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Compositional constraints on the launch pairing of three brecciated lunar meteorites of basaltic composition

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Abstract: Lunar meteorite EET 87/96 (paired stones Elephant Moraine 87521 and 96008) is a breccia consisting of fragments of a solidified, differentiated magma of basaltic composition. Small splits of the meteorite vary considerably in composition because they are heterogeneous mixtures of (1) a low-FeO differentiate with high Mg/Fe, high Cr/Sc, high Ca/Na, and low concentrations of incompatible elements and (2) a high-FeO differentiate with complimentary geochemical characteristics. Y79/98 (paired stones 793274 and 981031) and QUE (Queen Alexandra Range) 94281 are regolith breccias consisting of subequal proportions of material from the feldspathic highlands and fragments of mafic volcanic rock of mare-basalt-like composition. Previous studies have shown that (1) QUE 94281 and Y79/98 are very similar to each other and likely derive from the same source crater, (2) the texture and mineralogy of the volcanic components of all three meteorites are similar to each other yet distinct from mare basalts of the Apollo collection, and (3) all three meteorites were launched from the Moon at about the same time. We show that the volcanic component of Y 79/98 and QUE 94281 are compositionally indistinguishable from a point on the EET 87/96 mixing line. Thus, there is no compositional impediment to the hypothesis that all three meteorites originate from the same place on the Moon and were launched by a single impact.

key words: lunar meteorites, meteorite pairing, mare basalt, impact crater, geochemistry

1. Introduction

The subjects of this study are rocks originating from near the surface of the Moon that were (1) ejected from the Moon because they were accelerated to lunar escape velocity by impact of asteroidal meteoroids or possibly comets, (2) achieved orbits that eventually intersected the Earth, (3) survived passage through Earth's atmosphere, (4) landed intact in uninhabited and inhospitable places, (5) were found by humans thousands of years later, and (6) were recognized to be of lunar origin. Although the scenario constitutes a sequence of improbable events, we know that it has occurred approximately two dozen times, and we can reasonably assume that the first four steps have occurred countless times over solar system history and that the last two will occur again.

Most lunar meteorites originate from the feldspathic highlands; about a third derive from the basaltic maria or from near a boundary between a mare and the highlands (Fig. 1). This distribution is qualitatively reasonable for random source locations on a Moon dominated by feldspathic highlands and for which volcanic deposits cover only 17% of the surface (Head and Wilson, 1992). In this paper we present new compositional data for five meteorite samples that originate from regions of the Moon dominated by volcanic rocks; all were found in Antarctica. Y (Yamato) 981031 is a recently found regolith breccia (Kojima and Imae, 2000) consisting of subequal proportions of mafic volcanic and feldspathic highland materials. We show that Y981031 is almost indistinguishable from Y-793274 in composition, although it is somewhat more feldspathic. Our compositional data corroborate the conclusion of preliminary petrographical,

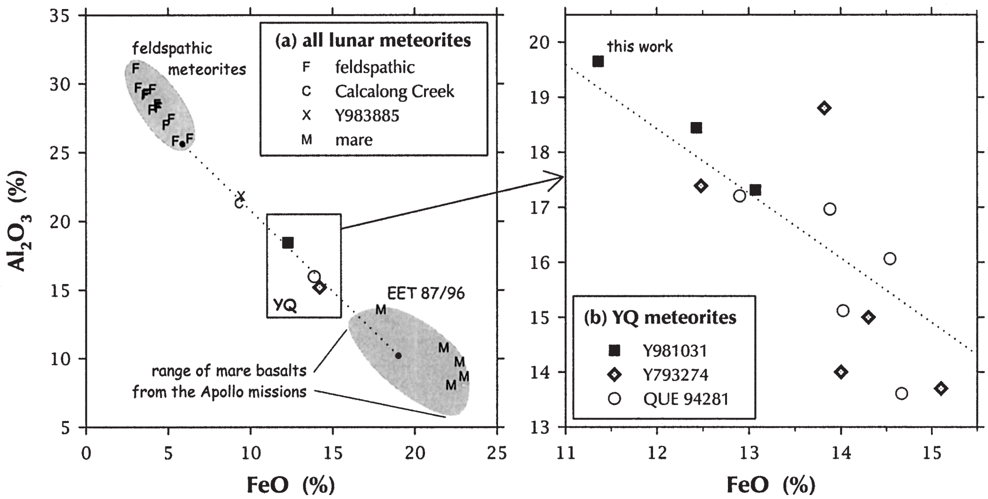

Fig. 1. *(a) Each point (letter or geometric symbol) represents the mean composition of a lunar meteorite. Except for paired stones Y-793274 and Y981031, known pairs are represented by a single point. Feldspathic meteorites ("F," e.g., Y-86032) originate from the highlands; all are breccias. Meteorites from the maria ("M") are either breccias (EET 87521 and EET 96008 at 18–19% FeO) or crystalline basalts (21–23% FeO, e.g., Y-793169). The YQ meteorites (and, probably, Calcalong Creek and Y983885) are breccias that are mixtures of FeO-rich volcanic and FeO-poor highland materials. The dotted line segment is a mixing line defined by the compositions of the inferred feldspathic and mare components of QUE 94281 (Jolliff et al., 1998). (b) Splits of the YQ meteorites contain variable proportions of mare and highland components; the split analyzed here by FB-EMPA (Table 3) is the most feldspathic (lowest FeO). Data are from the following sources: Arai and Warren (1999), Bischoff et al. (1987, 1998), Boynton and Hill (1983), Fagan et al. (2002), Fukuoka (1990), Fukuoka et al. (1986a,b), Greshake et al. (2001), Hill et al. (1991), Jolliff et al. (1991, 1998), Kaiden and Kojima (2002), Kallemeyn and Warren (1983), Karouji et al. (2002), Koeberl (1988), Koeberl et al. (1989, 1990, 1991a,b, 1993, 1996), Kojima and Imae (2000), Korotev et al. (1983, 1996), Laul et al. (1983), Lindstrom et al. (1986, 1991a,b, 1995), Ostertag et al. (1986), Palme et al. (1983, 1991), Spettel et al. (1995), Taylor et al. (2001a, b), Thalmann et al. (1996), Warren and Kallemeyn (1986, 1989, 1991a,b, 1993, 2001), Warren et al. (2001), and unpublished data of this laboratory.*

mineralogical, and cosmic-ray exposure studies showing that Y-793274 and Y981031 are paired (Arai *et al.*, 2002a,b; Lorenzetti and Eugster, 2002). We also compare Y-793274/981031 to QUE (Queen Alexandra Range) 94281 because there are similarities in composition, mineralogy, texture, and cosmic-ray exposure ages between the two meteorites (Jolliff *et al.*, 1998; Arai and Warren, 1999; Nishiizumi *et al.*, 1999). These similarities are so strong that, although the meteorites are not paired in the usual sense (they were found about 2500 km apart), the Yamato stones almost surely derive from the same place on the Moon as QUE 94281 and were launched from the Moon by a single impact (Arai and Warren, 1999). Here, we refer to the two Yamato stones together as Y79/98 and, following the lead of Arai and Warren (1999), we refer to Y79/98 and QUE 94281 together as YQ.

We also report new compositional data for EET (Elephant Moraine) 87521 and EET 96008, which are breccias with basaltic compositions and mineralogies. Because the two stones are paired (Lindstrom *et al.*, 1999; Mikouchi, 1999; Nishiizumi *et al.*, 1999; Snyder *et al.*, 1999a,b; Warren and Ulff-Møller, 1999; Eugster *et al.*, 2000), we will refer to them together as EET 87/96. We show that EET 87/96 likely consists of fragments of a solidified basaltic magma that had differentiated. We also show that (1) the volcanic components of YQ and EET 87/96, in addition to having many textural and mineralogical similarities (as shown by others), are compositionally indistinguishable and (2) there are, therefore, no significant impediments to the hypothesis (Arai and Warren, 1999; Warren and Ulff-Møller, 1999) that they were launched from the Moon by a single impact. Finally, we report new data for crystalline mare basalts Y-793169 and A (Asuka)-881757 and make compositional comparisons to the other meteorites from the lunar maria. A-881757 and Y-793169 have already been well described compositionally and petrographically (Takeda *et al.*, 1993; Koeberl *et al.*, 1993; Warren and Kallemeyn, 1993; Arai *et al.*, 1996; Oba and Kobayashi, 2001).

2. Samples and analysis

For chemical analysis, we used an approach that we have used for other lunar meteorites (Jolliff *et al.*, 1991, 1998; Korotev *et al.*, 1996; Fagan *et al.*, 2002). We first subdivided our allocated sample of each meteorite into several to many small splits for analysis by instrumental neutron activation (INAA, Korotev, 1991), a technique that provides concentrations for about 25 elements, mostly trace elements, in a nearly nondestructive manner. The compositional variation among small splits provides useful information about the components of a rock. We then select a representative INAA split (or unirradiated material), fuse it on a molybdenum strip heater, and analyze the resulting glass bead with an electron microprobe (Jolliff *et al.*, 1991). This technique, FB-EMPA (fused bead electron microprobe analysis), provides "whole rock" data for the major elements.

For Y981031, we subdivided the allocated sample into six splits for INAA by breaking it in an agate mortar and pestle. Each split consisted of 1–2 chips that ranged in mass from 23 to 39 mg. We were allocated two samples of EET 87521 and three samples of EET 96008. We subdivided the EET 87/96 samples by breaking them in an agate mortar and pestle. In total, we analyzed 7 splits of EET 87521 (mean mass: 53

mg, range: 29–64 mg) and 17 splits of EET 96008 (mean mass: 30 mg, range: 12–48 mg) by INAA. Each split consisted of 1 to 4 chips or residual fines. We received samples of A-881757,82 and Y-793169,83 as powders (Yanai *et al.*, 1993; Warren and Kallemeyn, 1993). For INAA, we analyzed three 72–77-mg splits of the A-881757 powder in one experiment. On the basis of elements determined with high precision, the powder is uniform in composition at the 75-mg mass level (Table 1). In a separate experiment, we analyzed the 19-mg sample of Y-793169 along with a 19-mg split of the A-881757 powder by INAA. The composition of the small split of A-881757 agrees well with the average of the three large splits, except that for Cr the concentration value is 2.3% greater in the 19-mg split. Table 2 presents the INAA results in the form of mass-weighted mean compositions of all analyzed splits of each of the five meteorite samples. Several of the figures, however, present data for the individual splits.

For FB-EMPA, we prepared two glass beads of A-881757 by fusing 10–15 mg of the powder on a molybdenum strip heater. For Y-793169, we powdered the neutron-irradiated sample and prepared two fused beads. For Y981031, we powdered all residual fines from crushing and prepared four beads from the powder. For elements that we determine in common by INAA and FB-EMPA, our results agree within analytical uncertainty except that (1) in some cases concentrations of Na obtained by FB-EMPA are only ~90% of those obtained by INAA and (2) for Y981031, Fe and Cr are 5–7% lower in the FB-EMPA splits (Table 3a). The difference for Na likely results from volatilization and loss of some Na during fusion, although the degree of loss is variable (~5–10%) because the amount of electrical power applied to the Mo strip during fusion cannot be reproduced exactly from sample to sample. We discuss the discrepancy for Y981031 in more detail below. Our INAA results for EET 87/96 show the meteorite to be very heterogeneous at the small mass of our splits, a characteristic that provides some useful information, as we demonstrate in the next section. We fused all or a portion of five of the neutron-irradiated splits and made a single bead of each for FB-EMPA (Table 3b). Because of the large intersplit variability, we have no reason to believe that any of the individual splits, or any type of mean calculated from the split data, necessarily represents well "average" EET 87/96.

Table 1. Relative sample standard deviations (RSD, in %) for some elements determined with high-precision by INAA in three 70–80 mg samples of Asuka-881757 powder.

	RSD		RSD
Na	0.79	La	2.5
Sc	0.22	Sm	1.2
Fe	0.25	Eu	3.1
Cr	0.28	Yb	1.6
Co	0.24	Hf	3.8

Table 2. Mean results of INAA.

	unit	Asuka-881757	Yamato-793169	anal. unc.	QUE 94281	Yamato 981031	anal. unc.	Y98 s.d.	EET 87521	EET 96008	anal. unc.
		1	2	3	4	5	6	7	8	9	10
Na_2O	%	0.254	0.280	0.003	0.396	0.413	0.004	0.013	0.403	0.387	0.004
CaO	%	11.9	12.2	0.6	12.7	13.1	0.3	0.3	12.8	11.9	0.6
Sc	μg/g	93.9	80.7	0.9	28.9	25.1	0.3	0.8	34.2	37.2	0.004
Cr_2O_3	%	0.302	0.231	0.003	0.261	0.285	0.003	0.018	0.267	0.285	0.003
FeO(t)	%	23.0	21.0	0.3	13.30	12.23	0.13	0.53	16.64	18.66	0.18
Co	μg/g	24.1	19.7	0.3	45.6	39.8	0.5	2.9	45.7	48.9	0.5
Ni	μg/g	<150	<170		295	150	20	14	80	60	40
Sr	μg/g	140	170	70	115	120	20	12	100	95	30
Zr	μg/g	135	<350	90	95	100	40	8	100	105	40
Cs	μg/g	<0.7	<0.7		<0.2	<0.15			<0.2	<0.2	
Ba	μg/g	60	100	30	76	81	9	8	70	69	10
La	μg/g	3.31	4.75	0.10	6.66	6.80	0.07	0.70	6.96	7.06	0.07
Ce	μg/g	9.1	13.2	0.6	17.8	18.8	0.3	1.8	18.0	18.5	0.7
Nd	μg/g	<35	12	3	10	12	2	2	12	11	2
Sm	μg/g	3.00	4.19	0.04	3.17	3.26	0.03	0.35	3.41	3.43	0.04
Eu	μg/g	1.02	1.22	0.07	0.83	0.90	0.02	0.03	0.84	0.80	0.02
Tb	μg/g	0.85	1.10	0.07	0.68	0.67	0.02	0.08	0.72	0.72	0.02
Yb	μg/g	3.57	4.56	0.10	2.44	2.47	0.03	0.22	2.55	2.60	0.04
Lu	μg/g	0.534	0.663	0.010	0.341	0.344	0.006	0.03	0.350	0.363	0.007
Hf	μg/g	2.53	3.19	0.13	2.51	2.48	0.05	0.14	2.57	2.62	0.06
Ta	μg/g	0.32	0.40	0.07	0.32	0.37	0.03	0.06	0.30	0.30	0.03
Ir	ng/g	<12	n.a.		10.7	3.6	1.1	0.7	<8	<7	
Au	ng/g	<9	n.a.		3	2	2	1.0	<9	<8	
Th	μg/g	0.45	0.74	0.03	1.03	1.08	0.04	0.11	1.00	0.90	0.04
U	μg/g	<0.75	<0.3		0.26	0.30	0.06	0.04	0.28	0.21	0.07
N		4	1		28	6			7	17	
mass	mg	246.3	19.0		463.7	177.4			373.2	503.6	

FeO (t)	Total Fe as FeO.
N	Number of splits analyzed.
1,5,8,9	Mass-weighted mean of all splits.
2	Results for a single split. We previously presented the data of columns 1 and 2 in an abstract (Jolliff *et al.*, 1993).
3,6,10	Estimated analytical uncertainty (1-σ) of an analysis of a single split.
4	Mass-weighted mean of 28 splits of QUE 94281 (Jolliff *et al.*, 1998), for comparison.
7	Sample standard deviation of splits of column 5.

3. Results and discussion

3.1. *Elephant Moraine 87521 and 96008*

EET 87/96 is classified as a fragmental breccia (Warren and Kallemeyn, 1989; Warren and Ulff-Møller, 1999; Mikouchi, 1999), but the description of Mikouchi (1999) argues that it is marginally a regolith breccia in that it contains rare agglutinates and glass spherules. The meteorite consists mainly of VLT (very low Ti) mare basalt or gabbro, although it contains some clasts of nonmare derivation (Delaney, 1989; Warren and Kallemeyn, 1989; Arai *et al.*, 1996; Lindstrom *et al.*, 1999; Mikouchi, 1999; Warren

Table 3a. Results of electron microprobe analysis of fused beads (FB-EMPA) and comparison to results from instrumental neutron activation analysis (INAA).

	Asuka-881757		Yamato-793169		Yamato 981031	
	mean	±	mean	±	mean	±
			FB-EMPA			
SiO_2	46.1	0.5	46.4	0.5	45.90	0.15
TiO_2	2.4	0.2	2.11	0.08	0.56	0.07
Al_2O_3	10.0	0.7	11.8	0.3	19.6	0.2
Cr_2O_3	0.31	0.03	0.22	0.02	0.27	0.03
FeO(t)	22.6	0.5	20.7	0.4	11.36	0.17
MnO	0.34	0.03	0.30	0.03	0.15	0.03
MgO	6.04	0.13	5.58	0.08	8.12	0.11
CaO	11.50	0.09	12.00	0.12	13.32	0.07
Na_2O	0.235	0.011	0.261	0.015	0.367	0.019
K_2O	0.035	0.005	0.054	0.004	0.072	0.006
P_2O_5	0.039	0.014	0.048	0.011	0.053	0.009
Σ	99.6		99.5		99.8	
beads*	2		2		4	
spots†	9		8		32	
			INAA			
Cr_2O_3	0.302	0.003	0.231	0.003	0.285	0.003
FeO	23.0	0.3	21.0	0.3	12.23	0.13
CaO	11.9	0.6	12.2	0.6	13.1	0.3
Na_2O	0.254	0.003	0.280	0.003	0.413	0.004

Concentration values are in mass percent; FeO represents total Fe as FeO. For FB-EMPA, uncertainties (±) are 95% confidence limits. For INAA, uncertainties are those of Table 2.

*number of beads

†total number of spots

and Ulff-Møller, 1999; Arai, 2001). On average, the composition of EET 87/96 is consistent with that of an aluminous (12–14% Al_2O_3), very-low-Ti (0.8% TiO_2) mare basalt or gabbro (Warren and Kallemeyn, 1989; Figs. 1 and 2).

In total, we analyzed 24 splits of EET 87/96 by INAA. For several of the precisely determined elements, differences between mean concentrations in EET 87521 and EET 96008 considerably exceed values expected on the basis of analytical uncertainty. For example, concentrations of Fe, Sc, Cr, and Co are 7–12% greater, on average, in our EET 96008 sample than in our EET 87521 sample. For lithophile elements, however, when the standard deviation of the concentrations for the individual splits is considered (*t*-test), there is no statistically significant difference between the mean compositions of our samples of the two EET stones (Table 2), thus our data provide no evidence that the two stones are not paired. The splits are highly variable in composition, with concentrations that span a factor of 2 for Fe, Sc, and Cr and more than a factor of 10 for Ba, La, Ta, and Th (Fig. 3). EET 87/96 displays the greatest degree of compositional variation that we have observed among small splits of a lunar meteorite. For example, among small splits of crystalline mare basalt NWA (North-

Table 3b. Results of electron microprobe analysis of fused beads (FB-EMPA) and comparison to results from instrumental neutron activation analysis (INAA) for five small splits of EET 87/96.

split	87521 79a1	87521 79a2	87521 79b1	96008 14b2	96008 14b5	±
			FB-EMPA			
SiO_2	46.5	47.2	47.3	45.9	46.5	0.8
TiO_2	0.73	0.74	0.60	0.64	0.36	0.21
Al_2O_3	14.3	13.2	18.6	16.8	14.3	1.0
Cr_2O_3	0.28	0.29	0.20	0.31	0.30	0.04
FeO(t)	16.9	17.6	12.5	14.2	16.8	0.7
MnO	0.24	0.23	0.17	0.19	0.22	0.03
MgO	8.1	8.4	6.9	9.1	10.0	0.5
CaO	11.9	11.4	13.1	12.4	11.0	0.3
Na_2O	0.38	0.34	0.47	0.33	0.29	0.03
K_2O	0.047	0.055	0.058	0.019	0.042	0.009
P_2O_5	0.07	0.07	0.06	0.04	0.04	0.02
sum	99.3	99.5	100.0	100.0	99.9	3.7
beads*	1	1	1	1	1	
spots†	8	8	16	10	6	
			INAA			
Cr_2O_3	0.307	0.303	0.216	0.320	0.327	0.003
FeO(t)	16.57	18.43	11.62	13.88	17.35	0.18
CaO	12.7	12.1	14.0	12.3	11.2	0.3
Na_2O	0.370	0.353	0.457	0.333	0.274	0.004
mg	59	55	55	13	12	

See Table 3a. For the EET 87521, the fused beads were prepared from a 10–15-mg portion of the large (55–59 mg), pulverized INAA splits. For EET 96008, the entire INAA split (12–13 mg) was pulverized and fused. Split 79a2 is most typical of "average" EET 87/96 (all literature data). Split 79b1 is highly anomalous and apparently contains a large proportion of feldspathic material. Splits 14b2 and 14b5 best represent the Mg-rich end of the mixing trend.

west Africa) 032 (mean split mass: 15 mg, compared to 37 mg in EET 87/96), FeO concentrations range over only a factor of 1.1 (Fig. 3). Even among large whole-rock samples of EET 87/96 analyzed for major elements, differences among splits is significant (Fig. 3; data of Warren and Kallemeyn, 1991b; Karouji *et al.*, 2000).

The compositional variation among the EET 87/96 splits is systematic in that the factor of 2 variation in FeO concentration is accompanied by correlated variations in the concentrations of other lithophile elements (Figs. 2 and 3). (This and other generalizations made here ignore one of the EET 87521 splits, that with the lowest FeO concentration of Figs. 2 and 3. The anomalous split, 79b1, appears to contain a significant amount of highland material, as discussed in more detail below.) Because the meteorite is a breccia and the variation trends are approximately linear, we assume that the trends reflect mixing of a low-FeO and high-FeO component. Both the components are nominally basaltic or gabbroic on the basis of Al_2O_3 and CaO concentrations (Fig. 2; Table 3b). Although Al_2O_3 increases with decreasing FeO, the low-FeO component

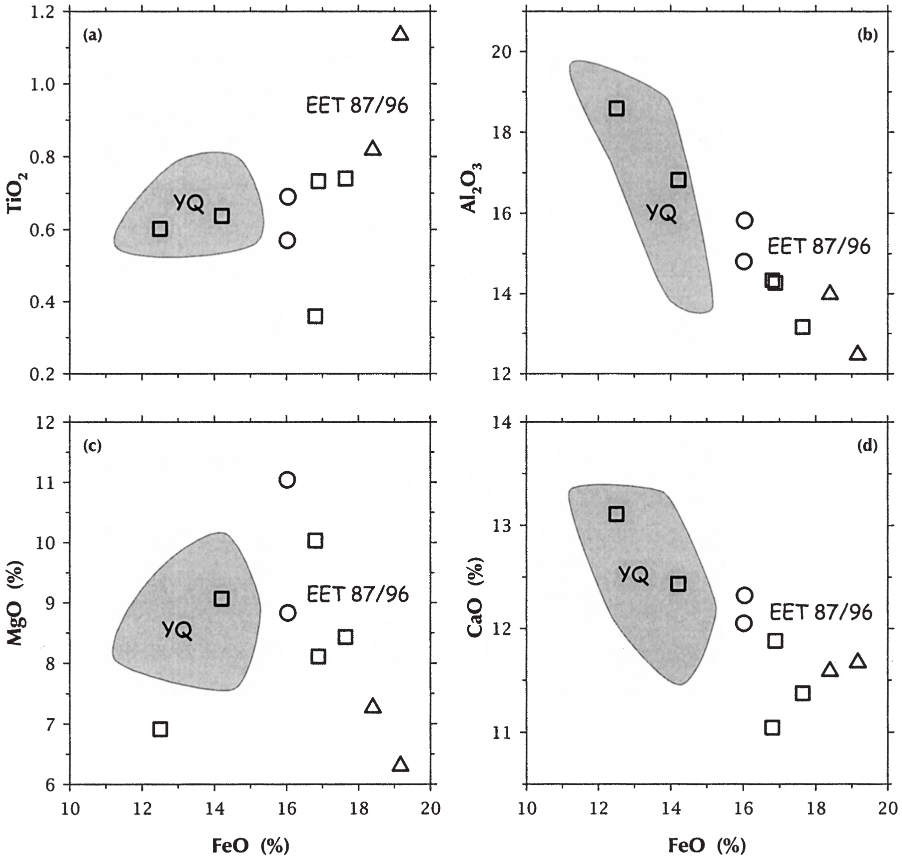

Fig. 2. Symbols represent samples of EET 87521 and 96008. Key and sources of data: squares, this work, Table 3 (EET 87 and 96); triangles, Warren and Kallemeyn (1991b; EET 87); and circles, Karouji et al. (2002; EET 87 and 96). In (c), note that except for one anomalous, low-FeO split (the same split is anomalous in Fig. 3), MgO anticorrelates with FeO. The gray fields represent the range of all analyses of YQ (Fukuoka et al., 1990; Lindstrom et al., 1991b; Warren and Kallemeyn, 1991b; Koeberl et al., 1991b; Jolliff et al., 1998; Arai and Warren, 1999; Kojima and Imae, 2000; Karouji et al., 2002, and this work). The YQ mixing trends of Fig. 6 are not evident in YQ fields of this figure probably because the data of this figure derive from many labs using different analytical techniques.

is not a feldspathic highland material, as in YQ (next section), because it contains at least 12% and not more than ~15% FeO on the basis of the lowest-Sm subsamples of Fig. 3b. The high-FeO component of the mixing trend contains at least 24% FeO (Fig. 3). On the basis of data for our small splits (Table 3b, excluding split 79b1) and the large-split data of Warren and Kallemeyn (1991) and Karouji *et al.* (2002), MgO anticorrelates with FeO ($[\%\text{MgO}] = -0.67 \cdot [\%\text{FeO}] + 20$; $R^2 = 0.482$, simple linear regression), implying that the 2× variation in FeO among our small splits is accompanied by an anticorrelated variation of ~3× in MgO. As recognized by Lindstrom *et al.* (1999), the low-FeO extreme of the compositional range is "primitive" in the igneous differentiation sense in having high Mg/Fe, high Cr/Sc, high Ca/Na, and low concentrations of incompatible elements. The high-FeO extreme is "evolved," with low Mg/Fe, low Cr/Sc, low Ca/Na, and high concentrations of incompatible elements

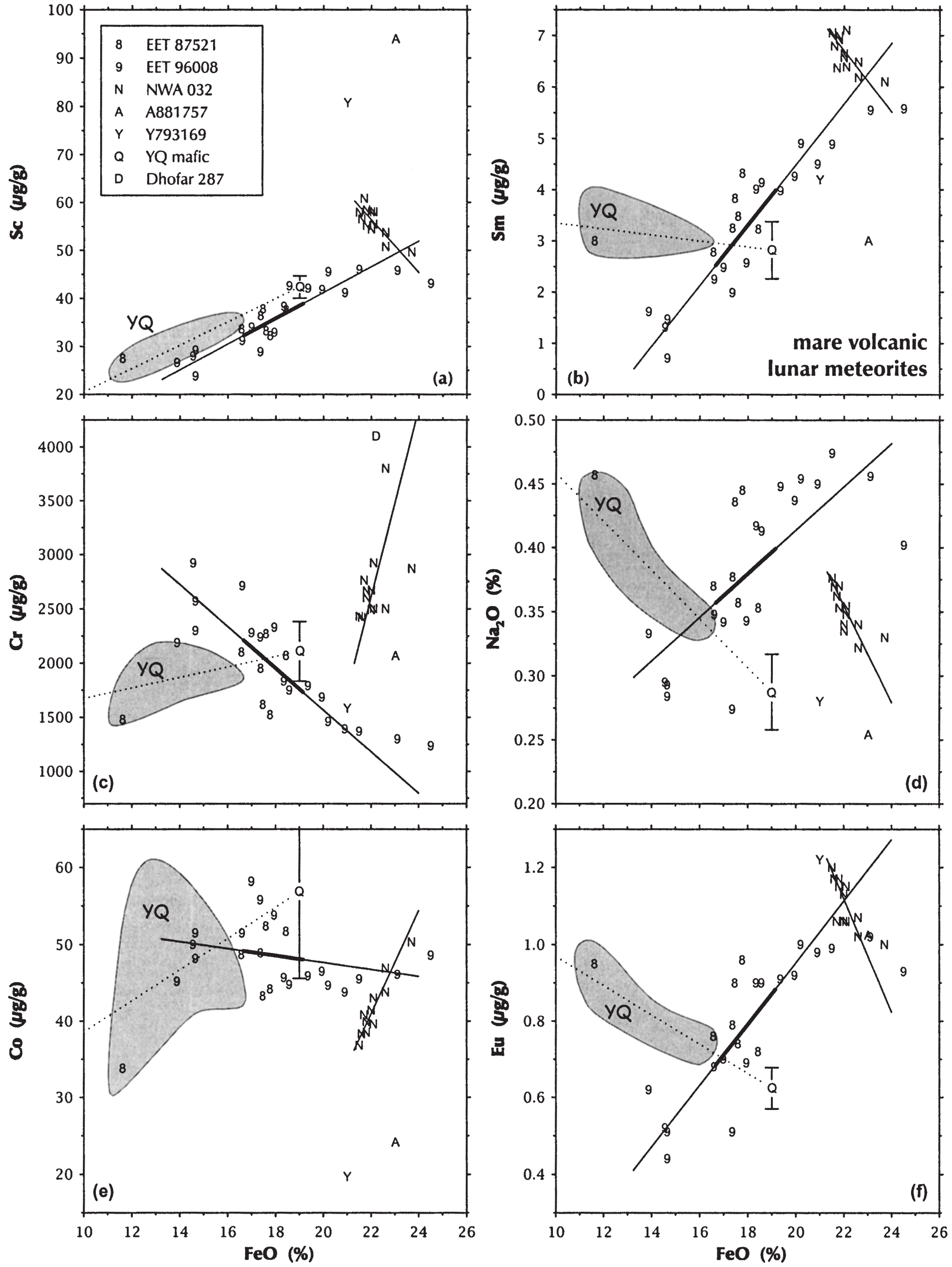

Fig. 3.

(Figs. 2 and 3).

We previously observed systematic compositional variations among small splits of NWA 032 (Fagan *et al.*, 2002). NWA 032 is an olivine-rich, crystalline mare basalt, and the variations are caused by small differences in the relative abundance of olivine phenocrysts among the splits, reflecting that the mass of the analyzed splits (~15 mg) is too small to be consistently representative of the whole rock. In NWA 032, the olivine is the high-FeO component of the variation trends because it has a greater FeO concentration (34–53%; Fagan *et al.*, 2002) then the whole rock (21–24%; Fig. 3). In EET 87/96 the trends are usually of opposite slope to those of NWA 032 and are caused by a different mineralogical effect. The high-FeO component is rich in late-stage fractionation products such as lithic clasts of fayalite-hedenbergite-silica assemblages and clasts of K- and Si-rich glass with RE (rare earth)-merrillite (whitlockite; Snyder *et al.*, 1999a; Mikouchi, 1999; Arai, 2001). We have made a preliminary petrographic study of one of the low-FeO, high-MgO splits and find it to be dominated by a pigeonite (En_{50-60})-plagioclase assemblage. We will provide a more thorough petrographic study of the high-Mg/Fe component of EET 87/96 in a subsequent work.

If, in fact, EET 87/96 is dominated by a "single lithology (or a single group of closely-related lithologies)" (Warren and Kallemeyn, 1989), then the compositional variation among splits (Fig. 3) is consistent with mixing of differentiates of a basaltic liquid. Because (1) the rock is a breccia, (2) the intersplit trends are linear (*e.g.*, Sm *vs.* FeO; Fig. 3b), and (3) the points are distributed approximately evenly along the trends but with most points clustering at the middle, the trends more likely reflect mixing of the differentiation products of a fractionated system than a continuous igneous differentiation trend. In this scenario, we would expect similarly sized (*i.e.*, small)

Fig. 3 (opposite). Compositional variation of lithophile-element concentrations in small splits of EET 87/96 ("8" and "9"), a breccia composed mainly of mare volcanic rock (data of this work). For comparison, data for other lunar meteorites that are unbrecciated mare basalts are also shown: (1) splits of NWA 032 ("N; " Fagan et al., 2002), (2) mean compositions of A-881757 ("A") and Y-793169 ("Y; " Table 2), and (3) preliminary data for a sample of Dhofar 287 ("D"; Taylor et al., 2001b; plot c only). Also shown are the YQ mixing lines of Fig. 6 (dotted) and the inferred composition of the mare component of the YQ meteorites ("Q," data of Fig. 6 and similar plots) that is based on our previous assumption that the mare component of YQ has 19% FeO (Jolliff et al., 1998). The error bars on Q represent the 95% confidence range based on simple linear regression (Fig. 6). The solid diagonal lines represent linear regressions to data for splits of EET 87/96 and NWA 032. For NWA 032, the correlations reflect variable proportions of modal olivine among small splits (mean mass: 15 mg; splits with greater FeO have a greater proportion of olivine). For EET 87/96, the correlations reflect mixing of components of a differentiated gabbroic source. The thick portion of the lines depicts the 95% confidence range for the mean composition of EET 87/96. The plot shows three things. (1) It is unlikely that mare basalts A-881757, Dhofar 287, NWA 032, or Y-793169 are related to EET 87/96. (2) The mean FeO concentration of EET 87/96 (or the breccia "unit" it represents) is probably less than the 19.2% obtained by Warren and Kallemeyn (1989) on the first EET 87/96 sample to be analyzed; it might be as low as 16.7% (see also Fig. 2). (3) If the mean FeO concentration of EET 87/96 is ~17%, then the EET 87/96 gabbro or basalt largely qualifies as the volcanic component inferred for YQ (Jolliff et al., 1998; Arai and Warren, 1999; Warren and Ulff-Møller, 1999).

splits of the unbrecciated precursor rock to show even greater compositional variability. Alternatively, the trends of Fig. 3 may result because EET 87/96 is either (1) a polymict breccia composed of unrelated or distantly related volcanic lithologies, *e.g.*, a basalt and a gabbro arising from different batches of magma or (2) a single basaltic magma containing high-Mg/Fe xenoliths. We favor the first hypothesis, however, because of its simplicity.

A characteristic feature of the Elephant Moraine lunar meteorites is the occurrence of coarse pyroxene grains with exsolution lamellae (Warren and Kallemeyn, 1989; Arai *et al.*, 1996; Mikouchi, 1999; Arai, 2001). Such lamellae are rare to absent in mare basalts of the Apollo missions. The occurrence of coarse, exsolved pyroxene grains and coarse intergrowths or separate grains of fayalite, hedenbergite, and silica indicate that the magmas from which these coarse basaltic or gabbroic rocks solidified—and from which the breccias derive— cooled slowly. Thus the likely source of the EET meteorites is either a shallow differentiated gabbroic intrusion or a thick, ponded basalt flow (Warren and Kallemeyn, 1989; Arai *et al.*, 1996; Warren and Ulff-Møller, 1999) in which there was physical separation of early and late crystallized phases. Because our splits are small, the scale of the separation might also have been small, *e.g.*, millimeters to decimeters. We are unaware of any sample from a mare site in the Apollo collection that is texturally similar to EET 87/96, that is, a fragmental breccia or nonglassy regolith breccia composed mainly of mineral grains from a coarse-grained volcanic rock. (However, little work has been done on mare breccias. Many of the breccias from the central valley of the Apollo 17 site, for example, have not been classified or studied in thin section; Neal and Taylor, 1993a,b.) Thus, there is no particular reason to assume that the mafic component of EET 87/96 actually derives from a magma extruded into an impact basin, that is, a mare. It may represent a shallow intrusion of mare-basalt-like magma.

In contrast to most mare basalts from the Apollo missions, EET 87/96 has a high La/Sm ratio (Fig. 4) and relative concentrations of incompatible elements that are similar (but not identical, as we discuss below) to those of nonmare rocks from the Apollo missions identified as KREEP (*e.g.*, Apollo 16 regolith; Fig. 5), an acronym reflecting the high concentrations of K, REE (rare earth elements), P and other incompatible elements in such rocks (*e.g.*, Warren and Wasson, 1979; Heiken *et al.*, 1991). This similarity might reflect either (1) assimilation by a basaltic magma during ascent through the crust of high-REE, late-stage residual liquid from crystallization of a global magma ocean, the urKREEP of Warren and Wasson (1979), or (2) incorporation in the source region of a KREEP-like trapped melt retained in the mantle cumulate. We cannot exclude these scenarios, but neither provides a satisfying explanation for the observations. On average, absolute concentrations of incompatible elements in EET 87/96 (*e.g.*, 3.4μg/g Sm) are in the lower half of the range for low-Ti and very-low-Ti basalts of the Apollo and Luna collection, thus, if it contains KREEP, it doesn't contain much. If we assume an original basaltic magma with 1μg/g Sm, the lowest concentration observed among Apollo mare basalts (Apollo 17 VLT; Wentworth *et al.*, 1979; Lindstrom *et al.*, 1994), and a high-REE KREEP component with 48 or 49μg/g Sm (Warren and Wasson, 1979; Warren, 1989), then the 3.4μg/g Sm of EET 87/96 (Table 2) corresponds to a 5% component of KREEP. In this scenario, 28% of the Sm in the

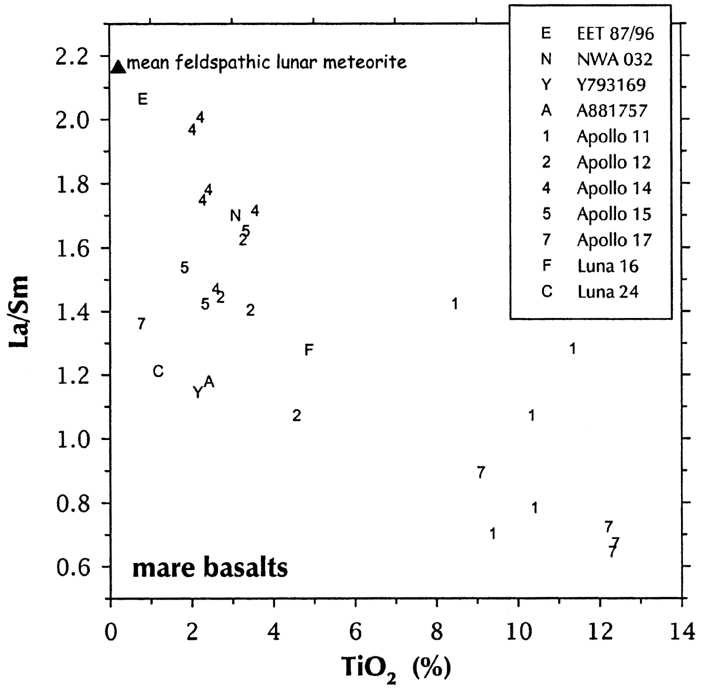

Fig. 4. Variation of La/Sm ratio with TiO$_2$ concentration in crystalline mare basalts from the Apollo and Luna missions and basaltic lunar meteorites. Each point represents the average of most available data (the data were compiled from too many sources to list). For the Apollo sites, different points for a given site each represent the mean composition of different compositional types (e.g., Apollo 12 ilmenite basalt, Apollo 12 olivine basalt, etc.). The plot shows that EET 87/96 is distinct and resembles only the aluminous, low-Ti basalts of Apollo 14 (Dickinson et al., 1985) with regard to its high La/Sm ratio.

meteorite ($[0.95 \times 1]/3.4$) derives from the original (pre-assimilation) magma (the proportion is similar for other incompatible elements) and 72% from the KREEP component. Because the non-KREEP proportion is large, the original magma must necessarily also have had relative abundances of incompatible elements similar to KREEP in order to account for the KREEP-like whole-rock concentrations. Other reasonable boundary conditions (greater Sm in original magma, lower Sm in assimilated KREEP) exacerbate the problem in that they require that an even greater fraction of the KREEP-like incompatible elements in EET 87/96 were associated with the original magma. Thus, a scenario involving assimilation or mixing of a high-REE KREEP component does not uniquely account for the KREEP-like concentrations of incompatible elements in EET 87/96.

In detail, relative abundances of incompatible elements in EET 87/96 (whole rock) deviate from those of KREEP. For example, ratios of Th and U to trivalent REE average 60% of those of the KREEP component of Warren (1989). Some low-Ti basalts with greater concentrations of incompatible elements then EET87/96 have non-KREEP-like relative abundances of incompatible element (*e.g.*, NWA 032, Fig. 5).

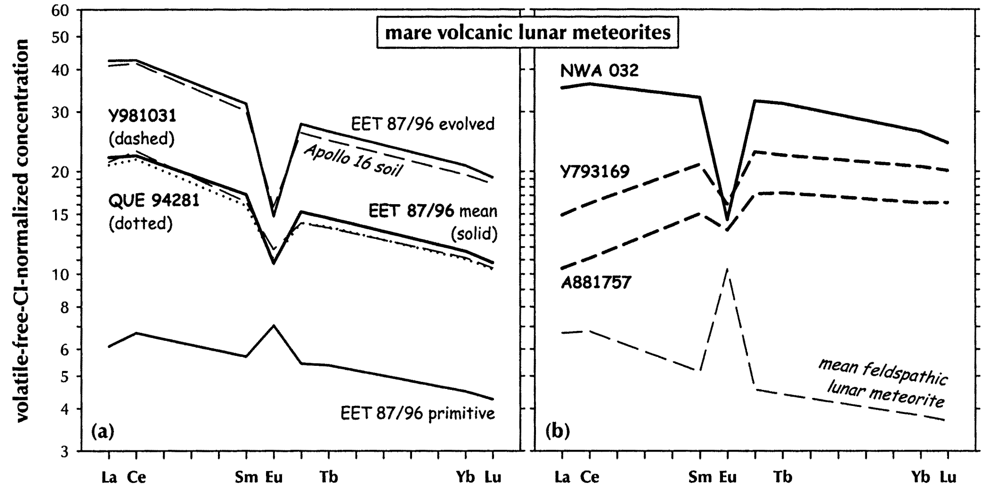

Fig. 5. Concentrations of rare earth elements as a function of atomic number in meteorites from the lunar maria. Meteorites of (a) have relative abundances of trivalent REE that resemble those of KREEP. For reference, data for typical mature regolith ("soil") from Apollo 16 is shown. The Apollo 16 regolith, although feldspathic, derives 82–86% of its trivalent REEs from KREEP-rich impact-melt breccias (Table 8 of Korotev, 1997). As a consequence, it has relative abundances of REE similar to KREEP as well as absolute abundances similar to the meteorites. For EET 87/96, the mean concentrations are shown as well as extreme concentrations inferred for the evolved (high-FeO) and primitive (low-FeO) components (Fig. 3). These compositions were derived from correlations against FeO such as that of Fig. 3b extrapolated to 13.5% and 24.5% FeO, that is, the extremes of the range of the EET 87/96 splits. The mare basalts of (b) have REE abundances that are more typical of mare basalts from the Apollo missions. Most notably, they have lower La/Sm ratios. The NWA 032 data are from Fagan et al. (2002). The REE concentration values were normalized by 1.36 C, where the C values are the "Mean C1 Chondr." values of Anders and Grevesse (1989). The factor 1.36 normalizes to a volatile-free basis, as in ordinary chondrites (e.g., Nakamura, 1974). The plot is based on only the labeled elements, i.e., those determined by INAA. Values for other elements are interpolated, except that Gd (between Eu and Tb) values are estimated (mean of Ce-Sm and Yb-Tb extrapolations).

Thus, the coincidence of "REE patterns" between EET 87/96 and KREEP-bearing nonmare samples (Fig. 5a) may not require assimilation of a late-stage material related to global differentiation of a magma ocean. It may be a consequence of the simple mineralogy of lunar rocks (*i.e.*, olivine, pyroxene, and plagioclase-dominated systems) in that differentiation in some small-scale lunar systems leads, at some point, to liquids with KREEP-like interelement ratios of incompatible elements (Jolliff, 1998).

Of the lunar meteorites that are regolith or fragmental breccias, EET 87/96 has the lowest concentrations of siderophile elements (Ni, Ir, Au; Table 2), suggesting that its components have had minimal exposure at the surface of the Moon compared to other brecciated lunar meteorites. This hypothesis is consistent with the moderately low concentrations of trapped solar noble gases (Eugster *et al.*, 2000) and with the observation that the rock is either a fragmental breccia or highly immature regolith breccia.

3.2. Yamato 981031

Y981031 is similar in composition to both Y-793274 and QUE 94281 (Table 2, Figs. 1b and 6). As a group, the YQ meteorites are distinct from other lunar meteorites in being subequal mixtures of VLT volcanic rock (basalt or gabbro) and material of the feldspathic highlands (Jolliff *et al.*, 1998; Arai and Warren, 1999). As a consequence (and with the exceptions discussed below), the YQ meteorites plot between the fields for the feldspathic lunar meteorites and mare basalts on 2-element plots of most major lithophile elements (*e.g.*, Fig. 1a).

At the small masses typically used for analysis (10–60 mg), YQ is heterogeneous and small splits from the three stones plot along mare-highland mixing lines because of differences in the proportions of mafic volcanic and feldspathic highland components in each split (Fig. 1b). Scatter about the mixing lines occurs because (1) the highland component, which is probably a regolith, is itself polymict and not of uniform composition and (2) the volcanic component, like EET 87/96, is also not uniform in composition.

There is considerable overlap of the compositional ranges of the three YQ stones (Fig. 1b and 6). The Y981031 split from which we determined major-element concentrations by FB-EMPA (Table 3a) has a lower concentration of iron (11.4% FeO) than (1) any of our six INAA splits (11.9–12.9% FeO), (2) other Y981031 samples (12.4% and 13.1%; Kojima and Imae, 2000; Karouji *et al.*, 2002), and (3) any "bulk" or "matrix" samples of Y-793274 and QUE 94281 (12.5–15.2%; Fig. 1b). In other words, the composition of our FB-EMPA split is more feldspathic than that of other YQ "bulk" samples. The material that we fused for major-element analysis (FB split) consisted of fines generated from subdividing the sample for INAA. It is possible that this procedure biased the FB split. Nevertheless, other samples of Y981031 are also at the low-FeO end of the range of the YQ meteorites (Fig. 1b).

Largely on the basis of trends such those of Figs. 1b, 6a, and 6b, Jolliff *et al.* (1998) were able to estimate the average concentrations of major elements in the highland and mare components of QUE 94281, and similar estimates have been made by Arai and Warren (1999) and Warren and Ulff-Møller (1999). The mafic component of YQ corresponds in composition to VLT basalt (0.8% TiO_2) and is discussed in detail by Jolliff *et al.* (1998) and Arai and Warren (1999). The inferred nonmare component of YQ resembles the feldspathic lunar meteorites in that it is similarly feldspathic. It differs, however, in that the inferred concentrations of both incompatible elements and the plagiophile elements Na and Eu are considerably greater in the feldspathic component of YQ than they are in any of the feldspathic lunar meteorites (Fig. 6). For incompatible elements, the correlation with FeO is poor (Fig. 6c, $R^2=0.11$), but the data taken as a whole suggest that the feldspathic component is 5–20% richer in incompatible elements than the Y981031 "whole rock" of Table 2.

Among plagioclase-rich, Sm-poor samples from the lunar highlands, there are strong correlations between concentrations of Na and Eu (also Sr). Eu increases with the mean albite content of the plagioclase (Fig. 7a). Although Y-82192/86032 is somewhat enriched in Na and Eu compared to other feldspathic lunar meteorites; the inferred feldspathic component of YQ is even more albitic (Fig. 7b). The difference corresponds approximately to mean anorthite (An) contents of 96.5% in the plagioclase of the feldspathic lunar meteorites and 93.7% in the plagioclase of the feldspathic component of YQ. Although anomalous with respect to feldspathic lunar meteorites, the feldspathic component of YQ is not unusual compared to regolith samples from

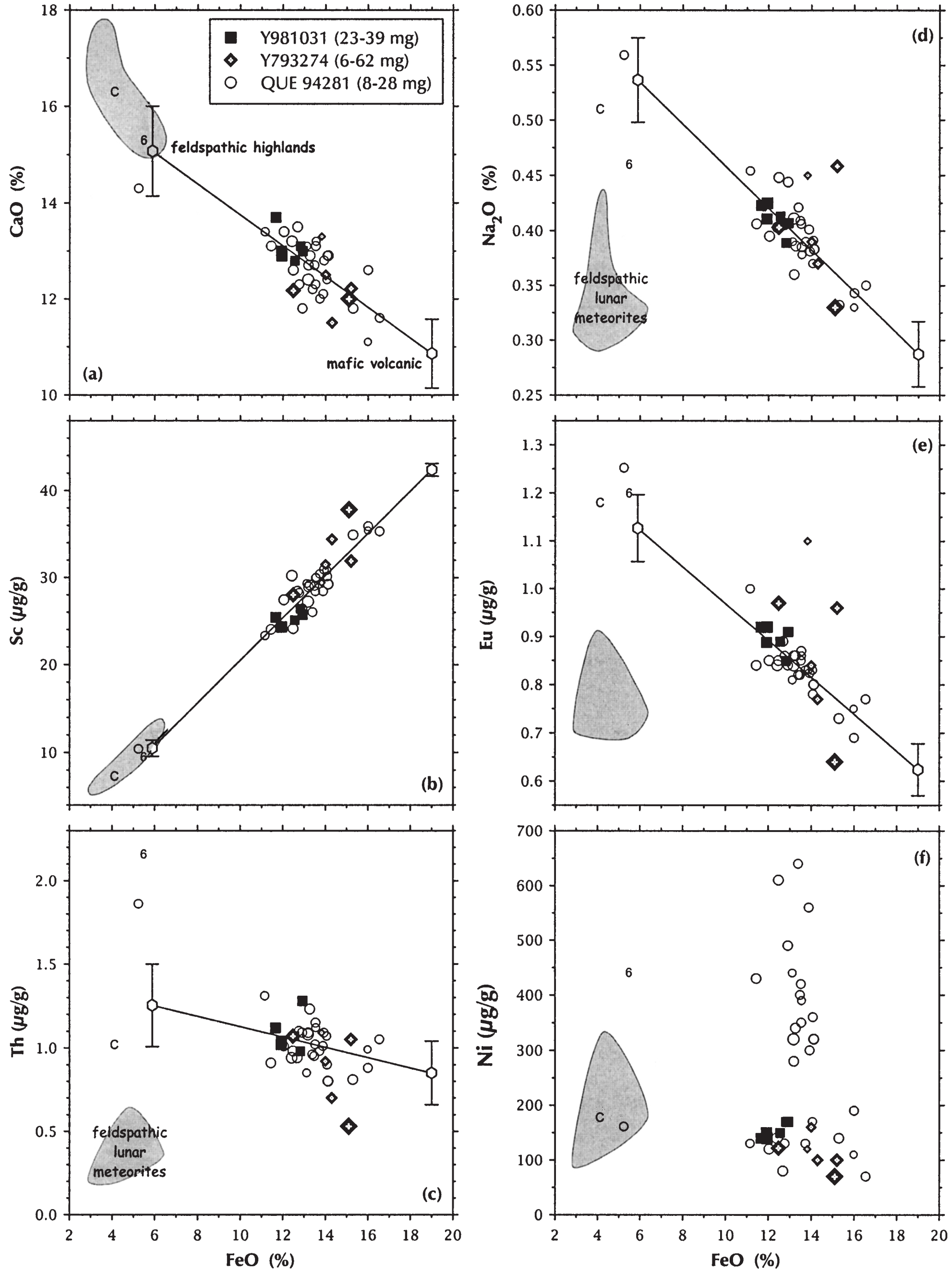

Fig. 6.

Apollo 16 (Fig. 7). Apollo 16 regolith has relatively high concentrations of Na and Eu because (1) it is composed in part of KREEP-bearing impact-melt breccias and (2) some samples, particularly those from North Ray Crater, contain plagioclase that is slightly more albitic than the An_{96-97} typical of ferroan anorthosite (James *et al.*, 1989; Korotev, 1996). Overall, the inferred composition of the feldspathic component of YQ is in the range of regolith samples from the edge of North Ray Crater of Apollo 16 (Korotev, 1996). Unlike North Ray Crater regoliths, however, clasts of KREEP-bearing impact-melt breccias have not been reported from YQ. Thus, it is unlikely that there is any actual connection between the feldspathic components of YQ and the Apollo 16 regolith other than that both originate from the highlands, which are not everywhere identical in composition.

Y981031 has concentrations of siderophile elements equivalent to those of Y-793274 and the feldspathic lunar meteorites but substantially less, on average, than those of QUE 94281 (Fig. 6f). Jolliff *et al.* (1998) thus suggested that the Y-793274 derived from a deeper regolith than QUE 94281, one that did not receive as high an exposure to micrometeorites. However, concentrations of trapped solar noble gases are less in QUE 94281 than in Y-793274 (Polnau and Eugster, 1998) and some large samples of QUE 94281 (Arai and Warren, 1999) have siderophile-element concentrations equivalent to or lower than those of Y981031, so the evidence for different depths is not compelling. The QUE 94281 samples of Jolliff *et al.* (1998) clearly have a heterogeneous distribution of siderophile elements (Fig. 6f) and may be anomalously rich in siderophile elements overall.

3.3. Launch pairing of EET 87/96 and YQ

Lunar meteorites Y-793169, A-881757, Dhofar 287, and NWA 032 are each unbrecciated mare basalts (Dhofar 287 contains a small brecciated portion, however; Taylor *et al.*, 2001b) that have little compositional (Fig. 3) or textural resemblance to either EET 87/96 or the inferred basaltic component of YQ. In contrast, EET 87/96 and YQ have overlapping launch ages (Arai and Warren, 1999; Nishiizumi *et al.*, 1999)

Fig. 6 (opposite). For lithophile elements (a–e), samples from the YQ meteorites plot along mixing lines between a feldspathic highland component and a mafic volcanic component represented by the hexagonal symbols. For reference, in each plot, the FeO concentrations of the two components (hexagons) are those estimated by Jolliff et al. *(1998) for QUE 94281 (5.9% and 19.0%). All data for Y981031 and QUE 94281 are INAA data of this laboratory (this work and Jolliff* et al.*, 1998). The diagonal lines represent simple linear regressions using only data for Y981031 and QUE 94281, except that data for the anomalously feldspathic point for QUE 94281 at 5.2% FeO were excluded. The error bars represent 95% confidence limits on the extrapolated values for the estimated end members. Data for Y-793274 (not used in regressions) are from Fukuoka (1990), Koeberl* et al. *(1991b), Lindstrom* et al. *(1991b), and Warren and Kallemeyn (1991b). For the YQ samples, the diameter of the points scale with the approximate size (diameter, if the analyzed mass of sample were a sphere) of the splits they represent. The symbol "6" represents the average composition of mature regolith from Apollo 16 (Korotev, 1997) and the symbol "C" is the average composition of regolith samples from the rim of North Ray crater at Apollo 16 (Korotev, 1996). The range of feldspathic lunar meteorites is shown by the gray field in each plot.*

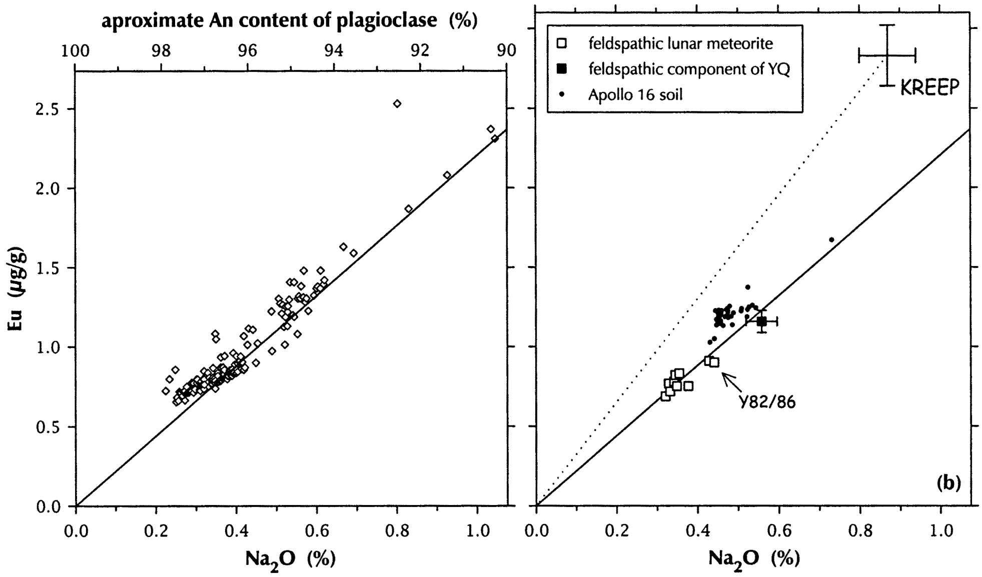

Fig. 7. Variation of Eu with Na_2O in feldspathic regoliths. (a) Data for 157 highly feldspathic ($<2.5\%$ FeO) and KREEP-poor ($<1\ \mu g/g$ Sm) lithic fragments from the Apollo 16 regolith (Jolliff and Haskin, 1995; Korotev, 1997; unpub. data, this lab). The diagonal line ($Eu = 2.20 \cdot Na_2O$) is defined by the origin and the point corresponding to the mean of the data. Points with anomalously low Na_2O concentrations with respect to the line represent glass spherules or fragments that lost some sodium from volatilization during an impact. (b) The feldspathic lunar meteorites and the feldspathic component of YQ plot along the line (solid) of (a) with Y-82192 and 86032 having higher concentrations than the other feldspathic lunar meteorites. The feldspathic component of YQ has Na_2O and Eu concentrations more similar to Apollo 16 regoliths than to the feldspathic lunar meteorites. Apollo 16 regolith samples plot off the line to higher Eu concentrations in part because they contain a component of KREEP-bearing impact-melt breccia, which has a greater Eu/Na ratio (dotted line) than plagioclase in highland rocks (Korotev, 1997, 2000).

and many compositional, mineralogical, and textural features in common (Arai *et al.*, 1996; Arai and Warren, 1999; Warren and Ulff-Møller, 1999; Mikouchi *et al.*, 1999; Arai, 2001). Some of these features, *e.g.*, low TiO_2 concentrations and coarse-grained, exsolved pyroxenes, make them more similar to each other than either is to any mare basalts in the Apollo collection.

On the basis of their various similarities, Arai and Warren (1999) and Warren and Ulff-Møller (1999) consider the possibility that EET 87/96 and YQ were ejected from the Moon by a single impact, but "tentatively reject" (Warren and Ulff-Møller, 1999) the hypothesis because the inferred mafic volcanic component of YQ has lower concentrations of Na and Eu and higher concentrations of Cr and V than EET 87/96 (*e.g.*, Fig. 3). We suggest that the compositional data are, in fact, consistent with a common mafic component for EET 87/96 and YQ when the range of EET 87/96 compositions is taken into account.

Because of the large sample-to-sample compositional variability, the mean composition of EET 87/96 is not precisely known and the mean composition of the basaltic or gabbroic body from which it derives is even less well known. Our own samples of EET 87521 (373 mg) and EET 96008 (504 mg), for example, differ by 8% and 11% in their mean concentrations of Sc and FeO (Table 2). The mean composition of EET 87/96 likely plots somewhere along the middle third of the mixing lines of Fig. 3, *i.e.*, at 16–20% FeO. Based on the mean and standard deviation of our own data ($N=24$), the 95%-confidence range for the mean FeO concentration is large, 16.7–19.2%. Likewise, the composition of the volcanic component of YQ is not known well because (1) it must be estimated from the adequate, but not particularly good, correlations such as those of Fig. 6 and (2) a value for the FeO (or Al_2O_3, Sc, etc.) concentration must be assumed. Jolliff *et al.* (1998) assumed 19% FeO, and that estimate is depicted in Figs. 1a, 3, and 6. Arai and Warren (1999) assumed 18% FeO. However, it is evident from Fig. 3 that if the inferred volcanic component of YQ has ~17% FeO, that is, in the range of the point where the two mixing lines intersect, then the estimated concentrations of other elements fall within the range of the mean concentrations of EET 87/96, even for the elements of concern to Warren and Ulff-Møller (1999). The EET 87521 samples of Warren and Kallemeyn (1989, 1991b) are, ironically, at the high-FeO end of the EET 87/96 mixing trend whereas the inferred volcanic component of YQ corresponds to a point on the low-FeO end of the trend. Most of the differences discussed by Warren and Ulff-Møller (1999) are not so great for EET 87/96 splits with ~17% FeO. We cannot address vanadium as we did not determine its concentration in EET 87/96, but because Cr fits (Fig. 3c), V is likely to fit. Finally, we note that EET 87521 split 79b1, which is represented by the anomalous, lowest-FeO points of Figs. 2 and 3 that plot in the YQ fields, is very similar in composition to one of our six splits of Y981031 (Table 4). This comparison provides weak evidence that not only is the volcanic component of YQ the same as that of EET 87/96, but that the feldspathic component of EET 87/96 is similar to that of YQ.

In summary, we see no strong compositional, mineralogical, or lithological impediment to the hypotheses that the volcanic components of EET 87/96 and YQ are one and the same and that EET 87/96, Y79/98, and QUE 94281 all derive from the same small area of the Moon. Present estimates for the time of ejection from the Moon allow that Y-793274, QUE 94281, and EET 87/96 (Arai and Warren, 1999; Nishiizumi *et al.*, 1999) could all have been launched by a single impact. At the Apollo 15 and 17 sites, regoliths such as EET 87/96 that consist mainly of volcanic material occur within a few kilometers of regoliths such as YQ that consist of ~50:50 mixtures of mafic and feldspathic highland material (Korotev, 1987; Korotev and Kremser, 1992). It would require a significant coincidence for two different impacts to have ejected rocks with volcanic components as similar to each other as those of Y79/98, QUE 94281, and EET 87/96, given the mutual dissimilarity of their volcanic components to Apollo mare basalts. The most parsimonious hypothesis is that all three meteorites were launched from the Moon by a single impact.

If, in fact, the three meteorites are launch paired, the site of the launch is likely to be a place where highland material overlies mare volcanic material. YQ, a regolith breccia, derives from near the surface and EET 87/96, a fragmental breccia, derives from a deeper position, one with little admixed highland material. The volcanic

Table 4. Comparison of compositions (INAA) for selected small splits from Y981031 and EET 87521.

Meteorite split	Y981031 99d	EET 87521 79b1	Y/EET
Na_2O	0.42	0.46	0.93
CaO	13.7	14.0	0.98
Sc	25.4	27.5	0.92
Cr	1934	1480	1.31
FeO	11.7	11.6	1.00
Co	36.6	33.8	1.08
Ni	140	110	1.27
Ba	82	77	1.06
La	7.3	6.3	1.16
Sm	3.5	3.0	1.18
Eu	0.92	0.95	0.97
Yb	2.6	2.2	1.17
Lu	0.37	0.30	1.21
Hf	2.5	2.1	1.23
Ta	0.34	0.26	1.29
Ir	2.7	3.3	0.82
Au	2.0	1.9	1.05
Th	1.12	1.07	1.05
U	0.28	0.33	0.85
mg	32	55	

component of EET 87/96 appears to be less well mixed than that of YQ. For example, for our EET 87/96 subsamples, that portion of the standard deviation in Sc concentrations not correlated with the FeO concentration (Fig. 3a) is 9% of the mean Sc concentration whereas it is 5% for YQ (Fig. 6b), despite the larger split size for EET 87/96. This observation argues that the volcanic component of YQ has a finer grain-size distribution than that of EET87/96, which in turn suggests the volcanic material of YQ is exposed to a greater degree of regolith maturation that that of EET 87/96 (McKay *et al.*, 1974). Finally, if the volcanic body is vertically differentiated, we would expect the upper, less dense portion to have a lower FeO concentration than the lower portion. This stratification would account for the apparent lower FeO concentration of the YQ volcanic component compared to "average" EET (*e.g.*, Fig. 3b).

4. Summary and conclusions

Small (35±20 mg) subsamples of breccia EET 87/96 (lunar meteorite Elephant Moraine 87521 and its pair 96008) are highly variable in composition. Most subsamples have compositions corresponding to mixtures of two extreme components, both of basaltic composition: (1) a primitive component with low FeO, high Mg/Fe, high Ca/Na, and low concentrations of incompatible elements (1 μg/g Sm) and an evolved component with high FeO, low Mg/Fe, low Ca/Na, and high concentrations of incompatible elements (5–6 μg/g Sm). The protolith of the meteorite appears to have been a differentiated volcanic body with a bulk composition corresponding to VLT (very-low-Ti) mare basalt.

Y (Yamato)-793274 and Y981031 are regolith breccias consisting feldspathic highland material and mare-like volcanic material. Others have shown on the basis of similarities in composition, petrography, texture, and cosmic-ray exposure that the Y79/98 stones are paired (Snyder *et al.*, 1999a,b; Lindstrom *et al.*, 1999; Warren and Ulff-Møller, 1999; Arai *et al.*, 2002a,b; Lorenzetti and Eugster, 2002). We show that the composition of Y981031 overlaps with that of Y-793274, but that Y981031 contains a greater proportion of feldspathic material. The difference corresponds approximately to 52% normative plagioclase in Y981031 compared to 43% in Y-793274.

Like Y79/98, QUE (Queen Alexandra Range) 94281 is a regolith breccia consisting of volcanic material with the composition of VLT mare basalt and feldspathic material from the highlands (Jolliff *et al.*, 1998; Arai and Warren, 1999). Assuming that the YQ meteorites (Y79/98 and QUE 94281) are all samples of a common regolith, as proposed by Arai and Warren (1999), the feldspathic component of that regolith differs from the numerous feldspathic lunar meteorites in two respects: (1) it is richer in Na and Eu because it contains plagioclase that is slightly more albitic and (2) it is richer in incompatible elements, *e.g.*, 1–1.5 μg/g Th compared to 0.2–0.6 μg/g in the feldspathic lunar meteorites.

The inferred volcanic component of the YQ meteorites is compositionally similar to small splits of EET 87/96 with about 17% FeO. Previous works have demonstrated textural and mineralogical similarities among the volcanic components of the three meteorites (Arai *et al.*, 1996, 2000a,b; Arai and Warren, 1999; Mikouchi, 1999; Arai, 2001). The range of likely ejection ages from the Moon for the YQ and EET 87/96 meteorites overlap (Arai and Warren, 1999; Nishiizumi *et al.*, 1999). On the basis of these similarities, we conclude that all three meteorites, EET 87521/96008, QUE 94281, and Y-793274/981031, are sufficiently similar to each other, yet mutually dissimilar to Apollo samples, that it is unlikely that they derive from two or more different places on the Moon. Given the rarity of lunar meteorites and the low frequency of impacts having launched lunar meteorites that are found on Earth today (Warren, 1994), the probability is high that all three meteorites were ejected from the Moon by a single impact.

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