LUNAR METEORITES AND IMPLICATIONS FOR COMPOSITIONAL REMOTE SENSING OF THE LUNAR SURFACE. R. L. Korotev, Department of Earth and Planetary Sciences, Washington University, Campus Box 1169, St. Louis, MO 63130, USA (rlk@levee.wustl.edu).

Lunar meteorites (LMs) are rocks found on Earth that were ejected from the Moon by impact of an asteroidal meteoroid. Three factors make the LMs important to remote sensing studies: (1) Most are breccias composed of regolith or fragmental material, (2) all are rocks that resided (or breccias composed of material that resided) in the upper few meters of the Moon prior to launch [e.g., 15], and (3) most apparently come from areas distant from the Apollo sites.

How Many Lunar Locations? At this writing (June, 1999), there are 18 known lunar meteorite specimens (Table 1). When unambiguous cases of terrestrial pairing are considered, the number of actual LMs reduces to 13. (Terrestrial pairing: A single piece of lunar rock entered earth's atmosphere, but multiple fragments were produced because the meteoroid broke apart on entry, upon hitting the ground or ice, or while being transported through the ice.)

We have no reason to believe that LMs preferentially derive from any specific region(s) of the Moon, i.e., we believe that they are samples from random locations [15]. However, we do not know how many different locations are represented by the LMs; mathematically, it could be as few as 1 or as many as 13. The actual maximum is <13 because in some cases a single impact appears to have yielded more than one LM. Y(amato)-793169 and Asuka-881757 (Table 1, N = 12 & 13) are considered "source-crater paired" [15] or "launch paired" [1] because they are compositionally and petrographically similar to each other and distinct from the others, and both have similar cosmic-ray exposure (CRE) histories [12]. The same can be said of QUE94281 and Y-793274 (Table 1, N = 9 & 10) [1]. Thus the 13 meteorites of Table 1 probably represent a maximum of 11 locations on the Moon.

The minimum number of likely source craters is debated and in flux as new data for different isotopic systems are obtained. Conservatively, considering CRE data only, a minimum of about 5 impacts are required. Compositional and petrographic data offer only probabilistic constraints. An extreme, but not unreasonable viewpoint, is that such data offer *no* constraint. For example, if one were to cut up the Apollo 17 landing site (which was selected for it's diversity) into softball-sized pieces, some of those pieces (e.g., sample 70135) would be crystalline mare basalts like Y-793169 whereas others (e.g., sample 73131 would be feldspathic regolith breccias like MAC88104/88105. However, nature is not so devious. Warren argues that LMs come from craters of only a few kilometers in diameter [15]. If so, even though CRE data allow, for example, that ALHA81005 and Y-791197 (Table 1, N = 6 & 7) were launched simultaneously from the same crater, the probability is nevertheless low because the two meteorites are compositionally and mineralogically distinct. Thus, within the allowed range (5–11) for the number of locations represented by the LMs, values at the high end of the range are probably more likely.

Mare Meteorites: Three LMs consist almost entirely of mare basalt. Two, Y-793169 and Asuka-881757 (Table 1, N = 12 & 13), are unbrecciated, low-Ti, crystalline rocks that are compositionally and mineralogically similar (but not identical) to each other; they probably derive from a single lunar mare location [16,12]. The third, EET87521/96008, is a fragmental breccia consisting predominantly of VLT mare basalt. Thus these LMs probably represent only two lunar mare locations. The basaltic LMs have mineral and bulk compositions distinct from Apollo mare basalts.

"Mixed" Meteorites: The petrography of Calcalong Creek has not been described in detail, but compositionally it is unique in that it corresponds to a mixture (breccia) of about ½ feldspathic material (i.e., the mean composition of the feldspathic lunar meteorites, below), ¼ KREEP norite, ¼ VLT mare basalt (like EET87521) and 1% CI chondrite. With 4 µg/g Th (Table 1) and correspondingly high concentrations of other incompatible elements, it is the only lunar meteorite that is likely to have come from within the Procellarum KREEP Terrane (PKT; see [3] for discussion of the terrane concept).

Y-793274 and QUE94281 are together distinct in being fragmental breccias containing subequal parts of feldspathic highland material and VLT mare basalt. Jolliff et al. [4] estimate a mare:highland ratio of 54:46 for QUE94281 and 62:38 for Y-793274; this difference is well within the range observed for soils collected only centimeters apart (in cores) at interface site like Apollos 15 and 17 [11]. Although the two meteorites were found on opposite sides of Antarctica, they are probably launch paired. The strongest evidence is that the pyroclastic glass spherules that occur in both are of two compositional groups and the two groups are essentially the same in both meteorites [1].

Y-791197 (Table 1, N = 7) is nominally a feldspathic lunar meteorite (below), but among FLMs, it probably contains the highest abundance of clasts and glasses of mare derivation. As a consequence, its composition is at the high-Fe, low-Mg´ end of the range for FLMs and is not included in the FLM average of Table 1. Its composition is consistent with ~10% mare-derived material [8]. Similarly, the two small (Y-82) pieces of Y-82192/82193/86032 (Table 1, N = 5) are more mafic than the large (Y-86) piece, probably as a result of ~7% mare-derived material [8] (the mass-weighted mean composition is listed in Table 1).

Feldspathic Lunar Meteorites (FLMs). All Apollo missions went to areas in or near the PKT and, consequently, all Apollo regolith samples are contaminated with Th-rich material from the PKT [7]. At the nominally "typical" highland site, Apollo 16, ~30% of the regolith (<1-mm fines) is Th-rich ejecta from the Imbrium impact [5,7] and ~6% is mare material probably derived from mare basins [5]. Thus Apollo 16 regolith is not typical of the highlands. Among Apollo *rocks*, the compositions of the FLMs correspond most closely to the feldspathic granulitic breccias of Apollos 16 and 17 [2,13].

The FLMs of Table 1, consequently and ironically, are especially important in that among lunar samples, they provide the best estimate we have of the composition of the Feldspathic Highlands Terrane [6]. All are regolith or fragmental breccias and, as such, are more likely to represent the composition of the upper crust in the area from which they were launched than any igneous rock that might have been excavated and launched from depth. FLMs contain little mare material (probably <<5%, on average). All have low concentrations of Th and other incompatible elements, indicating that they are also minimally contaminated (<3%) with material from the PKT. Thus, Th concentrations of the FLMs provide a reasonable lower limit to values that might be expected for large areas of the lunar farside as detected by Lunar Prospector [9].

The mean FeO concentration of the FLMs, 4.45± 0.6% (Table 1; ± = 95% confidence limit) is remarkably similar to the "global mode" of 4.5±1.0% obtained from analysis of Clementine spectral reflectance data [10]. (Because the FLM's consist of near-surface regolith material, a significant fraction of the Fe in the FLMs is of meteoritic origin, largely from micrometeorites. For the purpose of estimating the composition of the upper few kilometers of feldspathic crust, this component must be removed, yielding 4.2% FeO for the upper crust [6]. However, for comparisons to Clementine results, the FLM mean of Table 1 is more appropriate.) Similarly, the mean TiO_2 concentration of the FLMs, 0.35± 0.15%, agrees well with the value obtained from Clementine, 0.45±1.0% [10], giving credence at low TiO_2 concentration to the technique used to derive the Clementine-based estimates.

The six FLMs are all similar in composition. Such similarity is expected if all were to derive from the same source crater. However, both Clementine and Lunar Prospector show that vast areas of the farside are consistent with the FLM composition, thus it is reasonable that the FLMs may represent as many as six source craters. Among FLMs, ALHA81005 is distinct in being richer in MgO and having a correspondingly higher *Mg´* (Table 1). Although bulk compositions of the other FLMs are generally consistent with their derivation mainly from rocks of the ferroan-anorthosite-suite [14], the mafic minerals, at least, in ALHA81005 cannot derive from a source dominated by ferroan-anorthosite-suite rocks. Mafic rocks of the magnesian suite of lunar plutonic rocks are probably all special products of the PKT [7]. Thus ALHA81005, as well as the high-*Mg´* variety of Apollo feldspathic granulitic breccias [13,5], suggest that there are regions of the feldspathic crust dominated by non-ferroan (i.e., high-*Mg´*) feldspathic lithologies. Locating such areas should be a high-priority goal of remote-sensing missions.

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Table 1. Lunar meteorites (lunaites) - A list in order of increasing Fe concentration.

N	name	lunar rock type	mass (g)	where found	Al_2O_3 (%)	TiO_2 (%)	FeO (%)	MgO (%)	*Mg´* (%)	Th µg/g
feldspathic lunar meteorites (FLMs)										
1	Dar al Gani 400	regolith breccia	1425	Libya	*28.9*	*0.18*	*3.8*	*5.1*	*71*	*?*
2	MAC88104/88105	regolith breccia	61+663	Antarctica	28.1	0.23	4.28	4.05	63	0.39
3	Dar al Gani 262	regolith breccia	513	Libya	28.4	0.24	4.35	*5.0*	*67*	0.37
4	QUE93069/94269	regolith breccia	21+3	Antarctica	28.5	0.23	4.43	4.44	64	0.53
5	Yamato-82192/82193/86032	fragm. or reg. breccia	37+27+648	Antarctica	28.3	0.19	4.36	5.23	68	0.20
6	ALHA81005	regolith breccia	31	Antarctica	25.7	0.27	5.47	8.2	73	0.28
	mean FLM				**28.0**	**0.22**	**4.45**	**5.3**	**67**	**0.35**
"mixed" meteorites										
7	Yamato-791197	regolith breccia	52	Antarctica	26.4	0.31	6.1	6.1	64	0.35
8	Calcalong Creek	regolith breccia	19	Australia	21.3	0.83	9.7	*7.7*	*59*	4.0
9	QUE94281	regolith breccia	23	Antarctica	17.2	0.59	13.1	9.6	57	1.0
10	Yamato-793274	regolith breccia	9	Antarctica	15.7	0.60	14.2	9.0	53	0.9
mare lunar meteorites										
11	EET87521/96008	fragmental breccia	31+53	Antarctica	13.2	0.97	18.8	6.8	39	1.0
12	Yamato-793169	mare basalt	6	Antarctica	11.4	2.15	21.0	5.7	32	0.75
13	Asuka-881757	mare basalt	442	Antarctica	10.0	2.42	22.6	6.2	33	0.45

italics = preliminary or highly uncertain values. *Mg´* = bulk mole % Mg/(Mg+Fe). Data compiled from a large number of literature sources.