyroxenes and olivines also show varied compositions. The compositional range in pyroxene is

$En_{30.1}$ to $En_{75.2}$, $Fs_{16.2}$ to $Fs_{47.0}$, $Wo_{3.1}$ to $Wo_{38.0}$. Olivines are $Fo_{48.7}$ to $Fo_{81.1}$. Y-82193 is similar to Y-82192 in most respects, including petrography, chemistry, textures and types of clasts, but Y-82193 is slightly different from Yamato-791197 in some properties of its matrix.

2.7. *Yamato-86032*

The Y-86032 was found on the bare ice surface near the location of Y-82192/193, and was collected by JARE-27 in the 1982–1983 field season. It was recognized as a lunar meteorite when it was recovered in the field on December 9, 1986 by Dr. F. NISHIO, who also noticed that this meteorite was similar to Y-82192/193 (F. NISHIO, personal communication, 1987).

The Y-86032 is the fifth lunar meteorite identified in the Yamato meteorite collections, and its location of find is shown in Fig. 2 together with those of other lunar meteorites. The location of Y-86032 is very close (within few km) to that of Y-82192/193, but it is more than 30 km from the locations of Y-793169 and Y-793274. Y-86032 is the largest lunar meteorite recovered until 1986, and is an individual meteorite. It weighs 648.43 g and measures $10.7 \times 9.0 \times 6.3$ cm. It has the typical appearance of lunar meteorites, with white to gray clasts set in a light gray more comminuted matrix (Fig. 2). It is characterized by the presence of numerous impact melt veins and deep narrow cavities. Impact melts characterized by a compact gray glassy appearance without clasts are seen on the surface. A part of the fusion crust, with a smooth curved surface, is visible on the surface together with a number of large white clasts.

The Y-86032 is a feldspathic lunar highland breccia, consisting of lithic and mineral clasts set in a fine-grained matrix of comminuted minerals (Fig. 2). It shows some characteristics of regolith breccias from the lunar highlands, but also resembles feldspathic fragmental breccias (MCKAY *et al.*, 1986). The abundance of regolith components such as glass spherules and agglutinates is less than in ALHA81005 and Y-791197. It may be a very immature regolith breccia or a part of a megaregolith.

Glassy materials are present in vitric clasts, as matrix and as veins. The matrix glasses are penetrated by brown clast-laden glassy veins with flow textures. The most characteristic feature of Y-86032 is a clast-laden impact melt vein penetrating the breccia. The shapes of clasts facing the vein tend to be modified and show smooth, curved surfaces. These features are similar to those of Y-82192/193. The glass matrix may be devitrified crystalline on a micron scale.

The mineral fragments consist of plagioclase, pyroxene, and olivine. Mafic silicates are more abundant than in Y-791197 (OSTERTAG *et al.*, 1986). Lithic clasts include many impact melt clasts, light feldspathic clasts, and granulitic breccias consisting of plagioclase, olivine, and pyroxene. Granulitic clasts and clast-laden vitric (devitrified) breccias are dominant.

Microprobe analyses show that feldspar ranges from $An_{90.4}$ to $An_{97.4}$, with a strong mode at approximately An_{97}. Pyroxene and olivine are variable in composition, pyroxene with $En_{18.6}$ to $En_{80.4}$, $Fs_{8.4}$ to $Fs_{48.6}$, $Wo_{2.6}$ to $Wo_{40.5}$, and olivine with $Fo_{16.5}$ to $Fo_{97.4}$, and a strong mode at Fo_{19} to Fo_{21}. The MnO contents of the both pyroxene and olivine are lower than those of all achondrites, but are comparable to those of lunar rocks.

2.8. *Elephant Moraine (EET) 87521*

The EET87521 is a basaltic breccia and is the first lunar meteorite composed of predominantly mare material. EET87521 was collected from Elephant Moraine, Victoria Land by the U. S. party during the 1987–1988 field season. This specimen weighs 30.7 g and measures 3.7×2.5×2 cm. A microscopic description of the specimen given by SCHWARZ and LINDSTROM (1990) is as follows: "About 30% of this smooth, rounded specimen is covered with black to brown shiny fusion crust. The interior of this coherent breccia is dark and fine-grained and contains numerous small white and yellow inclusions. Two 2–3 mm clasts are visible on the surface: one is a white clast consisting of plagioclase with 10–15% yellow and black mafic minerals; the other is a buff-colored clast made up of plagioclase and 35–50% yellow and black mafic minerals."

The petrography of the EET87521 was described by DELANEY (1989), and WARREN and KALLEMEYN (1989). DELANEY and WARREN (1990) described it briefly as follows: "EET87521 was originally classified as a eucrite. However, more detailed investigations indicate that it is a very-low-titanium (VLT) basaltic breccia of lunar derivation. The modal mineralogy is 5 to 10% olivine, 45 to 50% pyroxene, 35 to 40% plagioclase and 1 to 2% ilmenite, chromite, ulvöspinel/magnetite, sulfide, silica minerals, and FeNi-metal. The matrix of the meteorite also contains several percent of glass similar in composition to the bulk meteorite (Fig. 2). The olivine ranges in composition from Fo_{65} to Fo_5, a range typical of VLT mare basalts, and shows a strong bimodality with clusters centered at Fo_{57} to Fo_{65} and Fo_5 to Fo_{15}. Intermediate olivine compositions are uncommon. Molar Fe/Mn ratios of the olivine are 90 to 100. The pyroxene is pigeonite/subcalcic augite/augite with a composition range of En_{65} Wo_{5-10} to En_{20} Wo_{15-40}. Most pyroxenes are iron-rich and are comparable to eucrite pyroxenes, but more calcic. The pyroxene does not show the bimodal distribution of the olivine. Pyroxene Fe/Mn ratios are 50 to 75. These ratios are typical of mare basalts, and are much higher than those of basaltic achondrites (30 to 40). The feldspar is mostly An_{93-97}, with a few more sodic grains present. Several clasts within the thin sections have survived, with textures little altered by brecciation. These clasts tend to be relatively coarse-grained, by mare basalt standards. EET87521 contains a small (1 mm) clast of what is probably a highlands impact melt breccia. This extremely fine-grained clast contains at least 70% plagioclase. It also contains the only observed grains of FeNi-metal, with composition (average 94.1% Fe, 4.53% Ni, 0.37% Co) typical of metals derived as 'contamination' from metal-rich meteorites."

CLAYTON (1990) reported the oxygen isotopic composition of the meteorite that it is $\delta^{18}O=+5.39$ $\delta^{17}O=+2.79$. These analyses are comparable to those of previously analyzed lunar meteorites and Apollo lunar samples and distinct from those of eucrites.

2.9. *Asuka-31 (tentative name)*

The Asuka-31 was collected December 20, 1989, from the Nansen Ice Field near Asuka Station (the third Japanese Base), Sør Rondane Mountains, East Antarctica by the most recent Japanese party. It was recognized as an unusual specimen among over 2000 meteorites collected, and identified as the first sample of unbrecciated igneous rock with gabbroic texture, which came from the Moon. The specimen was tentatively named Asuka-31. It will be named officially Asuka-881xxx in the near futuie, because the naming of the Japanese collections has been carried out systematically in the order of date of find, and the Asuka-87 and -88 collections have not yet been completed. Asuka-31 weighs 442.12 g and measures $8.0 \times 8.0 \times 5.8$ cm.

Asuka-31 is nearly half of a whole original stone and has a broken surface without fusion crust and other half has a very smooth rounded surface covered by a shiny-black fusion crust. It has a coarse-grained, unbrecciated interior composed of pale flesh-colored to brown pyroxene and translucent plagioclase with some black ilmenite. The stone has the appearance of very coarse-grained cumulate eucrites and ureilites in the field.

Examination of thin sections shows that Asuka-31 is a coarse-grained and unbrecciated rock, consisting mainly of pyroxene and plagioclase (completely maskelynitized) with ilmenite and troilite, and traces of olivine, apatite, silica phase (quartz?) and nickel-iron (Fig. 2). Asuka-31 has a typically subhedral granular texture, consisting of chains of pyroxene and isolated plagioclase crystals, ranging 2 to 4 mm, and 1 to 3 mm, respectively. The mode is roughly 59% pyroxene, 30% plagioclase, 6% ilmenite and 5% others phases, including troilite and symplectite around opaque minerals.

Pyroxene is the dominant mineral. It occurs in transparent and almost colorless, apparently twinned, subhedral grains showing slight cracks and wavy extinction due to shock effects. The composition of the pyroxene is remarkably heterogeneous, ranging from $En_{7.8}$ to $En_{43.6}$, $Fs_{30.7}$ to $Fs_{68.2}$, $Wo_{11.6}$ to $Wo_{40.9}$. Some pyroxene grains show weak chemical zoning with Mg-rich core and Ca-rich rims, and others show Fe-rich core, Mg- and Ca-rich rims, although there do not seem to be any systematic trends in their zoning of individual crystals. Typical pyroxene analyses are presented in Table 1. The pyroxenes of Asuka-31 have an average FeO/MnO=61, within the range of average lunar pyroxenes and clearly different from pyroxenes of basaltic achondrites.

Olivine is not a major mineral, and it was only found as tiny grains in symplectites. The olivine is Fe-rich, ranging from $Fa_{86.6}$ to $Fa_{94.6}$. Most olivines are very fine-grained crystals in contact with opaque minerals or rimmed by symplectites, in which olivines formed around opaque minerals.

Plagioclase is completely maskelynitized and occurs as isolated grains in chains of pyroxene crystals. Twinning and zoning are not observable under the microscope, but relatively clear compositional zoning of Ca-rich core, and Na- and K-rich rims are recognized by electron microprobe. Plagioclase in Asuka-31 has a substantial range from An_{74} to An_{96}, with a strong mode at approximately An_{90} to An_{95}. Only a few among several dozen plagioclases analyzed are as sodic as $An_{74}Ab_{23}Or_{3.4}$.

Several grains of ilmenite with chromian ulvöspinel were found as one of several minor minerals in each of the thin sections. Ilmenite grains are subhedral, isolated from each other, and relatively coarse-grained, ranging from 2 to 3 mm. Most

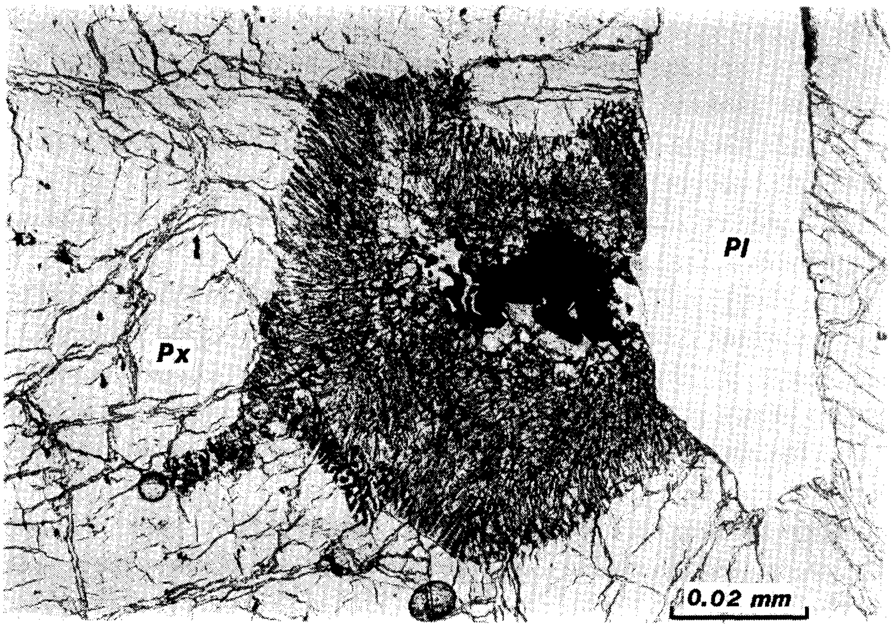

Fig. 4. Photomicrograph of symplectite in Asuka-31. Troilite (black) rimmed by olivine is surrounded by symplectite halo. Symplectite shows the worm-like texture composed mainly of an olivine-pyroxene-plagioclase intergrowth. Pl (plagioclase: anorthite), Px (pyroxene).

ilmenites are surrounded by symplectite. Troilite is fine-grained (10 to 30 microns), and there are two different occurrences; one as isolated grains mostly rimmed by symplectite, and the other as sporadic very tiny grains in most of the symplectites.

Symplectite surrounds the opaque minerals (ilmenite and troilite) as halos (Fig. 4), and consists mainly of very fine-grained olivine, pyroxene, apatite, plagioclase (anorthite), Fe-Ni metal (?) and silica phase (quartz?). The worm-like texture is composed mainly of an olivine-pyroxene-plagioclase intergrowth. Symplectite is one of the most characteristic features of the Asuka-31 gabbroic meteorite.

2.10. *MacAlpine Hills (MAC) 88104/105*

MAC88104 and MAC88105 were found in the moraine at the MacAlpine Hills, Transantarctic Mountains, nearly 85° south, by the U. S. party in the recent field season of 1988–1989. The small specimen weighs 61.2 g, and measures 4×4.5×2.5 cm. The large specimen weighs 662.5 g, and measures 11×7.5×6.5 cm. MAC88105 is the largest lunar meteorite ever recovered. MAC88104 and MAC88105 are identified from the preliminary work as anorthositic microbreccias with glass matrices.

The macroscopic description by SCORE (1989) is as follows: "MAC88104 and MAC88105 are paired fragments of a polymict breccia. Both specimens have thin gray-green fusion crust which covers approximately 30% of the exterior surface. Other parts of the exterior surface are dark gray and weathered, with numerous clasts and vugs where clasts have been plucked out by weathering. A minute amount of evaporite minerals is evident in the minor cracks in the fusion crust. The interior is blue gray and mostly fine-grained, but glassy in some areas. Veins of dark vesicular glass surround some clasts, but do not transect any clasts. The meteorite contains abundant angular feldspathic clasts and fine-grained gray, black and beige clasts. The largest clast exposed (1.5×1 cm) is fine-grained and anorthositic, with scattered mafic minerals. Other clasts are medium-grained and more mafic."

The petrographic descriptions were carried out by MASON (1989) and DELANEY (1990). DELANEY (1990) described as follows: "The MAC88105 meteorite is an anorthositic microbreccia dominated by plagioclase with very fine-grained olivine, pyroxene, ilmenite, Ti-chromite and sulfide (Fig. 2). Grain size in this section is generally 5 to 50 μm and the section shows few petrographically distinctive features other than fine-grained breccia clasts in fine-grained breccia. The silicates have Fe/(Fe+Mg) ratios ranging from 0.05 to 0.95 with most silicates having Fe/(Fe+Mg) between 0.3 and 0.45. On the basis of linescans across the section MAC88105 has a mode of at least 95% plagioclase or plagioclase rich glass and a few % each of olivine and pyroxene. Other phases include a variety of spinel phases (30 to 55% Al_2O_3), ilmenite, sulfide and metal.

Olivine occurs as both mineral clasts in the breccia and as grains in very fine-grained impact melted clasts. The range of composition is from Fo_{95} to Fo_{45} (Fig. 2). With the exception of a few Mg-rich grains in the breccia, almost all the olivine is more Fe-rich than Fo_{76}. Fe/Mn in the olivine is fairly uniform (85 to 105), with a slight increase as a function of Fe/(Fe+Mg). Pyroxene is also present in both lithic and mineral clasts and is more Fe-rich than the olivine. While most pyroxenes have compositions between En_{78} and En_{40} and Wo contents ranging up to Wo_{40}, a few very Fe-rich 'pyroxenes' are present extending the range to En_5Wo_{25}. The most Fe-rich material appear, however, to be present as small fine-grained lithic clasts, possibly of mare origin. No very Mg-rich pyroxene has yet been found and the majority of the pyroxene has a comparable range of Fe/(Fe+Mg) to the olivine. Most of the pyroxenes analyzed appear to be pigeonitic, although some augite is present. The feldspar is very calcic, with most analyses falling between An_{95} and An_{99}. Feldspar clasts are the only grains larger than about 100 μm.

The lithic fragments are almost invariably breccia clasts or impact melts and provide little evidence of their original petrogenesis. However, the very wide range of Fe/(Fe+Mg) ratios in the mafics suggests that MAC88105 is polymict and may contain a small mare component, in addition to the dominant anorthosite$\pm$gabbroic anorthosite."

3. Mineral Compositions of the Lunar Meteorites

Compositions of pyroxene, olivine and plagioclase are determined in 10 of the 11 lunar meteorites, using the electron microprobe analyzer (EPMA) at NIPR. The results are shown in Figs. 5a and b.

3.1. Pyroxene

There are at least three compositional varieties of pyroxenes (Fig. 5); the dominant variety is Mg-rich pyroxene; the other variety is characterized by a wide range of Mg-Fe pyroxene, and another is Mg-poor, Fe-rich pyroxene. Y-791197, ALHA81005,

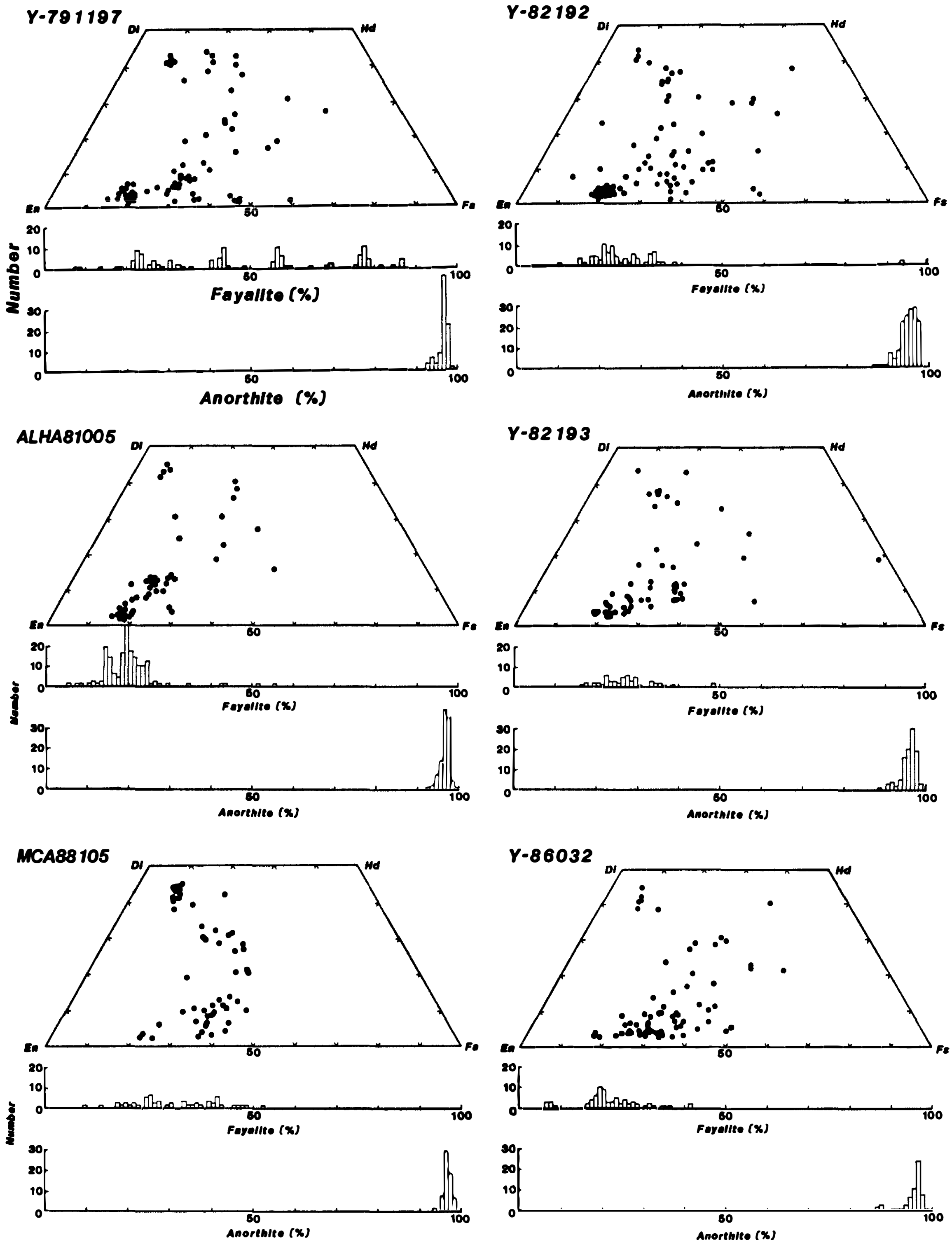

Fig. 5a.

Figs. 5a, b. Plots of the mineral compositions of each of the lunar meteorite. Top: Pyroxene compositions on the pyroxene quadrilateral. Middle: Histograms of olivine compositions. Bottom: Histograms of plagioclase compositions.

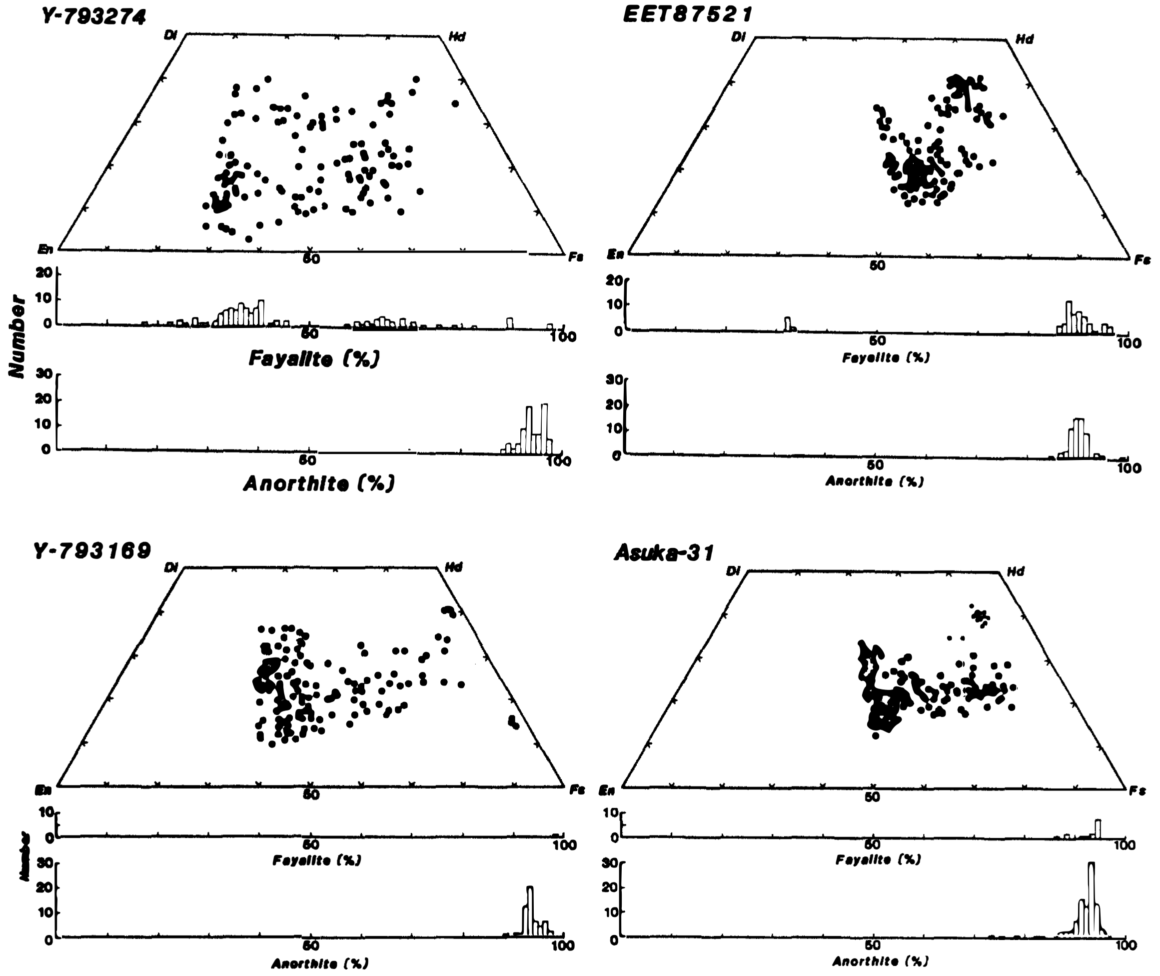

Fig. 5b.

Y-82192/193, Y-86032 and MAC88105 consist mainly of Mg-rich orthopyroxenes and clinopyroxenes, with a trace of Fe-rich pyroxenes. Y-793274 has a wide range of pyroxenes. On the other hand, Y-793169, EET87521 and Asuka-31 consist of Mg-poor (under En_{55}), Fe-rich pyroxenes with very high iron pyroxenes, and with only minor or no orthopyroxenes.

3.2. Olivine

All lunar meteorites contain olivine of variable abundance and composition (Fig. 5). Y-791197 and Y-793274 have olivines of a wide range of composition from forsterite to fayalite. ALHA81005, Y-82192/193, Y-86032 and MAC88105 have mostly Mg-rich olivines with Fo_{50}. However ALHA81005 and MAC88105 have less of the Fe-rich olivines with Fo_{50}. Y-793169 and Asuka-31 contain rare olivine grains with very high iron contents. One trace of olivine in Y-793169 is remarkably high in iron content of $Fa_{93.5}$ and, in Asuka-31, olivines have very high iron contents of over Fa_{85}, with a strong mode at approximately Fa_{94}. EET87521 also contains high iron olivines, ranging from Fa_{86} to Fa_{97}, but there are also Mg-rich olivines around Fo_{67} Fa_{33} as shown in Fig. 4. The differences in composition probably correspond to their sources with high-iron olivines derived from the lunar maria and Mg-rich olivines from the lunar highlands.

3.3. Plagioclase

Feldspar is one of the main constituent minerals in all lunar meteorites, and most feldspars are Ca-rich (anorthite) with values larger than An_{90}, except for EET-87521, which has minor amount of more sodic plagioclase. Plagioclase of EET87521 ranges from An_{67} to An_{99}, with a strong mode at approximately An_{88} to An_{92}. Most plagioclases have been partly to wholly maskelynitized, that is transformed to a glass by the high pressures generated in the intense bombardment of the early Moon's surface. Asuka-31 has been subjected to intense shock pressure, as its plagioclase is completely maskelynitized.

4. Bulk Compositions

The major element compositions of the seven lunar meteorites in the Japanese collections were determined by standard wet chemical analysis. The data are presented in Table 2, with those of other lunar meteorites and lunar samples (PAPIKE *et al.*, 1976; TAYLOR, 1982; PALME *et al.*, 1983).

Lunar meteorites may be divided into three groups on the basis of their bulk compositions. Y-791197, ALHA81005, Y-82192/193 and MAC88105 are high aluminum and high calcium rocks with abundant Ca-rich plagioclase (anorthite), and distinctly low in FeO+MgO, ranging from 9 to 13%. Therefore, they are lunar highland rocks. Y-793169, EET87521 and Asuka-31 have higher iron contents and

Table 2. Major element chemical analyses of the lunar meteorites

	Highland[1]	Y-791197	ALHA81005[2]	Y-82192	Y-82193	Y-86032
SiO_2	45	43.14	46.46	43.05	44.34	43.64
TiO_2	0.56	0.35	0.23	0.22	0.24	0.03
Al_2O_3	24.6	26.01	25.32	27.78	28.35	29.08
Fe_2O_3	—	0.04	—	1.47	0.37	0.05
FeO	6.6	7.02	5.40	3.69	4.96	5.03
MnO	—	0.08	0.08	0.08	0.04	0.03
MgO	6.8	6.22	7.92	5.64	5.26	5.03
CaO	15.8	15.33	15.11	16.28	15.76	16.63
Na_2O	0.45	0.33	0.31	0.45	0.44	0.44
K_2O	0.075	0.02	0.03	0.02	0.05	0.02
H_2O (−)	—	0.48	—	0.63	0.05	0.05
H_2O (+)	—	0.10	—	0.10	0.1	0.1
P_2O_5	—	0.31	—	0.15	0.09	0.06
Cr_2O_3	0.10	0.13	0.12	0.10	0.06	0.09
S	—	0.41	—	0.19	—	—
Total	99.98	99.97	100.98	99.85	100.11	100.28
FeO+MgO	13.4	13.24	13.32	9.33	10.22	10.06

Analyst: H. HARAMURA. [1]TAYLOR (1982), [2]PALME *et al.* (1983), [3]MASON (1989), [4]WARREN and lower calcium contents than the other lunar rocks. Their compositions are similar to those of lunar mare basalts, especially low-titanium and very low-titanium (VLT) lunar mare basalts. Y-793274 is intermediate in composition between the above two groups.

5. Discussion and Conclusion

The question of individual or paired lunar meteorites is discussed below, based on their lithologies, compositions and localities. Y-82192/193 and Y-86032 were collected in close proximity on the bare ice field in the Yamato Mountains (KATSUSHIMA *et al.*, 1984; NISHIO *et al.*, 1987). These authors identified these rocks as anorthositic fragmental breccias. They are very similar to each other in lithology, texture, mineral assemblages, mineral and bulk compositions, and terrestrial ages. Therefore, Y-82192/193 and Y-86032 probably paired and fell as a shower. MAC-88104/105 are anorthositic microbreccias and were paired, judging from their identical lithologies with glassy matrices and the close proximity of their find site (SCORE, 1989; MASON, 1989).

Y-791197 and ALHA81005 are similar in lithologies and were identified as anorthositic regolith breccias, with abundant Ca-rich plagioclase (anorthite) clasts and abundant Ca-rich plagioclase (anorthite) clasts. However, olivine compositions in Y-791197 widely range ($Fo_{92.1}$ to $Fo_{13.3}$) in comparison to those of ALHA81005 (Fig. 5). Y-793274 is a breccia with larger white clasts of anorthosite (Fig. 3), but also has abundant lithic clasts and mineral fragments of basaltic composition from the lunar mare. The bulk composition of Y-793274 is similar to that of some mare

compared with those of the Moon rocks, in weight percent.

MAC88105[3] glassy matrix	Y-793274	EET87521[4]	Apollo 17[5] VLT	Luna 24[6] VLT	Y-793169	Asuka-31
45	45.67	48.3	46.7	45.2	43.59	45.36
0.32	0.53	1.13	0.92	0.89	1.52	1.66
28	16.73	12.5	10.0	13.8	12.89	11.49
—	0.48	—	—	—	0.28	0.60
6.3	13.57	19.2	18.6	20.5	21.17	21.18
0.11	0.09	0.24	0.24	0.27	0.18	0.25
4.7	9.52	6.3	12.2	6.35	5.75	6.41
16	12.28	11.7	10.0	12.7	13.25	11.99
0.36	0.42	0.41	0.12	0.24	0.40	0.50
<0.1	0.08	0.07	—	0.01	0.13	0.04
—	0.05	—	—	—	0.00	0.00
—	0.1	—	—	—	0.18	0.0
—	0.08	—	—	—	0.29	0.05
—	0.15	0.21	0.74	0.19	0.11	0.17
—	—	—	—	—	0.48	0.19
	99.75	100.06	99.52	100.2	100.22	99.89
11.0	23.09	25.5	30.8	26.85	26.92	27.59

KALLEMEYN (1989), [5,6]PAPIKE *et al.* (1976).

basalts. The other three specimens, Y-793169, EET87521 and Asuka-31, are almost uniform in bulk composition (Table 2) which is similar to the low-titanium and VLT lunar mare basalts. However, their compositions are quite distinct from the 7 anorthositic breccias. Y-793169, EET87521 and Asuka-31 appear to be petrographically distinct from each other. EET87521 is a basaltic breccia with highland components, but Y-793169 and Asuka-31 are unbrecciated, coarse-grained igneous rocks with little difference in texture. Y-793169 is an unbrecciated diabase with coarse-grained texture, and Asuka-31 is a very coarse-grained gabbro with completely maskelynitized plagioclase.

Based on their lithology, texture, petrography, chemistry and mineral compositions, the lunar meteorites are divided into 4 or more different types, anorthositic breccias (including 3 to 4 different facies), basaltic-anorthositic breccias, basaltic breccias, unbrecciated diabase and gabbro. These types indicate that the samples may have originated from at least 7 different sites on the near- and far-side sites of the Moon's surface (Table 1). Such varieties of the lunar meteorites strongly suggest that there are unknown rock type (s) on the Moon, and that there are new meteorite types yet to be discovered in Antarctica.

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