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LUNAR METEORITE YAMATO-793274: MIXTURE OF MARE AND HIGHLAND COMPONENTS, AND BARRINGERITE FROM THE MOON

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Abstract: Two small samples of the new lunar meteorite Yamato-793274 have been studied for mineralogical, petrological, and geochemical composition. The meteorite has a coarse grained texture and consists of a dense breccia that contains relatively large and abundant mineral fragments (clinopyroxene, plagioclase, olivine, ilmenite), rare fine-grained granulitic (poikilitic) breccias, and some mostly brownish devitrified glass. The matrix is abundant, dense, and consists of mineral fragments and interstitial mostly recrystallized glass. One large recrystallized melt breccia of anorthositic-noritic-troctolitic (ANT) composition was found. All plagioclase fragments are highly anorthitic, and olivine compositions range from Fo_{46-72}. The occurrence of these breccias and plagioclases, as well as the chemistry of some matrix glass, is consistent with an origin from the lunar highlands. However, some glasses have a considerably more mafic composition and show admixture of a low *mg*-component. Pyroxenes are unusually abundant when compared with other lunar meteorites. They usually show exsolution lamellae, are heavily shocked, and their compositions show a bimodal distribution, with low-*mg* pyroxenes most probably of mare origin. Among opaque phases, kamacite, and a Co-rich taenite were found, and, for the first time in lunar rocks, the rare higher phosphide barringerite, $(Fe, Ni)_2P$. The bulk major and trace element composition is unlike the anorthositic lunar highland meteorites (*e.g.*, ALHA81005, Y-791197, Y-86032, MAC88104/5), but somewhat similar to the newly identified mare meteorite EET87521. The mineral compositions as well as the major and trace element compositions of the bulk show a close similarity to certain VLT mare basalts, *e.g.*, the Luna 24 ferrobasalts. This is obvious, for example, in a plot of molar Mg/(Mg+Fe) *vs.* TiO_2 content. The lithophile trace element abundances in Y-793274 are similar to EET87521 and Apollo 17 and Lunar 24 VLT's. The REE patterns show higher abundances (about 20–10 × C1) than the anorthositic meteorites and a small negative Eu anomaly. They are similar to EET87521 and some Apollo 14 green volcanic glasses. From the mineralogical and chemical data, pairing with any other lunar meteorite is very unlikely. Y-793274 is a shock lithified fragmental breccia containing a minor regolith component and numerous mafic mineral fragments and glasses. It is a mixture of about two thirds mare material and one third highland component, and therefore different from all previously known lunar meteorites.

1. Introduction

The collection of lunar meteorites in Antarctica continues to yield more samples every year, and is growing in importance augmenting the presently available lunar sample collection. At the time of writing, eleven lunar meteorites have been recovered by Japanese and American expeditions to Antarctica. Following the discovery of the first lunar meteorite in 1982 (MARVIN, 1983), other samples have been recovered from several geographically quite different locations in Antarctica. It is interesting to note that the first samples have all originated from the lunar highlands, and are of anorthositic composition (see, *e.g.*, PALME *et al.*, 1983; WARREN and KALLEMEYN, 1986, 1987; KOEBERL, 1988; TAKEDA *et al.*, 1989; KOEBERL *et al.*, 1989).

An important question has been, and still is, the number of individual source regions on the moon that are represented by the known lunar meteorites (WARREN, 1990; LINDSTROM, 1990). The last year has seen an important increase in the number of lunar meteorites discovered and studied. Two samples have been recovered from the MacAlpine Hills (MAC88104/88105; paired), with one of them weighing over 660 g. These samples are very similar to previously studied lunar meteorites, such as ALHA81005, Y-791187, and Y-82192/3. The fact that they were found far from the other lunar meteorites, plus some differences in petrology and geochemistry (LINDSTROM *et al.*, 1990; KOEBERL *et al.*, 1990a; PALME *et al.*, 1990), precludes pairing with the other samples.

With the discovery of MAC88104/5, the most likely number of source regions (or impact events) as derived from the previously studied lunar meteorites has therefore increased from three (1: ALHA81005; 2: Y-791197; 3: Y-82192/3, Y-86032) to four, with seven individual samples, all representing anorthositic lunar highland material. At the same time, however, a meteorite that has previously been classified as a eucrite—Elephant Moraine (EET)87521—was reclassified as a lunar sample on the basis of petrological and geochemical studies (WARREN and KALLEMEYN, 1989; DELANEY, 1989; DELANEY *et al.*, 1990). EET87521 turned out to be the first lunar meteorite predominantly composed of mare components. Previous to this discovery, anorthositic highland rocks (which are believed not to be a predominant rock type on the lunar surface) dominated the lunar meteorite collection.

This has now changed to the opposite. After the identification of EET87521, Y-793274 has been identified to be of at least partly mare origin (this work; WARREN, 1990; LINDSTROM and MARTINEZ, 1990; TAKEDA *et al.*, 1990; MORI *et al.*, 1990; YANAI and KOJIMA, 1990), and two other recently discovered lunar meteorites from the Japanese collection (which are not yet available for detailed study) seem to be of mare composition (YANAI, 1990a, b; YANAI and KOJIMA, 1990). The importance of the source region on the moon (mare *vs.* highlands) will be discussed later in this paper.

Yamato-793274 has been discovered by a Japanese Antarctic Research Expedition on January 3, 1980, in the Yamato Mountains in Antarctica and was first reported to be of lunar origin by YANAI and KOJIMA (1987a) (these authors suggested an association with anorthositic highland breccias). The sample is a single rock of 8.66 g and has a size of 2.6×1.8×1.2 cm with minor brownish to colorless vesicular fusion crust. Numerous relatively large mineral fragments and clasts are visible, set in a dark matrix. Some analytical data were given by YANAI and KOJIMA (1987a, b) and show a wide variation in plagioclase ($An_{88.3-97.4}$), pyroxene ($En_{4.2-67.5}$; $Fs_{16.4-64.3}$), and olivine ($Fa_{17.8-97.3}$) compositions. In view of the continuing interest in and the importance of lunar meteorites, following the discovery of new large rocks at the Yamato Mountains and MacAlpine Hills, some samples of Y-793274 have recently been made available for a consortium study.

In this paper we describe the results of our mineralogical, petrological, and geochemical studies of samples of the lunar meteorite Y-793274.

2. Samples and Analytical Methods

A consortium study of Y-793274 has recently been organized (TAKEDA *et al.*, 1990). Due to the small size of the sample, only a very limited amount of material was available, and only a small number of consortium members received samples.

We have received sample Y-793274 in two fragments (,93: 31 mg, and ,94: 51 mg). Part of the larger fragment was used for a polished thin section, on which the following preliminary petrological and mineralogical results are based. The sample chips show a coarse-grained texture, with some minor light brownish fusion crust on one side. The thin section shows a dense breccia consisting of relatively large and abundant breccia fragments, mineral fragments (clinopyroxene, plagioclase, olivine, ilmenite), rare granulitic (hornfelsic) breccias (very fine-grained), and some devitrified glass. According to TAKEDA *et al.* (1990), sample ,93 was taken from a large grayish clast (G1, 0.3×0.2 cm in size), while we do not have any information on the exact location of sample ,94. However, we assume (from optical microscopy) that these samples are essentially similar.

Section ,94 was studied microscopically, and selected areas and clasts were analyzed with an ARL-SEMQ electron microprobe following routine procedures. SEM studies and BSE images were obtained with a Jeol JSM-6400 scanning electron microscope at 20 kV acceleration voltage.

Sample Y-793274,93 was used for trace element analyses by instrumental neutron activation analysis (INAA). The sample was gently crushed in a boron carbide mortar, and a 28.88 mg bulk sample was selected together with two small handpicked white clasts (clast #1 and #2). Most of the INAA methods have been described previously (see, *e.g.*, KOEBERL, 1988; KOEBERL *et al.*, 1989); however, some new equipment (HpGe detectors, resolution 1.60 keV at 1332 keV; gated integrator spectroscopy amplifier; fast 1.5 μs ADC, Ethernet-VAX based data acquisition system) has been used. After the INAA measurements and several months cooling time, polished sections of clasts #1 and #2 were also studied by electron probe microanalysis.

3. Sample Description

Initial petrological descriptions (YANAI and KOJIMA, 1987a) suggested an anorthositic affinity for Y-793274, but recently it was found that this meteorite contains non-highland components too. Our study of the polished thin section of sample, 94 shows that the sample is a fragmental breccia which consists mainly of metameltbreccias, hornfelsic metabreccias, mineral fragments (pyroxenes, olivine, plagioclase, silica, ilmenite, and rare metal grains), devitrified glass fragments, and matrix. The devitrified glass fragments are mostly brown to dark brown. The matrix is

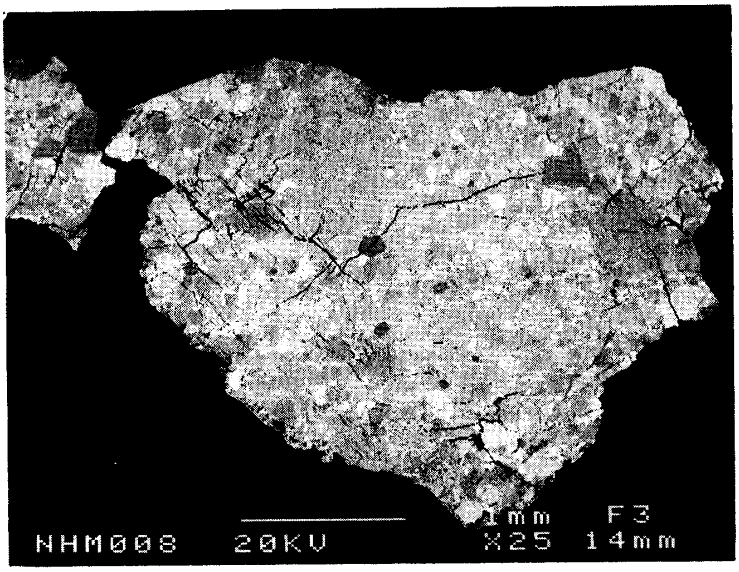

Fig. 1. BSE image of a portion of fragmental breccia Y-793274 ,94 ("gray clast" G1 of TAKEDA et al., 1990). The larger (rounded) clasts are meta-meltbreccias, hornfelsic metabreccias, and devitrified glass fragments. The dark fragment near the center of the section is silica.

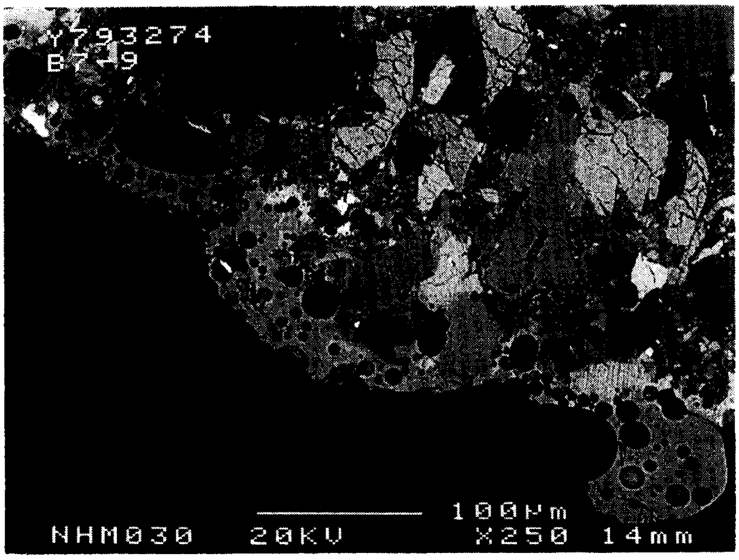

Fig. 2. BSE image of a section of the fusion crust (containing numerous voids) coating sample ,94, and part of the matrix.

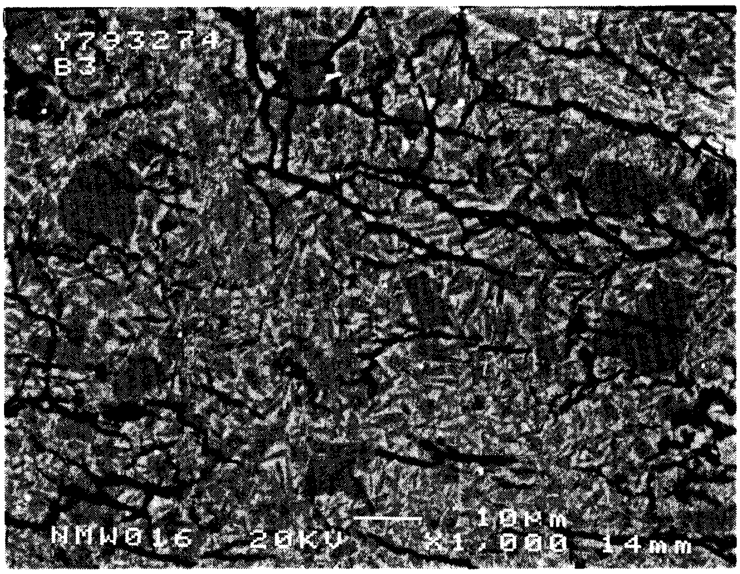

Fig. 3. BSE image of a devitrified melt breccia in sample ,94.

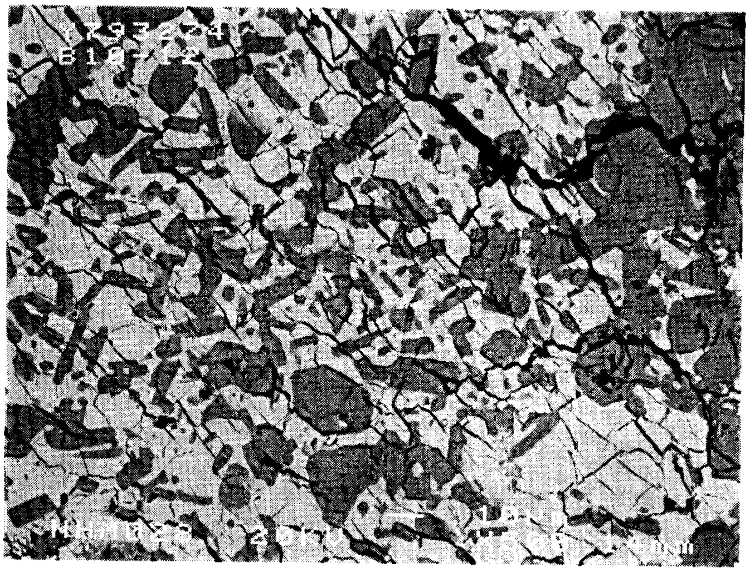

Fig. 4. BSE image of a pyroxene oikocryst from a hornfelsic metabreccia in sample ,94. The darker gray phase is anorthite.

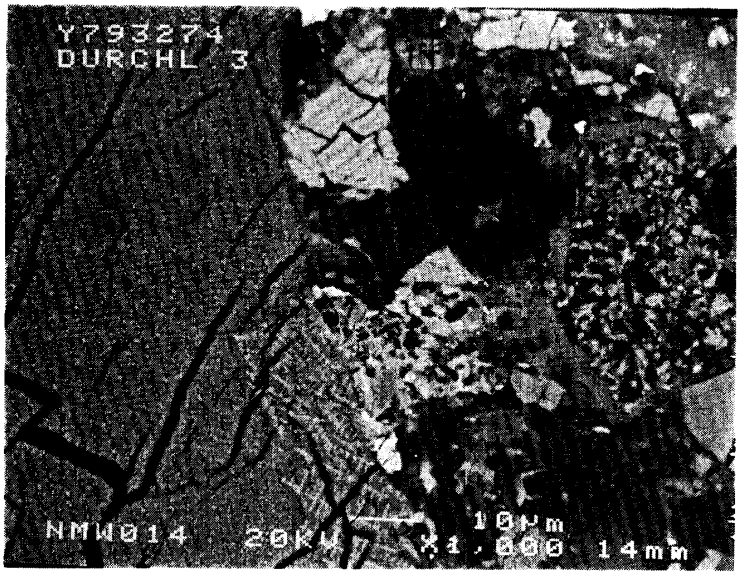

Fig. 5. BSE image of a devitrified glass clast (left, see Tables 2 and 3 – brown glass) and matrix of sample ,94. The matrix components are welded together by glass (now devitrified) of highly variable composition (different shades of gray). The dendritic recrystallization is visible in the lower part of the image. Note the abundance of cavities.

fairly dense, very abundant, consists of mineral fragments and is rich in interstitial partly recrystallized glass. Figure 1 shows a BSE image of most of the thin section of ,94, which is part of the large gray clast G1 (TAKEDA *et al.*, 1990) in Y-793274. Sample ,94 must have originated from the outer part of the rock because part of the section is rimmed with some vesicular brownish fusion crust, which is shown in Fig. 2.

One large brownish, fine-grained, recrystallized melt breccia was found in section ,94. It contains pyroxene and plagioclase relics and is of anorthositic-noritic-troctolitic (ANT) composition (see next section). Similar breccias of smaller size are present (see, for example, KURAT *et al.*, 1990). Figure 3 shows a BSE image of the fine-grained inner portion of a devitrified melt breccia in sample ,94, while Fig. 4 displays a pyroxene oikocryst from a hornfelsic metabreccia. These components are typical for an origin from the lunar highland regolith. However, they are mixed with distinctly non-highland components.

Throughout the thin section, pyroxenes are unusually abundant when compared to other lunar meteorites (*e.g.*, Y-791197, Y-82192/3, Y-86032; see, *e.g.*, Warren, 1990; Takeda *et al.*, 1989; Koeberl *et al.*, 1990b), and many are of pinkish color. They commonly show exsolution lamellae, and all phases are heavily shocked. Chemical data are given in the next section. Devitrified glass is common throughout the section, and matrix components are often welded together by such glass (Fig. 5). The recrystallized glass is commonly very fine-grained and shows dendritic growth (Fig. 5).

4. Results and Discussion

4.1. Phase compositions

Numerous analyses have been made of mineral and lithic fragments and matrix components. Some representative results are given in Tables 1 and 2. Table 1 gives analyses of matrix and minerals that are predominantly of compositions typical of lunar highlands. Some matrix glass is of anorthositic composition (column 3 in Table 1), very similar to glass found in melt rocks in anorthositic lunar meteorites such as Y-86032 (Koeberl *et al.*, 1990b). The composition of the ANT-breccia (columns 1 and 2 in Table 1) is similar to metabreccias found in Y-86032 (Takeda *et al.*, 1989; Koeberl *et al.*, 1990b) and other highland meteorites. The ANT-breccia probably contains glass as an additional phase; it is not identical to any of the fragments in Table 5 that have been analyzed for trace elements. All plagioclase fragments encountered are highly anorthitic (An_{95-99}; see Table 1). However, Takeda *et al.* (1990) describe ranges of An_{88-98} and some chemical zoning. Such extremes were not observed in our analyses.

As mentioned before, pyroxenes are very abundant in Y-793274. Although

Table 1. Bulk and mineral compositions of highland components in Y-793274, obtained by EPMA.

	ANT-Breccia		Anorthositic matrix glass	Pyroxenes (highland composition)		Plagioclase (highland composition)	
	bulk	Pl		Px	Px	Pl	Pl
SiO_2	44.7	43.7	42.4	51.8	51.4	44.5	44.3
TiO_2	0.29	0.09	0.30	0.53	0.28	0.03	0.03
Al_2O_3	29.4	37.3	28.0	1.45	2.69	35.8	37.1
Cr_2O_3	0.11	—	0.17	0.51	1.1	0.06	0.05
FeO	4.3	0.73	5.4	18.3	12.8	0.15	0.15
MnO	0.03	0.03	0.20	0.56	0.37	—	—
MgO	5.0	0.55	8.4	20.8	18.8	0.07	0.05
CaO	15.2	14.9	13.4	6.40	12.2	19.5	19.7
Na_2O	0.71	0.40	<0.05	—	—	0.17	0.40
K_2O	0.03	0.09	—	—	—	0.02	0.03
Total	99.78	100.79	98.27	100.39	99.64	100.30	101.81
Remarks		$An_{96.1}$		$En_{58.3}$ $Wo_{12.9}$	$En_{54.1}$ $Wo_{25.2}$	$An_{98.5}$	$An_{96.5}$

Pl = Plagioclase, Px = Pyroxene. All Fe as FeO.

Table 2. Electron microprobe analyses of mare components and co-existing phases in lithic fragments in Y-793274 (in wt%).

	Brown glass	Y-793274,94-B-1				Pyroxenes mare compos.		Y-793274,94-B-2		Y-793274,94-B-4		
		Glass	Ol	Pl	Ol	Px	Px	Px	Px	Pl	Ol Fe-poor	Ol Fe-rich
SiO_2	46.2	47.1	35.9	42.7	35.8	48.2	48.0	47.2	47.4	41.9	35.5	33.9
TiO_2	0.38	0.57	0.02	0.02	0.02	0.88	1.02	0.34	0.50	—	0.11	0.05
Al_2O_3	11.4	18.1	0.07	36.4	0.04	0.85	1.22	0.90	1.52	40.1	0.12	—
Cr_2O_3	0.51	0.36	0.04	—	0.13	0.33	0.34	0.36	0.64	0.09	0.14	—
FeO	17.1	12.3	29.7	0.52	32.6	33.1	25.3	31.4	20.6	0.34	25.3	44.8
MnO	0.25	0.22	0.36	0.07	0.59	0.49	0.29	0.67	0.48	—	0.40	0.63
MgO	14.8	6.00	31.6	0.13	31.4	7.90	9.20	12.2	11.1	0.22	36.6	21.8
CaO	10.2	12.7	0.30	18.3	0.27	8.60	13.8	5.10	15.4	15.2	0.14	0.38
Na_2O	0.19	0.48	—	0.50	—	—	—	—	0.07	0.40	—	—
K_2O	—	—	—	0.06	—	—	—	—	—	—	—	—
Total	101.03	97.90	98.12	98.70	101.00	100.35	99.17	98.25	97.81	98.25	98.31	101.56
Remarks			$Fo_{65.5}$	$An_{95.3}$	$Fo_{63.2}$	$En_{24.2}$ $Wo_{18.9}$	$En_{27.6}$ $Wo_{29.8}$	$En_{36.4}$ $Wo_{10.9}$	$En_{32.9}$ $Wo_{32.8}$	$An_{95.5}$	$Fo_{72.1}$	$Fo_{46.2}$

Px = Pyroxene, Ol = Olivine, Pl = Plagioclase. All Fe as FeO.

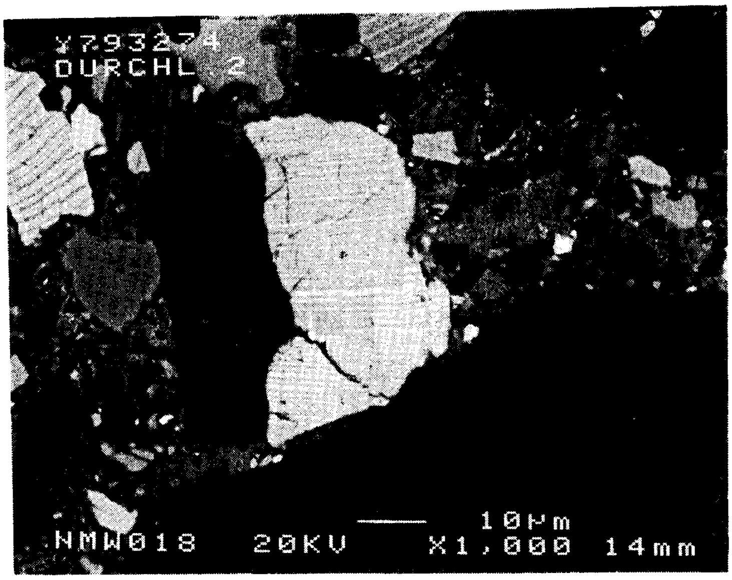

Fig. 6. BSE image of Fe-rich pyroxene with exsolution lamellae associated with silica (on the left side, dark gray) in matrix consisting of mineral fragments and devitrified glass. The large gray clast at the bottom of the image is plagioclase.

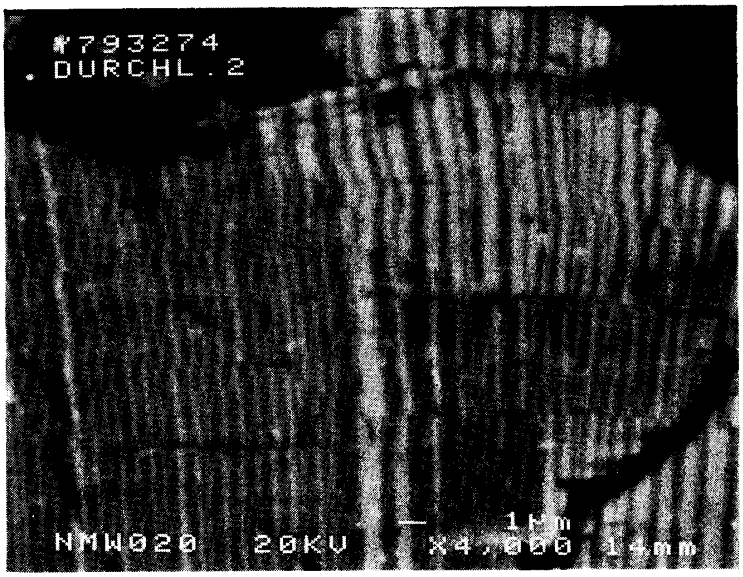

Fig. 7. Part of the pyroxene crystal shown in Fig. 6. The width of the exsolution lamellae varies in different sectors of the crystal. They also show some clearly visible displacements which are most probably due to shock.

there are some pyroxenes that are of highland composition (Table 1), the majority seems to be of mare composition (see Table 2 for representative analyses). Most pyroxenes show characteristic exsolution lamellae (Fig. 6). (There are, however, wider lamellae than the example depicted in Fig. 6.) There is a distinct chemical difference between the individual lamellae in the pyroxene crystals (see, *e.g.*, the B-2 analyses in Table 2). A close-up view of the exsolution lamellae shows clearly that there are displacements running at an angle of almost 90° to the lamellae (Fig. 7). These displacements, which are observed in the majority of the pyroxene fragments in ,94, are most probably due to shock. Such exsolution lamellae have not been observed before in VLT mare basalt pyroxenes. They are, however, in line with previously described compositional trends which are commonly meta-igneous with a distinct tendency for Fe-Mg equilibration between about $Fe/(Fe+Mg)=50–60$ (see, *e.g.*, equilibration trends of meta-ferrobasalt B33 of KURAT and KRACHER (1981), of pyroxene fragments in ALHA81005—Kurat and Brandstätter (1983) and Ryder and Ostertag (1983), and of pyroxenes in Asuka-31—Yanai (1990b)). These exsolution lamellae indicate that the source rocks cooled slowly enough to allow their formation—in contrast to mare rocks, which are usually chilled, and contain "unequilibrated" pyroxenes.

In general, pyroxene compositions (Fig. 8) are highly variable and show a bimodal distribution. The higher *mg*-pyroxenes (Table 1) are compatible with an origin from the lunar highlands, while the low-*mg* pyroxenes (Table 2) are probably of mare origin. Their composition is similar to pyroxenes described from the mare meteorite EET87521 (Warren and Kallemeyn, 1989), Luna 24 ferroan VLT basalts (Kurat and Kracher,

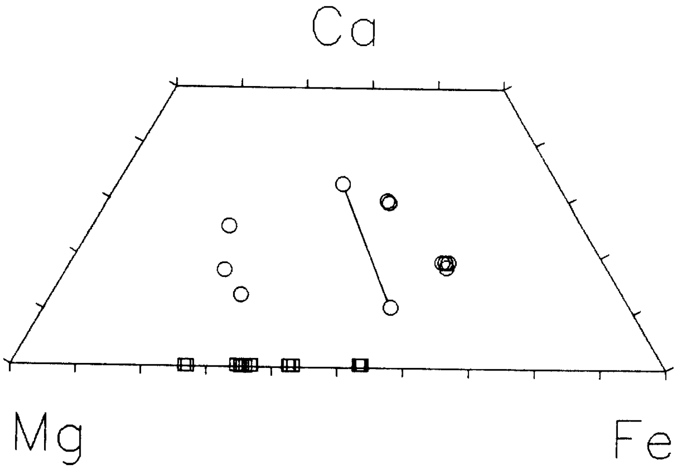

Fig. 8. Pyroxene and olivine compositions from matrix and lithic fragments in Y-793274 in the pyroxene quadrilateral, obtained by electron probe microanalysis. Squares are olivines, and circles are pyroxenes. A highly variable and bimodal distribution of pyroxene compositions is visible and indicates mare components.

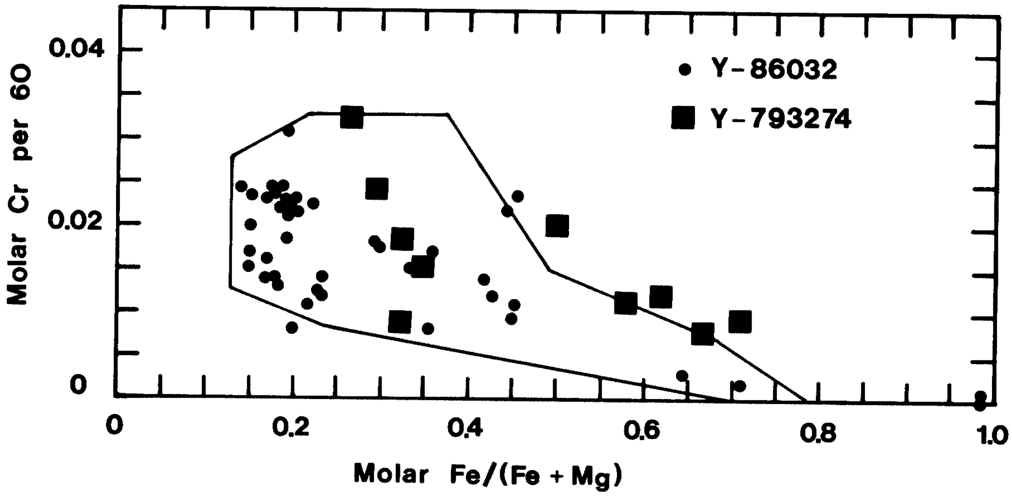

Fig. 9. Molar Cr in Y-793274 pyroxenes vs. molar Fe/(*Fe + Mg*) *ratio, compared to highlands breccia Y-86032, obtained by electron probe microanalysis. The Fe-rich pyroxenes plot partly outside the field defined by highland pyroxene compositions (see, e. g., Koeberl et al., 1990b), indicating the presence of mare components.*

Fig. 10. BSE image of devitrified glass of basaltic composition in sample ,94. Note the variable composition of the glass (different shades of gray) and the dendritic growth. Pyroxenes with exsolution lamellae are also visible.

Table 3. Comparison between Y-793274 bulk and mare components, EET87521, and Apollo and Luna 24 mare basalts (in wt%).

	Y-793274 bulk*	Y-793274 brown glass	EET87521 bulk[1)]	Apollo 15 green glass[2)]	Apollo 17 70008 VLT[2)]	Luna 24 24114 VLT[3)]
SiO_2	48.3	46.2	48.4	44.14	48.1	47.0
TiO_2	0.60	0.38	1.12	0.37	0.36	0.96
Al_2O_3	13.7	11.4	12.6	7.81	11.2	10.5
Cr_2O_3	0.29	0.51	0.21	0.33	0.60	0.18
FeO	15.2	17.1	19.0	21.1	18.2	20.1
MnO	0.22	0.25	0.24	—	0.26	0.27
MgO	9.0	14.8	6.34	16.7	11.0	7.30
CaO	12.2	10.2	11.6	8.41	10.2	13.9
Na_2O	0.46	0.19	0.41	0.13	0.15	0.24
K_2O	0.07	—	0.07	0.03	0.01	0.03
Total	100.04	101.03	99.99	99.02	100.1	100.48

All Fe as FeO.

* Data for Y-793274 bulk from this work (Ti, Cr, Fe, Mn, Mg, Na, K) and LINDSTROM and MARTINEZ (1990) (Si, Al, Ca).

1) WARREN and KALLEMEYN (1989).

2) BASALTIC VOLCANISM STUDY PROJECT (1981).

3) KURAT and KRACHER (1981).

1981), and mineral and VLT basalt fragments in ALHA81005 (TREIMAN and DRAKE, 1983; KURAT and BRANDSTÄTTER, 1983). This bimodal distribution also shows up in a plot of Fe/(Fe+Mg) *vs.* molar Cr content (Fig. 9). Some pyroxenes are magnesian in composition and plot in the field defined by lunar terrae pyroxenes (BASALTIC VOLCANISM STUDY PROJECT, 1981), similar to pyroxenes in, *e. g.*, Y-86032 (KOEBERL *et al.*, 1990). Others plot outside the field and are similar to Luna 24 VLT ferrobasalts (KURAT and KRACHER, 1981).

Other mare components were found among some large devitrified glass fragments

Fig. 11. BSE image of an intergrowth of silica (dark gray) and K-feldspar (lighter gray) in sample ,93.

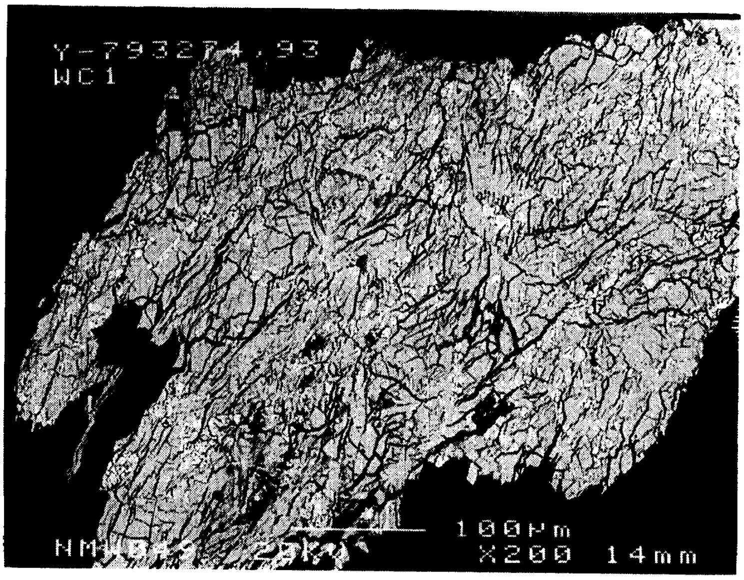

Fig. 12. BSE image of sample Y-793274,93—WC1 (white clast # 1, see Table 5 for minor and trace element composition), a shocked meta-igneous rock of ANT composition.

Fig. 13. BSE image of a meta-anorthositic gabbro clast from sample ,93 (part of clast WC2, see Table 5 for trace element data). The light gray ferromagnesian mineral in the upper part of the image is olivine, while the slightly darker mineral in the lower part is pyroxene.

(Fig. 10). The analysis of a similar dark brown glass (left part of Fig. 5; column 1 in Table 2) shows a very interesting composition. Its normative composition is highly mafic with 23 mol% olivine, 44 mol% pyroxene, and 32 mol% plagioclase of An_{95}. This composition is unusual for lunar highland rocks and shows some similarity to Apollo 15 green glass (see Table 3 and discussion below). The glass in part B-1 of section ,94 (Table 2) is considerably more mafic than typical highland glass and indicates admixture of a low-*mg* component of mare provenance.

Olivine compositions analyzed range from Fo_{46-72} (Fig. 8), and the Fe-poor and Fe-rich endmembers are given in Table 2 (last two columns). Several grains of silica with only minor concentrations of other elements were encountered. An unusual intergrowth of silica with K-feldspar was also found (Fig. 11) and may be classified as a pristine alkali-feldspar granite. These intergrowths are rare in lunar rocks (*e.g.*, SCLAR and BAUER, 1974). Similar lunar "granites" have been observed in Apollo 14 breccias (WARREN *et al.*, 1983) and may be the product of a (late stage) crystallization from a melt of K-feldspar + quartz.

Figure 12 shows a BSE image of clast ♯1 (see trace element section). Microprobe analyses show that it is a meta-igneous rock of ANT-composition (gabbroic anorthosite). It is very rich in plagioclase crystals and possibly is a member of the Mg-suite highland rocks. The clast is heavily cracked; this is probably due to shock fragmentation. Figure 13 shows part of clast ♯2, isolated from sample ,93. After INAA, a polished section was prepared (during which the clast broke into two fragments). Both fragments consist of a large meta-igneous rock fragment of ANT composition (about 2/3 of the total sample) and adhering compact matrix. The ANT fragment is rich in plagioclase (though not as rich as clast ♯1) and contains some olivine and pyroxene, probably of the Mg-suite. The fragment appears to be heavily shocked.

4.2. *Metal grains, and barringerite from the moon*

Few metal grains were encountered in our sections. Table 4 gives representative metal compositions. The composition of kamacite is similar to H-chondritic metal and is typical for the admixture of a meteoritic component, similar to grains observed in lunar soil and in the highland meteorite MAC88105 (KOEBERL *et al.*, 1990a). The composition of a taenite grain (Fig. 14) is also given in Table 4. This composition is rather unusual, because normally taenite shows lower Co abundances than kamacite, while here Co is relatively high (above 1%), which is not too common in metal particles from lunar rocks (see, *e. g.*, Fig. 7 in WARREN *et al.* (1982)). The high Co

Tabe 4. Electron microprobe analyses of metal and phosphide phases in Y-793274 (in wt%).

	Kamacite		Taenite		Barringerite	
Fe	91.8	91.8	81.4	81.5	75.3	74.8
Co	0.65	0.64	1.06	1.04	0.20	0.21
Ni	6.00	6.00	15.1	14.9	1.35	1.30
P	0.12	0.13	—	0.01	22.7	22.8
S	0.05	0.05	—	—	—	—
Total	98.62	98.62	97.56	97.45	99.55	99.11

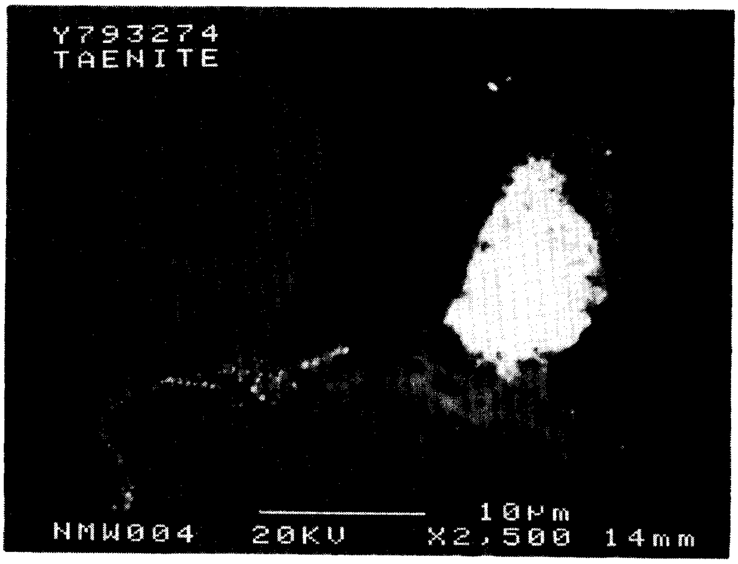

Fig. 14. BSE image of a taenite grain in sample ,94. On the lower left side of the image numerous small metal grains can be seen embedded in a glass "worm".

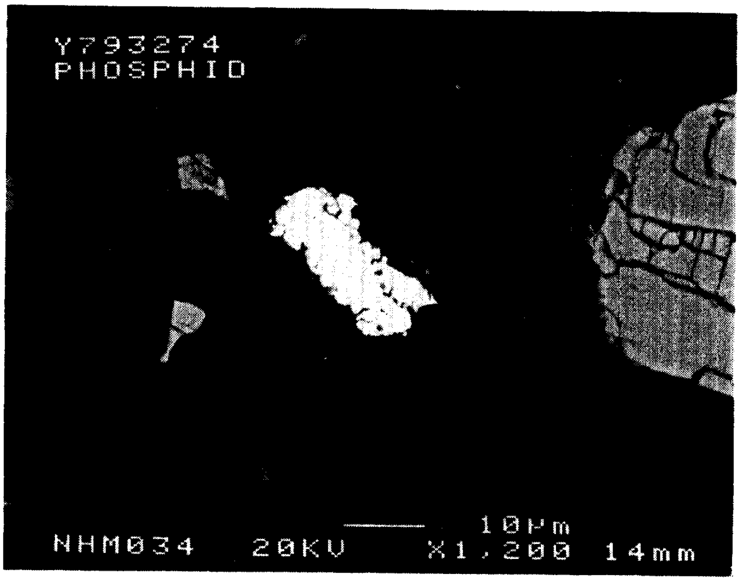

Fig. 15. BSE image of a grain (light gray, center) of the mineral barringerite, $(Fe,Ni)_2P$, in sample ,94. The is the first time this mineral is found in lunar rocks (see BRANDSTÄTTER *et al., 1991).*

composition is not in equilibrium with kamacite, and might be a martensite rather than taenite. Even in bulk iron meteorites, Co contents above 1 wt% are only very rarely found and restricted to a few anomalous iron meteorites (BUCHWALD, 1975). No sulfides have been encountered.

The search for opaque phases, however, yielded a very interesting discovery. One grain turned out to be a phosphide, containing about 23 wt% P (Fig. 15). From the composition it was identified as barringerite, $(Fe,Ni)_2P$, a rare higher phosphide. Barringerite was first described from a pallasite by BUSECK (1969), where it occurs along the contacts between troilite and schreibersite. The barringerite from this occurrence, however, shows a high Ni content (about 34 wt%), which differs from our fragment (containing only about 1.3% Ni). It is therefore closer to an iron barringerite described from China by CHEN *et al.* (1984). Barringerite is a very rare mineral, and this grain is the first reported from lunar rocks, and probably the first confirmed cosmic occurrence (see BRANDSTÄTTER *et al.* (1991), for more details on the barringerite).

4.3. *Bulk and trace element composition*

The bulk composition of Y-793274 is given in Tables 3 and 5. Table 5 gives the results of our trace element analyses of a bulk and two clast samples by INAA, and comparison data for other selected lunar meteorites. It is obvious that the general

Table 5. Trace elements in Y-793274 and comparison data, by neutron activation analysis.

	Y-793274 bulk 28.88 mg	Y-793274 clast1 0.14 mg	Y-793274 clast2 0.76 mg	EETA87521 bulk1)	MAC88105 bulk2)	Y-86032 average3)
Na (%)	0.34	0.65	0.41	0.31	0.29	0.32
K	550	—	—	570	190	165
Ca (%)	8.73	14	15.8	8.34		
Sc	31.9	6.47	19.4	44.0	8.64	8.27
Cr	2010	720	1270	1470	655	666
Mn	1680	880	1380	1890	520	458
Fe (%)	11.8	5.13	8.29	14.9	3.34	3.27
Co	41.4	73.2	39.5	46	16.1	14.4
Ni	100	<1400	280	29	163	131
Zn	49	100	61	3.1	29	9.1
Ga	4.04	5.0	5.3	5.27	4.12	3.66
As	0.053	<1	0.27	—	0.06	0.27
Se	0.28	3.3	<1	—	0.26	0.4
Br	0.21	0.8	<0.8	<0.4	0.12	0.12
Rb	<2	<200	<30	<4	0.9	<1
Sr	100	<1000	<350	104	150	161
Zr	81	<2000	<300	140	44	27
Sb	0.048	<1	0.10	—	0.04	<0.015
Cs	0.1	<5	0.6	0.041	0.059	0.05
Ba	97	<1000	<200	88	25	27
La	7.00	17.4	13.4	8.3	2.54	1.33
Ce	17.9	35.7	28.1	20.9	6.41	3.51
Nd	12.0	—	19.2	13.0	4.1	1.88
Sm	3.56	6.3	5.96	3.86	1.22	0.63
Eu	0.96	0.89	1.02	0.98	0.77	0.93
Gd	4.19	—	7	—	1.3	0.9
Tb	0.76	1.4	1.28	0.80	0.26	0.15
Dy	4.64	9.0	8.0	4.8	1.71	1.5
Yb	2.73	5.95	4.14	3.19	1.05	0.60
Lu	0.376	0.9	0.62	0.48	0.16	0.087
Hf	2.96	<7	5.1	2.88	0.88	0.47
Ta	0.34	<4	0.5	0.37	0.09	0.06
W	0.19	<1.5	1.0	—	0.2	0.36
Ir (ppb)	6.2	<5	3	0.51	5.8	5.3
Au (ppb)	3	<15	<10	0.22	3.5	2.4
Th	1.05	3.5	1.9	0.95	0.33	0.22
U	0.26	1.3	0.44	0.23	0.095	0.051

All data in ppm, except where marked.

References: 1)WARREN and KALLEMEYN (1989, 1991), 2)KOEBERL *et al.* (1990), 3)KOEBERL *et al.* (1989).

trace element chemistry is unlike the previously analyzed lunar highland meteorites (*e. g.*, MAC88105 and Y-86032), but somewhat similar to the newly identified mare meteorite EET87521 (WARREN and KALLEMEYN, 1989). The agreement between our data and the data of other laboratories (LINDSTROM and MARTINEZ, 1990; LINDSTROM *et al.*, 1991; WARREN and KALLEMEYN, 1990, 1991; FUKUOKA, 1990) is generally very good. However, the meteorite seems to be rather inhomogeneous, as documented by the differences between the individual analyses of different laboratories, and between the laboratories themselves.

Some volatile elements show a larger spread, and/or larger differences between the individual laboratories. This spread is obvious for elements such as Ga, Se, Sb, and Au. Our Au content of 3 ppb is in good agreement with the whole rock range of 0.31–10.7 ppb obtained by RNAA by LINDSTROM *et al.* (1991), and with the 2.4 ppb of WARREN and KALLEMEYN (1991). The Zn content shows a larger disagreement between our INAA result and the RNAA data of LINDSTROM *et al.* (1991). However, our (higher) value is the average of three counts that gave virtually the same result; in addition, a sample of Allende (which is usually incorporated with all our meteorite analyses for precision control) showed (within 3 rel. %) the literature value of Zn. We therefore have to assume sample inhomogeneity as the cause for this discrepancy.

Figure 16 gives the classical Fe/Mn plot, which is further proof of the lunar origin of Y-793274. All lunar meteorites (black dots) plot on or close to the line defined by the lunar Fe/Mn ratio, and far from the field occupied by the HED achondrites (WARREN *et al.*, 1989). The anorthositic highland meteorites cluster in the part of the diagram with lower Fe and Mn contents, while the dot with the highest Fe content

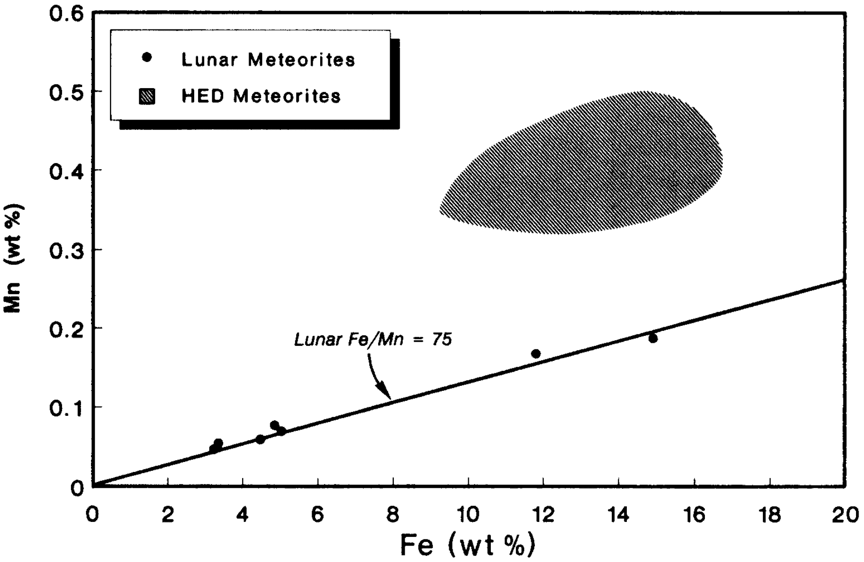

Fig. 16. Ratio of Fe vs. Mn in bulk lunar meteorites. All lunar meteorites plot on or near the line defined by the composition of lunar rocks (Fe/Mn=75), and far from the field defined by HED achondrites (WARREN and KALLEMEYN, 1989), which is additional proof of the lunar origin of these samples. Y-793274 is the sample with the second-highest Fe content, while the one with the highest Fe content is EET87521. The other lunar meteorites cluster at lower Fe abundances, typical for highland rocks.

represents the mare meteorite EET87521. Y-793274 has the second-highest Fe and Mn contents, and thus plots at a position that is intermediate between the mare and highland meteorites. It has been noticed before mainly from petrological studies that Y-793274 contains mare and highland components and therefore comprises a mixture of these two components at a ratio of approximately 2: 1 (LINDSTROM and MARTINEZ, 1990; TAKEDA *et al.*, 1990; WARREN, 1990; KURAT *et al.*, 1990; this work). This is also supported by our geochemical studies. Another indication for this mixture comes from Fig. 17, which shows a plot of molar Mg/(Mg+Fe) *vs.* Sm content. Y-793274 again plots in between EET87521 and the cluster defined by the highland meteorites.

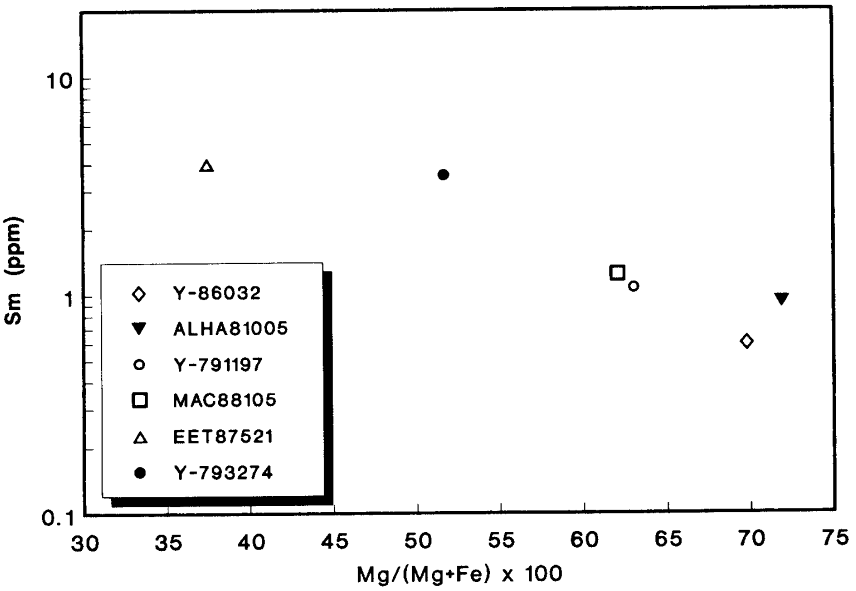

Fig. 17. Mg-number vs. Sm content in the bulk samples of lunar meteorites. The highland meteorites (ALHA81005, Y-791197, Y-86032, and MAC88105) cluster at lower Sm and higher mg-values, EET87521 shows a mare composition, while Y-793274 has an intermediate composition, in agreement with the mixture between mare and highland components.

It is interesting to consider the bulk chemical composition of Y-793274, and its similarity to other lunar materials. Table 3 gives such a comparison. It is obvious that there are some similarities to EET87521 as well as to Apollo 17 and Luna 24 VLT basalts. This relation becomes even more obvious in a plot of molar Mg/(Mg+Fe) *vs.* TiO_2 content (Fig. 18). In this diagram, the high Ti basalts, low Ti basalts, and VLT basalts occupy distinctly different areas (BASALTIC VOLCANISM STUDY PROJECT, 1981). The bulk composition of Y-793274 plots clearly within the field defined by VLT basalts. The same is true if certain mineral fragments or the brown glass of basaltic composition (Table 2) would be plotted in this diagram. This is another clear indication of a VLT mare basalt component in Y-793274.

Other trace elements show a similar relation to the composition of EET87521. This relation is especially obvious for most lithophile refractory elements, such as Ca, Sc, Sr, Zr, Ba, the REE, Hf, Ta, Th, and U. It should be noted that some of this

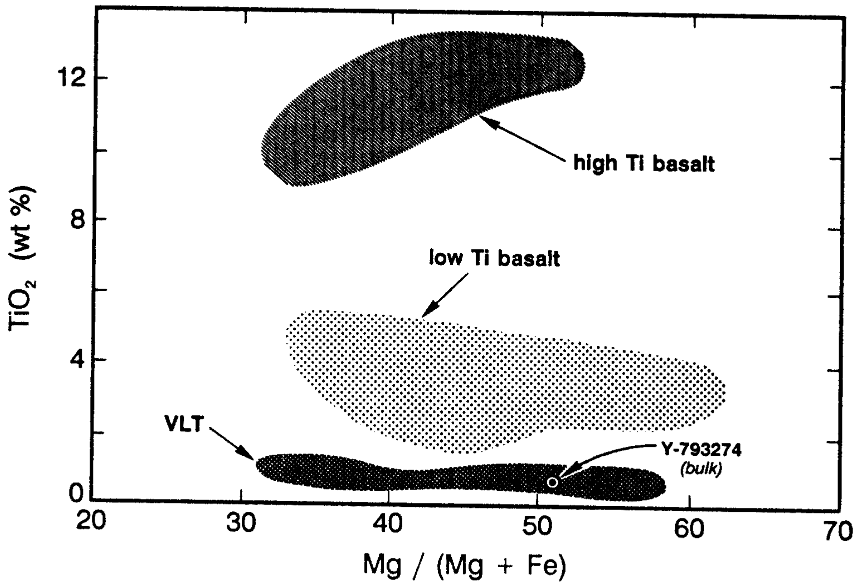

Fig. 18. Plot of mg-number (molar Mg/(Mg+Fe)) vs. TiO_2 content. The shaded areas represent the different types of lunar mare basalts (Basaltic Volcanism Study Project, 1981). The bulk composition of Y-793274 plots clearly within the VLT-basalt area and therefore indicates association of Y-793274 with this type of mare basalt.

similarity also extends to certain Luna 24, Apollo 14, and Apollo 17 basalts, as given in Warren and Kallemeyn (1989) (however, these VLT basalts are free of highland KREEP contamination and therefore have lower REE abundances than Y-793274 or EET87521). The contents of these trace elements (and some others) are distinctly different from the compositions of the highland meteorites, *e. g.*, MAC88105 (Koeberl *et al.*, 1990a; Palme *et al.*, 1990; Lindstrom *et al.*, 1990; Warren *et al.*, 1990), Y-86032 (Koeberl *et al.*, 1989, 1990b; Eugster *et al.*, 1989), Y-82192 (Warren and Kallemeyn, 1987; Koeberl, 1988), Y-791197 (Warren and Kallemeyn, 1986; Koeberl, 1988), or ALHA81005 (Palme *et al.*, 1983).

The chondrite normalized REE element patterns of the Y-793274 bulk sample and the two clasts are given in Fig. 19. The higher REE concentrations and the negative Eu anomaly are in clear contrast to the lower REE concentrations and the large positive Eu anomaly commonly displayed by the anorthositic highland meteorites and may indicate a KREEP component in Y-793274. From the petrology of clasts ♯1 and ♯2, a positive Eu anomaly would be expected; this is not observed. At present we do not have a conclusive explanation for this behavior (but KREEP contamination from glass within the clasts might be possible).

Figure 20 gives the REE pattern of Y-793274 in comparison with the bulks of other lunar meteorites. As mentioned above, a very close similarity exists between Y-793274 and EET87521. It should be noted, however, that neither EET87521 (Warren and Kallemeyn, 1989) nor Y-793274 shows a REE pattern that is identical to most VLT basalts. Even though some components of Y-793274 (the brown basaltic glass) are similar in composition to Apollo 15 green glass (Table 3), the REE patterns of Apollo 15 green glass (Ma *et al.*, 1981) are different from the Y-793274 patterns. The closest similarity can be observed with some Apollo 14 green volcanic glasses

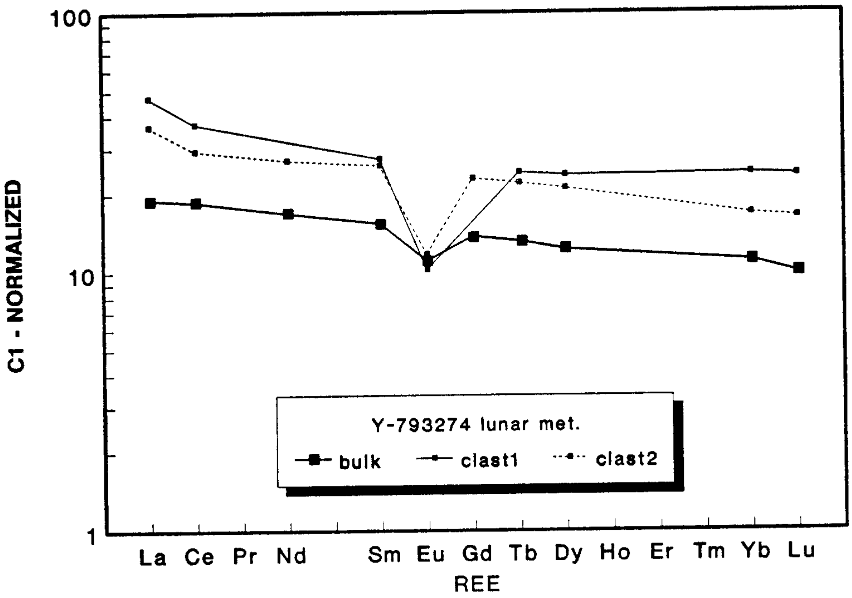

Fig. 19. Cl-normalized REE abundance patterns of a bulk and two clast samples from Y-793274,93. Normalization factors from Taylor *(1982).*

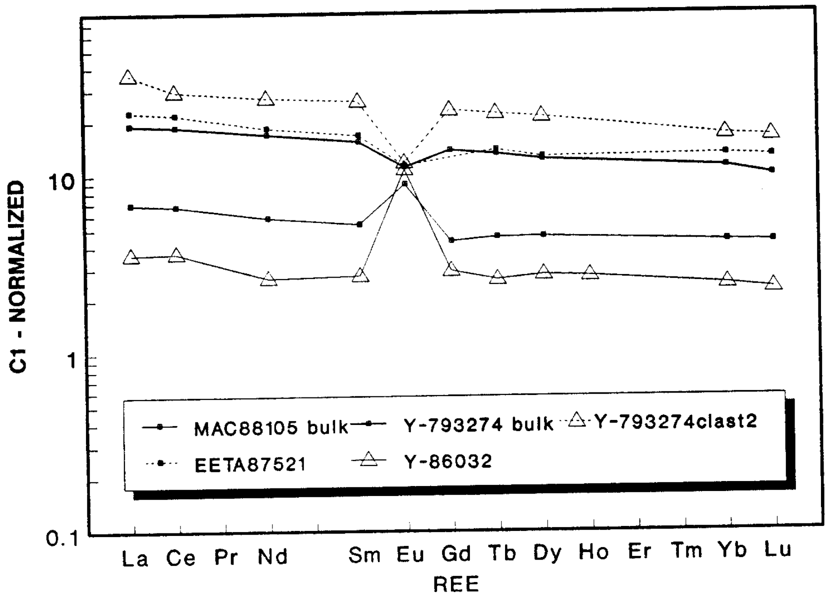

Fig. 20. Cl-normalized REE abundance patterns in Y-793274 compared to other lunar meteorites (for data sources see Table 5). A close similarity of the pattern with EET87521 is clearly visible.

recently analyzed by ion microprobe by Shearer *et al.* (1990); however, they are different from Apollo 14 VLT glasses.

The siderophile element content of Y-793274 is in part similar to that of other lunar meteorites. A chondrite-normalized plot of the siderophile elements Ni, Co, Ir, Au, and Se is given in Fig. 21. Most highland rocks show similar siderophile element patterns, indicating the admixture of a meteoritic (chondritic?) component

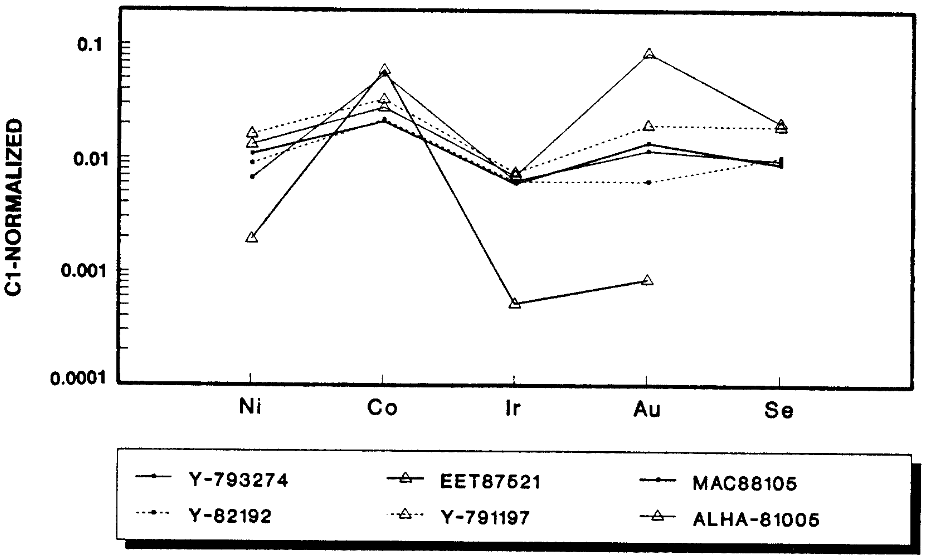

Fig. 21. Siderophile elements in Y-793274 (bulk) and other lunar meteorites, normalized to C1-chondrites (normalizing factors from Taylor*, 1982). For data and sources see Table 5. The Co enrichment is characteristic of all lunar meteorites. EET87521 contains much lower Ir and Au abundances because it is composed of relatively pure VLT mare basalt.*

as also observed in lunar regolith. ALHA81005 and EET87521 show patterns that are somewhat different from the other samples (for EET87521, Ir and Au are very low at 0.51 and 0.22 ppb, respectively; Warren and Kallemeyn, 1991). The concentrations in EET87521 are lower than in Y-793274 because Y-793274 is a mixed regolith breccia, while EET87521 is a fragmental breccia composed of almost pure VLT basalt (Warren and Kallemeyn, 1989, 1991). Y-793274 seems to be intermediate between EET87521 and the highland samples (lower Ni, higher Co—note the occurrence of high Co taenite; see Section 4.2); however, Ir and Au show normal abundances.

4.4. Pairing with other lunar meteorites

From the present data, any direct pairing of Y-793274 with any other lunar meteorite known so far is highly unlikely. The chemistry of Y-793274 is distinctly different from the seven anorthositic highland meteorites (which, from cosmic ray exposure and noble gas data, are thought to represent at least two, but probably four individual sources; Eugster, 1988, 1989; Eugster *et al.*, 1986, 1989; Takaoka and Yoshida, 1990; Vogt *et al.*, 1990). This difference is also confirmed in a Pb-isotopic study by Tatsumoto (1990).

Y-793274 is also distinct from the other basaltic meteorites, Asuka-31, and Y-793169, which, however, have not yet been analyzed in detail (Yanai, 1990a, b; Yanai and Kojima, 1990). Eugster (1990), on the other hand, finds similarities between Y-793274 and ALHA81005 from cosmic ray produced and solar wind noble gases. In view of the obvious differences in mineralogy, petrology, and geochemistry between ALHA81005 and Y-793274, and the geographical separation of the finding locations, any such relationship is either by chance, or the impact has excavated a highly inhomogeneous source region on the boundary between mare and highland regions.

5. Conclusions

We have studied the mineralogy, petrology, and geochemistry of two sub-samples (,93 and ,94) of Yamato-793274. Y-793274 is clearly a lunar meteorite, as demonstrated by its bulk and mineral composition, its Fe/Mn ratio, and the major and trace element content. The meteorite is a dense breccia containing large and abundant mineral fragments (pyroxene, plagioclase, ilmenite), rare fine-grained granulitic breccias, meta-meltbreccias, and some brownish devitrified glass. The matrix is dense and consists of mineral fragments and interstitial glass. One large recrystallized ANT melt breccia was found. Plagioclase compositions are highly anorthitic and compatible with an origin from the lunar highlands. During the search for opaque phases, kamacite of H-chondritic metal composition, and a Co-rich taenite were found. In addition, we also encountered a grain of a rare higher phosphide, barringerite, which is the first occurrence of this mineral reported from lunar rocks, and probably the first confirmed extraterrestrial occurrence (see BRANDSTÄTTER *et al.*, 1991).

Some glasses in Y-793274 have a mafic composition and show admixture of a low-*mg*-component. Pyroxenes and silica are much more abundant than in normal highland meteorites and show a bimodal distribution of their compositions. The bimodal composition indicates highland and mare components. The bulk composition is unlike the previously studied anorthositic lunar meteorites and shows definitive similarities with the mare meteorite EET87521. The content of certain trace elements, mainly the lithophile refractories and the REE, as well as the mineral composition of certain phases, indicates a relation to VLT basalts. It is interesting to note that also EET87521, and possibly the newly described mare meteorites Asuka-31 and Y-793169, show components that seem to be of VLT heritage—a rather uncommon basalt variety among the Apollo and Luna samples. It seems that the composition of the lunar crust may be different from the expected composition that has been extrapolated from the Apollo and Luna coverage.

In conclusion, Y-793274 is a shock lithified fragmental breccia containing only a minor regolith component but an unusually high proportion of mafic mineral fragments, mostly ferroan pyroxenes of non-highland composition. This meteorite is distinctly different from previously described lunar highland meteorites because in addition to a typical highland component it contains a large mare component of possible VLT heritage. It also seems to contain a small KREEP component. From the mineralogical and geochemical data there is no indication for pairing with any of the other lunar meteorites known at this time. Any similarity with ALHA81005 in cosmic ray exposure data is either coincidental or indicative of an impact at a highlands-mare boundary. Y-793274 contains about two thirds of mare components and about one third of distinctive highland components.

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