LUNAR METEORITE YAMATO-791197: PETROGRAPHY, SHOCK HISTORY AND CHEMICAL COMPOSITION

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Abstract: Antarctic meteorite Yamato-791197 (Y-791197) is a polymict regolith breccia from the lunar highlands. It is composed of feldspathic lithic fragments, glasses and mineral fragments in a densely compacted, fine-grained, partly glassy matrix. Dominant lithologies are granulitic anorthosites, granulitic breccias, recrystallized fragmental breccias, microporphyritic and subophitic crystalline melt breccias, glass beads and irregularly shaped glassy particles. Some glasses are partly or totally devitrified. All mineral clasts are shocked, most plagioclase clasts are recrystallized. The shock effects in mineral and lithic clasts indicate pressures below 25 GPa except for rare maskelynite and the shock-produced glassy particles. There is no indication that the meteorite as a whole has been shocked to more than 20 GPa, consequently the shock pressures during the ejection event were less than 20 GPa. Despite these low shock pressures, the breccia may have formed by shock-lithification caused by the ejection event. Chemical analyses of the bulk sample and of individual components indicate a source area free of KREEP, probably on the lunar farside. Differences in chemical composition (major and minor elements) may exist between the lunar frontside and the lunar farside. The content of Ga and Zn is remarkably high but heterogeneously distributed and may speak in favor of a moon-wide redistribution of volatile elements. The noble gas contents of Y-791197 are typical of lunar regolith and yield an exposure age of 450 Ma. Y-791197 has a higher content in REE and noble gases and is more ferroan than lunar meteorite ALHA81005. Both differ compositionally from other lunar samples and despite their differences may be related to the same impact event.

1. Introduction

Petrographic, chemical, and shock studies of the lunar meteorite Y-791197 address several problems pertinent to the other lunar meteorites, lunar samples in general, and to meteorites from other large bodies of our solar system. One problem is whether the lunar meteorites are pieces of a single fall, and the ejection of material from the lunar surface was a singular event, or if such a process did occur more often even in recent times, *i.e.* within the lifetime of the glaciers in Antarctica where all lunar meteorites have been found. Petrographic analyses of the mineral and lithic clast content and the investigation of textures of breccia clasts provide information for the decision whether the lunar meteorites are genetically related or not. The chemical analyses of the bulk sample and clasts should help to elucidate the nature of the parent body and yield information about the chemical and mineralogical composition of the lunar crust apart from the sites on the lunar front side sampled so far. Noble gas analyses give independent evidence of the nature of the parent body and yield information about the exposure time of the sample on the surface of its parent body. The lunar meteorites may thus hold additional clues to deciphering the early history of the moon.

The study of lunar meteorites also has obvious consequences for meteorites from other large bodies of our solar system, especially the SNC-meteorites which have been assigned to be of Martian origin (*e.g.* WOOD and ASHWAL, 1981). One major argument against a possible Martian origin of the SNC-meteorites was the lack of lunar meteorites. This problem has now been overcome by the discovery of two lunar meteorites (ALHA81005, Y-791197) and two likely candidates (Y-82192 and Y-82193) (SCORE and MASON, 1982; YANAI and KOJIMA, 1984; YANAI *et al.*, 1984). The remaining problem, however, relates to the ejection mechanism of samples from large planetary bodies. Shock studies are able to reveal the maximum shock pressure experienced by the sample during the acceleration from the surface of its parent body and therefore yield boundary conditions for dynamical models and calculations applied to explain the ejection mechanism.

We made a combined effort to analyze the petrography, the shock history, and the chemical composition of Y-791197 in order to obtain comprehensive information about this sample, its provenance and its history. We compared the results with those obtained from the study of the lunar meteorite ALHA81005 and our studies of Apollo 16 lunar highland samples.

2. Experimental Techniques and Samples

We had polished thin section Y-791197,73-2 and a 202 mg chip (Y-791197,87) available for our petrographic and chemical analyses. Another polished thin section (Y-791197,73-1) was kindly provided by Dr. Y. IKEDA (Mainz) for control studies. Microchemical analyses of lithic clasts, glass beads and the fusion crust were made with an ARL SEMQ-51 electron microprobe equipped with wave-length dispersive spectrometers (20 nA sample current, 15 kV accelerating voltage). The analyses were made with defocused beam (20 to 60 μm beam diameter) to prevent alkali loss. Standard procedures were employed for correction (BENCE and ALBEE, 1968).

Chip Y-791197,87 was heterogeneous, containing a large, light-colored anorthositic clast and a glass-rich matrix portion connected by a glass vein. Three subsamples were prepared for neutron activation analyses: YMF, consisting exclusively of the light clast; YMG, the glass-rich matrix portion; and YMB, the central part of the chip consisting of parts of the clast, the matrix and the glass vein. The last subsample was considered the best candidate for the bulk analysis. The samples were analyzed by INAA-techniques (WÄNKE *et al.*, 1977) in the same way as the ALHA81005 lunar meteorite, except that the Si content was not determined. The P content was again obtained by instrumental β-counting. Appropriate corrections for self-absorption were applied (WECKWERTH, 1985). Some of the elements (indicated by an asterisk in Table 3) were determined with lower accuracy because of small sample sizes.

A glass-rich subsample (4.31 mg) was used to determine the concentrations and isotopic compositions of He, Ne, and Ar as well as the concentration of ^{84}Kr and ^{132}Xe. Experimental procedures have been described by WEBER *et al.* (1983).

3. Results

3.1. Petrography

Y-791197 is a polymict breccia consisting of a variety of lithic and mineral clasts in a fine-grained, partly glassy matrix. Figure 1 is a sketch map of thin section Y-791197,73-2 displaying the distribution of major clast units larger than 0.1 mm except the mineral clasts. The most frequent lithic clasts are recrystallized feldspathic lithologies, fragments of crystalline impact melt breccias of variable textures, polymict breccia clasts, rare fragments of igneous lithologies, glass beads, and irregularly shaped glassy or devitrified particles. Plagioclase clasts are more frequent than pyroxene and olivine. Most pyroxenes are clinopyroxenes, coarsely exsolved inverted pigeonites are rare. The mineral clasts are angular to subrounded and show shock effects indicative of various peak pressures. The plagioclase clasts are recrystallized.

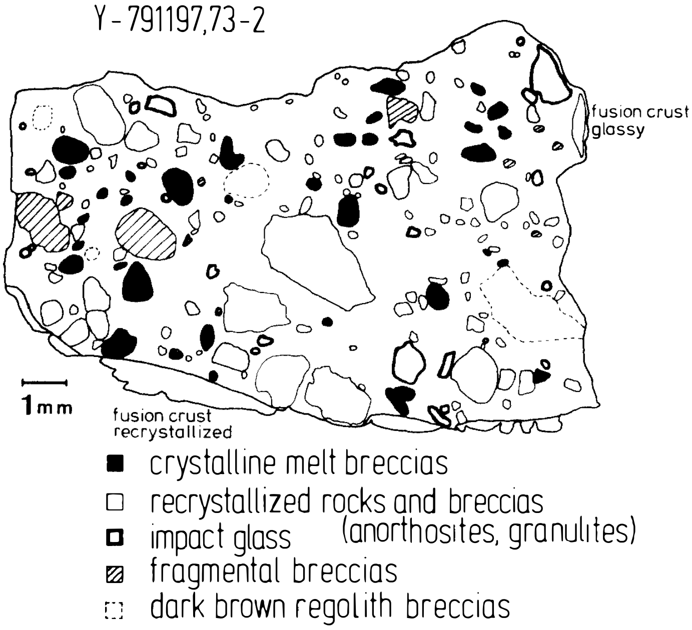

Fig. 1. Sketch map of thin section Y-791197,73-2 showing the distribution of major groups of lithic clasts and glasses >0.1 mm.

The matrix consists of densely compacted plagioclase clasts with subordinate pyroxene and olivine, pink spinel occurs as trace. Opaque minerals are rare, ilmenite and FeNi-particles dominate. The matrix minerals are connected by variable amounts of vesiculated intergranular melt which may be glassy or very finely crystallized. The amount of melt determines the color of the matrix which continuously or discontinuously changes from melt-poor light brown into melt-rich dark brown. Dark brown melt-rich matrix areas with distinct boundaries are interpreted as inclusions of older regolith breccias. A 2-mm sized inclusion in the matrix contrasts to its surroundings by its incompletely preserved smoothly curved glassy outlines and some spherulitically

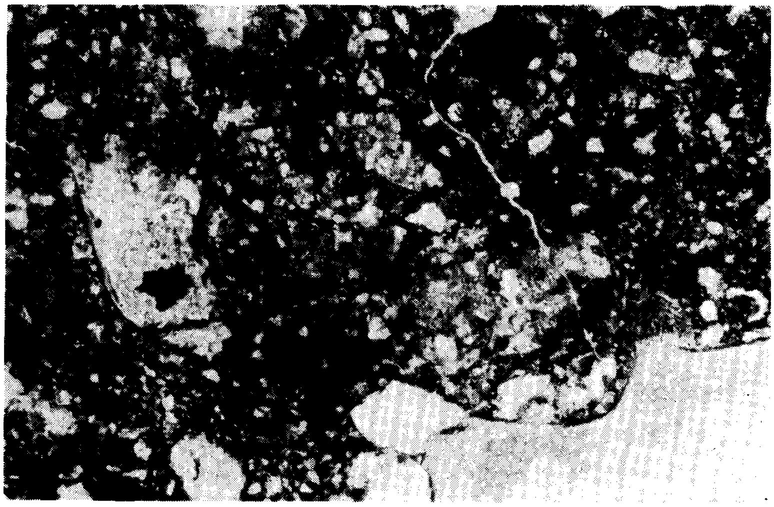

Fig. 2. Agglutinate with partly preserved smooth outlines in thin section Y-791197,73-2, field width 2.2 mm, one polarizer.

crystallized dark brown veins cutting through it. This inclusion strongly resembles a partly destroyed agglutinate (Fig. 2). A macroscopic inspection of chip Y-791197,87 revealed the existence of glass veins independent of inclusions. The feldspathic nature of matrix and clasts, the textures and variety of clasts, and the texture of the matrix are typical of a lunar highland regolith breccia but are distinctly different from any other achondrites. The petrography of Y-791197 strongly resembles lunar meteorite ALHA-81005, but in contrast to thin section ALHA81005,8 brown swirly glassy blebs are missing and the overall glass content is lower in Y-791197,73-2.

In thin sections Y-791197,73-1 and 73-2 the meteorite is partly covered by a highly vesicular fusion crust which is zoned in terms of color, devitrification features, and size of vesicles. The thickness of the fusion crust is variable, anorthositic clasts are only covered by a thin veneer of light yellow fusion crust, whereas the fusion crust adjacent to the breccia matrix is zoned and up to 0.7 mm thick. Undigested or only partly digested mineral and lithic clasts are common. The outer part of the fusion crust is light yellow and displays a variolitic to subophitic crystallization texture of lathy plagioclase with interstitial pyroxene. This recrystallization of a fusion crust is unusual and may be attributed to the feldspathic nature of the meteorite, although the fusion crust of lunar meteorite ALHA81005 which is of similar bulk composition did not recrystallize (OSTERTAG and RYDER, 1983). However, at a different side of the meteorite in thin section 73-2 there is a second type of fusion crust which is zoned as well but is not recrystallized. The central part of the fusion crust is dominated by large vesicles in a dark brown glassy material. The interface between fusion crust and meteorite matrix is characterized by a light brown vesicular layer which is followed by a zone of enrichment of tiny opaques and small vesicles. Beneath this layer the matrix appears to be annealed.

3.2. Petrography of clasts and clast population studies

Thin section Y-791197,73-2 contains about 32 vol% mineral and lithic clasts larger than 0.1 mm. A total of 195 lithic and 50 mineral clasts larger than 0.1 mm were mapped and classified according to the classification scheme for lunar highland rocks and breccias (STÖFFLER *et al.*, 1980). Maximum clast sizes are 3 mm for a recrystallized polymict feldspathic fragmental breccia, 0.8 mm for anorthite, and 0.3 mm for mafic minerals.

The results of the clast population study are given in Fig. 3 and in Table 1. Figure 3 displays the frequency distribution of lithic clasts in Y-791197 in comparison to ALHA81005 (BISCHOFF and STÖFFLER, 1984). The recrystallized lithologies amount to more than half of all clasts measured in accordance with the data obtained from the ALHA81005 clast population studies (BISCHOFF and STÖFFLER, 1984). Recrystallized lithologies and polymict fragmental breccias are slightly more abundant in Y-791197 than in ALHA81005 while crystalline melt breccias and glasses occur more frequently in ALHA81005. In Y-791197 feldspathic crystalline melt breccias are more abundant than mafic crystalline melt breccias in contrast to ALHA81005 where the mafic crystalline melt breccias dominate (Table 1).

Granulitic breccias (Fig. 4a) are characterized by a matrix consisting of granoblastic plagioclase occasionally with triple junctions, and tiny isometric or stubby mafic min-

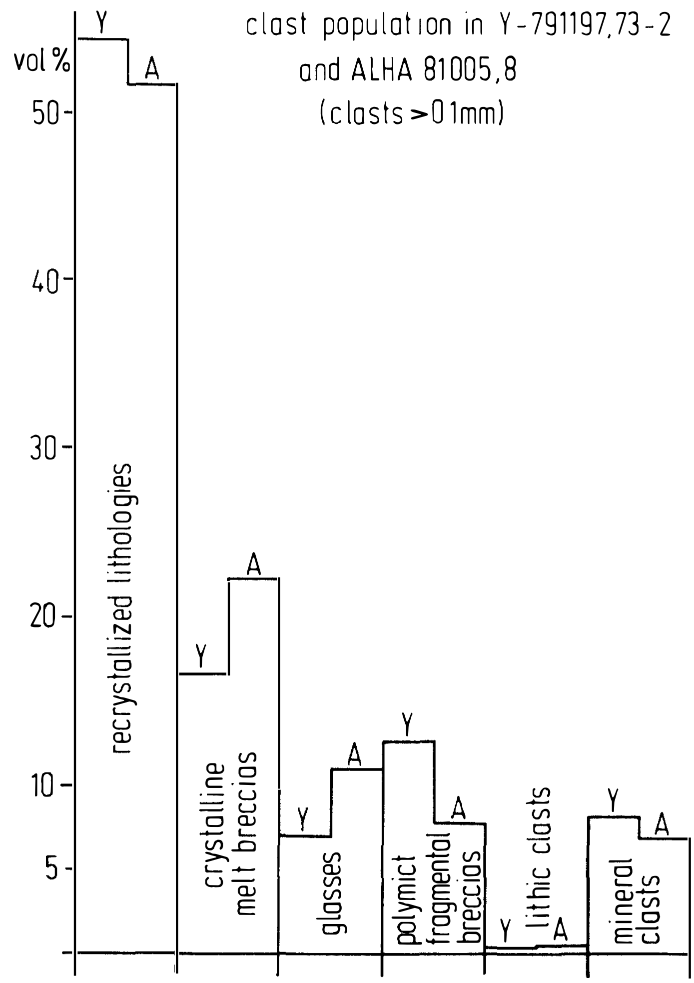

Fig. 3. Frequency distribution of clasts >0.1 mm in Y-791197,73-2 compared to ALHA81005,8 (BISCHOFF and STÖFFLER, 1984).

Table 1. Clast population in lunar meteorites Y-791197,73-2 and ALHA81005,8 (vol % of clasts >0.1 mm), cf. BISCHOFF *and* STÖFFLER *(1984).*

Clast type	Y-791197,73-2	ALHA81005,8
Recrystallized lithologies		
Granulitic breccias	10.4	20.1
Granulitic anorthosites	6.1	13.1
Recrystallized cataclastic anorthosites (intragranular)	13.7	17.6
Recrystallized polymict fragmental breccia (mafic-rich)	12.8	0
Recrystallized light-colored feldspathic fragmental breccia	12.4	0
Mafic granulite	0	0.9
Crystalline melt breccias		
Feldspathic fine-grained intergranular to microporphyritic	12.9	6.5
Feldspathic subophitic to microporphyritic	1.0	0
Fine-grained subophitic	1.1	12.2
Subophitic noritic-anorthositic (mafic)	1.6	0
Other mafic melt breccias	0	3.5
Vitric or devitrified glasses		
Glass beads	0.3	0.4
Glasses of irregular shape	0.4	1.5
Partly or completely devitrified glasses	6.3	9.1
Fragmental breccias		
Polymict fragmental breccias	12.6	7.4
Feldspathic fragmental breccias	0	0.3
Lithic fragments		
Lithic fragments	0.4	0.5
Mineral fragments		
Plagioclase (incl. recrystallized plagioclase)	6.8	5.6
Mafic minerals	1.3	1.3
Total	100.1	100.0

erals. Plagioclase fragments and mafic mineral clasts are embedded in the matrix. All plagioclase mineral clasts in the granulitic breccias have been shocked and recrystallized. The mafic mineral contents and their grain sizes in the granulitic breccia matrix vary. Ilmenite is rare and occasionally grows in a skeletal shape. Recrystallized cataclastic anorthosites (Fig. 4b) are up to 1.6 mm across showing intergranular and intragranular recrystallization textures. Another variety of a recrystallized lithology is represented by fine-grained feldspathic polymict breccia clasts (Fig. 4c) with intergranular crystallization textures.

The population of impact melt breccias in Y-791197 can be grouped into several textural varieties. The dominant variety is a light brown or yellowish finely grained feldspathic melt breccia with abundant plagioclase fragments (Fig. 4d), rare mafic mineral clasts, devoid of opaque mineral phases. Some of the plagioclase clasts show evidence of strong shock and recrystallization. The rare mafic mineral fragments are angular and display minor shock effects. The matrix of this crystalline melt breccia is fine-grained intergranular to microporphyritic, consisting of feldspar laths and minor amounts of pyroxene. This type can be classified as a clast-rich feldspathic microporphyritic melt breccia. A second variety is a fine-grained subophitic crystalline melt breccia (Fig. 4e) consisting of lathy plagioclase and interstitial pyroxene. Some

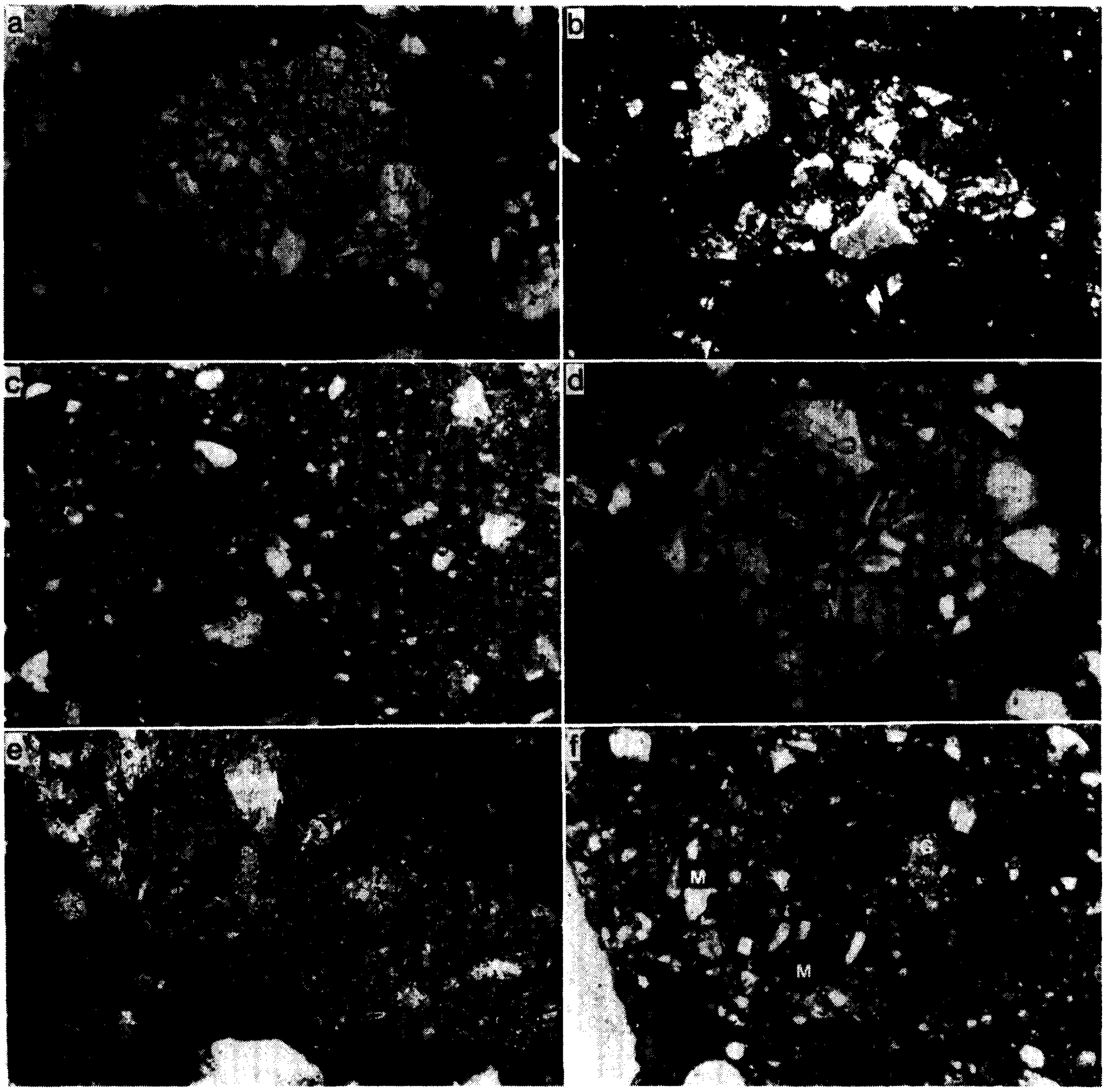

Fig. 4. Micrographs of prominent lithic clasts in Y-791197,73-2; a) granulitic breccia with mineral fragments, one polarizer, field width 2.2 mm; b) recrystallized anorthositic breccia, crossed polarizers, field width 2.2 mm; c) recrystallized feldspathic polymict breccia clast, one polarizer, field width 2.2 mm; d) feldspathic fine-grained microporphyritic melt breccia, one polarizer, field width 1.1 mm; e) fine-grained subophitic crystalline melt breccia, one polarizer, field width 1.1 mm; f) polymict fragmental breccia clast consisting of mineral fragments, impact melt breccia clasts (M), and a granulitic breccia clast (G) in a clastic matrix, one polarizer, field width 1.1 mm.

rare examples of micropoikilitic crystalline melt breccias with intergrowth of clinopyroxene and plagioclase were observed. Dark brown mafic-rich breccias with a very fine-grained matrix were interpreted as fragments of older regolith breccias due to their glass content.

A polymict fragmental breccia (Fig. 4f) consists of feldspathic lithologies such as anorthosite clasts, granulites, and impact melt clasts in a clastic matrix. This polymict fragmental breccia clast in Y-791197 shows the well-known breccia-in-breccia texture of impact formations. The granulitic breccia clast is enclosed in a polymict fragmental breccia which itself is part of a regolith breccia. Glassy inclusions in Y-791197 occur either as beads or as irregularly shaped bodies. Both varieties display a range of crystallization features from completely glassy to totally crystallized in a variolitic to subophitic texture with plagioclase laths and interstitial pyroxene.

Fragments of igneous rocks are rare in thin section Y-791197,73-2, only three small pieces of a mafic-rich anorthositic lithology amounting to 0.4 vol% of all clasts have been found. These consist of variable amounts of clinopyroxene, anorthite, and minor ilmenite and may be classified as gabbroic anorthosites or anorthositic gabbros depending on their pyroxene content. Due to the small size of the clasts (<0.2 mm) an unambiguous classification was not possible. Two clasts resemble a mare basalt. Mare basalt clasts in Y-791197 were described by LINDSTROM et al. (1985).

3.3. *Chemical composition of melt breccias and glasses*

The crystalline melt breccias in Y-791197 are highly feldspathic (Table 2), all microporphyritic melt breccias have an Al_2O_3 content higher than 27 wt%. The subophitic crystalline melt breccia is slightly less aluminous. The analyses for the devitrified and the vitric fusion crust differ in their Al_2O_3 content but are intermediate between the dark brown regolith breccias and the feldspathic microporphyritic melt breccias. The mg' value ($mg' = 100 \times [MgO]/([MgO]+[FeO])$) for the melt breccias and the fusion crust ranges between 58 and 62, only the subophitic melt breccia is slightly higher. The data points for the melt breccias and the fusion crust form a straight mixing line between an anorthite and a pyroxene endmember (Fig. 5). CIPW norm calculations of these impact melt breccias yielded less than 8 wt% olivine.

Most of the glass beads are richer in MgO than the melt breccias, their normative olivine content is between 13 and 20 wt%, and their mg' values are between 64 and 82,

Table 2. Chemical composition of fusion crust, glass beads, and impact melt clasts in Y-791197,73-2 (microprobe analyses).

Oxide (wt %)	Fusion crust recrystal-lized	σ	Glass beads glassy	σ	c	σ	d	σ	e	σ	f	σ	g	σ
SiO_2	43.4	0.45	44.8	0.46	41.1	0.43	39.8	0.42	41.0	0.43	44.7	0.46	40.3	0.43
Al_2O_3	27.2	0.44	23.9	0.40	29.8	0.47	28.1	0.45	30.7	0.49	25.1	0.41	31.9	0.50
CaO	15.8	0.29	15.1	0.28	17.0	0.30	16.7	0.30	17.0	0.30	14.5	0.27	18.0	0.32
MgO	4.8	0.14	5.6	0.15	6.4	0.16	6.4	0.16	5.7	0.15	5.8	0.15	5.2	0.15
FeO	5.7	0.15	6.5	0.15	6.2	0.15	6.3	0.15	2.25	0.09	6.5	0.16	4.3	0.13
MnO	0.08	0.02	0.11	0.02	0.07	0.02	0.08	0.02	0.01	0.01	0.08	0.02	0.03	0.01
K_2O	0.06	0.01	0.06	0.01	0		0.03	0.01	0.03	0.01	0.02	0.01	0	
Na_2O	0.28	0.05	0.26	0.05	0		0		0.07	0.03	0.11	0.03	0	
TiO_2	0.29	0.05	0.29	0.05	0.36	0.06	0.30	0.06	0.16	0.04	0.23	0.05	0.23	0.05
Cr_2O_3	0.07	0.02	0.10	0.02	0.10	0.02	0.14	0.03	0.10	0.02	0.14	0.03	0.09	0.02
P_2O_5	0.06	0.04	0.06	0.04	0.09	0.04	0.11	0.04	0.03	0.03	0		0.19	0.06
Total	97.6		96.78		101.12		97.96		97.05		97.18		100.24	
N	3		3		1		1		3		1		1	
mg'	0.60		0.61		0.65		0.64		0.82		0.61		0.68	

N: number of analyses.

Table 2 (continued).

Oxide (wt %)	Impact melt breccias										Dark regolith breccias			
	subophitic		intergranular to microporphyritic											
	h	σ	a	σ	b	σ	j	σ	l	σ	i	σ	m	σ
SiO_2	44.0	0.45	44.2	0.45	44.5	0.46	43.9	0.45	44.4	0.50	45.3	0.46	44.6	0.46
Al_2O_3	25.7	0.42	27.2	0.44	27.4	0.44	30.3	0.47	29.5	0.50	21.2	0.35	26.8	0.44
CaO	15.6	0.28	15.4	0.28	15.7	0.28	17.1	0.30	16.7	0.30	13.6	0.28	15.9	0.29
MgO	5.5	0.15	5.0	0.14	4.8	0.14	2.42	0.10	3.4	0.12	6.6	0.17	5.1	0.15
FeO	5.6	0.15	5.4	0.15	5.5	0.14	3.1	0.10	4.2	0.10	8.2	0.18	6.1	0.15
MnO	0.09	0.02	0.07	0.02	0.08	0.02	0.05	0.02	0.05	0.02	0.11	0.02	0.09	0.02
K_2O	0.04	0.01	0.04	0.01	0.05	0.01	0.03	0.01	0.03	0.01	0.14	0.02	0.05	0.01
Na_2O	0.30	0.05	0.30	0.05	0.34	0.05	0.34	0.05	0.34	0.05	0.35	0.05	0.26	0.05
TiO_2	0.23	0.05	0.27	0.05	0.29	0.05	0.16	0.05	0.19	0.05	0.29	0.06	0.28	0.05
Cr_2O_3	0.12	0.02	0.13	0.03	0.11	0.02	0.04	0.02	0.07	0.02	0.24	0.04	0.10	0.02
P_2O_5	0.05	0.05	0.04	0.04	0.02	0.02	0.05	0.04	0.05	0.04	0.05	0.04	0.05	0.05
Total	97.23		98.05		98.79		97.49		98.93		96.08		99.33	
N	3		4		5		6		9		5		4	
mg′	0.64		0.62		0.61		0.58		0.59		0.59		0.60	

N: number of analyses.

except for bead "f" which closely represents the average composition of Y-791197. The glass beads were derived from mafic-poor anorthositic source rocks which were slightly more magnesian than the source lithologies of the melt breccias. However, all crystalline melt breccias and the glass beads except glass bead "e" (Table 2) can be assigned to a ferroan source lithology. This is in contrast to the magnesian nature of the majority of glasses in ALHA81005 (Ryder, 1983). Obviously, magnesian lithologies are less

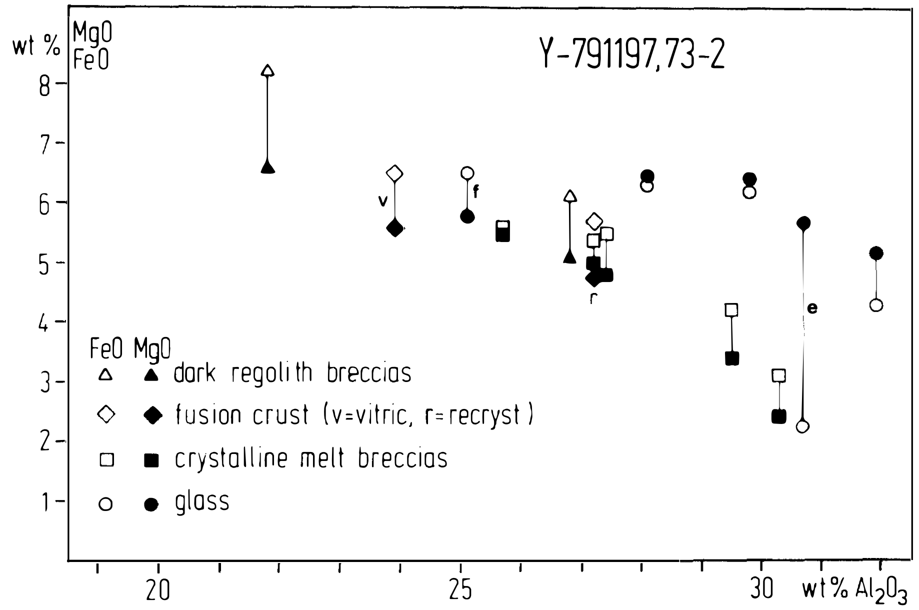

Fig. 5. Chemical composition of crystalline melt breccias, glass beads, dark regolith breccias, and fusion crust of Y-971197,73-2. Note the higher MgO content of glasses as compared to crystalline melt breccias.

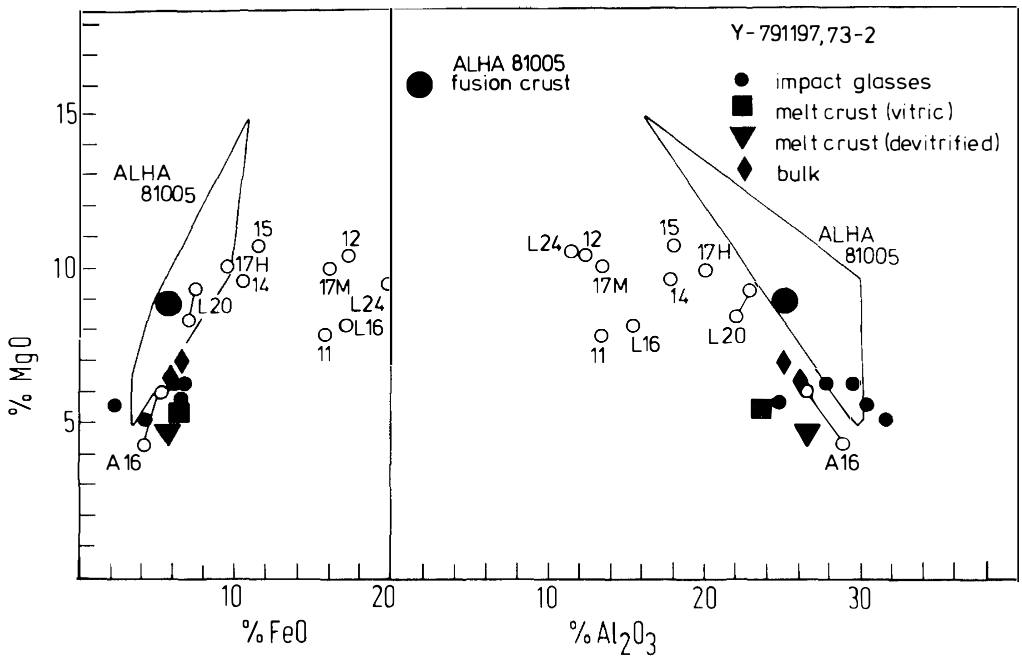

Fig. 6. Chemical composition of glass beads, fusion crust, and bulk sample of Y-791197 compared to analyses of ALHA81005,8 glasses and lunar soils (cf. RYDER and OSTERTAG, 1983). The MgO content of Y-791197 is lower than in most other lunar soils.

frequent in the Y-791197 source area as compared to the ALHA81005 source.

The chemical composition of 5 clear glass beads in thin section Y-791197,73-2 was compared to glass analyses of ALHA81005 (RYDER and OSTERTAG, 1983) and the chemical composition of soils from various landing sites (Fig. 6). The Y-791197 glasses display a narrow range in their MgO, FeO, and Al_2O_3 contents. The analyses cluster around the composition of the fusion crust and the bulk composition of the meteorite. The MgO and FeO contents of the Y-791197 glasses are lower and the Al_2O_3 content is higher than those of most other lunar soil and glass samples taken for comparison but are similar to those of Apollo 16 soils.

3.4. Shock effects

Shock effects in a regolith breccia such as Y-791197 have to be grouped into those which were the result of shock events that affected the breccia components prior to their incorporation into the regolith, and those which were caused by the shock-lithification of the breccia or any later impact event. Only shock effects which undoubtedly are the result of an impact event affecting the bulk sample can give an indication of the pressure during the event that caused the ejection of Y-791197 from the moon.

Mineral and lithic clasts in thin section Y-791197,73-1 and 73-2 show a wide range of shock effects and recrystallization. All clasts were shocked to some degree, unshocked mineral and lithic clasts are lacking. Shock effects in plagioclase are the most sensitive indicators for an estimate of shock pressures. The shock metamorphic features in plagioclase are dominated by fracturing, undulous extinction, mosaicism, and in one clast the occurrence of short, non-decorated planar elements in an anorthite crystal. These shock effects are indicative of peak shock pressures well below 25 GPa.

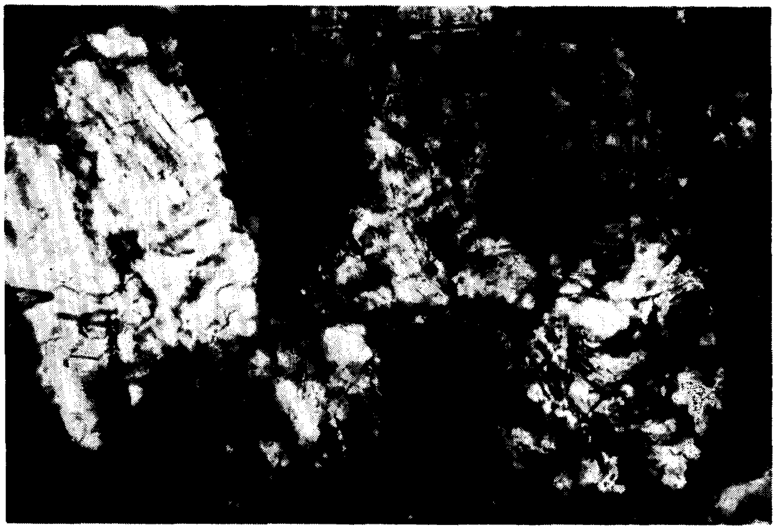

Fig. 7. Shocked igneous-textured clast in Y-971197,73-2. Plagioclase is transformed to maskelynite; field width 0.22 mm, partly crossed polarizers. White: pyroxene with planar deformation structures and mosaic extinction; gray: diaplectic plagioclase glass.

Two completely isotropic diaplectic plagioclase glasses were observed in the matrix, and in one gabbroic clast in Y-791197,73-2 the anorthite is also converted to diaplectic plagioclase glass (maskelynite) (Fig. 7). The maskelynites display no indication of shock melting. Consequently, the source rocks of these mineral and lithic clasts suffered a maximum shock pressure in excess of 30 GPa but less than 52 GPa (STÖFFLER, 1974; OSTERTAG, 1983). Unrecrystallized maskelynite was not observed in ALHA-81005 (OSTERTAG and RYDER, 1983).

Pyroxene crystals in both, the igneous rock and impact melt fragments and pyroxene clasts in the matrix display shock features indicative of the same peak shock pressures as determined for plagioclase. Irregular fracturing and fracturing along cleavage planes is common and is produced by low shock pressures. More highly shocked pyroxenes show mechanical twinning and mosaicism. These features can be produced by a wide range of shock pressures, therefore an exact pressure estimate can not be given. Olivine crystals in the matrix are irregularly fractured and occasionally show mosaicism.

Evidence of shock melting is apparent from the glass beads and irregularly shaped glasses and melt veins in Y-791197. In order to produce whole-rock glasses of bulk rock composition shock pressures of >80 GPa in solid rock and of at least 45.8 GPa in loose regolith are necessary (SCHAAL *et al.*, 1979). However, the petrographic relationships between clasts and matrix and their different degrees of shock metamorphism imply that the clasts were enclosed in the matrix after having been shocked.

The most important information about the maximum shock pressure that could have occurred during the ejection event is in the shock features of the regolith matrix. Incipient formation of intergranular melt in porous regolith starts at shock pressures above 10 GPa (KIEFFER, 1975; GIBBONS *et al.*, 1975; SCHAAL *et al.*, 1979) in contrast to solid rock where shock pressures in excess of 50 GPa are required to initiate shockinduced selective melting. The percentage of melt produced by shock in regolith increases with increasing shock pressure and simultaneously a significant amount of plagioclase is being transformed to maskelynite already at 20.5 GPa (GIBBONS *et al.*, 1975). These experimental data bracket the peak shock pressure experienced by Y-791197. The existence of intergranular melt as well as shock-produced glassy or finely crystalline veins in the matrix set the lower pressure limit to more than 10 GPa while the scarcity of maskelynitization of plagioclase clasts defines the upper pressure limit to considerably less than 20 GPa. Note again that the maskelynite could also have formed prior to its incorporation in the breccia. The maximum pressures that affected the bulk sample were of the order of 10 to 20 GPa. The pressures during ejection from the lunar surface did not exceed this range.

Effects of thermal annealing are common in Y-791197 glasses, rocks, and mineral fragments. Most of the plagioclase clasts in crystalline impact melts, granulitic breccias, and in the matrix are recrystallized. Shock pressures in recrystallized plagioclases can be determined by comparison of the recrystallization textures with those of experimentally shocked and recrystallized plagioclase (OSTERTAG and STÖFFLER, 1982). The plagioclase crystals in Y-791197 experienced a broad variety of shock pressures which in some cases were high enough to cause melting (more than 52 GPa). The majority of the glass beads and shards are devitrified, either partly with fibrous crystals emanating from their rims towards their centers or they are completely recrystallized showing subophitic textures.

The annealing most probably took place before the incorporation of the clasts into the regolith. The occurrence of not devitrified glass beads in the matrix and diaplectic glass in one of the gabbroic clasts contradicts any *in-situ* annealing. The time during which high temperatures could have prevailed is limited by the fact that even the fusion crust which is similar in composition to the glass beads did crystallize. The fusion crust certainly was quenched quickly but nevertheless crystallized, so the assumption is correct that the regolith breccia Y-791197 never was exposed to high temperatures for an extended period of time. This observation also limits the maximum post-shock temperature and consequently the maximum shock pressure experienced by Y-791197, and is consistent with the low shock pressures determined from the analyses of the shock effects in the matrix.

The shock and annealing history of Y-791197 can be explained by the incorporation of shocked and annealed mineral and lithic clasts and vitric or devitrified glass beads into a loose regolith. The shock-lithification by the production of intergranular melt and veins of glassy or microcrystalline material in the matrix formed during later impact events. These results are essentially identical to those of shock studies of ALHA81005 (OSTERTAG and RYDER, 1983). The equilibrium shock pressure experienced by both meteorites as bulk samples never exceeded 20 GPa.

3.5. Chemical composition

The major and trace element compositions of Y-791197 (Table 3) provide independent evidence for its lunar origin. The Fe/Mn ratio, for example, is in the same range as those of lunar highland rocks (YANAI and KOJIMA, 1984), including lunar meteorite ALHA81005. Figure 8 shows a comparison of Fe/Mn ratios of various

Table 3. Concentration of major, minor and trace elements in Y-791197 compared to ALHA81005 (PALME et al., 1983).

%	YMB 59.3 mg	YMG 34.7 mg	YMF 10.7 mg	Error %	ALHA81005 128 mg	Error %
Si					21.72	3
Mg	4.25	3.85		5	4.78	5
Al	13.30	13.85		3	13.4	3
Ca	11.4	10.6	8.56	5	10.80	3
Ti	0.22	0.19	1	10	0.14	10
Fe	5.05	4.57	5.22	3	4.20	3
ppm						
Na	2410	2340	1900	3	2250	3
P	100			30	90	25
K	290	240*	220*	5	230	5
Sc	16.5	13.0	16.4	3	9.24	3
V	39	37		10	26	8
Cr	1034	908	1010	3	862	3
Mn	734	634	758	3	587	3
Co	16.9	18.5	15.7	3	20.2	3
Ni	100	200		15	186	5
Zn	50	34	44	20	18*	10
Ga	9.87	3.0*	7.8*	5	2.8	5
Se					0.6	
Rb					1.5	
Sr	118	117	110	20	128	10
Zr					30	
Ba	34	32		25	34	20
La	3.24	2.12	2.12*	4	2.44	3
Ce	8.76	5.5	5.73*	8	6.9	5
Nd	5.24	3.7	3.6*	10	3.9	10
Sm	1.56	1.13	1.11	4	1.18	3
Eu	0.723	0.706	0.574	3	0.704	3
Gd					1.4	20
Tb	0.33	0.25	0.27*	10	0.27	5
Dy	2.22	1.76	1.79	5	1.7	10
Ho	0.48	0.40	0.39	10	0.37	15
Tm	0.23			20	0.18	20
Yb	1.34	1.04	1.09*	4	1.06	5
Lu	0.19	0.15*	0.16*	4	0.15	3
Hf	1.11	0.82	0.85*	5	0.92	3
Ta	0.16	0.12	0.20*	8	0.12	8
Ir	0.0059	0.0078		15	0.0073	10
Au	0.0013	0.0021		15	0.0021	7
Th	0.43	0.36	0.25*	15	0.35	8
U	0.14	0.10	1.10*	15	0.103	15

* Accuracy reduced by a factor of 2.
YMB: bulk sample.
YMG: matrix-rich sample.
YMF: clast-rich sample.

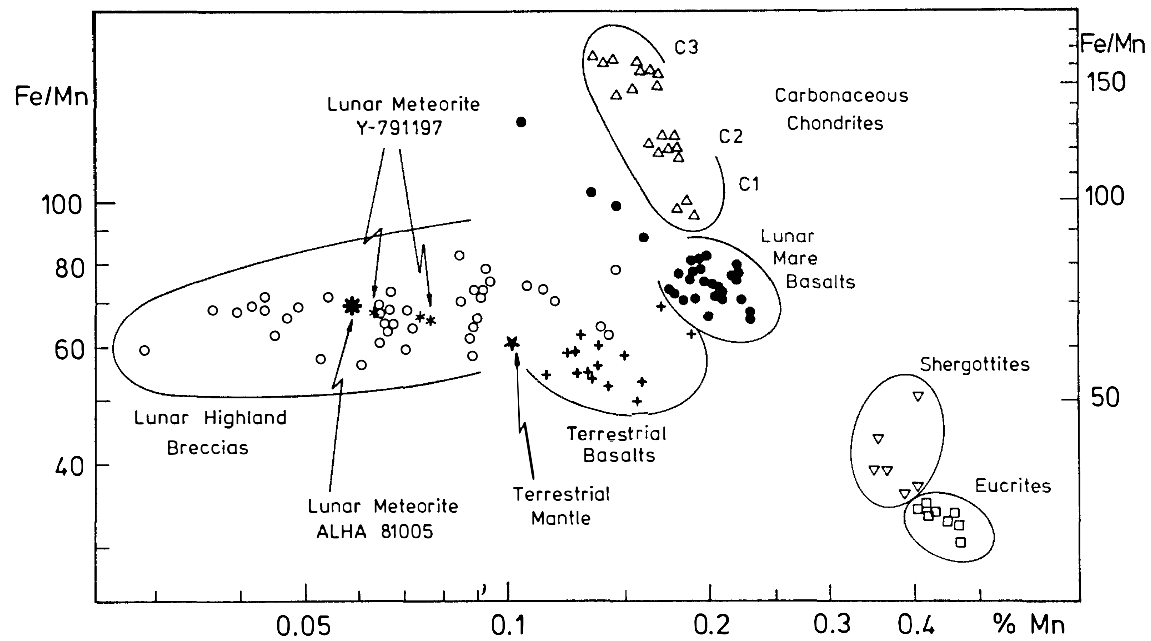

Fig. 8. Fe/Mn vs. Mn in lunar, terrestrial and meteoritic rocks. The Fe/Mn-ratio of lunar rocks has been corrected for the presence of metallic iron (WÄNKE et al., 1975). The two lunar meteorites plot in the field of lunar highland rocks.

terrestrial and extraterrestrial materials. In constructing this figure we have corrected the FeO content of lunar highland rocks for the presence of metallic iron which is thought to be of meteoritic origin. The fraction of metallic iron is calculated from the measured Ni content with the assumption that this metallic iron contains about 7% Ni. The correction procedure has been described by WÄNKE *et al.* (1975). These authors found that the average Fe(total)/Mn ratio of around 80 for lunar highland rocks and soils is reduced to about 70, when corrected. The mean Fe/Mn of the three Y-791197 samples analyzed is 69.9, compared to 71.6 for ALHA81005 (uncorrected for 200 ppm Ni). This is exactly in the range of lunar highland rocks and soils.

The P/Nd ratio is also diagnostic for lunar samples. Y-791197 has nearly the same low P/Nd ratio as ALHA81005 (Fig. 9). The low P/Nd of these meteorites are in the range of lunar rocks, but significantly different from other terrestrial and meteoritic materials. Details about the significance of the low P content of the moon are given by NEWSOM and DRAKE (1983).

The overall chemical composition of Y-791197 is very similar to that of lunar meteorite ALHA81005 (Table 3). This corresponds to the approximate average lunar highland composition. Some granulitic rocks of the Apollo 16 and 17 landing site resemble this composition very closely (PALME *et al.*, 1983). The pattern of incompatible elements (Fig. 10) for example is nearly identical in the two lunar meteorites and in some granulitic rocks such as lunar sample 78155. This pattern is distinctly different from the KREEP pattern which is so dominant in frontside samples. An origin away from the Apollo landing sites is also suggested by siderophile element abundances. The Y-791197 samples lie on the same Ni-Co correlation line as ALHA81005 and granulites (Fig. 11). In this plot we also included data from other laboratories on

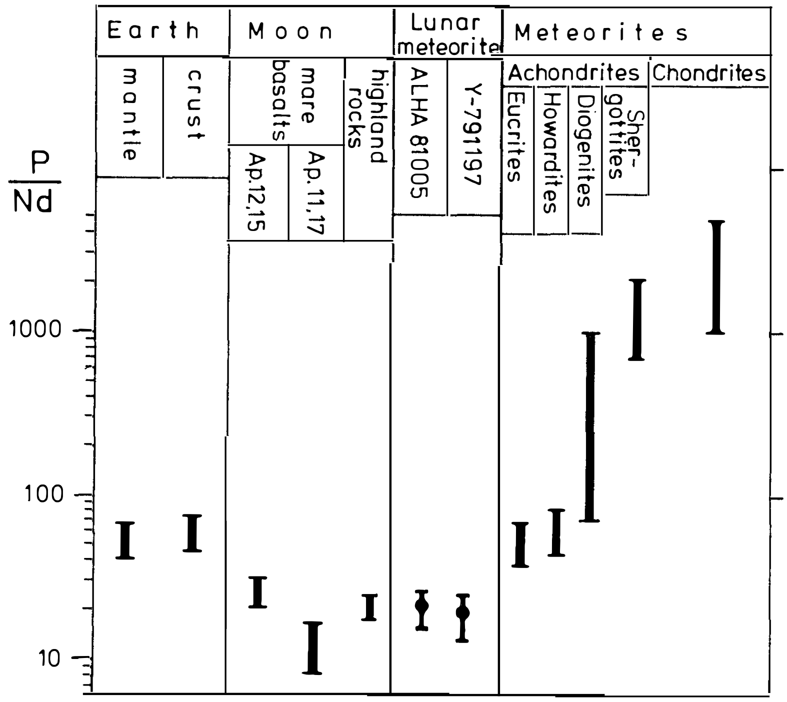

Fig. 9. P/Nd diagram showing the uniquely low P/Nd ratio of lunar rocks including the two lunar meteorites. Figure adopted from PALME *et al.* (*1983*).

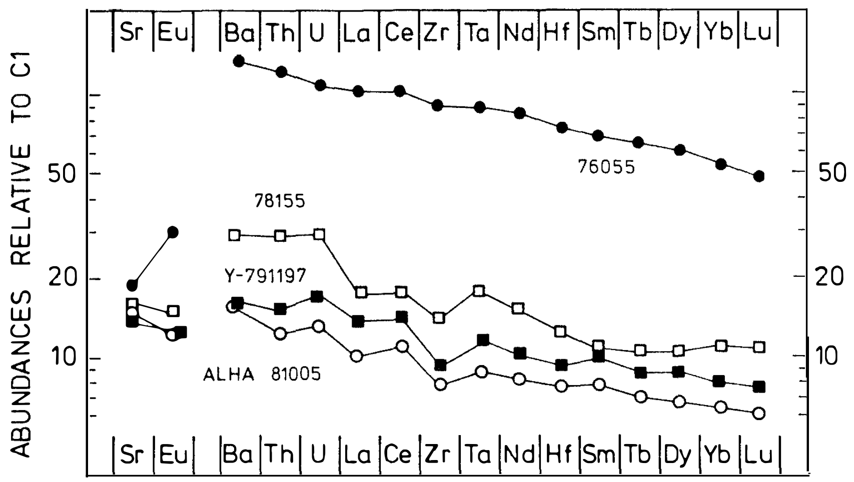

Fig. 10. The chondrite-normalized incompatible element pattern of Y-791197 is very similar to that of ALHA81005 and some lunar rocks but different from the KREEP pattern of lunar sample 76055. Figure adopted from PALME *et al.* (*1983*).

Y-791197 (WARREN and KALLEMEYN, 1985; FUKUOKA *et al.*, 1985; LINDSTROM *et al.*, 1985).

In Fig. 12 we have plotted Cl-normalized siderophile element abundances. The Co abundance in Fig. 12 was corrected for indigenous Co which was calculated from the Ni-Co correlation (Fig. 11) as the ordinate intercept for Ni=0 (PALME *et al.*, 1983). The resulting siderophile element pattern is chondritic and therefore different from the patterns of most Apollo 16 and 17 highland rocks. The absence of KREEP and

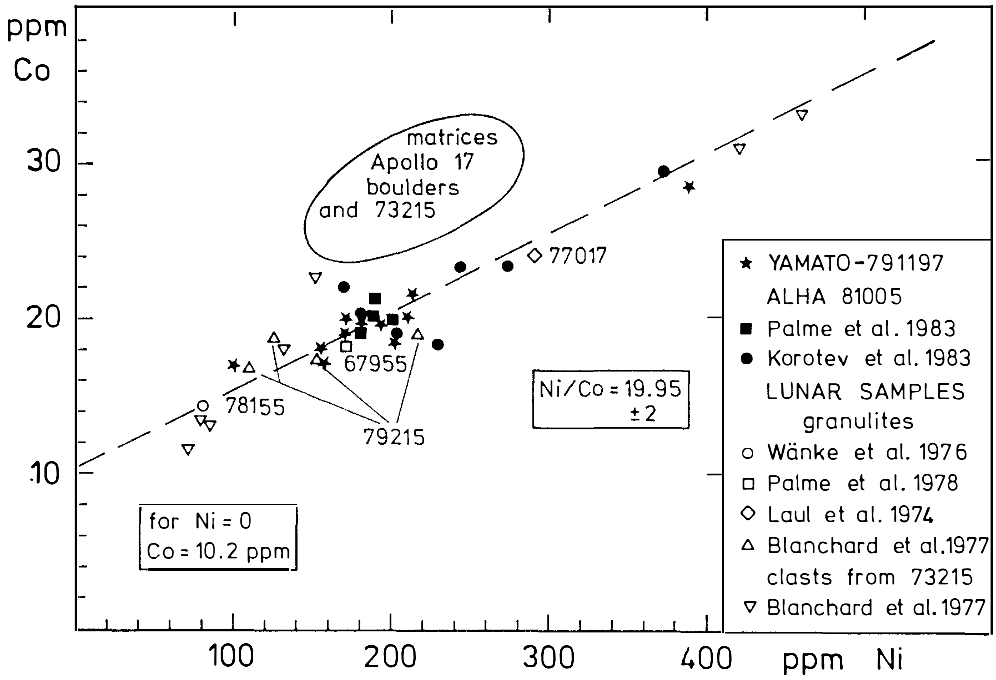

Fig. 11. Ni/Co-correlation of lunar granulites and samples of the two lunar meteorites. Data for Y-791197 from WARREN *and* KALLEMEYN *(1985),* FUKUOKA *et al. (1985),* LINDSTROM *et al. (1985) and this paper. Figure adopted from* PALME *et al. (1983).*

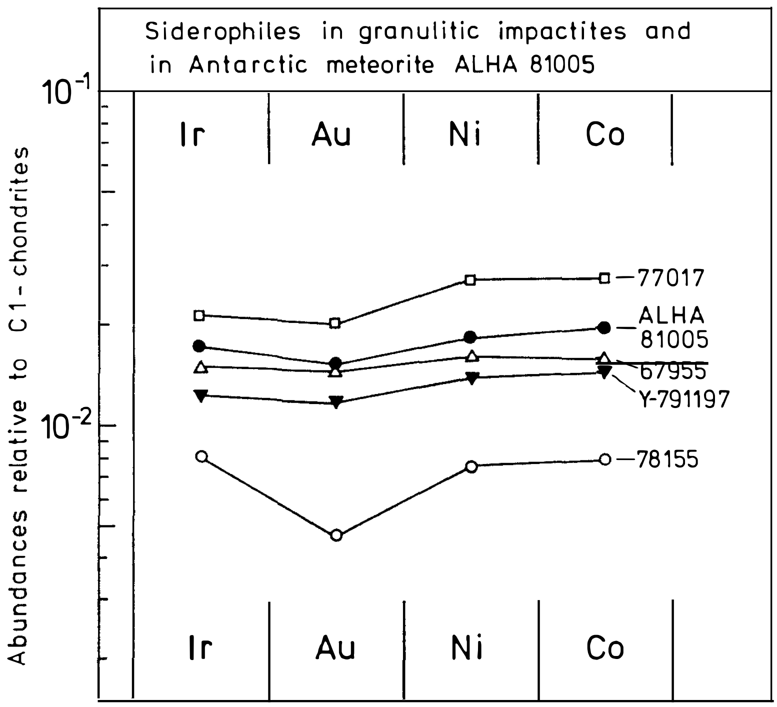

Fig. 12. Pattern of siderophile elements in lunar granulites and for lunar meteorites. Data for YMG and YMB (this work) have been averaged for this plot. The Co content is corrected by 10.2 ppm to account for indigeneous Co. The resulting pattern is chondritic. Figure adopted from PALME *et al. (1983).*

the siderophile element pattern suggest that the Y-791197 meteorite is derived from a selenographic area away from the great basins on the frontside. The same reasoning has been applied to ALHA81005. Both meteorites may therefore be samples from the lunar farside.

Despite the general similarities in chemistry between Y-791197 and ALHA81005 there are some significant differences. Y-791197 has a higher Fe/Mg ratio than ALHA81005 and most Apollo and Luna highland samples. The Fe/Sc-ratio of Y-791197 (3000–3500) is slightly lower than the average lunar highland ratio of ~4000 and some 30% less than the ratio in ALHA81005. This shows that the comparatively high Fe content of Y-791197 is overcompensated by a still higher Sc content. The chemical composition of ALHA81005 did marginally fit into the multi-element mixing diagram for highland rocks (WÄNKE *et al.*, 1976). The above mentioned chemical differences between the two Antarctic lunar meteorites are sufficiently large to make the Y-791197 composition completely incompatible with compositions covered by the mixing diagram. There is a possibility that the Y-791197 composition resembles the lunar farside highland composition. The frontside composition in this case would not only differ from the farside with respect to incompatible and siderophile trace elements, but also with respect to the major element composition. Other lunar meteorites may hopefully provide more clues to answer this question.

Another important signature of Y-791197 is its high content of volatile elements

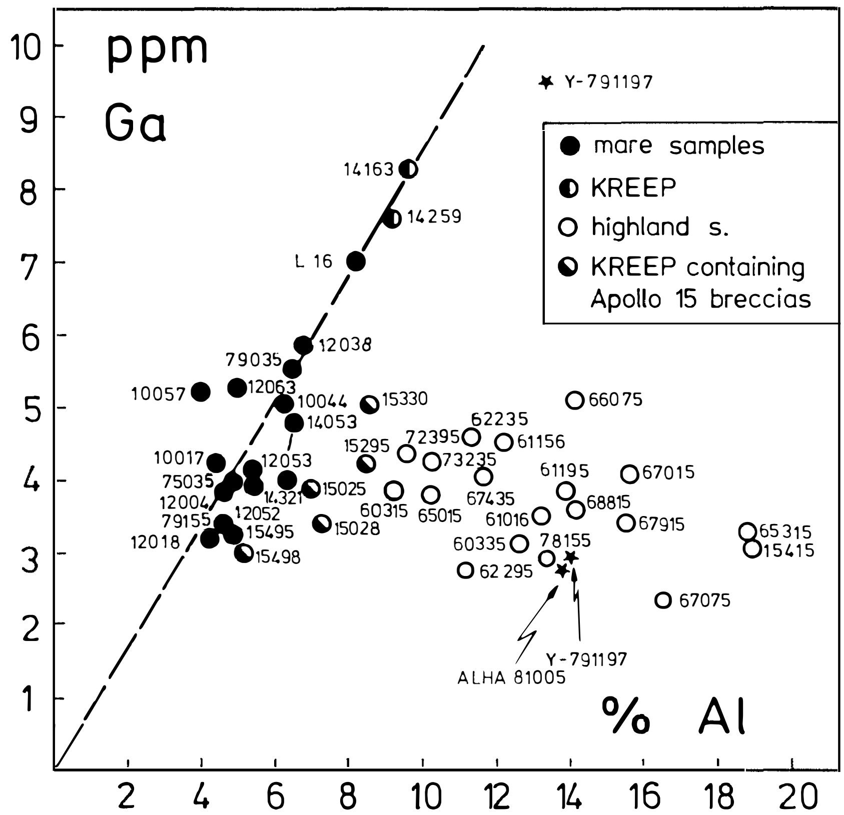

Fig. 13. Uniquely high Ga content in one sample of Y-791197. An even higher Ga content was reported by KACZARAL *et al. (1985). Figure adopted from* WÄNKE *et al. (1976).*

which in some cases is comparable to the volatile-rich rusty rock 66095 (KACZARAL *et al.*, 1985). The remarkably high contents of Ga in some fragments of Y-791197 (Table 3) are surprising (Fig. 13). Simultaneous enrichment of Zn in our Ga-rich sample and the data from KACZARAL *et al.* (1985) leave no doubt that the Ga enrichment is a result of a general enhancement of volatile elements. Redistribution of volatile elements may therefore have been a moon-wide phenomenon. There is abundant evidence for these processes to have occurred on the frontside 3.9–4.0 Ga ago. Some preliminary data may suggest that volatilization and recondensation on the farside, as evidenced by Y-791197 may have occurred at the same time (NAKAMURA *et al.*, 1985). Precise age determination of Y-791197 and its components are required to further elucidate this point.

3.6. *Noble gas analyses*

The results of the noble gas analyses are given in Table 4, and Fig. 14 shows the concentrations of trapped noble gases of Y-791197. Noble gas concentrations for lunar meteorite ALHA81005 (BOGARD and JOHNSON, 1983) and of four Apollo 16 lunar soils (HINTENBERGER and WEBER, 1973) are given for comparison.

With the exception of ^{4}He the solar-wind implanted component is about a factor of 2.5 higher in Y-791197 than in ALHA81005 which implies that the source regolith

Table 4. Concentration and isotopic composition of noble gases in Y-791197 (in 10^{-8} ccSTP/g).

^{4}He	453000	$^{4}He/^{3}He$	2560
^{20}Ne	97500	$^{20}Ne/^{22}Ne$	12.44
^{36}Ar	36600	$^{22}Ne/^{21}Ne$	26.1
^{84}Kr	22	$^{40}Ar/^{36}Ar$	2.58
^{132}Xe	2.5	$^{36}Ar/^{38}Ar$	5.30

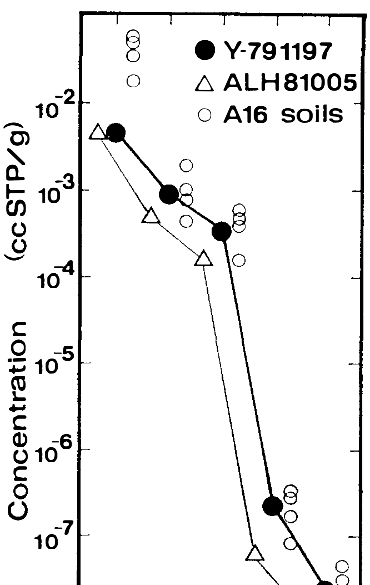

Fig. 14. Trapped noble gas concentrations for Y-791197 compared to ALHA-81005 (BOGARD and JOHNSON, 1983) and four Apollo 16 soils (HINTENBERGER and WEBER, 1973). The noble gas fractionation patterns of the lunar meteorites are typical for lunar soils.

of Y-791197 was more mature than the ALHA81005 source regolith. The noble gas mass fractionation patterns of all three materials are very similar and it is concluded that implanted solar wind particles cause the high noble gas concentration of Y-791197. This is also in agreement with the isotopic composition of the noble gases. The low $^{40}Ar/^{36}Ar$ indicates the presence of parentless ^{40}Ar which is a typical and unique feature of lunar regolith material. The results of our noble gas analyses are in very good agreement with the data obtained from a bulk sample of Y-791197 by TAKAOKA (1985).

The exposure age of this meteorite can be calculated from the cosmogenic ^{21}Ne which is 54×10^{-8} ccSTP/g. Assuming a production rate of 0.12×10^{-8} ccSTP/gMa an exposure age of 450 Ma is obtained for Y-791197. This exposure age is very similar to exposure ages of lunar soils but significantly higher than that of any other stone meteorite. It compares with the range of cosmic ray exposure ages given for ALHA81005 (200–1000 Ma; BOGARD and JOHNSON, 1983). Both lunar meteorites are breccias, therefore the calculated ages might be those of the average of individual breccia components but not that of the breccia itself. Nevertheless, all observations are strong indications for a lunar origin of Y-791197.

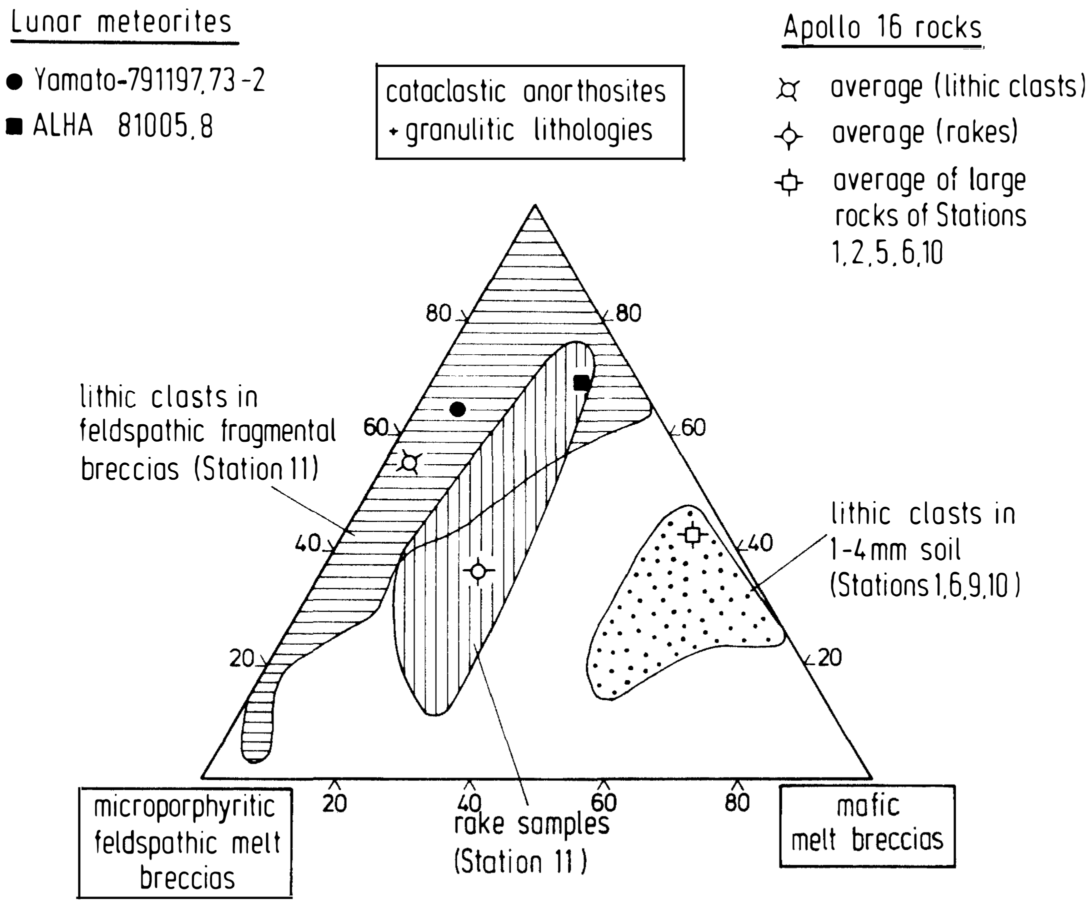

Fig. 15. Frequency distribution of clast types in Y-791197,73-2 and ALHA81005,8 compared to Apollo 16 breccias from the Descartes Formation (Station 11) and Cayley Plains (Stations 1, 6, 9, 10). Lunar meteorites presumably are derived from the east of the Apollo 16 landing site because they differ significantly from rocks from the lunar frontside (Cayley Plains). Figure adopted from STÖFFLER et al. (1985a).

4. Discussion

4.1. Comparison with Apollo 16, Station 11 samples

Samples from Apollo 16, Station 11 which is located at the rim of the 1 km diameter North Ray crater are the best documented lunar highland breccias in terms of chemical composition, modal mineralogy, clast population studies, shock studies, petrography, and age (*e.g.* STÖFFLER *et al.*, 1985a). The lunar meteorite Y-791197, a lunar highland breccia of unknown source area, provides an ample opportunity to compare its chemical and textural characteristics with the data of the North Ray crater samples in order to determine similarities and dissimilarities of the respective source areas.

Figure 15 is a three-component plot of the populations of cataclastic anorthosites and granulitic lithologies *vs.* feldspathic microporphyritic and mafic melt breccias in Y-791197,73-2 and lunar meteorite ALHA81005,8 compared to the respective clast populations in Apollo 16 feldspathic fragmental breccias, rake samples, and 1–4 mm soils (*cf.* Fig. 5 in STÖFFLER *et al.*, 1985a). The clast populations of both lunar meteorites are richer in cataclastic anorthosites and granulitic lithologies than the averages of Apollo 16 Station 11 lithic clasts and rakes. They contain less mafic melt breccias than the soil sample from Apollo 16 Stations 1, 6, 9, and 10 which were located in the Cayley Plains containing mafic material presumably transported there by the Imbrium

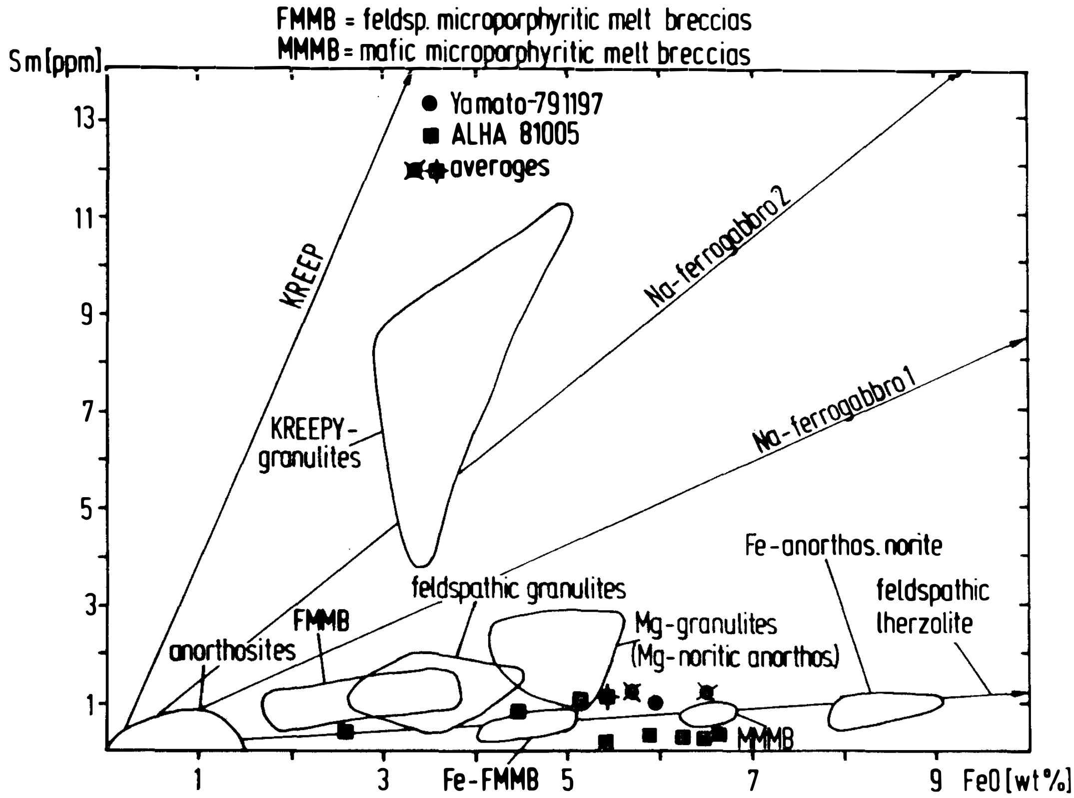

Fig. 16. Sm vs. FeO of Y-791197 and clasts of ALHA81005 (GOODRICH et al., 1984) compared to Apollo 16 lithic clasts and pristine lunar rocks. The lunar meteorites are similarly low in KREEP as crystalline melt breccias and granulites from the Descartes Formation. Compositional ranges for Apollo 16 rocks adopted from STÖFFLER et al. (1985a).

event. The clast population studies of both meteorites imply an origin from a highly feldspathic source area on the lunar highlands a considerable distance apart from any large impact crater connected with mafic impact melts or mare components.

Figures 16 and 17 show the concentration of Sm and Cr *vs.* FeO, respectively, of clasts in Y-791197,73-2 and ALHA81005 (GOODRICH *et al.*, 1984) in comparison to Apollo 16 breccias and rocks (*cf.* Figs. 8 and 9 in STÖFFLER *et al.*, 1985a). Both lunar meteorites contain clasts which appear to represent mixtures of a ferroan anorthosite and a mafic-rich component such as the feldspathic lherzolite 67667. KREEP is remarkably low if at all present. Consequently, the source area of both lunar meteorites must be KREEP-poor or KREEP-free which precludes an origin from most parts of the lunar frontside.

With respect to their low KREEP content the lunar meteorites are more similar to soils from Apollo 16, Station 11 than to soils from Station 5. Station 11 was located at the rim of North Ray crater and contains Descartes material which is interpreted as Nectaris ejecta derived from old highland lithologies to the east of the Apollo 16 landing site (STÖFFLER *et al.*, 1985a). In contrast, Station 5 sampled KREEP-bearing material from the Cayley Plains which probably are genetically related to the Imbrium event to the north-west of the Apollo 16 landing site. The source region of the lunar

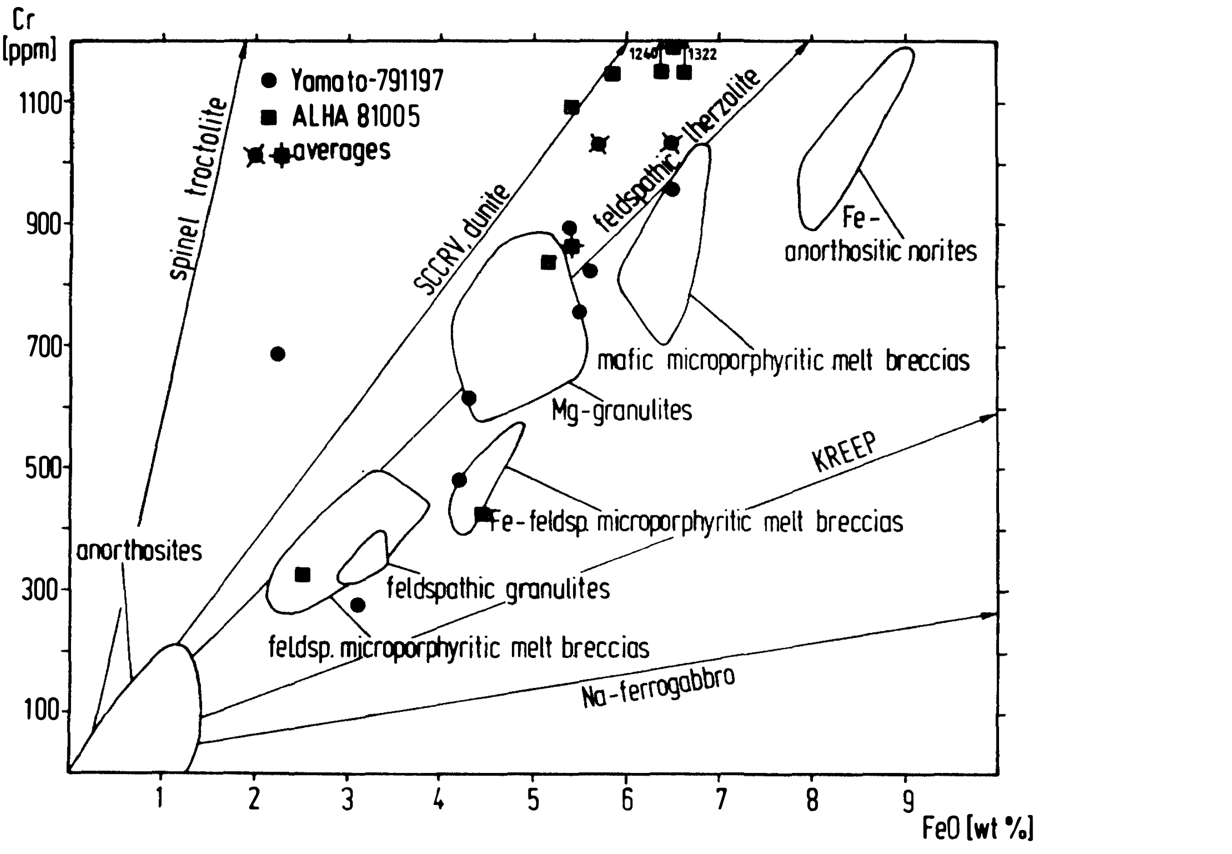

Fig. 17. Cr vs. FeO of Y-791197 and clasts of ALHA81005 (GOODRICH et al., 1984) compared to Apollo 16 lithic clasts and pristine lunar rocks. The lunar meteorites can be modeled from a mixture of ferroan anorthosite and a mafic-rich feldspathic lithology. Compositional ranges for Apollo 16 rocks adopted from STÖFFLER et al. (1985a).

Table 5. Composition of Y-791197 as deduced from mixing calculations based on Apollo 16 and 17 primary magmatic components compared to lunar meteorite ALHA81005 and Apollo 16 regolith; Station 5: Cayley Plains, Station 11: Descartes Formation. For chemical composition of primary components see STÖFFLER *et al. (1985a).*

	Anorthosites	Sodic ferrogabbro	Feldspathic lherzolite	Gabbronorite	Dunite	Spinel troctolite	KREEP	Meteoritic component	Square sum of residuals
Y-791197,73-2 fusion crust (recryst.)	50.56	1.06	1.30	44.41	0	0	1.94	0.72	30.3
Y-791197,73-2 fusion crust (glassy)	51.76	0.22	13.69	31.78	0	0	1.82	0.72	16.5
ALHA81005[1]	60.75	0	10.99	20.79	4.78	0	1.41	1.27	3.63
ALHA81005[2]	65.92	0	30.26	2.31	0.003	0	0	1.51	19.17
Apollo 16 Station 5 regolith[3]	62.6	4.0	15.3	3.1	0	0	11.7	3.4	1.5
Apollo 16 Station 11 regolith[3]	75.1	2.9	14.5	2.1	0	0	4.1	1.3	5.4

Chemical compositions: [1] PALME *et al.* (1983); [2] KALLEMEYN and WARREN (1983); [3] KOROTEV (1981).

meteorites is likely to have been east of the Apollo 16 landing site.

Y-791197 is a polymict highland regolith breccia and its bulk composition is the result of mechanical mixing of various precursor rocks. In order to determine the nature of these precursors and to derive the chemical and petrographic characteristics of the lunar crust at the source area of Y-791197, mixing calculations were performed following the procedure described in STÖFFLER *et al.* (1985a). These mixing calculations are based on the chemical composition of primary magmatic components which were observed in thin section. KREEP and a meteoritic component are added. As the primordial magmatic components at the source areas of ALHA81005 and Y-791197 are not known well enough, the primordial magmatic components of the Apollo 16 landing site were taken as endmembers for the calculations. The results were compared with mixing calculations of ALHA81005 and Apollo 16 regolith samples (Table 5). According to these calculations, the source area of Y-791197 consisted of anorthosite and feldspar-bearing mafic-rich lithologies ("feldspathic lherzolite" 67667 and gabbronorites). KREEP is rare in accordance with the composition of ALHA81005 but in contrast to the Apollo 16 regolith. There are minor amounts of a sodic ferrogabbro and a meteoritic component, but olivine-rich lithologies are lacking. The lack of dunite, the lower amount of anorthosite, and the different ratios of feldspathic lherzolite to gabbronorite distinguish Y-791197 from ALHA81005. The source areas of both lunar meteorites consist of less KREEP, anorthosite, and sodic ferrogabbro than the Apollo 16 landing site but contain a higher amount of mafic-rich feldspathic lithologies.

Compared to the other samples, the square sum of residuals as a measure of the data fit is higher in Y-791197, *i.e.* the data fit is less satisfying than for the Apollo 16 and ALHA81005 analyses. This could be accounted for by differences in chemical composition of the primary mixing components between the Apollo 16 landing site and the source area of Y-791197.

4.2. Sample provenance

There remains no reasonable doubt that Y-791197 is of lunar origin. We would like to re-emphasize the low P/Nd ratio, the REE pattern, the siderophile element content, and the Ni/Co-ratio as proof for a lunar origin of Y-791197. The presence of parentless ^{40}Ar and an exposure age of 450 Ma is similar to lunar soils but dissimilar to that of any other stone meteorite. The petrographic data, especially the lithic clast content with its predominance of feldspathic crystalline melt breccias and recrystallized feldspathic rocks and breccias, as well as the matrix texture define Y-791197 as a lunar highland regolith breccia. Its bulk composition is that of o noritic anorthosite.

Based on the clast content and the chemical composition of Y-791197, its source area is predominantly composed of ferroan anorthositic lithologies with some contributions of mg-suite rocks (TAKEDA *et al.*, 1985), and minor amounts of mare components (LINDSTROM *et al.*, 1985), but is largely devoid of KREEP. These petrographic and chemical characteristics strongly resemble those of the "Old Eostern Highland Rock Suite" as defined by STÖFFLER *et al.* (1985a) for the Descartes Formation at the Apollo 16 landing site. However, the lack of KREEP in Y-791197 precludes a frontside origin and instead indicates a source area to the east of Apollo 16 most probably on the lunar farside.

This contention is supported by the comparison of elemental abundances in Y-791197 with those of the lunar farside. There is a distinct difference in the concentrations of a number of chemical elements between the lunar frontside and the lunar farside (ANDRE and STRAIN, 1983). The areal distributions of TiO_2, FeO, Th, Mg, Al on the lunar surface when compared to the concentrations of these elements in the lunar meteorites can therefore be used as a criterion to determine probable source areas of the lunar meteorites. Figure 18 gives the relative frequency of TiO_2, FeO, and Th for the lunar frontside (solid lines) and the lunar farside (dashed lines). The curves are redrawn from ANDRE and STRAIN (1983). The concentrations for the crucial elements in Y-791197 and in ALHA81005 consistently lie in the range of lunar farside compositions. Only Apollo 16 regolith samples derived from the Descartes Formation have similarly low concentrations for Th (METZGER *et al.*, 1981), Al_2O_3, FeO, and TiO_2 (ANDRE and EL-BAZ, 1981). Again a source area to the east of the Apollo 16 landing site is indicated.

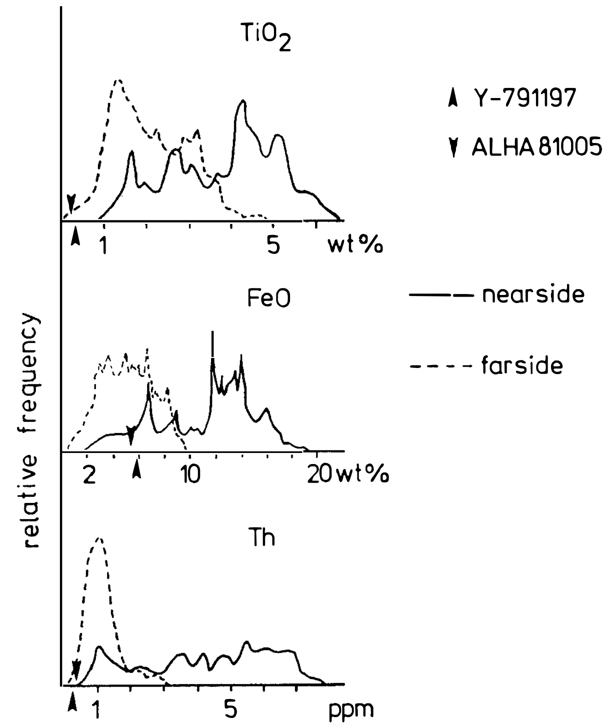

Fig. 18. The concentrations of TiO_2, FeO and Th in Y-791197 and ALHA81005 are typical for lunar farside compositions. Figures redrawn from ANDRE and STRAIN (1983).

In addition, dynamical considerations provide an independent means to establish the possible source area of lunar meteorites. These calculations favor the eastern part of the moon as a possible source area. For most of the impact angles considered in the calculations, the probability of a direct trajectory of ejecta crossing the Earth's orbit is higher for material from the eastern part than from the western edge of the moon (GAULT, 1983). If these conclusions are valid, Y-791197 is the second sample derived from the lunar farside, because the arguments used here also apply for the ALHA81005 lunar meteorite (RYDER and OSTERTAG, 1983).

5. Conclusions

There are intriguing chemical and textural similarities but also some remarkable differences between ALHA81005 and Y-791197. The main differences are in the higher volatile content, the higher noble gas content and the more ferroan nature of Y-791197 as compared to ALHA81005. This data spread is comparable to the variations observed for Apollo 16 soils sampled at different locations (KOROTEV, 1981). Both lunar meteorites are derived from chemically, petrographically and selenographically very similar source areas. Equally short transit times in space (SUTTON and CROZAZ, 1983; CROZAZ, 1985) make it probable that the two meteorites are related to the same impact event.

First results of preliminary studies of the two other possible lunar meteorites, Y-82192 and Y-82193, indicate that these are regolith breccias as well (YANAI *et al.*, 1984). This fact is highly significant in terms of the ejection mechanism that spawned these samples off the lunar surface. Apparently only material from the uppermost 10–12 m of lunar surface formations has been accelerated beyond lunar escape velocity into an Earth-crossing orbit.

However, the fact that only regolith breccias were accelerated from the lunar surface is inconsistent with the sample frequency statistics at the Apollo lunar highland landing sites. Although a direct correlation between the number of regolith samples and other breccias and rocks is not possible for Station 11, Apollo 16, because regolith breccias were not sampled at North Ray Crater (FRULAND, 1983) the total number of Apollo 16 regolith breccias in general is less than that of other breccias at the Apollo 16 landing site (MCKINLEY *et al.*, 1984).

Moreover, about half the number of regolith breccias sampled at Apollo 16 and a large fraction of regolith breccias at Apollo 17 are less than 5 g in weight (FRULAND, 1983), which is considerably less than the weight of ALHA81005 (31.4 g) and Y-791197 (52.4 g). Regolith breccias are more friable than impact melt breccias or granulitic breccias and should be more susceptible to comminution during the impact that caused the ejection. From these considerations one should rather expect other lithologies, such as the frequently occurring coherent crystalline melt breccias or granulitic breccias instead of friable regolith breccias to be ejected from the lunar surface. A possible reason for the predominance of regolith breccias among the lunar meteorites might be that they formed by shock-lithification during the impact that caused the ejection from the lunar surface. Shock-lithification of porous material was observed to start at shock pressures as low as 4 GPa (BISCHOFF and LANGE, 1984) and pressures of less than 20 GPa would be sufficient to form breccias from loose regolith (KIEFFER, 1975).

The equilibrium shock pressures estimated from the shock effects in ALHA81005 and Y-791197 provide important constraints for the dynamical calculations of the ejection mechanism. So far no completely shock-melted meteorites have been found, neither among the lunar meteorites, nor among the SNC-group of meteorites. Evidently, surface samples are the most likely to be accelerated beyond escape velocity and the shock pressures during ejection were low in the lunar case and moderate at best for the shergottites (STÖFFLER *et al.*, 1985b).

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