# 6

# ANSMET Meteorites from the Moon

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"The occurrence of secondary craters in the rays extending as much as 500 km from some large craters on the moon shows that fragments of considerable size are ejected at speeds nearly half the escape velocity from the moon (2.4 km/sec). At least a small amount of material from the lunar surface and perhaps as much or more than the impacting mass is probably ejected at speeds exceeding the escape velocity by impacting objects moving in asteroidal orbits. Some small part of this material may follow direct trajectories to the earth, some will go into orbit around the earth, and the rest will go into independent orbit around the sun. Much of it is probably ultimately swept up by earth."

*Shoemaker et al*. [1963]

## 6.1. INTRODUCTION

Despite the prediction of *Shoemaker et al*. [1963], it took another 19 years before the first lunar meteorite was recognized, Allan Hills 81005, a 31-g stone discovered during an ANSMET search in January of 1982 (Table 6.1) [*Marvin et al*., 1983; *Cassidy*, 2003]. As of 2013, ANSMET has collected 24 lunar meteorite stones representing, when pairings are taken into account, 14 different meteorites (Table 6.1). In total, 22% of the known lunar meteorites have been found in Antarctica,17% by ANSMET and 7% by searches done by the NIPR (National Institute of Polar Research) of Japan; the rest have been found in hot deserts (Australia: 2%, Africa 46%, and Oman: 29%).

Unlike the asteroids, the Moon did not accrete directly from dust and planetesimals. Instead, the Moon is the likely product of a giant impact between two differentiated bodies [*Hartmann and Davis*, 1975; *Cameron and Ward*, 1976; *Canup and Asphaug*, 2001]. It subsequently experienced further differentiation and a more prolonged period of igneous geologic activity than any asteroid. As a result, lunar meteorites are more diverse, particularly in terms of chemical composition, than meteorites from any other solar system body. The Moon is differentiated both vertically and laterally. Vertically, it has a small, most likely metallic core, a thick mantle (which itself may be layered) consisting mainly of olivine and pyroxene, and a crust that is rich in the anorthite extreme of plagioclase feldspar [*Wieczorek et al*., 2006]. Laterally, many of the huge impact basins that formed early in lunar history are filled with basalt from volcanism: melting of the mantle from the heat of radioactive decay with the magmas rising to fill the low spots in the crust. This lateral heterogeneity is very evident, even from Earth, with the light-colored feldspathic "terra" or "highlands" pockmarked by dark circular "maria" (seas; singular: "mare;" Figure 6.1). Chemically, the maria are rich in iron, magnesium, and in some places titanium (olivine, pyroxene, ilmenite), whereas the highlands are rich in aluminum and calcium (anorthite). Although the mare-highlands dichotomy has been recognized for at least hundreds of years, it was not until samples were collected during the *Apollo* missions (1969–1972) and the composition of the lunar surface was systematically mapped by the Lunar Prospector mission (1998–1999) that a second lateral heterogeneity was discovered. The geochemically incompatible elements such as K, REE (rare earth elements), P, Zr, Th, and U, which do not partition into the major minerals of the lunar crust (plagioclase, pyroxene, olivine, and ilmenite), are concentrated in the northwest quadrant of the nearside in a region known as the Procellarum KREEP Terrane (Figure 6.2). The last basin-forming impact to occur on the nearside of the Moon, Imbrium, occurred in the Procellarum KREEP Terrane (Figure 6.2), spreading KREEP-rich rocks (i.e., rocks with high concentrations of Th and other incompatible elements) over the surface of the Moon [*Haskin*, 1998]. The lunar meteorites reflect the

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*35 Seasons of U.S. Antarctic Meteorites (1976–2010): A Pictorial Guide to the Collection, Special Publication 68*, First Edition. Edited by Kevin Righter, Catherine M. Corrigan, Timothy J. McCoy and Ralph P. Harvey.

**Table 6.1.** ANSMET lunar meteorites.

| Plot symbol | Stone name | Paired with | New | Mass (g) | Norm. plag. (%) | Lithology | Find date | Likely or possible launch pairs |
|---|---|---|---|---|---|---|---|---|
| A | ALH A81005 | | 1 | 31.4 | 71.5 | FRegBrx | 1982-01-18 | |
| E | EET 87521 | EET 96008 | 1 | 30.7 | 38.4 | BRegBrx | 1987-12-20 | Yam 793274/981031, QUE 94281, NWA 4884 (YQEN) |
| e | EET 96008 | EET 87521 | | 52.97 | 38.4 | BRegBrx | 1996-12-14 | |
| G | GRA 06157 | | 1 | 0.788 | 79.9 | FRegBrx | 2007-01-08 | |
| 1 | LAP 02205 | other 5 LAPs | 1 | 1226.3 | 28.1 | MB | 2002-12-18 | NWA 4734, NWA 032/479 (NNL) |
| 2 | LAP 02224 | other 5 LAPs | | 252.5 | 28.1 | MB | 2002-12-12 | |
| 3 | LAP 02226 | other 5 LAPs | | 244.1 | 28.1 | MB | 2002-12-13 | |
| 4 | LAP 02436 | other 5 LAPs | | 58.97 | 28.1 | MB | 2002-12-12 | |
| 5 | LAP 03632 | other 5 LAPs | | 92.566 | 28.1 | MB | 2004-01-01 | |
| 6 | LAP 04841 | other 5 LAPs | | 55.992 | 28.1 | MB | 2005-01-03 | |
| L | LAR 06638 | | 1 | 5.293 | 82.9 | FRegBrx | 2007-01-03 | |
| m | MAC 88104 | MAC 88105 | 1 | 61.2 | 79.5 | FRegBrx | 1989-01-13 | Dhofar 1428 |
| M | MAC 88105 | MAC 88104 | | 662.5 | 79.5 | FRegBrx | 1989-01-13 | |
| T | MET 01210 | | 1 | 22.83 | 46.4 | BRegBrx | 2001-12-23 | Yam 793274, Asuka 88175 MIL 05035 (YAMM) |
| B | MIL 05035 | | 1 | 142.216 | 26.7 | MB | 2005-12-11 | Yam 793274, Asuka 88175 MET 01210 (YAMM) |
| I | MIL 07006 | | 1 | 1.368 | 75.6 | FRegBrx | 2007-12-31 | Yam 791197,Dhofar 1436/1443 |
| £ | MIL 090034 | MIL 090070 & 090075 | 1 | 195.565 | 86.0 | FRegBrx | 2009-12-18 | |
| ¥ | MIL 090036 | | 1 | 244.830 | 76.1 | FRegBrx | 2009-12-22 | |
| $ | MIL 090070 | MIL 090034 & 090075 | | 137.461 | 86.8 | FRegBrx | 2009-12-20 | |
| ¢ | MIL 090075 | MIL 090034 & 090070 | | 143.523 | 82.7 | FRegBrx | 2009-12-20 | |
| P | PCA 02007 | | 1 | 22.372 | 72.8 | FRegBrx | 2003-01-05 | |
| Q | QUE 93069 | QUE 94269 | 1 | 21.4 | 80.1 | FRegBrx | 1993-12-11 | |
| q | QUE 94269 | QUE 93069 | | 3.2 | 80.1 | FRegBrx | 1994-12-10 | |
| U | QUE 94281 | | 1 | 23.4 | 44.9 | BRegBrx | 1994-12-12 | Yam 793274/981031, EET 87/96, NWA 4884 (YQEN) |
| Total | 24 | | 14 | 3733.4 | | | | |

*Note:* New = first or only stone of a pair group; Norm. plag. = normative plagioclase abundance based on data of Table 6.2; BRegBrx = basaltic regolith breccias; FRegBrx = feldspathic regolith breccias; MB = mare basalt.

Moon's lateral variability. Among the 14 ANSMET lunar meteorites, 9 are feldspathic regolith (soil) breccias from the lunar highlands, 2 are basalts from the maria, and 3 are regolith breccias dominated by mare material but containing some feldspathic material (Table 6.1). Among the ANSMET lunar meteorites, concentrations of incompatible elements vary by a factor of 10 (Figures 6.3 and 6.4).

In this chapter we review the characteristics of the ANSMET lunar meteorites and compare them with *Apollo* samples and lunar meteorites from elsewhere.

## 6.2. EXPERIMENTAL METHODS

We present here new compositional data obtained by INAA (instrumental neutron activation analysis) and EPMA (electron probe microanalysis) of fused powders for some ANSMET lunar meteorites. The analytical procedures are described in detail in *Korotev et al.* [2009b]. Briefly, we analyzed multiple (2–16, typically 6–10) subsamples (typically 25–35 mg in mass) of each stone. Mass-weighted mean concentration values and total mass analyzed are presented in Table 6.2 and data for individual

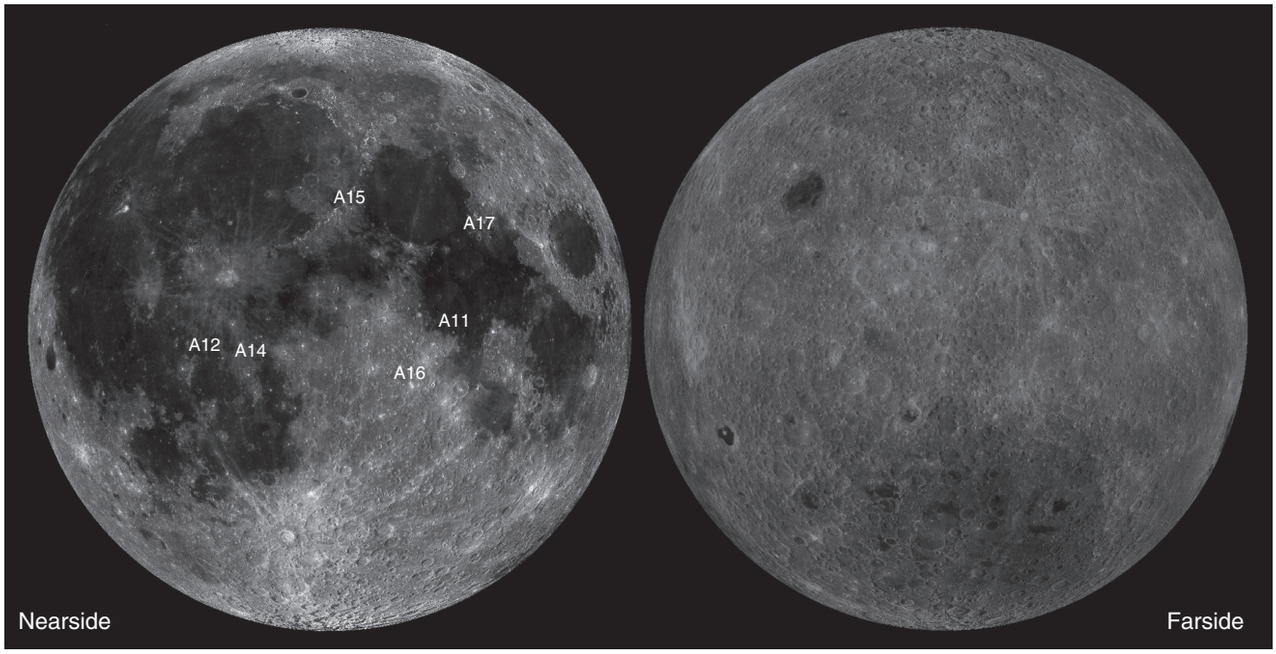


**Figure 6.1.** The nearside and farside of the Moon as captured by the wide angle camera on the *Lunar Reconnaissance Orbiter* mission. Compare with the terranes map of Figure 6.2. The dark, circular maria are prominent on the nearside, where the locations of the six *Apollo* landing sites are indicated. Images courtesy of NASA/GSFC/Arizona State University.

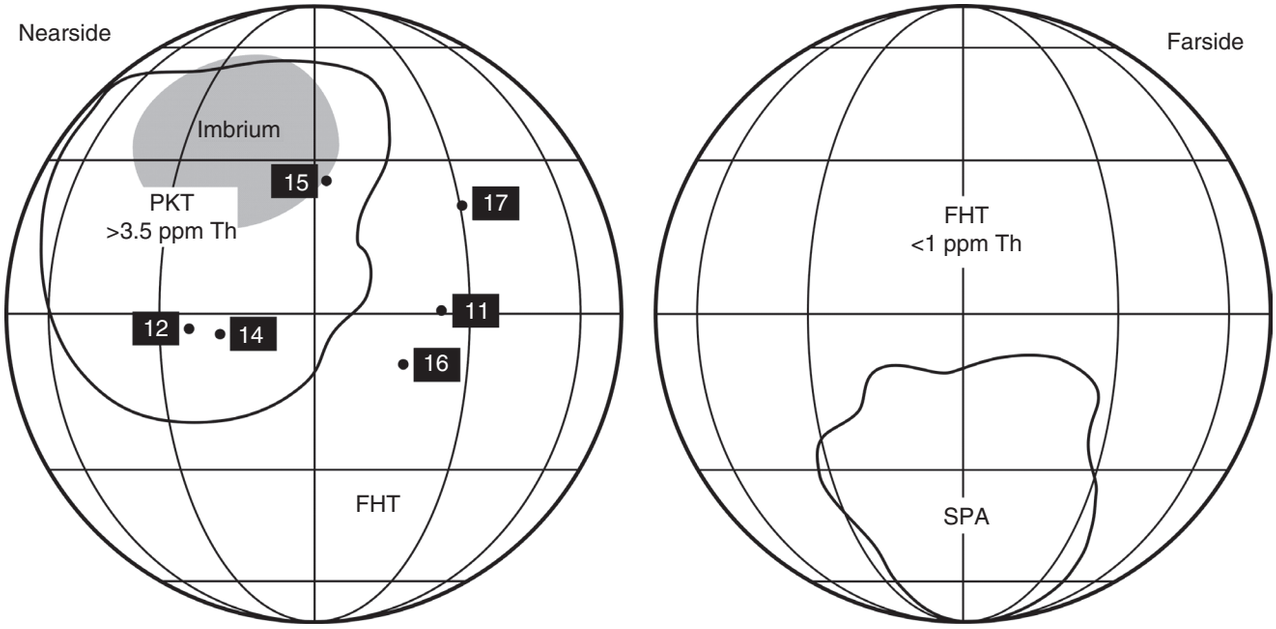


**Figure 6.2.** Schematic terrane map of the Moon after *Jolliff et al*. [2000]. The six *Apollo* landing sites were all near the center of the nearside. The distance between *Apollo* 12 (west) and *Apollo* 17 (east) is 16% of the lunar circumference. Three of the missions (12, 14, and 15) landed in the geochemically anomalous Procellarum KREEP Terrane (PKT), a region with high concentrations of incompatible elements such as Th [*Lawrence et al*., 2000; *Jolliff et al*., 2000]. All pixels with >3.5 ppm Th in the Th map of *Lawrence et al*. [2000] lie within the PKT boundary of *Jolliff et al*. [2000], as depicted here. The *Apollo* 11, 12, 15, and 17 lunar modules landed in areas resurfaced by mare basalt. Only *Apollo* 16 landed in the Feldspathic Highlands Terrane (FHT) distant from a mare. The South Pole-Aitken Terrane encompasses the giant and ancient South Pole-Aitken (SPA) basin on the farside.

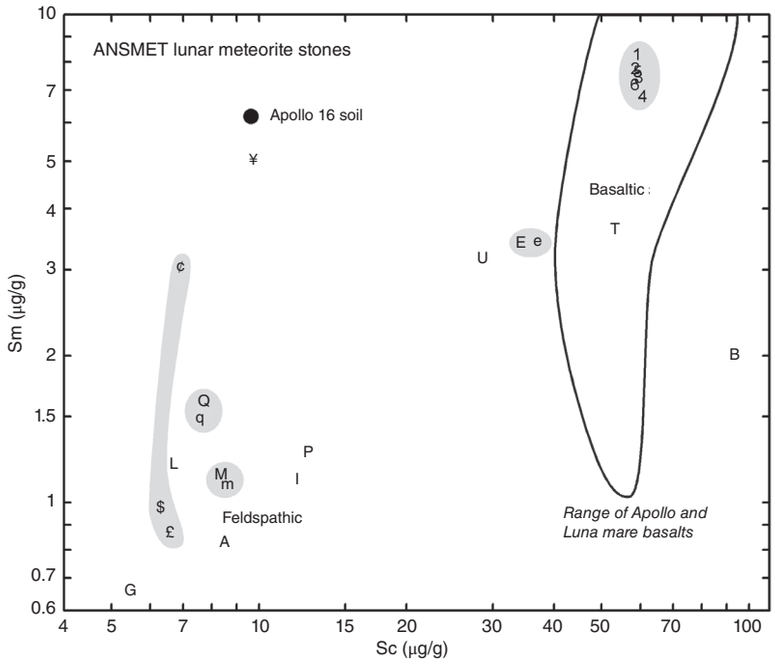


**Figure 6.3.** ANSMET lunar meteorites in Sc-Sm space; note logarithmic axes. Each point represents the mean composition of a named stone; see Table 6.1 for symbol key. Gray fields encompass paired stones. For reference, the mean composition of typical mature regolith from *Apollo* 16 is represented by the filled circle [*Korotev*, 1997]. Sc increases with increasing pyroxene abundance. For the nonbasaltic meteorites, Sm increases with increasing abundance of KREEP components.

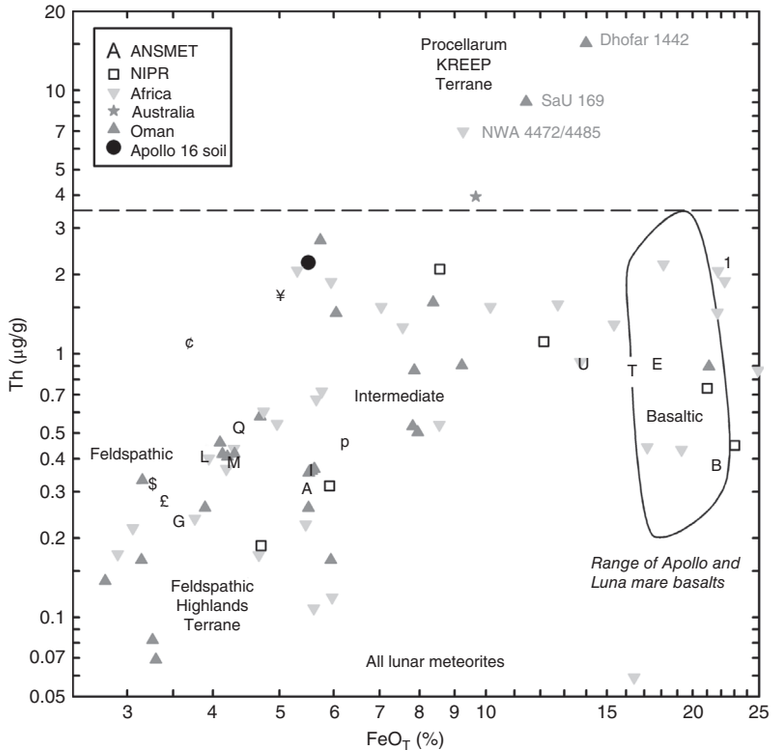


**Figure 6.4.** Comparison of compositions of ANSMET lunar meteorites to lunar meteorites from other locations in FeO-Th space (total Fe as $FeO_T$); note logarithmic axes. Each point represents the mean composition of a meteorite. For paired ANSMET meteorites, the symbol is that for the largest stone (see legend in Table 6.1). The two "Africa" points that overlap with the LAP 02205 point (symbol "1" representing the mean of all six LAP stones) are NWA 032 and NWA 4734. Meteorites with 7%–12% FeO are absent in the ANSMET collection as are Th-rich meteorites. The horizontal dashed line represents the Procellarum KREEP Terrane boundary of Figure 6.2.

**Table 6.2.** Mean compositions of ANSMET lunar meteorites.

| | Unit | ALH A81005 | EET 87/96 | GRA 06157 | LAP $N=6$ | LAR 06638 | MAC 88104/5 | MET 01210 | MIL 05035 | MIL 07006 | MIL 090034 | MIL 090036 | MIL 090070 | MIL 090075 | PCA 02007 | QUE 93/94 | QUE 94281 | %±* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | % | 44.9 | 46.9 | 44.1 | 45.3 | 44.6 | 45.1 | 44.6 | 47.1 | 45.1 | 44.3 | 45.4 | 44.5 | 45.2 | 44.2 | 44.7 | 47.3 | 0.4 |
| $TiO_2$ | % | 0.27 | 0.73 | 0.17 | 3.23 | 0.16 | 0.24 | 1.53 | 1.45 | 0.27 | 0.15 | 0.57 | 0.14 | 0.21 | 0.28 | 0.25 | 0.69 | 6 |
| $Al_2O_3$ | % | 25.8 | 13.6 | 28.8 | 9.9 | 29.9 | 28.7 | 16.6 | 9.45 | 27.2 | 31.0 | 27.1 | 31.3 | 29.8 | 26.2 | 28.9 | 16.0 | 1.9 |
| $Cr_2O_3$ | % | 0.13 | 0.27 | 0.08 | 0.30 | 0.08 | 0.09 | 0.22 | 0.31 | 0.12 | 0.07 | 0.10 | 0.06 | 0.08 | 0.14 | 0.08 | 0.26 | 1.0 |
| $FeO_T$ | % | 5.47 | 17.75 | 3.55 | 22.5 | 3.90 | 4.29 | 16.36 | 21.7 | 5.54 | 3.40 | 5.01 | 3.26 | 3.70 | 6.24 | 4.37 | 13.93 | 1.0 |
| MnO | % | 0.07 | 0.23 | 0.05 | 0.29 | 0.09 | 0.06 | 0.22 | 0.32 | 0.08 | 0.05 | 0.07 | 0.05 | 0.05 | 0.09 | 0.07 | 0.19 | 12 |
| MgO | % | 8.20 | 8.35 | 6.81 | 6.45 | 4.52 | 4.11 | 6.31 | 7.3 | 5.33 | 2.84 | 5.18 | 2.75 | 3.85 | 6.84 | 4.58 | 8.52 | 5 |
| CaO | % | 14.9 | 11.4 | 15.5 | 11.1 | 16.4 | 16.9 | 13.1 | 11.8 | 15.8 | 17.1 | 15.5 | 17.0 | 16.6 | 15.3 | 16.4 | 12.4 | 1.2 |
| $Na_2O$ | % | 0.30 | 0.37 | 0.36 | 0.35 | 0.34 | 0.33 | 0.30 | 0.26 | 0.35 | 0.37 | 0.62 | 0.37 | 0.39 | 0.34 | 0.34 | 0.36 | 1.0 |
| $K_2O$ | % | 0.02 | 0.05 | 0.03 | 0.09 | 0.02 | 0.03 | 0.05 | 0.03 | 0.02 | 0.03 | 0.10 | 0.04 | 0.06 | 0.03 | 0.03 | 0.07 | 11 |
| $P_2O_5$ | % | 0.02 | 0.05 | 0.02 | 0.12 | 0.05 | 0.03 | 0.11 | 0.04 | 0.02 | 0.02 | 0.10 | 0.02 | 0.06 | 0.02 | 0.03 | 0.06 | 22 |
| Σ | % | 100.1 | 99.7 | 99.5 | 99.6 | 100.1 | 99.9 | 99.4 | 99.8 | 99.8 | 99.4 | 99.7 | 99.5 | 100.0 | 99.6 | 99.8 | 99.8 | — |
| *Mg'* | % | 72.8 | 45.6 | 77 ± 4 | 33.9 | 67.4 | 63.0 | 40.7 | 37. | 63.2 | 59.8 | 64.8 | 60.1 | 65.0 | 66.1 | 65.1 | 52.2 | — |
| Sc | μg/g | 9.07 | 41.5 | 5.45 | 58.2 | 6.69 | 8.60 | 54.9 | 95.3 | 12.0 | 6.62 | 9.77 | 6.29 | 6.90 | 12.70 | 7.50 | 34.2 | 1 |
| Co | μg/g | 21.0 | 47.9 | 13.4 | 37.0 | 21.1 | 15.2 | 29.3 | 24.0 | 17.6 | 8.1 | 17.8 | 8.1 | 11.1 | 28.1 | 22.7 | 44.2 | 1 |
| Ni | μg/g | 201 | 61 | 96 | <150 | 280 | 152 | 196 | <200 | 174 | 45 | 218 | 43 | 83 | 339 | 308 | 213 | 2 |
| Sr | μg/g | 135 | 107 | 159 | 129 | 153 | 155 | 155 | 117 | 147 | 159 | 198 | 161 | 162 | 141 | 152 | 106 | 2–15 |
| Zr | μg/g | 31 | 110 | 15 | 193 | 30 | 36 | 96 | 42 | 30 | 24 | 153 | 27 | 94 | 42 | 43 | 113 | 5–50 |
| Ba | μg/g | 30 | 73 | 24 | 149 | 34 | 32 | 80 | 33 | 31 | 26 | 131 | 27 | 78 | 46 | 43 | 72 | 2–16 |
| La | μg/g | 2.18 | 7.31 | 1.37 | 12.7 | 2.63 | 2.57 | 6.04 | 2.03 | 2.21 | 1.80 | 11.11 | 2.15 | 6.78 | 2.52 | 3.38 | 6.21 | 1 |
| Ce | μg/g | 5.69 | 19.5 | 3.57 | 34 | 6.51 | 6.54 | 14.2 | 5.67 | 5.72 | 4.72 | 29.0 | 5.38 | 17.2 | 6.72 | 8.54 | 15.6 | 2 |
| Nd | μg/g | 3.38 | 11.9 | 2.05 | 23 | 3.97 | 4.14 | 10.3 | 4.86 | 3.54 | 2.99 | 17.2 | 3.31 | 10.4 | 4.38 | 5.01 | 9.7 | 10 |
| Sm | μg/g | 0.99 | 3.52 | 0.66 | 7.45 | 1.20 | 1.20 | 3.59 | 2.01 | 1.12 | 0.86 | 5.04 | 0.98 | 3.02 | 1.35 | 1.54 | 3.09 | 1 |
| Eu | μg/g | 0.687 | 0.870 | 0.845 | 1.25 | 0.825 | 0.804 | 1.07 | 0.836 | 0.801 | 0.839 | 1.38 | 0.860 | 0.941 | 0.804 | 0.817 | 0.813 | 1 |
| Tb | μg/g | 0.21 | 0.75 | 0.14 | 1.82 | 0.25 | 0.25 | 0.88 | 0.56 | 0.25 | 0.18 | 0.98 | 0.20 | 0.61 | 0.31 | 0.32 | 0.65 | 1 |
| Yb | μg/g | 0.85 | 2.73 | 0.58 | 6.43 | 0.95 | 1.01 | 3.45 | 2.90 | 0.99 | 0.70 | 3.25 | 0.78 | 2.22 | 1.10 | 1.21 | 2.41 | 1 |
| Lu | μg/g | 0.128 | 0.39 | 0.081 | 0.92 | 0.134 | 0.145 | 0.50 | 0.42 | 0.140 | 0.099 | 0.45 | 0.110 | 0.30 | 0.157 | 0.173 | 0.35 | 1 |
| Hf | μg/g | 0.76 | 2.58 | 0.45 | 5.2 | 0.86 | 0.89 | 2.51 | 1.34 | 0.84 | 0.62 | 3.86 | 0.66 | 2.31 | 0.95 | 1.16 | 2.27 | 1 |

(*Continued*)

**Table 6.2.** (Continued)

| | Unit | ALH A81005 | EET 87/96 | GRA 06157 | LAP *N* = 6 | LAR 06638 | MAC 88104/5 | MET 01210 | MIL 05035 | MIL 07006 | MIL 090034 | MIL 090036 | MIL 090070 | MIL 090075 | PCA 02007 | QUE 93/94 | QUE 94281 | %±* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ta | µg/g | 0.09 | 0.32 | 0.07 | 0.73 | 0.11 | 0.11 | 0.23 | 0.13 | 0.10 | 0.08 | 0.44 | 0.08 | 0.26 | 0.17 | 0.15 | 0.29 | 1–10 |
| Ir | ng/g | 6.7 | 0.6 | 3.2 | <8 | 12.3 | 6.8 | 7.1 | <8 | 6.6 | 1.9 | 8.7 | 2.4 | 3.0 | 16.8 | 15.4 | 6.6 | 3 |
| Au | ng/g | 2.2 | 0.4 | 0.8 | <8 | 3.7 | 2.8 | 1.9 | <5 | 1.6 | 0.2 | 1.8 | 0.0 | 0.2 | 6.7 | 4.8 | 1.7 | 25 |
| Th | µg/g | 0.31 | 0.92 | 0.23 | 2.17 | 0.41 | 0.39 | 0.85 | 0.37 | 0.36 | 0.28 | 1.65 | 0.32 | 1.11 | 0.44 | 0.52 | 0.91 | 2 |
| U | µg/g | 0.103 | 0.26 | 0.069 | 0.54 | 0.22 | 0.102 | 0.28 | 0.11 | 0.098 | 0.073 | 0.46 | 0.126 | 0.33 | 0.126 | 0.14 | 0.23 | 4–50 |
| INAA | mg | | | 57 | 1271 | | | | 423 | 153 | 481 | 556 | 318 | 326 | | | | |
| sources of data | | 5, 14, 18, 24, 29, 34, 37 | 8, 15, 20, 31, 35, 36 | 1 | 1, 2, 6, 11 | 1 | 9, 13, 16, 25, 30, 37, 37 | 4, 7, 13, 22 | 1, 12, 27 | 1 | 1 | 1 | 1 | 1 | 7, 13, 21 | 1, 17, 19, 23, 26, 28, 32, 33, 38 | 3, 7, 10, 15, 20 | |

*Note:* $FeO_T$ = Total Fe as FeO; *Mg'* = Mole % MgO/(MgO + $FeO_T$);

*Analytical uncertainties for data of this lab: 95% confidence limits, in percentage of mean value, based on counting statistics and number of subsamples analyzed (INAA data) or EPMA spots analyzed ($SiO_2$, $TiO_2$, $Al_2O_3$, CaO, $K_2O$, and $P_2O_5$). Uncertainties associated with sampling are considerably greater (e.g., *Korotev et al.*, 2009; *Korotev*, 2012).

Sources of data: 1. This work. 2. *Anand et al*. [2006]. 3. *Arai and Warren* [1999]. 4. *Arai et al*. [2010]. 5. *Boynton and Hill* [1983]. 6. *Day et al*. [2006a]. 7. *Day et al*. [2006b]. 8. *Dreibus et al*. [1996]. 9. *Jolliff et al*. [1991]. 10. *Jolliff et al*. [1998]. 11. *Joy et al*. [2006b]. 12. *Joy et al*. [2008]. 13. *Joy et al*. [2010a]. 14. *Kallemeyn and Warren* [1983]. 15. *Karouji et al.* [2002]. 16. *Koeberl et al*. [1991a]. 17. *Koeberl et al*. [1996]. 18. *Korotev et al*. [1983]. 19. *Korotev et al*. [1996]. 20. *Korotev et al*. [2003b]. 21. *Korotev et al*. [2006]. 22. *Korotev et al*. [2009b]. 23. *Kring et al*. [1995]. 24. *Laul et al*. [1983]. 25. *Lindstrom et al*. [1991a]. 26. *Lindstrom et al*. [1995]; 27. *Liu et al*. [2009]; 28. *Nishiizumi et al*. [1996]. 29. *Palme et al*. [1983]. 30. *Palme et al*. [1991]. 31. *Snyder et al*. [1999]. 32. *Spettel et al*. [1995]. 33. *Thalmann et al*. [1996]. 34. *Verkouteren et al*. [1983]. 35. *Warren and Kallemeyn* [1989]. 36. *Warren and Kallemeyn* [1991a]. 37. *Warren and Kallemeyn* [1991b]. 38. *Warren et al*. [1995].

subsamples are presented in some figures. After INAA, we pulverized two or three representative INAA subsamples in an agate mortar and pestle, fused the resultant powders into glass with a Mo strip heater, and analyzed the glasses by EPMA to determine concentrations of major elements [*Korotev et al.*, 2009b]. For those meteorites for which literature data are available, means calculated from all data are presented in Table 6.2.

Also presented here are petrographic descriptions of ANSMET lunar meteorites. For "historical" lunar meteorites (pre-2001), the descriptions are culled and summarized from literature sources. For more recently recovered meteorites, particularly for meteorites found since 2006, more detailed petrography is provided from our own research on the meteorites. The petrographic descriptions are based on optical, electron, and x-ray imaging of polished thin sections of the meteorites, coupled with quantitative mineral analyses obtained by wavelength-dispersive EPMA [*Zeigler et al.*, 2005].

## 6.3. LUNAR FRAGMENTAL AND REGOLITH BRECCIAS

The lunar crust has been battered by countless impacts of very large to very small meteorites since its formation 4.5 billion years ago. The Moon has virtually no atmosphere, so asteroidal materials impact the Moon at very high velocities, tens of kilometers per second. The shock and heat of meteorite impacts both break large rocks into smaller rocks and fuse small rocks into larger rocks. As a consequence, nearly all rocks from the lunar highlands are breccias: rocks consisting of fragments of older rocks. Most brecciated lunar meteorites are fragmental and regolith breccias.

Fragmental breccias consist of material of the megaregolith (upper few kilometers of unconsolidated material) that has been lithified by shock compression and sintering during meteorite impacts. Regolith breccias are fragmental breccias consisting of fine-grained material ("soil") of the upper few meters of the Moon that has been mixed by many small impacts. Regolith breccias are recognized by the presence of lithologies that formed at (e.g., agglutinates, small glassy breccias formed by impacts of micrometeorites) or above (volcanic and impact glass spherules) the lunar surface [*Stöffler et al.*, 1980; *Stöffler and Grieve*, 2007]. Most brecciated lunar meteorites are regolith breccias derived from material that was within about 3 m of the lunar surface [*Warren*, 1994]. The relative abundance of regolith breccias among the lunar meteorites is greater than that among *Apollo* samples. There are at least three possible explanations for this discrepancy: (1) astronaut selection bias, (2) differences in coherency between rocks of the lunar regolith and the subset that can survive being launched from the Moon and landing on Earth, and (3) the possibility that some meteorites were lithified by the impact that accelerated them to lunar escape velocity [*Warren*, 2001].

For no lunar meteorite has the source crater been identified, although from the first lunar meteorite to be recognized it has been fashionable, if not mandatory, to speculate about possible craters or general source locations on the basis of mineralogy and composition [e.g., *Palme et al.*, 1983; *Ryder and Ostertag*; 1983; *Pieters et al.*, 1983; *Anand et al.*, 2006; *Joy et al.*, 2008; *Arai et al.*, 2010]. Most lunar meteorites were launched by impacts making craters less than a kilometer in diameter [*Warren*, 1994; *Head*, 2001; *Basilevsky et al.*, 2010]; thus, locating the source crater of a lunar meteorite is a challenging assignment. Perhaps the best constrained are SaU (Sayh al Uhaymir) 169 from Oman [*Gnos et al.*, 2004], NWA (Northwest Africa) 4472/4485 [*Joy et al.*, 2011], and Dhofar 1442 from Oman [*Korotev*, 2012]. Because of their high concentrations of Th (Figure 6.4), the source craters of these meteorites are limited to only a few regions within the Procellarum KREEP Terrane (Figure 6.2) [*Lawrence et al.*, 2000].

In at least two respects, the fact that most lunar meteorites are regolith breccias makes them especially valuable. First, regolith breccias consist of well-mixed, near-surface materials. We can reasonably assume, on the basis of our experience with *Apollo* regolith samples, that their compositions represent the surface of the Moon where they originated on the scale of a few kilometers at a minimum, for example, the *Apollo* 15 or 17 sites, and more realistically on a scale of a few tens of kilometers, for example, the *Apollo* 11, 12, or 16 sites [*Warren*, 1994; *Korotev et al.*, 2003a]. Second, although we do not know the precise point of origin for any lunar meteorite, we do know, to first order, that lunar meteorites come from randomly distributed locations on the lunar surface [*Warren*, 1994, *Korotev et al.*, 2009b]. Effects of spatially nonuniform cratering rates on the Moon are not large [*Warren*, 1994; *Gallant et al.*, 2009; *Le Feuvre and Wieczorek*, 2008]. These two features have led to use of the mean composition of the feldspathic lunar meteorites as an estimate of the typical composition of the lunar highlands surface and, by inference, the upper crust [*Palme et al.*, 1991; *Warren*, 1994; *Korotev et al.*, 1996, 2003a; *Warren*, 2005] and to providing "ground truth" for orbital remote sensing, particularly for Lunar Prospector [*Korotev et al.*, 2003a; *Gillis et al.*, 2004; *Korotev*, 2005; *Warren*, 2005].

Regolith exposed at the surface of the Moon undergoes a variety of space weathering effects and "matures" with time [e.g., *McKay et al.*, 1991; *Lucey et al.*, 2006]. Consequences of space weathering include decrease in mean grain size, increase in the relative abundance of agglutinates, increase in the relative abundance of solar wind–implanted gases such as $^{36}$Ar, increase in the


**Figure 6.5.** The thick, vesicular fusion crust on regolith breccia QUE 93069. The cube is 1 cm in dimension. NASA photo.

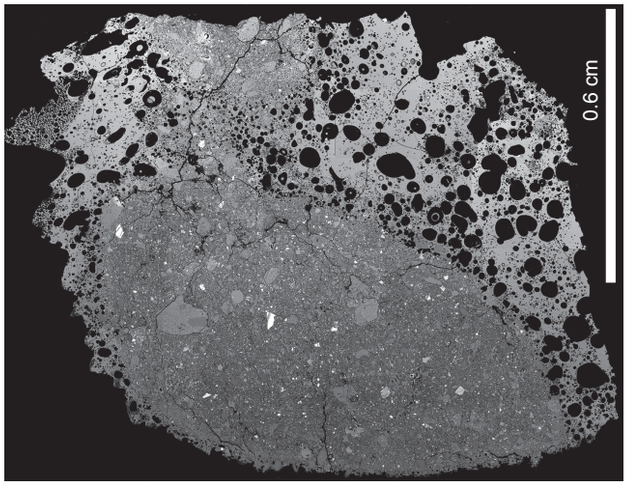


**Figure 6.6.** BSE (backscattered electron) image of a thin section of PCA 02007, a regolith breccia. At the top of the image is the thick, vesicular fusion crust caused largely by release, during atmospheric entry, of gases implanted by the solar wind while the material of the meteorite was fine-grained regolith on the lunar surface. The lower part of the image shows typical regolith-breccia texture. In BSE images, brightness increases with mean atomic mass. The darkest areas are rich in plagioclase (Al) and the lightest areas are rich in mafic (Fe-bearing) minerals.

concentration of siderophile elements like Ni and Ir, which are mainly derived from impacts of micrometeorites, and increase in the magnitude of the ferromagnetic resonance parameter $I_S$/FeO [*McKay et al.*, 1974, 1986; *Morris*, 1978; *Korotev et al.*, 2006]. Most samples of regolith fines collected on the *Apollo* missions are submature ($30 < I_S/\text{FeO} < 59$) or mature ($I_S/\text{FeO} \geq 60$) [*Morris*, 1978). Most regolith breccias from *Apollo* 15 and 16, however, are immature ($I_S/\text{FeO} < 29$) [*McKay et al.*, 1986]. Unfortunately, $I_S$/FeO has been measured on only three lunar meteorites. ALH A81005 ($I_S/\text{FeO} = 5$) [*Morris*, 1983] and MAC 88105 ($I_S/\text{FeO} = 0.8$) [*Lindstrom et al.*, 1995] are highly immature. QUE 93069 was formed from submature regolith ($I_S/\text{FeO} = 34$) [*Lindstrom et al.*, 1995].

Fusion crusts of nearly all stony meteorites are vesicular from release of gases at the surface of the meteorite during atmospheric entry [*Genge and Grady*, 1999]. A prominent characteristic of several ANSMET lunar regolith breccias is the presence of thick and highly vesicular fusion crusts. These vesicular crusts are most apparent on those meteorites that have high abundances of gaseous solar wind–implanted elements (e.g., H, He, N, Ne, Ar), most notably ALH A81005, QUE 93069/94269 (Figure 6.5), QUE 94281, and PCA 02007 (Figure 6.6). (Vesicular fusion crusts are seldom seen on hot-desert meteorites because the crusts on those meteorites have largely been eroded away by dust-bearing wind.) As *Thaisen and Taylor* [2009] warn, however, unbrecciated, basaltic lunar meteorites LAP 02005 and MIL 05035 also have vesicular fusion crusts, and these are not likely due to solar wind–implanted gases. Nevertheless, it is among the regolith-breccia meteorites where thick, vesicular fusion crusts are most evident.

## 6.4. COMPOSITIONAL SYSTEMATICS

To a good first approximation, compositions of polymict lunar samples (breccias and regolith) can be modeled as mixtures of three classes of material [*Korotev*, 2005; *Lucey et al.*, 2006]: rocks of the Feldspathic Highlands Terrane [*Jolliff et al.*, 2000], rocks of the Procellarum KREEP Terrane [*Jolliff et al.*, 2000], and rocks (and pyroclastic glass beads) from the basaltic maria, which occur in both terranes. Rocks of the Feldspathic Highlands Terrane (Figure 6.2) are mainly anorthosites, noritic anorthosites, troctolitic anorthosites, and their brecciated derivatives. They are characterized by low concentrations of elements associated with mafic minerals (e.g., Fe and Sc; Figures 6.3 and 6.4), high concentrations of $Al_2O_3$ and CaO (Figure 6.7), and low concentrations of incompatible elements (e.g., Sm and Th; Figures 6.3 and 6.4). Materials of the Procellarum KREEP Terrane are typically noritic in composition, with intermediate concentrations of FeO and $Al_2O_3$ but high concentrations of incompatible elements. Rocks and glass from the basaltic maria are rich in FeO and Sc but poor in $Al_2O_3$, with low to intermediate concentrations of incompatible elements. This *Apollo* view of lunar meteorites may be oversimplified in that some lunar meteorites of intermediate FeO concentration (Figure 6.4) may not be mixtures of feldspathic material and mare basalt. Rather, they may represent mixtures that include moderately mafic material of the Feldspathic Highlands Terrane unlike that sampled by the *Apollo* missions [*Korotev et al.*, 2009b].

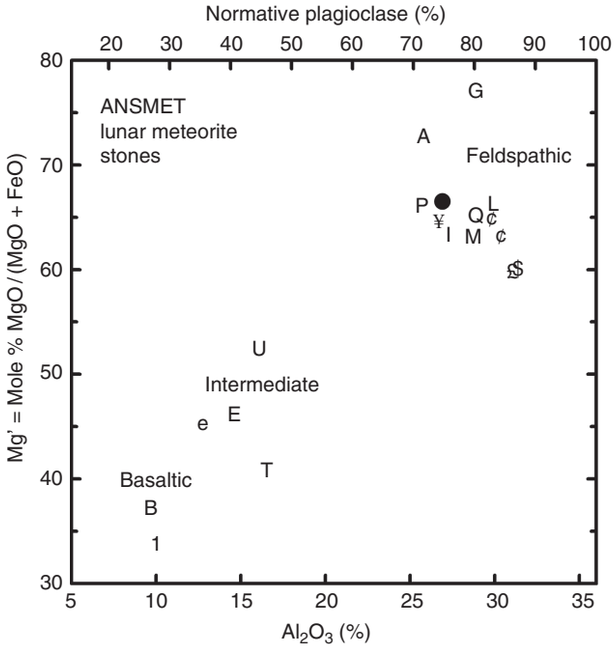


**Figure 6.7.** *Mg'* varies considerably among ANSMET feldspathic lunar meteorites. Each point represents a named stone; see Table 6.1 for symbol key. For reference, the mean composition of typical mature regolith from *Apollo* 16 is represented by the filled circle [*Korotev*, 1997]. The normative plagioclase axis assumes an $An_{96}$ composition for the plagioclase.

## 6.5. ROSTER OF ANSMET LUNAR METEORITES

Below, we discuss the ANSMET lunar meteorites in order of discovery. Few data are available for the most recently discovered meteorites. In contrast, we are aware of 38 peer-reviewed papers reporting data for Allan Hills 81005.

### *6.5.1. Allan Hills A81005*

ALH A81005, the first meteorite recognized to be from the Moon [*Marvin*, 1983; *Cassidy*, 2003], was collected nine years after the last *Apollo* mission (Plate 64). The rock is a regolith breccia from the lunar highlands. Like most feldspathic regolith breccias, lithic clasts are mainly other types of breccias: granulitic breccias, impact-melt breccias, and monomict breccias all derived from anorthosites, noritic anorthosites, troctolitic anorthosites, and their more mafic variants. The meteorite also contains rare clasts of mare basalts and impact-glass spherules all set in a dark matrix of minerals clasts and impact-derived vesicular glass [*Korotev et al.*, 1983; *Kurat and Brandstätter*, 1983; *Marvin*, 1983; *Ryder and Ostertag*, 1983; *Simon et al.*, 1983; *Treiman and Drake*, 1983; *Warren et al.*, 1983; *Goodrich et al.*, 1984; *Gross and Treiman*, 2010]. Petrographically the most unusual feature is the wide range of magnesium numbers (*Mg'* = mole% MgO/(MgO + FeO) in the mafic minerals associated with the feldspathic lithologies, 36–87 [*Goodrich et al.*, 1984; *Gross and Treiman*, 2010; *Gross et al.*, 2014].

Early compositional studies [*Boynton and Hill*, 1983; *Kallemeyn and Warren*, 1983; *Korotev et al.*, 1983; *Laul et al.*, 1983; *Palme et al.*, 1983] noted that ALH A81005 had low concentrations of elements associated with KREEP compared to polymict materials (regoliths and breccias) from the *Apollo* 16 site (Figure 6.3), the only *Apollo* mission to have landed in the feldspathic highlands at a point distant from basalt-filled impact basins (Figure 6.1). As more feldspathic lunar meteorites were found and data from the Lunar Prospector mission [*Lawrence et al.*, 2000] were assimilated, it became apparent that the meteorites are, in fact, typical of the feldspathic highlands, and it is the *Apollo* 16 site that is anomalous as a result of its proximity to the Procellarum KREEP Terrane (Figure 6.2) and the presence of high-Th Imbrium ejecta at the site [*Korotev et al.*, 2003a] (Figure 6.4). The meteorite remains among the most magnesian (high *Mg'*) of the feldspathic lunar meteorites (Figure 6.7) [*Korotev*, 2012; *Gross et al.*, 2014].

### *6.5.2. Elephant Moraine 87521 and 96008*

EET 87521 was originally classified as a brecciated eucrite but was later recognized to be a lunar meteorite composed mainly of brecciated VLT (very low Ti, <1% $TiO_2$) mare basalt [*Delaney*, 1989; *Warren and Kallemeyn*, 1989]. A paired stone, EET 96008, was found nine years later. Prior to EET 87/96, VLT basalt was known only from small fragments in the *Apollo* 17 and *Luna* 24 regoliths [*Vaniman and Papike*, 1977; *Ma et al.*, 1978]. The VLT basalt of EET 87/96 has a crystallization age of about 3.5 Ga (Figure 6.8; Plate 65).

Early works classified the meteorite as a fragmental breccia, but the presence of rare glass spherules and agglutinates [*Mikouchi*, 1999] confirm that it is a highly immature regolith breccia. The meteorite is characterized by coarse pyroxenes with exsolution lamellae and intergrowths of silica, fayalite, and hedenbergite; both features are rare in *Apollo* basalts [*Anand et al.*, 2003; *Warren and Kallemeyn*, 1989; *Takeda et al.*, 1992]. The meteorite is also unusual in that there are no breccias in the *Apollo* collection that, like EET 87/96, consist mainly of mineral grains from coarse-grained volcanic rocks and have such little glass [*Korotev et al.*, 2003b].

Although petrographic evidence for feldspathic clasts is rare [*Warren and Kallemeyn*, 1989; *Anand et al.*, 2003; *Takeda et al.*, 1992; *Warren and Ulff-Møller*, 1999], the FeO concentration of the meteorite

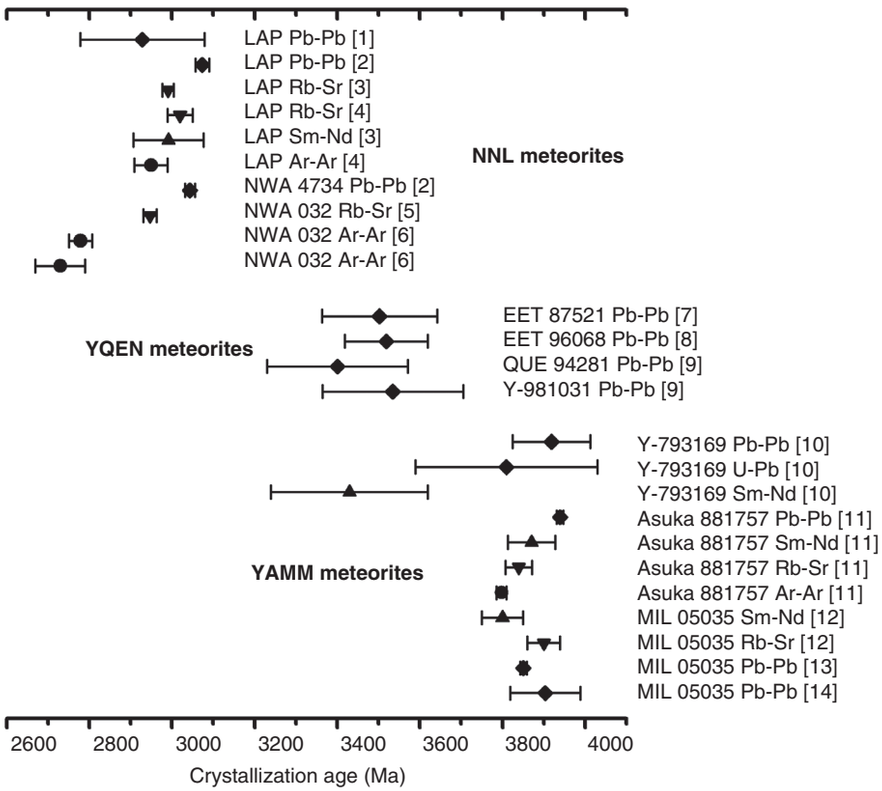


**Figure 6.8.** Crystallization ages of the basalt lithology in ANSMET basaltic lunar meteorites and comparison to lunar meteorites from elsewhere that are likely or possible launch pairs. At least three different age groups are indicated. Symbol shapes represent different isotopic techniques. Sources of data: [1] *Anand et al.*, 2006; [2] *Wang and Hsu*, 2010; [3] *Rankenburg et al.*, 2007, [4] *Nyquist et al.*, 2005; [5] *Borg et al.*, 2009; [6] *Fernandes et al.*, 2003; [7] *Terada et al.*, 2005; [8] *Anand et al.*, 2003; [9] *Terada et al.*, 2006; [10] *Torigoye-Kita et al.*, 1995; [11] *Misawa et al.*, 1993; [12] *Nyquist et al.*, 2007; [13] *Zhang et al.*, 2010; and [14] *Terada et al.*, 2007). The YQEN also group includes NWA 4884 [*Korotev et al.*, 2009b], for which there are no isotopic data.

is at the low end of the range for mare basalts from the *Apollo* and *Luna* missions (Figure 6.4), suggesting that the meteorite may contain a non-negligible proportion of nonmare material. *Arai and Warren* [1999] suggest 5%–10%. If the proportion is even that great, then the nonmare material is petrographically cryptic, presumably because it is finer grained than the mare material. Compositionally, the meteorite is heterogeneous and consists of two mafic components, (1) a primitive component with 12%–15% FeO, high *Mg'*, and low concentrations of incompatible elements; and (2) an evolved component with >24% FeO, low *Mg'*, and moderate concentrations of incompatible elements [*Lindstrom et al.*, 1999; *Korotev et al.*, 2003b]. Curiously, concentrations of solar wind–implanted gases [*Eugster et al.*, 1996, 2000] are two to three times greater in EET 87/96 than in MAC 88105 [*Eugster et al.*, 1991; *Palme et al.*, 1991], which is more obviously a regolith breccia. EET 87/96 does, however, have the lowest concentration of Ir of the brecciated ANSMET meteorites (Figure 6.9), indicating little input of asteroidal meteorite material.

### *6.5.3. MacAlpine Hills 88104 and 88105*

The two MAC 88104/05 stones (Plate 68) were found close together in the field and are indistinguishable compositionally and petrographically [*Jolliff et al.*, 1991; *Lindstrom et al.*, 1991a,b; *Neal et al.*, 1991]. The meteorite is a feldspathic regolith breccia (Figure 6.10). The bulk composition is typical of that for a feldspathic lunar meteorite (Figs. 6.3 and 6.4), but *Mg'* is at the ferroan end of the range (Figure 6.7). Lithic clasts are dominated by granulitic and impact-melt breccias, but the meteorite shows a wide variety of relict igneous clasts nearly all associated with the ferroan-anorthositic suite of lunar plutonic rocks [*Warren*, 1990]. *Cohen et al.* [2005] have dated ($^{40}Ar$–$^{39}Ar$) nine clasts of feldspathic and K-poor impact-melt breccia in MAC 88105. Ages ranged from 2.5 ± 1.5 Ga to 3.9 ± 0.1 Ga, all similar to or younger than the ubiquitous 3.8–3.9 Ga obtained for the K-rich impact-melt breccias in the *Apollo* collection [*Haskin et al.*, 1998]. The meteorite also contains impact glasses mainly of nonmare origin and rare fragments of mare basalt [*Delano*, 1991;

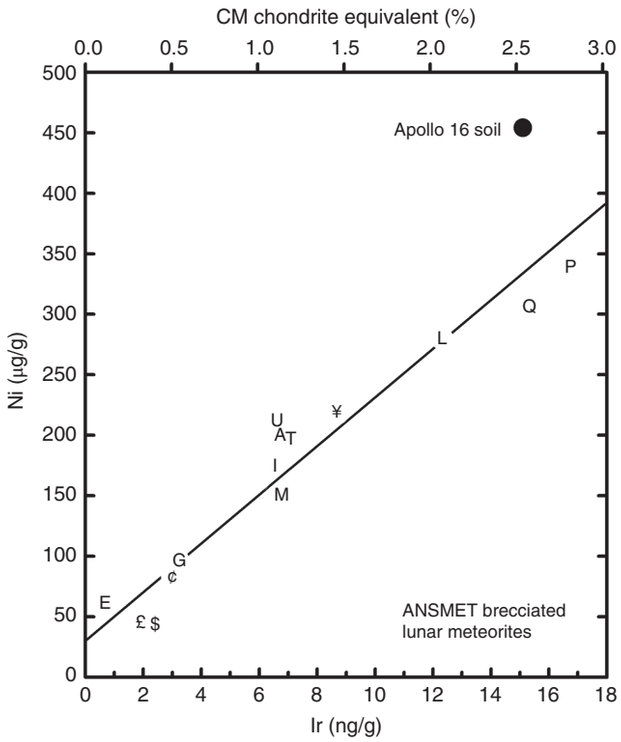


**Figure 6.9.** Concentrations of Ir and Ni in ANSMET brecciated lunar meteorites and comparison to mature *Apollo* 16 regolith [*Korotev*, 1997]. Igneous and plutonic lunar rocks have effectively zero ng/g Ir; all of the Ir and most of the Ni in lunar regoliths and breccias derive from asteroidal meteorites that have impacted to Moon. Much of the Ir in the lunar regolith derives from micrometeorites of CM chondrite composition [*Wasson et al.*, 1975]. At *Apollo* 16, a significant fraction also derives from an iron meteorite component with a non-chondritic Ni/Ir ratio [*Korotev*, 1997]. For reference, the diagonal line is a mixing line between an assumed lunar component with 0 ng/g Ir and 30 µg/g Ni and CM chondrites [*Wasson and Kallemeyn*, 1988]. Data are from Table 6.2. Symbol key is in Table 6.1.

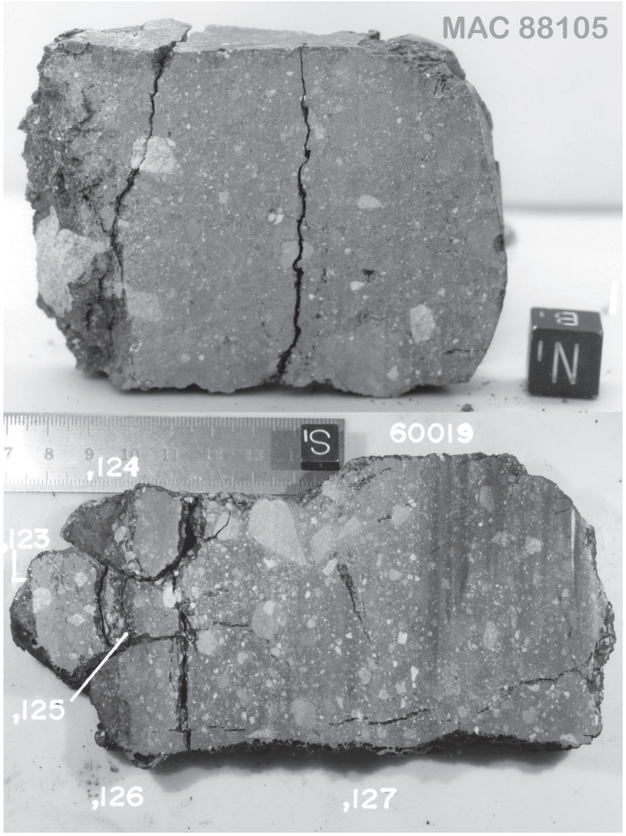


**Figure 6.10.** Sawn faces of two regolith breccias from the lunar highlands, lunar meteorite MAC 88105 (top) and *Apollo* 16 sample 60019 (bottom). Note that the clasts show no size sorting or preferred orientation, they are only moderately rounded, and their aspect ratios are rarely greater than 3:1. Both rocks are highly coherent. Clasts and matrix have equal strength as fractures pass from matrix through clasts without deviation. (Many *Apollo* regolith breccias are highly friable, however, and clasts can easily be separated from the matrix.) The clasts are mainly impact-melt breccias and granulitic breccias. Although the clasts are lighter colored than the matrix, they are not more feldspathic. The matrix is dark because it is fine grained and space weathered. NASA photos.

*Jolliff et al.*, 1991; *Koeberl*, 1991a; *Lindstrom et al.*, 1991b; *Neal et al.*, 1991; *Palme et al.*, 1991; *Takeda et al.*, 1991; *G J. Taylor*, 1991; *Warren and Kallemeyn*, 1991a; *Robinson and Treiman*, 2010]. *Joy et al.* [2010b] report the occurrence of a rare magnesian troctolitic clast in MAC 88105. Dhofar 1428 from Oman is similar in composition to MAC 88104/5 and may be a launch pair [*Korotev*, 2012], that is, both rocks may have been ejected from the Moon by a single impact but fell to Earth at different times and places. MAC 88105 has the lowest concentrations of solar wind implanted gases among the five ANSMET meteorites for which gas concentrations have been measured. CRE (cosmic-ray exposure) data indicate a lunar ejection age of 275 ± 15 ka and a long terrestrial age of 230 ± 70 ka [*Nishiizumi et al.*, 1996; Figure 6.11].

### *6.5.4. Queen Alexandra Range 93069 and 94269*

QUE 03069/94269 is a feldspathic, glass-rich regolith breccia. The two stones, found a year apart, are identical in composition [*Warren et al.*, 2005] and have the same CRE history [*Nishiizumi et al.*, 1996; *Polnau and Eugster*, 1998]. The bulk composition is typical of that for feldspathic lunar meteorites (Figure 6.3). The rock is dominated by lithic and mineral clasts from feldspathic rocks; clasts of mafic nonmare rocks and mare basalt are rare. *Cohen et al.* [2005] dated five clasts of feldspathic and K-poor impact-melt breccia in QUE 93069. Similar to MAC 88105, all are younger than 3.7 ± 0.5 Ga.

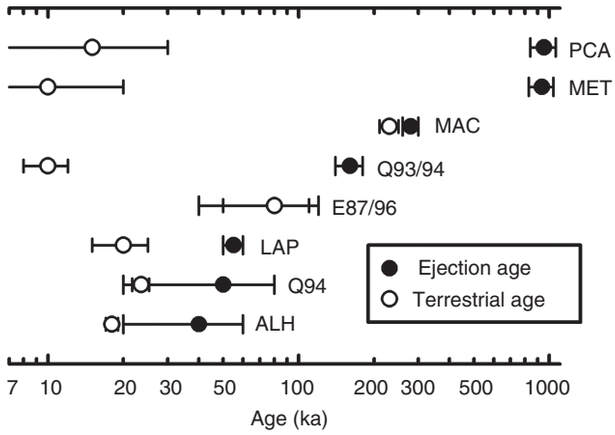


**Figure 6.11.** Ejection ages and terrestrial ages for ANSMET lunar meteorites ALH A81005, QUE 94281, LAP 02205 and pairs, EET 87521/96008, QUE 93069/94269, MAC 88015, MET 01210, and PCA 02207 [after *Nishiizumi et al*., 1996; *Nishiizumi*, 2003]. Data are from *Jull* [2006], *Nishiizumi* [2003], *Nishiizumi and Caffee* [1996], *Nishiizumi et al*. [1991, 1996, 1999, 2006], and *Thalmann et al*. [1996].

The meteorite is rich in impact-glass spherules and fragments. Most glasses have feldspathic compositions, but a small fraction have mafic composition, some corresponding to medium-Ti mare basalt. Glass concentrations have a wide range of *Mg'* (55–96) and some have high-aluminum, silica-poor [*Naney et al*., 1976] compositions. Agglutinate clasts are present and grains of FeNi metal are abundant [*Bischoff*, 1996; *Grier et al*., 1995; *Koeberl et al*., 1996, *Korotev et al*., 1996; *Robinson and Treiman*, 2010; *Spettel et al*., 1995; *Warren and Kallemeyn*, 1995; *Warren et al*., 2005].

The most unusual aspect of the meteorite is that the regolith of which it is composed is more mature than that of most meteoritic regolith breccias. As a consequence of the high surface exposure, concentrations of solar wind–implanted noble gases [*Thalmann et al*., 1996], siderophile elements (Figure 6.9) [*Korotev et al*., 2006], and impact-glass spherules and fragments are all at the high end of the ranges observed among lunar meteorites. The meteorite also has a strikingly vesicular fusion crust from release of the solar wind–implanted gases from the surface melt during atmospheric entry (Figure 6.5).

### *6.5.5. Queen Alexandra Range 94281*

QUE 94281 is a clast-rich regolith breccia consisting of both basaltic and feldspathic material. "The matrix is very heterogeneous. In most areas, it is a fine-grained, glass-poor fragmental material, but several large regions—up to 5 mm across—have extremely fine-grained (glassy aphanitic) dark-brown matrix along with relatively low fragment/matrix ratio" [*Arai and Warren*, 1999]. The meteorite contains agglutinates and abundant glass spherules. Lithic clasts are predominantly VLT basalt or gabbro, but feldspathic clasts are also present. Pyroxene grains in the basalt are coarse grained and finely exsolved, suggesting a hypabyssal setting [summary from *Jolliff et al*., 1998; *Arai and Warren*, 1999; and *Korotev et al*., 2003b].

There is no evidence to suspect that QUE 94281 is paired with QUE 93069/94269 (Figures 6.3, 6.7, and 6.11). There is, however, strong compositional, mineralogical, textural, and CRE evidence that QUE 94281 is launch paired with paired stones Yamato 793274 and Yamato 981031 [*Dreibus et al*., 1996; *Jolliff et al*., 1998; *Kring et al*., 1996; *Polnau and Eugster*, 1998]. *Arai and Warren* [1999] make the strongest argument by showing that the same two distinctive types of mare volcanic glass dominate the glass populations in each of the two meteorites. QUE 94281 and Yamato 79/98 are similar in composition (Figure 6.12). There is also strong evidence that the "YQ" meteorites [*Arai and Warren*, 1999] are launch paired with EET 87/96. Both compositionally and texturally, the coarse-grained basalt or gabbro component of the YQ meteorites is similar to that of EET 87/96 [*Kring et al*., 1996; *Korotev et al*., 2003b] (Figure 6.12). Crystallization ages of the basalt lithologies are the same, within uncertainty (Figure 6.8). Finally, NWA 4884 from the Sahara Desert is identical in composition to QUE 94281 for lithophile elements [*Korotev et al*., 2009b] (Figure 6.12). The preliminary petrographic description of NWA 4884 is consistent with that of QUE 94281 [*A. Irving and S. Kuehner*, in *Connolly et al*., 2007].

On any of a number of two-element plots, the "YQEN" meteorites (Yamato 79/98, QUE 94281, EET 87/96, and NWA 4884) plot along a mixing line between VLT basalt and a nonmare component that is richer in incompatible elements, $Na_2O$, and $TiO_2$ and is more magnesian than most feldspathic lunar meteorites (Figures 6.12 and 6.13) [*Korotev et al*., 2003b]. On the basis of compositional mass balance, *Jolliff et al*. [1998] estimated 46% nonmare material in QUE 94281, whereas *Arai and Warren* [1999] estimated ~33%; the difference reflects different assumptions about the compositions of the mare and nonmare components.

EET 87/96 is richer in the mare component than the other YQEN meteorites. As with the YAMM meteorites (next section), the YQEN meteorites appear to originate from a place where feldspathic ejecta overlies a deposit of mare basalt. EET 87/96 represents deeper, immature, basaltic regolith, whereas QUE 94281, Yamato 793274/981031, and NWA 4884 represent a shallower, more mature regolith consisting of basaltic material, feldspathic material, and perhaps some KREEP-bearing material.

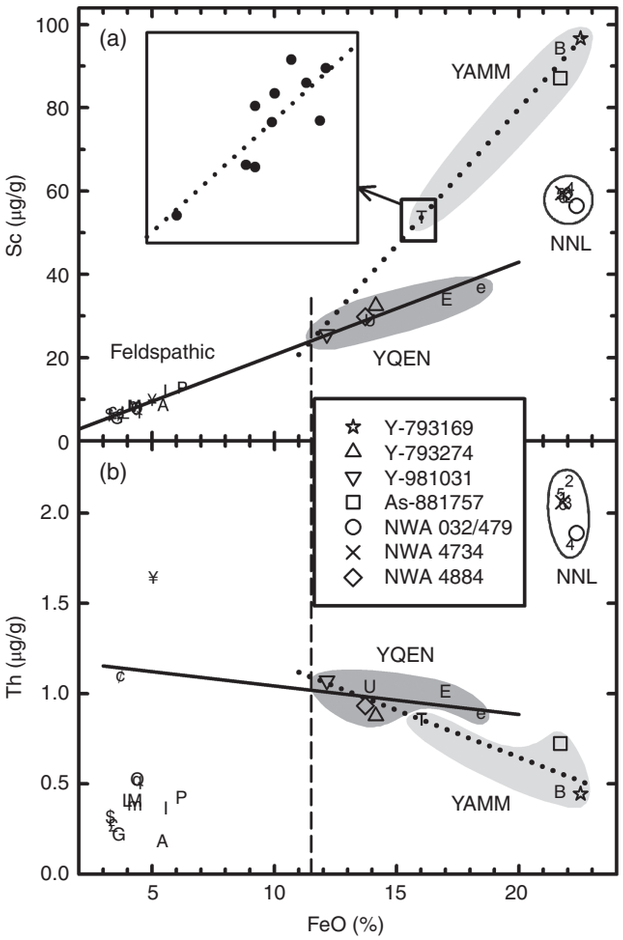


**Figure 6.12.** (a) Sc/FeO is nearly constant among feldspathic and very-low-Ti dominated, basaltic lunar meteorites (YQEN field). The diagonal solid line is a least-squares fit to the "feldspathic" and seven YQEN points. The dotted line is a least squares fit to the four YAMM meteorite points. If MET 01210 (T) is a simple binary mixture of mare basalt such as that of the high-FeO YAMM meteorites and some low-FeO, nonmare component, then the low-FeO component has a composition that is not highly feldspathic, having a composition at the intersection of the diagonal lines at 11.5% FeO. The inset shows data for 10 subsamples of MET 01210 [*Korotev et al.*, 2009b]. (b) The implied low-FeO component of MET 01210 (intersection of diagonal dotted line and dashed vertical lines) has about 1.1 µg/g Th, greater than most feldspathic lunar meteorites. The fact that the implied nonmare component plots near the field of the YQEN meteorites is a coincidence in that two launch-pair groups have different CRE exposure histories. The solid diagonal line is a least-squares fit to the seven YQEN points. If these breccias represent simple binary mixtures, then the feldspathic component is also richer in Th (~1.1 µg/g) than most feldspathic lunar meteorites. For the ANSMET meteorites, plot symbols are in Table 6.1. Data for the meteorites in the legend are from *Barrat et al.* [2005], *Fagan et al.* [2002], *Fukuoka* [1990], *Jolliff et al.* [1993], *Koeberl et al.* [1991b, 1993], *Korotev et al.*, [1993, 2009b], *Lindstrom et al.* [1991c], *Warren and Kallemeyn* [1991b, 1993], *Yanai and Kojima* [1991], *Zeigler et al.* [2005], and unpublished data (this lab).

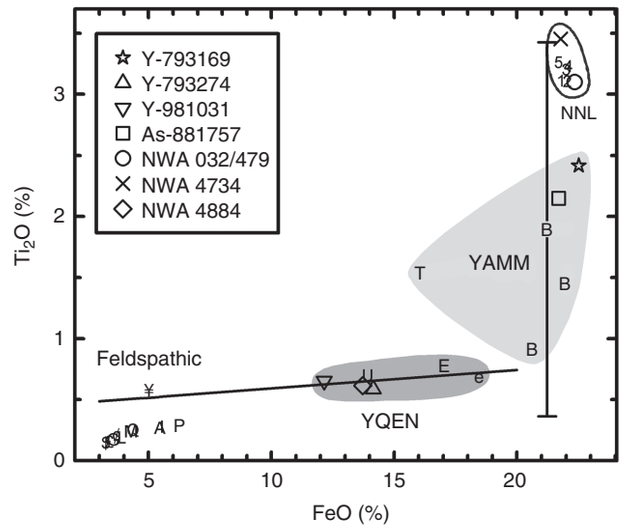


**Figure 6.13.** Comparison of $TiO_2$ concentrations in ANSMET (Table 6.1) basaltic meteorites (>12% FeO) to likely launch pairs (meteorites in legend). The diagonal line is a least-squares fit to the YQEN data showing that, with <1% $TiO_2$, the basaltic component is a VLT (very-low-Ti) basalt and that the feldspathic component is somewhat richer in Ti than most feldspathic lunar meteorites. For MIL 05035, three points are plotted (B), representing the data (low to high $TiO_2$) of *Joy et al.* [2008], *Liu et al.* [2009], and this work. The error bar for our data represents the 95% confidence interval based on analysis of 11 subsamples. The meteorite is very coarse grained.

### *6.5.6. Meteorite Hills 01210*

MET 01210 is a glassy-matrix regolith breccia dominated by low-Ti or VLT mare basalt. *Huber and Warren* [2005] note that "roughly half of the pyroxenes display exsolution to extents that vastly exceed the norm (<<0.1 µm typical lamella width) for *Apollo* mare basalts" and that "MET 01210 thus joins lunaites Y-793274, QU94281, EET87521, and (to a lesser degree) As-881757, in having undergone a remarkable extent of slow cooling or annealing, in comparison to *Apollo* mare basalts." There is no evidence that MET 01210 is related to the YQEN clan, however. CRE data for MET 01210 are distinct from that of QUE 94281 and EET 87/96 (Figure 6.11), and the compositions are different (Figures 6.12 and 6.13). The meteorite contains some feldspathic material in the form of impact-melt and granulitic breccias, symplectites from breakdown of pyroxferroite, and rare agglutinates and spherules [*Arai et al.*, 2005; *Huber and Warren*, 2005; *Zeigler et al.*, 2005; *Day et al.*, 2006b; *Joy et al.*, 2006a; 2010a].

*Arai et al.* [2005] note that a basalt clast in MET 01210 is very similar to that of gabbroic lunar meteorite Asuka 881757, collected in Antarctica 2850 km away, and that the two meteorites might be "petrogenetically related."

The bulk composition of MET 01210 corresponds to a mixture of Asuka 881757 (also MIL 05035, below) and feldspathic material (Figure 6.12), suggesting that the meteorites are launch paired [*Zeigler et al*., 2007]. Asuka 881757 is believed to be launch paired with Yamato 793169, collected about 370 km away, on the basis of similar CRE histories [*Nishiizumi et al*., 1992; *Thalmann et al*., 1996], chemical composition [*Jolliff et al*., 1993; *Warren and Kallemeyn*, 1993], and crystallization ages [*Fernandes et al*., 2009] (Figure 6.8). Crystallization ages of the MET 01210 basalt are consistent with the pairing hypothesis (Figure 6.8) as are preliminary CRE data [*Nishiizumi et al*., 2006]. *Arai et al*. [2010] review the evidence for the launch pairing of the "YAMM" meteorites (Yamato 793169, Asuka 881757, MET 01210, and MIL 05035) and suggest that MET 01210 derives from a cryptomare, a place where mare volcanic deposits are overlain by feldspathic ejecta from an impact into the highlands [*Head and Wilson*, 1992] and where subsequent smaller impacts mixed the mare and highlands materials.

*Arai et al*. [2010] estimate that MET 01210 contains 32% nonmare material, whereas *Zeigler et al*. [2007] estimate 35%. Both estimates assume that the nonmare material is feldspathic. However, if MET 01210 is a simple binary mixture, then the low-FeO component is unlikely to have less than about 11.5% FeO (Figure 6.12), an anorthositic norite composition. A scenario that accounts for the data is that MET 01210 is a three-component mixture of (1) a high-Sc basalt like Asuka 881757 and a regolith with 11.5% FeO, which itself is a mixture of (2) feldspathic material and (3) a low-Sc (likely VLT) basalt. The fact that the MET 01210 subsample data do not scatter in a triangular pattern but trend along the YAMM mixing line (Figure 6.12, inset) argues that the feldspathic and low-Sc mare component are well mixed, that is, a regolith. Such regolith-rock mixing relationships are seen in other sample sets [*Jolliff et al*., 1996; *Korotev*, 1997].

### *6.5.7. Pecora Escarpment 02007*

PCA 02007 is a feldspathic regolith breccia with clasts set in a matrix that is partially glassy and partially fragmental. Most of the clasts are feldspathic. Our own interpretation is that "the lithic-clast population of PCA 02007 … consists entirely of clasts that have been modified by impacts, that is, there are no igneous lithic clasts, only clasts that have been extensively metamorphosed. The 100 clasts of this study fall into the following textural categories: glassy impact-melt breccias ($N = 84$), quenched mafic breccias (3), crystalline impact-melt breccias (8), regolith breccia (5), and agglutinates (3 or more)" [*Korotev et al*., 2006]. Others, however, have interpreted the textures of some clasts in terms of plutonic highlands rocks [*L. A. Taylor et al*., 2004; *Day et al*., 2006b; *Joy et al*., 2006a] and have observed clasts of mare basalt [*L. A. Taylor et al*., 2004; *Joy et al*., 2010a, *Vaughan et al*., 2011]. *Day et al*. [2006b] found an unusual lithic clast from a chondrite.

Perhaps because of the mare component (basalt clasts, impact glass, pyroclastic glass), PCA 02007 is compositionally at the mafic end of the range of feldspathic lunar meteorites (Figs. 6.3 and 6.4). Among ANSMET lunar meteorites it is the richest in siderophile elements (Figure 6.9), probably because the regolith from which it formed is moderately mature [*Korotev et al*., 2006; *Joy et al*., 2010a]. The meteorite has a thick, vesicular fusion crust (Figure 6.6). There are no data for any of the usual regolith-maturity parameters, however.

PCA 02007 and MET 01210 have the same ejection age (Figure 6.11), suggesting that PCA 02007 may be another member of the YAMM launch-pair group and that PCA-like feldspathic material might the feldspathic component of MET 01210. As noted above, however, the implied feldspathic component of MET 01210 is considerably richer in incompatible elements (~1.5 μg/g Th, Figure 6.12) than PCA 02007 (0.44 μg/g), so we suspect that the meteorites are unrelated.

### *6.5.8. LaPaz Icefield 02205, 02224, 02226, 02436, 03632, and 04841*

The six stones of the LaPaz Icefield lunar meteorite were found over three field seasons (Table 6.1; Plate 67). At 1.226 kg, LAP 02205 is the largest ANSMET lunar meteorite stone. The six stones are essentially identical in composition (e.g., Figures 6.3 and 6.14), texture, and mineralogy.

The meteorite is an unbrecciated low-Ti mare basalt. There are numerous petrographic descriptions [*Righter et al*., 2005; *Zeigler et al*., 2005; *Anand et al*., 2006; *Joy et al*., 2006b; *Day et al*., 2006a; *Hill et al*., 2009]. Modally, the meteorite is 50.2% pyroxene (with a ~3:1 augite to pigeonite ratio), 35.1% plagioclase, 3.1% olivine, 3.7% ilmenite, 3.5% fayalite, 2.1% silica (likely cristobalite), 0.3% chromite, ~1% shock-induced melt veins, and ~1% mesostasis glass [*Zeigler et al*., 2005; see also *Day et al*., 2006a]. Minor and trace phases include troilite, ulvöspinel, phosphates (RE-merrillite, fluorapatite), and FeNi metal of nonmeteoritic origin. Mesostasis areas (symplectites) contain pyroxferroite, fayalite, silica, baddelyite, barian K-feldspar, K-Si-rich glasses, and Si-rich glasses. Although unbrecciated, the meteorite is fractured, contains glassy melt veins, and some of the plagioclase is isotropic (maskelynite).

The LAP basalt is similar in composition to the low-Ti basalts of *Apollo* 12 and 15, but in detail it is not identical to any *Apollo* basalt. The crystallization age, ~3.0 Ga (Figure 6.8), is younger than that of the *Apollo*

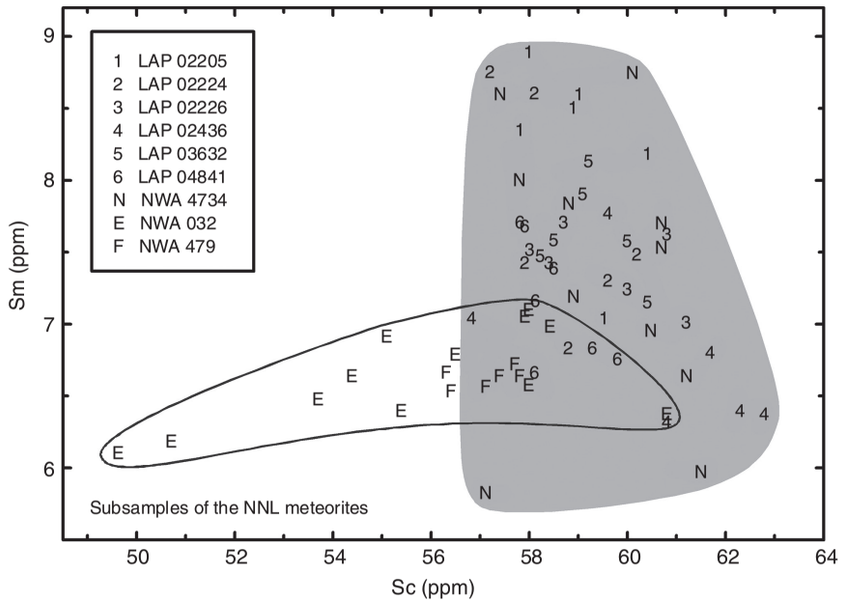


**Figure 6.14.** Each LAP point represents a 35-mg subsample and each NWA point represents a 25-mg subsample, on average. The six LAP basalts are indistinguishable in composition from each other and from NWA 4734 on any two-element plot such as this. NWA 032 and NWA 479 are paired. NWA 032/479 is richer in olivine than LAP and, consequently, poorer in Sc and richer in Co [*Zeigler et al.*, 2005]. All data are from the Washington University INAA lab [*Fagan et al.*, 2002; *Zeigler et al.*, 2005].

12 and 15 basalts (3.1–3.4 Ga) [Table 6 of *S. R. Taylor*, 1982]. The LAP basalt is all but identical, however, in composition and texture (Figure 6.14) [*Korotev et al.*, 2009a; *Fernandes et al.*, 2009] as well as crystallization age [*Korotev et al.*, 2009a; *Fernandes et al.*, 2009; *Wang and Hsu*, 2010; *Elardo et al.*, 2012, 2013] to 1.37-kg NWA 4734 from Morocco. These data strongly suggest that the LAP basalts and NWA 4734 are launch paired [*Korotev et al.*, 2009a].

Paired stones NWA 032 and NWA 479 have several chemical (Figures 6.12, 6.13, and 6.14) and petrographical features in common with the LAP stones, suggesting that the two meteorites are launch paired [*Jolliff et al.*, 2004; *Zeigler et al.*, 2005]. The crystallization ages are very similar (Figure 6.8) as are the ejection ages [*Nishiizumi et al.*, 2006]. However, the two meteorites have very different values of $\varepsilon_{Nd}$, making any simple genetic relationship unlikely [*Elardo et al.*, 2012, 2013]. Thus, the similarities between LAP and NWA 032/479 may be coincidental.

### *6.5.9. Miller Range 05035*

MIL 05035 is an unbrecciated low-Ti mare basalt with a coarse-grained, gabbroic texture (Plate 66). Pyroxenes range from 2 to 10 mm in size [*Arai et al.*, 2010]. Modally, the meteorite is 54%–62% pyroxene, 25%–36% plagioclase, 6%–7% symplectites, 0.6%–3.5% fayalite, 0.8%–1.0% silica, 0.5%–1.0% ilmenite, 0.5%–0.6% glass, and 0.2%–1.5% ulvöspinel, with trace amounts of silica, troilite, baddelyite, K- and Ba-rich alkali feldspar, and phosphates [*Joy et al.*, 2008; *Liu et al.*, 2009]. Pyroxenes are strongly shocked and all of the plagioclase has been converted to maskelynite with some recrystallization.

The whole rock $TiO_2$ concentration of MIL 05035 is not well constrained. For this work we obtained a mean of 1.9% ± 1.5% (95% confidence limits) on a 0.42-g sample (mean of 11 subsamples, Figure 6.13), *Joy et al.* [2008] obtained 0.9% on a 0.31-g sample, and *Liu et al.* [2009] obtained 1.44% on a 1.9-g sample. The mass-weighted mean, 1.45%, is listed in Table 6.2. From modal recombination of the data of *Joy et al.* [2008] and *Liu et al.* [2009] we estimate 1.6% $TiO_2$. Similarly, MgO concentrations range from 6.1% (this work) to 7.8% [*Joy et al.*, 2008] among the three laboratories. For comparison, *Thaisen and Taylor* [2009], who note that the composition of the fusion crust of MIL 05035 is highly variable from place to place, obtained means and standard deviations of 2.0% ± 0.9% $TiO_2$ and 5.8% ± 2.4% MgO from 170 analyses of the fusion crust.

It was recognized in the earliest studies of MIL 05035 that it was very similar in texture, mineralogy, and composition to Asuka 881757, collected 2500 km away in Antarctica, and that the two meteorites were thus likely launch pairs [*Arai et al.*, 2007; *Joy et al.*, 2007; *Liu et al.*, 2007; *Korotev and Zeigler*, 2007; *Zeigler et al.*, 2007]. Subsequent studies have shown that the crystallization ages also match (Figure 6.8). Although, as noted above,

Yamato 793169 and MET 01210 are also likely launch pairs to Asuka 881757, neither is as similar to Asuka 881757 as is MIL 05035.

### *6.5.10. Graves Nunataks 06157*

At 0.79 g, GRA 06157 is the smallest lunar meteorite so far recovered. It is a glassy-matrix regolith breccia containing abundant lithic and mineral clasts and a few small glassy spherules (Figure 6.15). All of the lithic clasts identified are granulite breccias. The mineral clast population is dominated by plagioclase, pyroxene, and olivine, with trace amounts of FeTiCr oxides, FeNi metal, and FeS. Our thin section (Figure 6.15) [also *Zeigler et al.*, 2012b] is roughly hemisphere shaped with a 5-mm diameter. It has a discontinuous vesicular fusion crust on the curved side (the exterior surface of the meteorite).

The most abundant type of lithic clasts are highly feldspathic (>90% plagioclase) granulite breccias consisting of large plagioclase grains ($An_{94–97}$) up to 1 mm in their longest dimension that contain tiny rounded inclusions of pyroxene almost always less than 2 μm wide. Rarely there are strings of larger pyroxene grains (up to 20 μm wide) present along the borders of some plagioclase grains. Augite is the dominant pyroxene ($En_{44}Wo_{42}Fs_{14}$), with rare occurrences of hypersthene ($En_{64}Wo_{3}Fs_{33}$); there is no compositional difference among the different-sized pyroxenes. Minor olivine grains also occur, with a relatively wide range in compositions ($Fo_{60–78}$). There are also troctolitic granulite clasts, including the largest lithic clast in the section (~1.5 mm on a side). These clasts contain up to 50% magnesian olivine ($Fo_{85–90}$), minor (<5%) amounts of magnesian augite ($En_{53}Wo_{37}Fs_{9}$), nearly end-member magnesian spinel, and trace amounts of bronzite ($En_{77}Wo_{2}Fs_{20}$). A few small (~150 μm) mafic granulite clasts (plagioclase is <20% by mode) are compositionally similar to the more feldspathic granulite clasts, albeit with slightly more ferroan pyroxene compositions ($En_{39}Wo_{42}Fs_{19}$; $En_{55}Wo_{2}Fs_{43}$).

Plagioclase compositions fall in a narrow range ($An_{94–98}$). In contrast, the olivine clasts analyzed span almost the

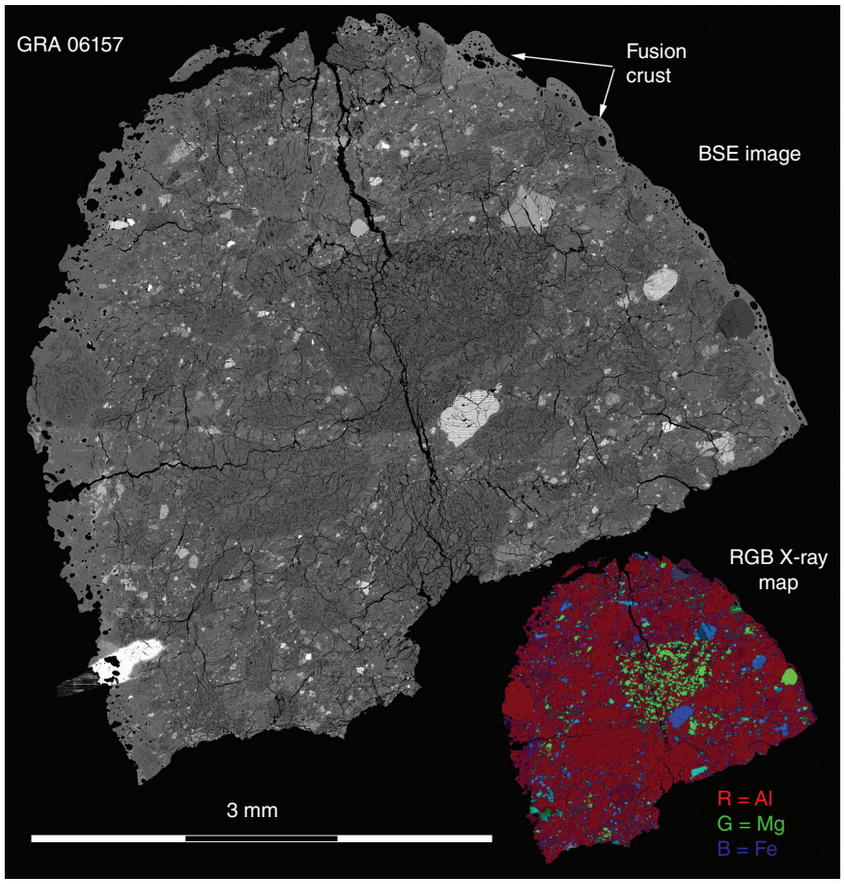


**Figure 6.15.** Back-scattered electron image (Figure 6.6) and an RGB elemental x-ray map of a thin section of lunar meteorite GRA 06157. In the x-ray map, areas rich in Al (e.g., plagioclase) are bright red, areas rich in Mg are bright green (e.g., olivine), and areas rich in Fe (e.g., pyroxene or FeNi metal) are bright blue. The scale bar applies only to the BSE image.

entire range of olivine compositions ($Fo_{7-93}$); most clasts are at the Mg-rich end of the range, however. Most pyroxene mineral clasts are exsolved, with augite and orthopyroxene lamellae ranging from submicron all the way up to nearly 100 μm thickness. A single large (200 × 150 μm) basaltic spherule is present. It is partially devitrified with magnesian olivine ($Fo_{78}$) quenching out of the glass. It has a bulk composition very similar to *Apollo* 15 yellow pyroclastic glass [*Shearer and Papike*, 1993].

Our bulk sample is only 57 mg in mass, from which we made two INAA subsamples, both of which we subsequently analyzed for major elements. Despite being a regolith breccia, GRA 06157 has low concentrations of siderophile elements compared to most regolith breccias [*Korotev et al.*, 2009a] (Figure 6.9). GRA 06157 is one of the most feldspathic meteorites studied here (29 wt.% $Al_2O_3$). Our sample is distinct in being more magnesian ($Mg' = 77 \pm 4$) than both any other lunar meteorite from Antarctica (Table 6.1) and any lunar meteorite composed of feldspathic regolith breccia of which we are aware (Figure 6.7). The magnesian nature is likely caused by the presence of the highly magnesian olivine present in the troctolitic granulite clasts and olivine mineral clasts.

### *6.5.11. Larkman Nunatak 06638*

LAR 06638 is another small (5.3 g) meteorite. The rock is a dark-matrix regolith breccia with millimeter-size light-colored clasts and one large (~1 cm), light-colored breccia clast that represents a significant proportion of the total mass of the meteorite [*Satterwhite and Righter*, 2007]. The large white clast is a fragmental breccia (there is no glassy matrix). The thin section in this study (LAR 06638,13) has both prominent lithologies present: 60% dark-matrix material and 40% light-colored clast material (Figure 6.16) [*Zeigler and Korotev*, 2013]. The dark-matrix area consists of granulite, impact-melt breccia, mineral, and glass clasts set in a glassy matrix, whereas the light-colored clast area consists of granulite and mineral clasts set in a fragmental matrix. The lithic clast population of the dark-matrix area is dominated by feldspathic granulite clasts, with a few feldspathic impact-melt breccia clasts also present. Both the granulite and impact-melt clasts are dominated by calcic plagioclase ($An_{95-99}$; almost always >90% by mode). The granulite clasts contain minor amounts of pyroxene and olivine that range widely in size (1–50 μm; typically <10 μm).

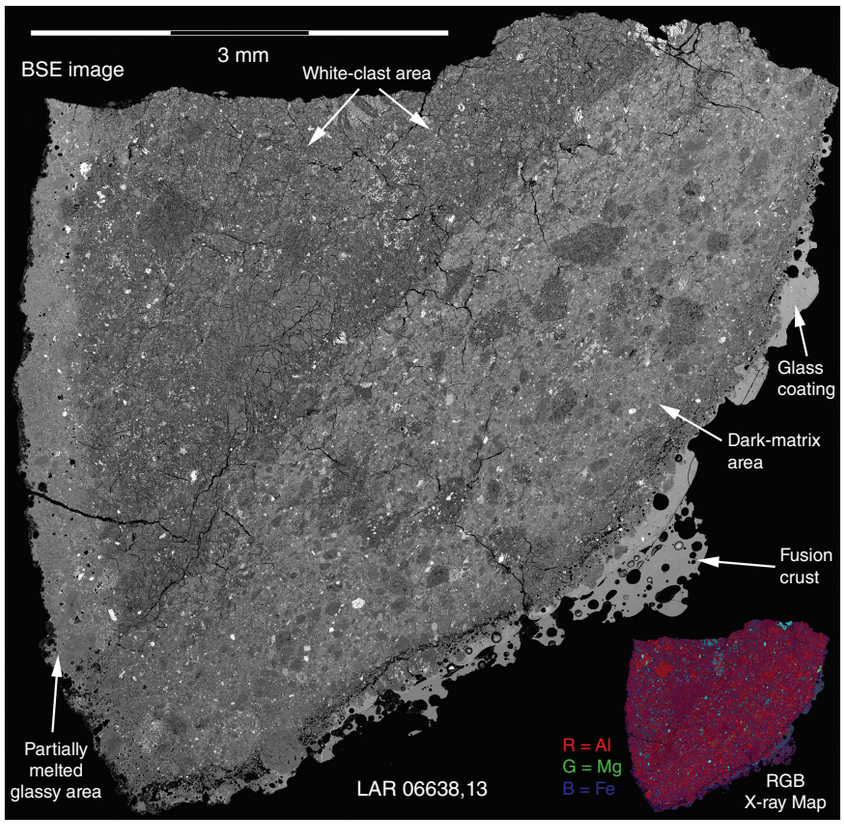


**Figure 6.16.** Back-scattered electron image (Figure 6.6) and an RGB (red, green, blue) elemental x-ray map of a thin section of lunar meteorite LAR 06638. The scale bar applies only to the BSE image.

Pyroxene compositions are typically high in Ca with a relatively constant Fe:Mg ratio ($En_{45–67}Wo_{9–35}$); minor amounts of low-Ca pyroxene are also observed ($En_{70–77}Wo_{2–4}$). Olivine grains have a restricted compositional range ($Fo_{63–76}$, most between $Fo_{64–68}$). Clasts of feldspathic impact-melt breccia typically have subparallel plagioclase laths with very thin "lamellae" (1–2 μm) of mafic glass separating them. The textures and mineral compositions observed in granulite clasts in the light-colored clast area are identical to those described in the dark-matrix area.

Mineral clast populations in both lithologies are dominated by plagioclase ($An_{95–98}$), with minor amounts of pyroxene ($En_{40–50}Wo_{18–40}$; $En_{60–70}Wo_{2–4}$) and olivine ($Fo_{65–76}$), and with trace amounts of FeTiCr oxides, FeNi metal, and Fe sulfide. Glass clasts are found only in the dark-matrix area and range in shape from irregular fragments to spherules. They are typically feldspathic (<6 wt.% FeO) and incompatible-element poor (e.g., <0.05 wt.% $K_2O$; <0.3 wt.% $TiO_2$). A few glass clasts are moderately mafic (9–12 wt.% FeO) and richer in incompatible elements (0.2 wt.% $K_2O$; 2.5 wt.% $TiO_2$). The spherules are typically small (<50 μm) and have feldspathic compositions; the exception is a single large (400 micron) devitrified feldspathic spherule.

LAR 06638 has three distinct glass coatings (Figure 6.16). The inner, moderately mafic glass coating (16 wt.% FeO + MgO) is slightly vesicular and contains schlieren and abundant nanophase Fe globules. This inner glass layer is overlain by a more feldspathic fusion crust (10.4 wt.% FeO + MgO) that is highly vesicular and free of schlieren and nanophase Fe. Finally, a partially melted glassy area occurs, where many of the mafic silicate grains that occur in the adjacent textures are absent and presumably incorporated into the moderately mafic glass. The presence of multiple generations of glass coatings on LAR 06638 is, to our knowledge, unique among lunar meteorites. The more mafic, schlieren, and nano-phase-Fe-bearing glass is similar in morphology to the South Ray Crater glass coatings at the *Apollo* 16 site [see *McKay et al.*, 1986] and likely has a similar origin. The outer, more feldspathic glass has a morphology typical of fusion crust observed on other feldspathic lunar meteorites. It is unclear whether the partially melted glass area represents a partially formed fusion crust or incipient melting due to heating on the lunar surface, likely from an overlying (and possibly ablated) glass splash coating.

Overall, LAR 06638 is a highly feldspathic (30 wt% $Al_2O_3$), incompatible-element poor (0.4 μg/g Th) breccia. We obtained INAA data for both the dark-mafic and light-clastic lithologies. Although the compositions are similar, the dark-matrix material is slightly less mafic (0.8 × Sc, 0.95 × FeO) and slightly richer in both $Na_2O$ (1.06×) and siderophile elements (1.2× for Ni and Ir) than the large light-colored clast. The small differences in composition are likely explained by the incorporation of small amounts of more diverse material into the regolith breccia, for example, KREEPy glass clasts to account for the higher siderophile and incompatible-element concentrations and anorthosite to account for the lower concentrations of mafic elements and increased Na concentrations. Among lunar meteorites from Antarctica, LAR 06638 most closely resembles MAC 88104/5 in composition, although it is slightly more feldspathic (Figures 6.3 and 6.4) and 1.8 times richer in siderophile elements (Figure 6.9). Compositionally, however, it is more similar to Dhofar 490/1084 from Oman [*Korotev*, 2012].

### *6.5.12. Miller Range 07006*

MIL 07006 is a basalt-bearing, feldspathic regolith breccia with a dark, aphanitic-to-glassy matrix. The lithic clasts are predominantly granulitic and feldspathic impact-melt breccias [*Zeigler et al.*, 2012a]; however, clasts of VLT basalt have also been observed [*Joy et al.*, 2010a; *Liu et al.*, 2009]. The clasts have sharp boundaries with the surrounding glassy matrix, in contrast to the other regolith breccia meteorites from the MIL site (below). Plagioclase compositions in MIL 07006 are largely invariant ($An_{94–98}$). There is a dichotomy in the compositions of pyroxene ($En_{48–78}$) and olivine ($Fo_{40–80}$) in the lithic clasts when compared to mineral clasts of pyroxene ($En_{10–52}$) and olivine ($Fo_{6–61}$).

MIL 07006 is among the most Sc- and Fe-rich of the ANSMET feldspathic lunar meteorites (Figures 6.3 and 6.4) as a result of the presence of basaltic lithic and mineral clasts. Compositionally, MIL 07006 is similar to PCA 02007 and Yamato 791197 from Antarctica, but it is much more similar to Dhofar 1436/1443 from Oman [*Korotev*, 2012].

### *6.5.13. Miller Range 090034, 090070, and 090075*

MIL 090034, MIL 090070, and MIL 090075 are glassy-matrix, clast-rich, immature, feldspathic regolith breccias. Centimeter-sized lithic clasts are common in all three stones. The clasts are dominantly feldspathic impact-melt breccias (particularly the largest clasts), with lesser amounts of granulitic breccias and rare norites, troctolites, and gabbros [*Liu et al.*, 2011; *Korotev et al.*, 2011; *Zeigler et al.*, 2012a].

MIL 090070 and MIL 090075 were found close together in the field and there is no compositional [*Korotev et al.*, 2011; *Shirai et al.*, 2012] or petrographic [*Zeigler et al.*, 2012a] evidence to suspect that they are not paired. MIL 090034 was found 15 km away from the MIL 090070/75 stones. MIL 090034 and MIL 090070/75 appear different from each other in hand specimen [R. Harrington, in *Satterwhite and Righter*, 2010]. We were allocated three

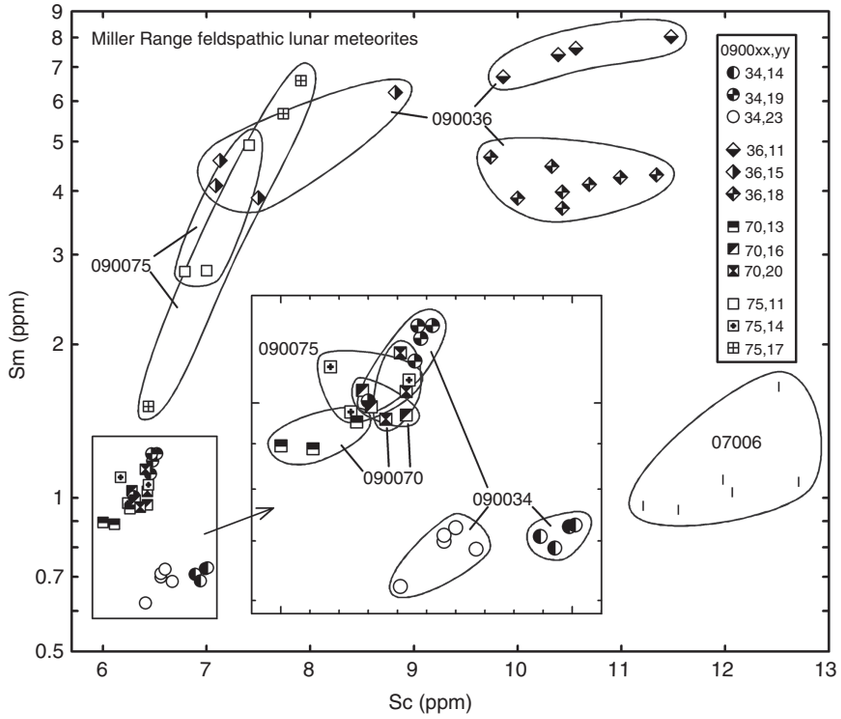


**Figure 6.17.** Subsamples (mean mass: 34 mg each; range: 20–41 mg) of the Miller Range feldspathic lunar meteorites in Sc-Sm space (compare with Figure 6.3). For the MIL 0900xx stones, we were allocated three different samples and analyzed four or more subsamples of each.

samples of each stone and analyzed 3–5 subsamples of each by INAA. For the most part, the stones are highly feldspathic (low Sc) and poor in incompatible elements (Figure 6.3). Two of the MIL 090075 samples, however, contain some Sm-rich lithology, but the third overlaps in composition with the three MIL 090070 samples and one of the MIL 090034 samples (Figure 6.17). Despite the differences, preliminary data of *Nishiizumi and Caffee* [2013] show that MIL090034, MIL 090070, and MIL 090075 all have similar concentrations of cosmogenic radionuclides. Thus, we assume that MIL090034 is paired with MIL 090070 and MIL 090075 and that the meteorite is compositionally heterogeneous at the scale of our sampling.

### *6.5.14. Miller Range 090036*

MIL 090036 is also a glassy-matrix, clast-rich, immature, feldspathic regolith breccia. Like MIL 090036/70/75, it is dominated by clasts of impact-melt breccias. Those in MIL 090036 are compositionally distinct, having more sodic plagioclase and more magnesian mafic silicates than the melt-breccia clasts in the other MIL 0900xx stones. As with MIL 090036/70/75, we analyzed multiple subsamples of three MIL 090036 samples. The three subsamples do not overlap in composition, again indicating that the meteorite is heterogeneous at the scale of our sampling (Figure 6.17). In detail, MIL 090036 shows no compositional overlap with the other three MIL 0900xx stones. It is significantly richer in incompatible elements Ti, Na, Eu, and siderophile elements (Table 6.2; Figures 6.3, 6.9, and 6.18) [*Korotev et al.*, 2011]. MIL 090036 is compositionally and petrographically similar to NWA 7022 [*Kuehner et al.*, 2012] (Figure 6.18), but the preliminary CRE data do not substantiate launch pairing [*Nishiizumi and Caffee*, 2013].

There is no petrographic or compositional evidence to suspect that any of the MIL 0900xx stones is paired with either MIL 05035 (basalt) or MIL 07006 (basalt-bearing feldspathic regolith breccia). None of the MIL 0900xx stones contain basaltic clasts [*Liu et al.*, 2011] and the texture of MIL 07006 is very different from those of any of the MIL 0900xx stones. The preliminary CRE data [*Nishiizumi and Caffee*, 2013] also argue that four distinct lunar meteorites have been found at the Miller Range site.

## 6.6. DISCUSSION AND SUMMARY

Lunar meteorites collected on ANSMET expeditions cover much of the compositional range observed among all lunar meteorites (Figure 6.4). Absent, however, are meteorites with 7% to 12% FeO and those with very high

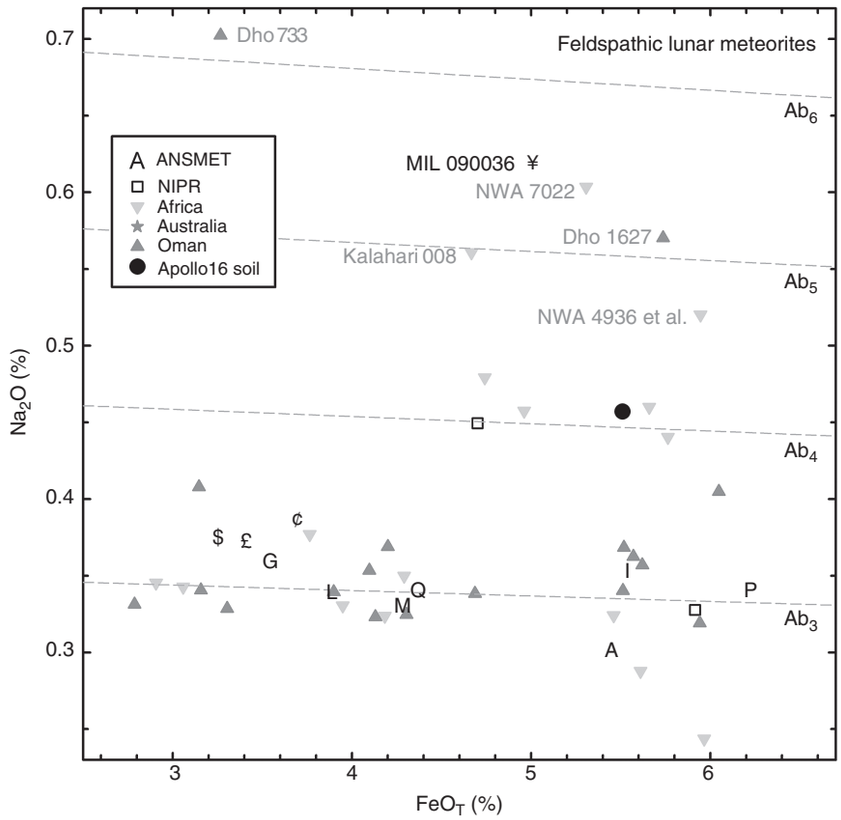


**Figure 6.18.** Whole-rock $Na_2O$ concentrations in feldspathic lunar meteorites reflect the average albite (Ab) content of the plagioclase. Most feldspathic lunar meteorites have $Na_2O$ concentrations corresponding to plagioclase of about $Ab_{97}$ composition, but some are more albitic. MIL 090036 is substantially richer in $Na_2O$ than all other ANSMET lunar meteorites.

concentrations of incompatible elements. Curiously, although a number of the feldspathic lunar meteorites from hot deserts have been identified as impact-melt or granulitic breccias [e.g., *Daubar et al.*, 2002; *Hudgins et al.*, 2011; *Kuehner et al.*, 2010; *Korotev*, 2012], all of the brecciated ANSMET lunar meteorites are regolith breccias.

Nearly two thirds (64%) of the ANSMET lunar meteorites are breccias from the feldspathic highlands. Until lunar meteorites were discovered, most of our knowledge of the composition, mineralogy, and petrography of the feldspathic highlands was based on samples from the *Apollo* 16 landing site. It was recognized at the time of the mission (April 1972) that the site geology had been influenced by the impact that formed the giant Imbrium basin (Figure 6.2), centered 1650 km to the northwest [*Muehlberger et al.*, 1980]. During the decade following the mission, however, the extent to which the Imbrium impact had affected the chemical composition of materials from the *Apollo* 16 landing site was largely unappreciated. Mafic (noritic and troctolitic), KREEP-bearing impact-melt breccias were common at the site, but because such breccias were also found at the *Apollo* 12, 14, 15, and 17 sites, it was assumed that such breccias were characteristic of the highlands [*Ryder and Wood*, 1977; *Spudis*, 1984]. Results from the *Apollo* orbiting gamma-ray spectrometers, however, showed that the Imbrium-Procellarum area was rich in Th (3–5 μg/g), whereas vast regions of the farside highlands were in the 0.3–0.5 μg/g range [*Metzger et al.*, 1977], much lower than the 2–2.5 μg/g characteristic of the *Apollo* 16 site (Figure 6.19). Thus, the low concentration of Th in the first lunar meteorite (0.3 μg/g, ALH A81005, Figure 6.19) led to immediate speculation that its point of origin was distant from the Imbrium-Procellarum area [*Kallemeyn and Warren*, 1983; *Korotev et al.*, 1983]. Most of the feldspathic lunar meteorites found after ALH A81005 have lower concentrations of Th and other incompatible elements than does the *Apollo* 16 regolith (Figures 6.4 and 6.19).

Among ANSMET meteorites, only MIL 090036 is comparable to the *Apollo* 16 regolith in concentrations of incompatible elements; thus, it is likely to originate from some place in the feldspathic highlands near the Procellarum KREEP Terrane. By the time of MAC 88104/5, the fourth feldspathic meteorite, it was clear that

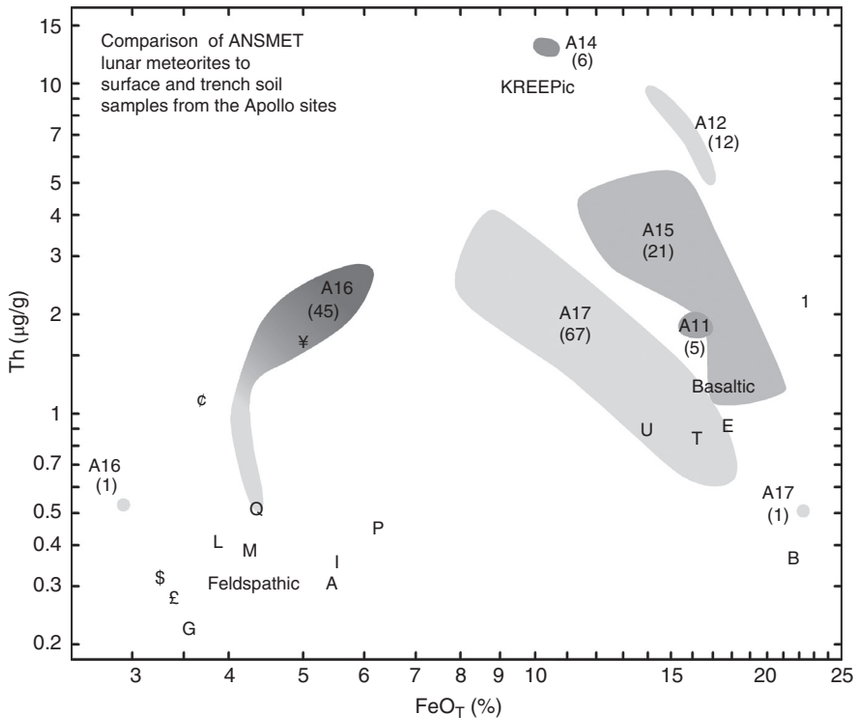


**Figure 6.19.** Like Figure 6.4, but comparison of ANSMET lunar meteorites, most of which are regolith breccias, to regolith (soil) samples from the *Apollo* missions (gray fields). Most feldspathic lunar meteorites have lower concentrations of incompatible elements (Th) than the *Apollo* 16 regolith. Most *Apollo* 16 regolith samples plot on the dark (high-Th) part of the field. The number in parentheses is the number of soil samples that define the field. The anomalous *Apollo* 16 sample is highly immature 67711 and the anomalous *Apollo* 17 sample is 74220, the "orange glass" soil. Symbol key is in Table 6.1.

the feldspathic lunar meteorites provided a more typical sampling of the upper crust of the feldspathic highlands, particularly its composition, than did the *Apollo* 16 samples [*Palme et al.*, 1991]. Another difference between the *Apollo* 16 collection and the feldspathic lunar meteorites involves anorthosite. A common lithology of the *Apollo* 16 regolith is shocked, but unbrecciated, highly feldspathic (>95% plagioclase) anorthosite of plutonic origin [e.g., *Warren*, 1990, 1993]. The ubiquity of "ferroan anorthosite" (*Mg'*: 50–70) at the *Apollo* 16 site supports the magma ocean model in which the Moon was mainly molten early in its history and the anorthosite was a flotation cumulate [*Warren*, 1985; *Wieczorek et al.*, 2006]. Recently, large exposures of anorthosite consisting of >99% plagioclase have been identified from orbit at numerous locations on the lunar surface [*Ohtake et al.*, 2009]. Thus, it is curious that lithic clasts of ferroan anorthosite are rare in feldspathic lunar meteorites [*Korotev et al.*, 2003a, 2009b]. Most lithic clasts in the feldspathic meteorites from ANSMET and hot deserts are granulitic and impact-melt breccias that are more mafic than the *Apollo* 16 ferroan anorthosites. The reason for this discrepancy is not yet understood. Perhaps the most unexpected observation about the crust to be revealed by the feldspathic lunar meteorites is that despite having a narrow range of normative plagioclase abundances (72–87%; Figure 6.7), the range in *Mg'* is large, 59–77. This observation provides a challenge for models of crust formation [*Korotev et al.*, 2003a; *Korotev*, 2005; *Arai et al.*, 2008; *Treiman et al.*, 2010; *Gross et al.*, 2014].

The remaining 36% of the ANSMET lunar meteorites, two basalts and three breccias, are of mare affinity. They probably originate from three source craters on the Moon, craters represented by the YQEN, YAMM, and NNL launch-pair groups (Table 1; Figures 6.8, 6.12, and 6.13). Compositionally and texturally, the NNL group (NWA 032/479, NWA 4734, and the LAP stones) resembles basalts of the *Apollo* 12 and 15 collection but are a bit younger. The basalts and basalt clasts of the YQEN (Yamato 793274/981031, QUE 94281, EET 87521/96008, and NWA 4884) and YAMM (Yamato 793169, Asuka 881757, MET 01210, and MIL 05035) meteorites are distinct in several ways from any *Apollo* mare basalt, most notably their compositions and evidence for slow cooling. In studies in which new analytical techniques are applied to mare basalts for the purpose of addressing planetary issues such as formation of the Moon, water on the

Moon, or basalt petrogenesis, it has become standard to include samples of MIL 05035 or a LAP basalt along with *Apollo* samples to increase the sample diversity [e.g., *Rankenburg et al*., 2006, 2007; *Day et al*., 2007; *Spicuzza et al*., 2007; *Zhang et al*., 2010; *Elardo et al*., 2012; *Paniello et al*., 2012; *Wang et al*., 2012].

The four YAMM stones are thought to have been launched from one crater on the Moon. The find sites for MET 01210 and MIL 05035 are separated by 400 km, those for Yamato 793169 and Asuka 881757 are separated by 380 km, and the ANSMET sites are >2500 km from the NIPR sites. These distances are all too great for the meteorites to be terrestrially paired. Thus, it is noteworthy that no prospective launch pairs of the four YAMM meteorites have been found outside of Antarctica.

For the five ANSMET lunar meteorites for which the parameters have been measured, ejection ages from the Moon range from 40 to 275 thousand years and terrestrial residence times range from 10 to 230 thousand years (Figure 6.11). On the basis of lunar meteorite finds from Oman, an average of 1.0 kg per year of lunar rocks in the 1-g to 10-kg mass range have reached the surface of the Earth in modern times [*Korotev*, 2012]. This calculation has not been done with the ANSMET collection, and such a comparison might be informative.

Among the ~19,000 named meteorite stones collected by ANSMET (through the 2011–2012 season), 0.13% are lunar. GRA 06157, the smallest lunar meteorite stone, was collected at a site where only 352 meteorites have been collected. Thirteen of the named ANSMET sites have produced 352 or more meteorites. Ten of those have produced at least one lunar meteorite. The Queen Alexandra Range site (3444 named stones) has yielded two unpaired lunar meteorites and the Miller Range site (2038) has yielded four.

The fact that launch-paired meteorites EET 87/98 (immature regolith breccia), QUE 94281 (heterogeneous glassy- and fragmental-matrix regolith breccia), and Yamato 79/98 (either glassy-matrix regolith breccia [*Arai et al*., 2002; *Koeberl et al*., 1991b] or fragmental-matrix regolith breccia [*Sugihara et al*., 2004]) are texturally and compositionally distinct from one another argues that a single impact on the Moon can, in fact, launch different kinds of rocks. The YAMM launch pairs are even more diverse in that MET 01210 is a breccia and MIL 05035, Asuka 881757, and Yamato 793169 are unbrecciated basalts.

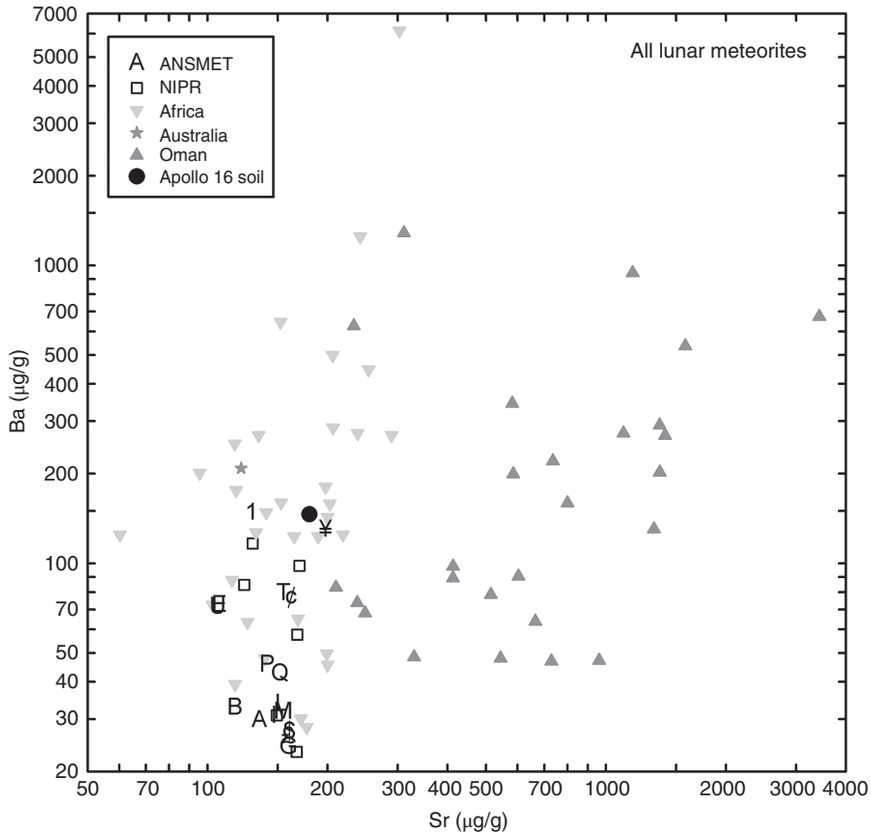


**Figure 6.20.** Many lunar meteorites from hot deserts are significantly contaminated with Sr, Ba, and other elements as a result of terrestrial alteration. Meteorites from Antarctica are not contaminated with these elements.

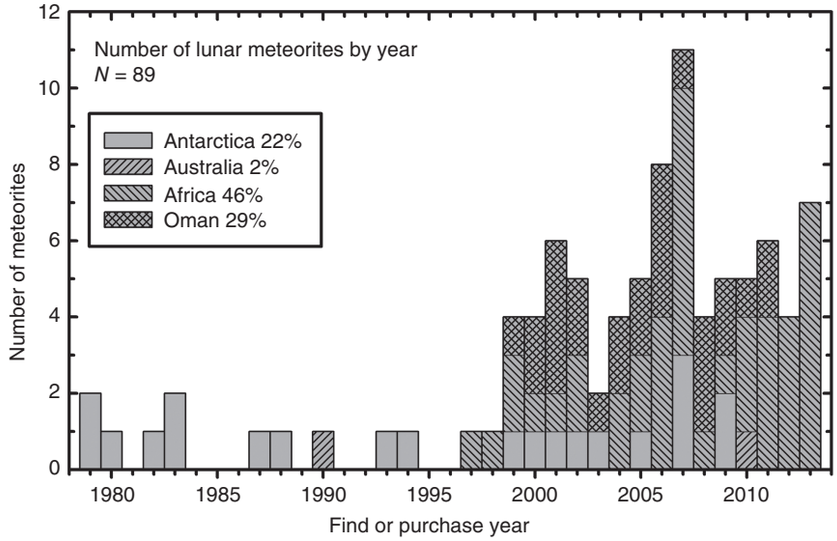


**Figure 6.21.** Number of lunar meteorites by find or purchase year. For paired stones, the find year of the first found stone of the pair group is represented. The rate of lunar finds from Antarctica (ANSMET and NIPR) has remained rather constant over the 35-year time period.

Although the number of lunar meteorites from hot deserts (about 78%) substantially exceeds those from Antarctica, most meteorites from hot deserts are contaminated, to varying degrees, with products of terrestrial alteration, whereas there is little evidence for even minor postfall changes in bulk composition among the lunar meteorites in the ANSMET and NIPR collection. Most hot-desert meteorites are seriously contaminated with Sr and Ba (Figure 6.20), but enrichments in Na, K, Ca, P, Zn, As, Se, Br, Sb, Au, U, carbonates, and sulfates have also been recorded [e.g., *Zeigler et al.*, 2006; *Korotev*, 2012].

Perhaps because of the systematic way in which ANSMET and NIPR searches are done, the find rate of lunar meteorites in Antarctica has been constant over the past 35 years (Figure 6.21). This constancy suggests that continued searching will yield more lunar meteorites from Antarctica.

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