

Meteoritic Material on the Moon¹

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Three types of meteoritic material are found on the Moon: micrometeorites, ancient planetesimal debris from the "early intense bombardment," and debris of recent, crater-forming projectiles. Their amounts and compositions have been determined from trace element studies.

The micrometeorite component is uniformly distributed over the entire lunar surface, but is seen most clearly in mare soils. It has a primitive, C1-chondrite-like composition, and comprises 1 to 1.5 percent of mature soils. Apparently it represents cometary debris. The mean annual influx rate is 2.4×10^{-9} g cm⁻² yr⁻¹. It shows no detectable time variation or dependence on selenographic position.

The ancient component is seen in highland breccias and soils more than 3.9 AE (AE = 10⁹ yr) old. Six varieties have been recognized, differing in their proportions of refractories (Ir, Re), volatiles (Ge, Sb), and Au. All have a fractionated composition, with volatiles depleted relative to siderophiles. The abundance patterns do not match those of the known meteorite classes. These ancient meteoritic components seem to represent the debris of an extinct population of bodies (planetesimals, moonlets) that produced the mare basins during the first 700 Myr of the Moon's history. On the basis of their stratigraphy and geographic distribution, five of the six groups are tentatively assigned to specific mare basins: Imbrium, Serenitatis, Crisium, Nectaris, and Humorum or Nubium.

A few properties of the basin-forming objects are inferred from the trace element data. They were independently formed bodies of roughly chondritic composition, not castoffs of a larger body. They were internally undifferentiated, had radii less than 100 km, contained between ~15 percent and ~40 percent iron, and struck the Moon at velocities generally less than 8 km/s. None match the Earth or Moon in bulk composition; in fact, several are complementary, being lower in refractories and higher in volatiles than the Earth or Moon. Possibly this implies a genetic link between these bodies, the Earth, and the Moon.

An attempt is made to reconstruct the bombardment history of the Moon from the observation that only $\sim 80 \pm 40$ basin-forming objects, totaling $\sim 2 \times 10^{-8}$ M_D, fell on the Moon after crustal differentiation ~ 4.5 AE ago, and that only one such body, of $\sim 5 \times 10^{-8}$ M_D, was left 3.9 AE ago. The apparent half-life of basin-forming bodies, ~ 100 Myr, is close to the calculated value for Earth-crossing planetesimals. According to this picture, a gap in radiometric ages is expected between the Imbrium (3.9 AE) and Nectaris (4.2 AE) impacts because all seven basins formed in this interval lie on the farside or east limb.

The crater-forming component has remained elusive. Only a possible hint of this component has been seen—in ejecta from Apollo 15 Dune Crater and Apollo 12 KREEP glasses of Copernican origin.

It was evident before the first lunar landing that three types of meteoritic matter would be found on the Moon.

¹This review is based in part on two earlier papers by the authors (refs. 1 and 2).

1. Micrometeorites and small meteorites: in the regolith
2. Debris from post-mare craters: in ray material and other ejecta
3. Debris from the "early, intense bom-

bardment" that produced the highland craters and mare basins (refs. 3 and 4) in ancient breccias and highlands regolith

The amount of meteoritic material had been estimated from crater scaling laws and observed fluxes of interplanetary matter (ref. 5). But the composition of this material could not be directly determined in the absence of a tangible sample.

A new vista opened up with the Apollo 11 mission. It then became possible to study the problem by modern laboratory techniques. Because meteoritic material is largely destroyed on impact with the lunar surface, it seemed more profitable to identify the debris by chemical techniques than by a search for surviving particles. Accordingly, we measured about 18 trace elements that were abundant in meteorites but were expected to be rare in lunar surface rocks (refs. 2 and

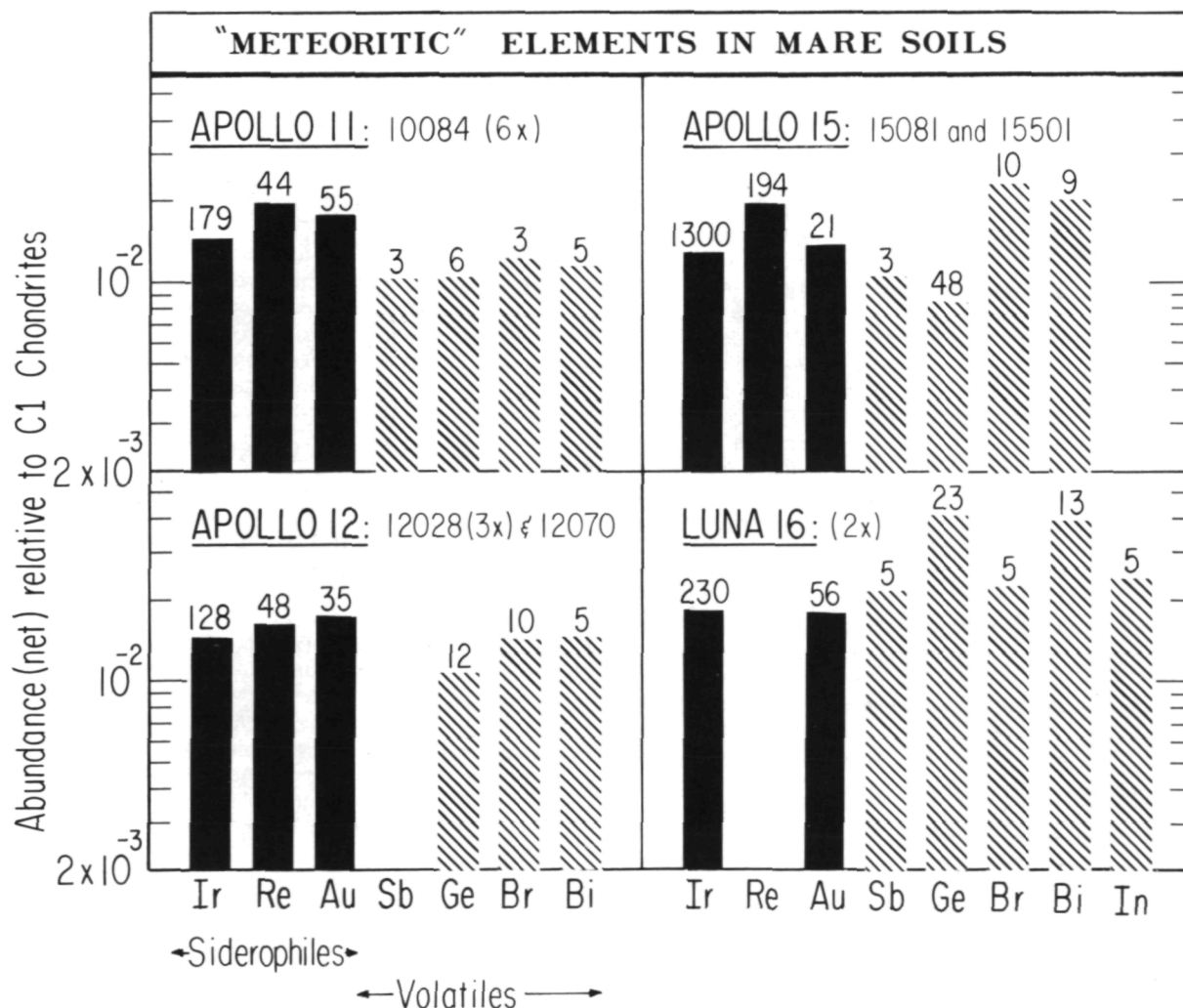


Figure 1.—All mare soils are enriched in "meteoritic" elements, relative to crystalline rocks. Net meteoritic component is obtained by subtracting an indigenous lunar contribution estimated from crystalline rocks. Numbers above histogram indicate ratio of net component to correction (ref. 1). Abundance pattern is flat, with siderophiles and volatiles almost equally abundant. Apparently the meteoritic component has a primitive composition (fig. 2). Data are mainly from this laboratory. (See ref. 11.)

6 through 13). Because many of these elements had abundances of 10^{-9} to 10^{-12} g/g, we used radiochemical neutron activation analysis.

Originally, it appeared that only siderophile elements (Ir, Au, Re, Ni, etc.) would be reliable indicators of meteoritic material. Because they concentrate in metal phase during planetary melting, they are strongly depleted on the surfaces of differentiated planets (e.g., by a factor of $\sim 10^{-4}$ on Earth). Accordingly, they had been used as indicators of meteoritic material in oceanic sediments or polar ice (refs. 14 and 15). However, a number of volatile elements (Ag, Bi, Br, Cd, Ge, Pb, Sb, Se, Te, Zn) turned out to be so strongly depleted on the lunar surface that it became possible to use some of them as subsidiary indicators of meteoritic matter.

The next section of this paper reviews the micrometeorite component, a well explored and essentially closed subject. The section following that, the major portion of the paper, discusses a less finished but more exciting topic: the ancient meteoritic component. The final part reviews the scanty information available on the crater-forming component.

The Micrometeorite Component

All lunar soils are enriched in "meteoritic indicator" elements compared to crystalline rocks from the same site. Not all this enrichment can be attributed to meteoritic material because each soil contains small amounts of exotic rock types not represented among the larger rocks collected at that site. Most important among these are alkali-rich (granitic and noritic) rocks, which account for the fact that soils are almost always richer in alkalis, U, and Th than the local rocks. In order to determine the net meteoritic component, the gross abundances must be corrected for an indigenous lunar contribution. For this correction we have used a mixture of local rocks with a small amount of alkali-rich rock, sufficient to account for the alkali content of the soils.

Data for four mare sites are shown in figure 1. They have been normalized to C1 chondrites to permit compositional characterization of the meteoritic component(s). Siderophile elements are shown by dark shading; volatiles by diagonal shading. Numbers indicate "signal-to-noise" ratio, i.e., ratio of gross abundance to indigenous correction. Only "mature" soils that come from intercrater areas and have high surface exposure age, are shown. Soils of low surface exposure age, from the rims of young craters, generally have lower abundances of meteoritic elements, owing to dilution by freshly excavated bedrock (ref. 11). Soil breccias, not plotted here, are similar to soils (ref. 7).

COMPOSITION

Soils from all four sites show essentially the same picture: siderophiles enriched to 1.5- to 2-percent C1-chondrite equivalent and volatiles enriched to a similar if more variable extent. The volatile enrichment is less well determined, owing to the lower signal-to-noise ratio, but the fact that all four sites consistently show an excess of volatiles suggests that this excess is indeed meteoritic. (Several other volatiles, such as Ag, Cd, Zn, and Te, seem to be largely meteoritic in many soils, but are less reliable indicators for various reasons: higher incidence of contamination, sporadically higher indigenous abundance, mobility in the soil, etc. (refs. 10, 12, 16, and 17).)

The abundance pattern rules out all fractionated meteorite classes (fig. 2, right). Ordinary chondrites, E5,6 chondrites, irons, and stony irons (not shown here) are too deficient in volatiles (especially Bi) relative to siderophiles. Achondrites, in turn, are too low in siderophiles. Thus, attention focuses on primitive meteorites (fig. 2, left), in which volatiles and siderophiles occur in comparable abundance: C1, C2, C3, E3,4, and unequilibrated ordinary chondrites (H3, L3, LL3, not shown here, but basically similar to C3's).

The original Apollo 11 data showed no sys-

tematic depletion of volatiles relative to siderophiles, and thus were most consistent with C1 chondrites (ref. 7). However, now that more data (and better indigenous corrections) are available, a hint of such depletion is discernible. In the three Apollo samples, seven of the 11 volatiles plot below the siderophiles. (Luna 16 soil shows the reverse trend, but this sample seems to be rather extensively contaminated.) This is probably due to an admixture of highland material, with its own fractionated meteoritic component (ref. 1). Still, it appears that the dominant component has C1 composition.

AMOUNT AND INFLUX RATE

The amount of meteoritic material in the soils is therefore most appropriately given as "percent C1 equivalent" (table 1). Evidently all four sites contain essentially similar amounts of meteoritic material. The figures based on siderophiles alone are better determined because the indigenous correction is smaller. On the other hand, they include a sizeable contribution from an ancient meteoritic component (ref. 1). Accordingly, we have given a "best estimate" of the net amount of C1 component. From the latter we

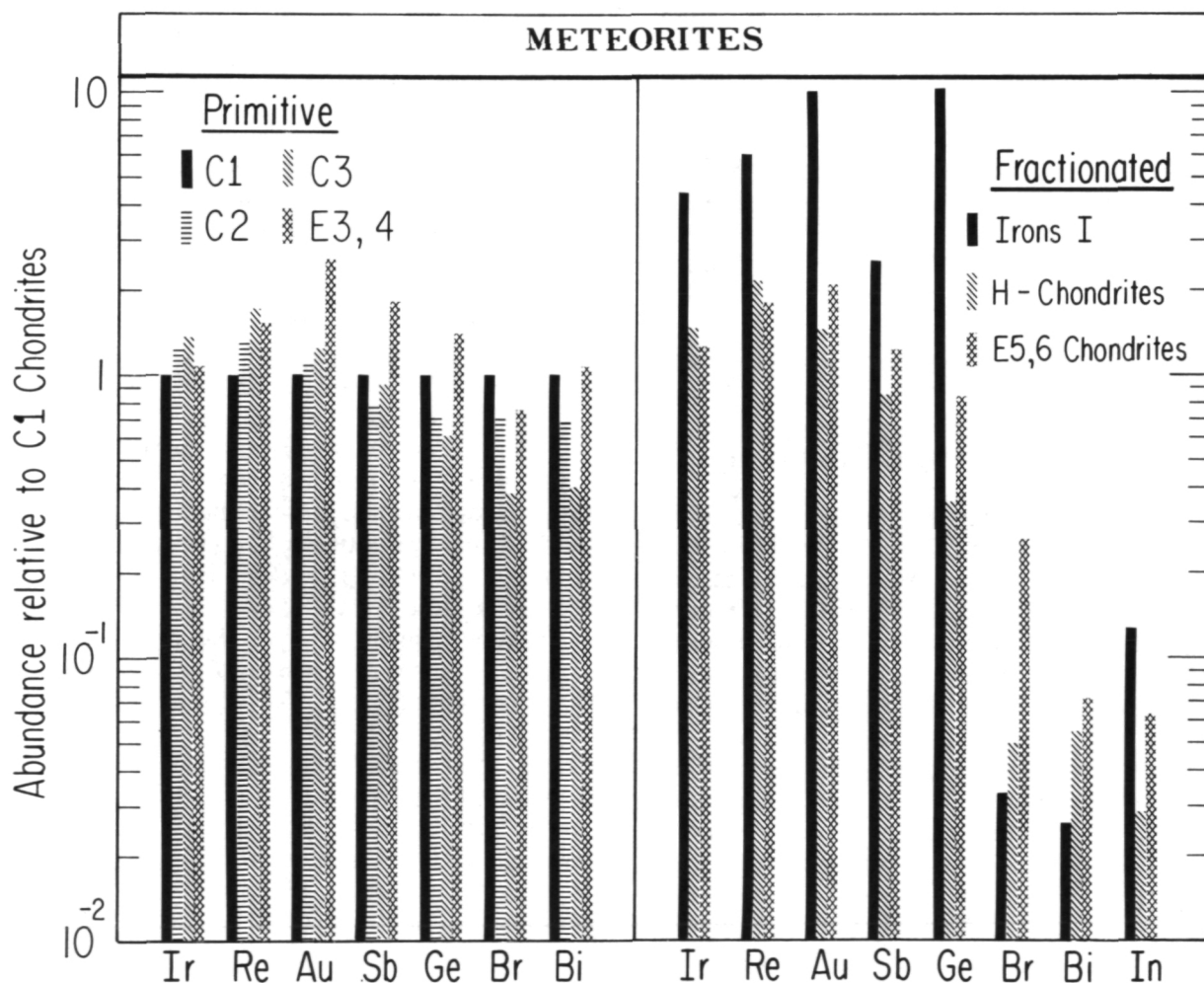


Figure 2.—Primitive meteorites (left) contain siderophiles and volatiles in comparable abundance. Fractionated meteorites (right) are depleted in volatiles (ref. 1). Data taken mainly from Mason (ref. 18).

Table 1.—*Meteorite Components in Mare Soils*
(percent C1 material or equivalent)

		Siderophiles				Volatiles						Best	Regolith		
		Ir	Re	Au	Ni	Sb	Ge	Br	Bi	Mean Sid.	Mean Volat.	Estimate C1-Comp.	Thickness (m)	Age (AE)	Influx Rate 10 ⁻⁹ g cm ⁻² yr ⁻¹
GROSS	Apollo 11	1.46	2.02	1.81	2.03	1.59	1.23	1.77	1.47	1.83	1.52				
	Apollo 12	1.47	1.68	1.80	2.00	—	1.14	2.60	1.86	1.74	1.87				
	Apollo 15	1.30	1.99	1.45	1.70	1.51	0.88	2.56	2.31	1.61	1.82				
	Luna 16	1.88	10.23	1.85	1.80	2.75	4.39	2.81	4.40	1.84	2.78				
NET	Apollo 11	1.45	1.98	1.77	1.88	(1.03)	1.05	1.23	1.15	1.77	1.12	1.14	4.6	3.65	2.32
	Apollo 12	1.46	1.64	1.75	1.80	—	1.08	(1.46)	1.48	1.66	1.34	1.28	4.6	3.26	2.83
	Apollo 15	1.30	1.98	1.38	1.55	1.05	0.86	2.32	2.06	1.55	1.57	0.96	4.6	3.32	2.15
	Luna 16	1.88	10.19	1.81	1.66	2.19	4.20	2.27	3.94	1.78	2.23	≤1.6	4.6?	3.42	<3.5?
CI Chondrites (abundance in ppb)		514	35.2	152	10300	138	31200	4810	110						

NOTES:

Italicized values: contamination suspected.

Parenthesized values: relatively uncertain because indigenous contribution is estimated (or suspected) to be larger than one-third of gross abundance.

Lunar samples: see Morgan et al. (ref. 11) for references.

CI chondrites: from Krähenbühl et al. (ref. 13), except Br (ref. 19).

have calculated the average influx rate at each site, as in ref. 7. The most uncertain factor in this calculation is the mean thickness of the regolith, which has been estimated to be 4.6 m at all four sites (ref. 20). The mean influx rate for the three Apollo sites is $2.4 \times 10^{-9} \text{ g cm}^{-2}\text{yr}^{-1}$.² It agrees rather well with pre-Apollo estimates by Whipple (ref. 21) and Öpik (ref. 5): $1.3 \times 10^{-8} \text{ g cm}^{-2}\text{yr}^{-1}$ (total) and $1.05 \times 10^{-8} \text{ g cm}^{-2}\text{yr}^{-1}$ (micrometeorites only).

At low approach velocities, the meteor impact rate should vary strongly with selenographic position (ref. 22). From the graph given by Wiesel, the following relative fluxes would be expected at the four landing sites: Apollo 11 = 1.3, Apollo 12 = 2.0, Apollo 15 = 1.6, and Luna 16 = 1.0. The data in table 1 do not show any such trend; Luna 16 has, if anything, the highest rather than the lowest flux. The reason for this discrepancy is Wiesel's deliberate choice of a velocity distribution peaking at 4 km/s, far below the actual mean velocity of meteors.

SOURCE

It appears that the C1-like component in lunar soil comes largely from micrometeorites. Two other sources make minor contributions. Solar wind accounts for about 3 to 4 percent of the siderophile elements in the soil (recalculated from ref. 7, with the latest abundance data and solar wind flux). Crater-forming objects provide a somewhat larger fraction, perhaps 5 to 20 percent (refs. 5 and 7). This estimate is rather uncertain because it depends on a host of poorly known quanti-

ties: projectile velocity distribution, crater scaling laws, mixing efficiency of projectile and target material as a function of throw-out distance, etc. The total mass of crater-forming projectiles is more than sufficient to account for the meteoritic material in the soil (fig. 3). However, much of this material seems to remain in the crater or in the ejecta blanket and does not find its way into the soil (see p. 684). Both the ubiquity of the C1 component and its lower abundance in crater-rim soils point to micrometeorites, rather than crater-forming objects as the main source. Indeed, Dohnanyi (refs. 25 and 26) has shown that his best estimate of the micrometeorite flux, based on satellite and photographic meteor data, gives an influx rate very close to the chemically determined value from table 1: 2.0×10^{-9} versus $2.4 \times 10^{-9} \text{ g cm}^{-2}\text{yr}^{-1}$. A lower value (by a factor of 4 to 6) was obtained from lunar microcraters (refs. 26 and 27), but the discrepancy was within the range of uncertainty of the cratering data.

If the C1 component in lunar soil indeed comes from micrometeorites, it may provide some important clues to the composition of comets because there is good reason to believe that comets are the principal source of micrometeorites (21, 26, 28, and 29). Apparently comets have a composition close to that of C1 chondrites, as proposed by Herbig (ref. 30), Anders (ref. 31), Whipple (ref. 32), and others. The present characterization is based entirely on trace elements, but is also supported by spectroscopic studies of Millman (ref. 33), showing that nine Giacobinid meteors have chondritic abundances of Na, Mg, Ca, and Fe. Further evidence comes from lunar microcraters which appear to have been made by volatile-rich projectiles, e.g., hydrated silicates (ref. 34). The only known meteorites consisting mainly of hydrated silicates are C1 chondrites.

Yet, it would be wrong to conclude that C1 chondrites proper come from comets. All C1 chondrites show signs of a preterrestrial exposure to liquid water (ref. 35) and contain solar-wind gases suggestive of irradiation in a regolith (ref. 36). Comets probably

² No reliable value could be calculated for Luna 16, for a variety of reasons. The sample itself was a sieve fraction, finer grained than the Apollo soils ($< 125 \mu\text{m}$ versus $< 1000 \mu\text{m}$) and, hence, presumably enriched in meteoritic material. Contamination seems to have been more severe than in the Apollo soils (ref. 23), and so the volatile abundances, at least, should perhaps be viewed as upper limits. Finally, the regolith thickness at the Luna 16 site is poorly known. Vinogradov (ref. 24) estimates it as 0.5 to 1 m, but suggests that it is similar to that in Oceanus Procellarum which he gives as 1 to 3 m, rather than the 4.6 m cited by Oberbeck and Quaide (ref. 20).

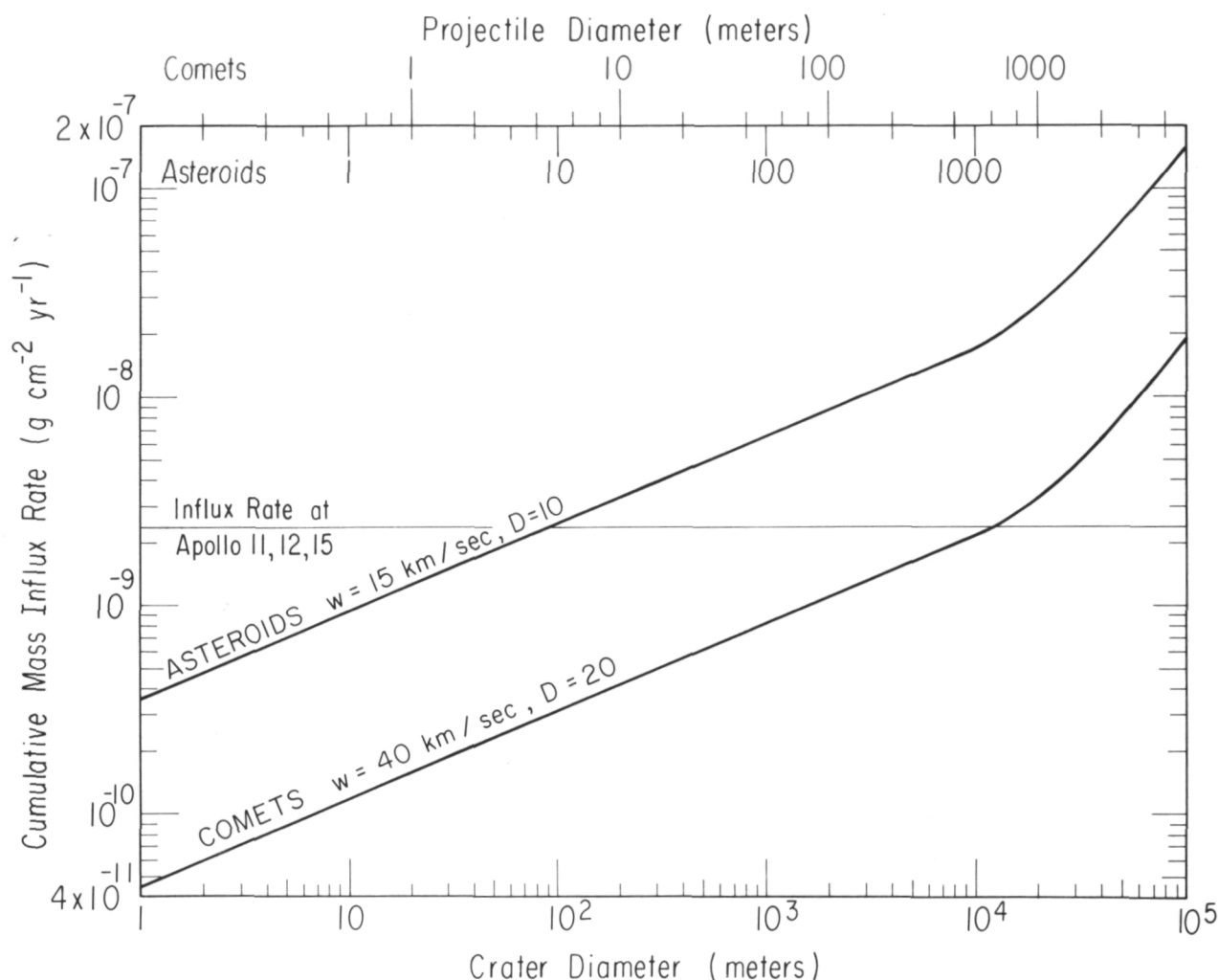


Figure 3.—Mass influx rates predicted from observed crater density in Mare Tranquillitatis for asteroidal and cometary projectiles (w = impact velocity, D = ratio of crater diameter to projectile diameter). Though crater-forming objects contribute more meteoritic material than is actually observed in mare soils (horizontal line), most of this material remains buried in the crater or its ejecta blanket and does not contribute to the fine soil (ref. 1).

are too cold to hold liquid water, too small (~ 10 km) to retain a regolith, and too far from the Sun to accumulate a significant amount of solar wind. Thus, larger bodies at closer distances are needed—perhaps asteroids in the outer part of the belt (refs. 37 and 38).

Interestingly, Johnson and Fanale (ref. 39), Chapman and Morrison (ref. 40), and Gaffey and McCord (ref. 41) have found that C1 and C2 chondrites resemble some aster-

oids in albedo and spectral reflectivity. Thus it seems that asteroids are a possible source of C1 chondrites.

The Ancient Meteoritic Component

Highland soils show a markedly different pattern, as first seen by Apollo 14 (ref. 42) and later at four other sites (refs. 1, 43, and 44). Siderophiles are more abundant than

volatiles and often show ratios (Ir/Au, Re/Au) well below the C1 chondrite value.

The excess siderophiles come from highland breccias, the source rocks of the soils. Two lines of evidence suggest that these siderophiles are extraneous, having been added to the breccias during the early intense bombardment.

First, the siderophiles are greatly overabundant in breccias compared to crystalline rocks. This is true of all highland rock types: anorthosites, norites, and granites. Figure 4 shows an alkali-poor and an alkali-rich highland breccia (black circles and black squares). Each is matched with a crystalline rock of similar bulk composition and Rb, Cs, and U content (open symbols). Most of the 16 elements have comparable abundances in the breccia and its crystalline counterpart,

except for the first five, siderophile elements which are enhanced in the breccias by factors of 10^2 to 10^3 . Nickel, not plotted here, behaves similarly.

Second, the lowest abundances of siderophiles in highland rocks, e.g., < 0.05 ppb Au (fig. 5), are consistent with measured metal-silicate distribution coefficients which range from 10^4 to 10^6 (ref. 45). It appears that these abundances represent true indigenous levels. On the other hand, the more common, high abundances around 1 to 10 ppb (fig. 5) exceed equilibrium solubilities in silicates by several orders of magnitude. The extraneous nature of these siderophiles is shown by the fact that they reside largely in discrete metal grains (refs. 9 and 46), which comprises 0.1 to 1 percent of highland breccias and impact melts (refs. 47 and 48). A suspension of

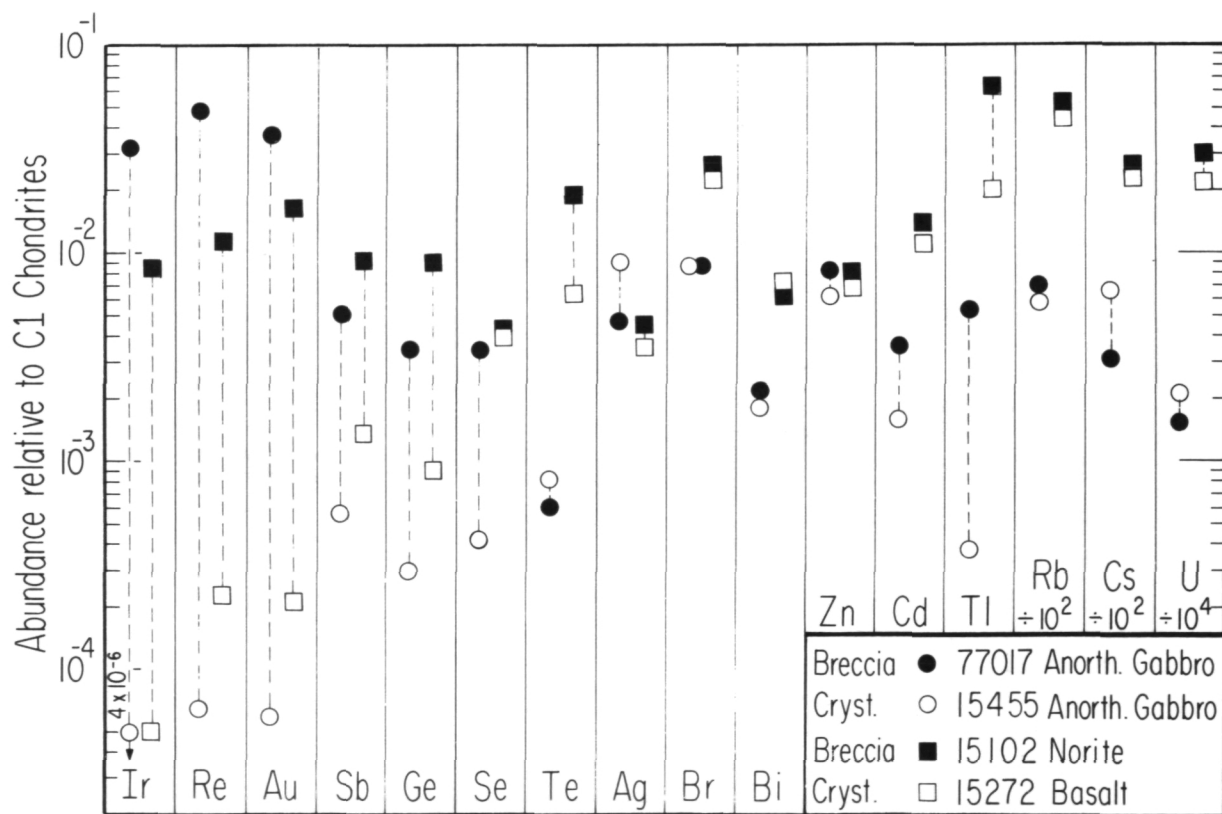


Figure 4.—Highland breccias (solid symbols) are strongly enriched in the first five siderophile elements compared to crystalline rocks of the same Rb, Cs, and U content (open symbols). The enrichment is due to an ancient meteoritic component dating from the era of intense bombardment.

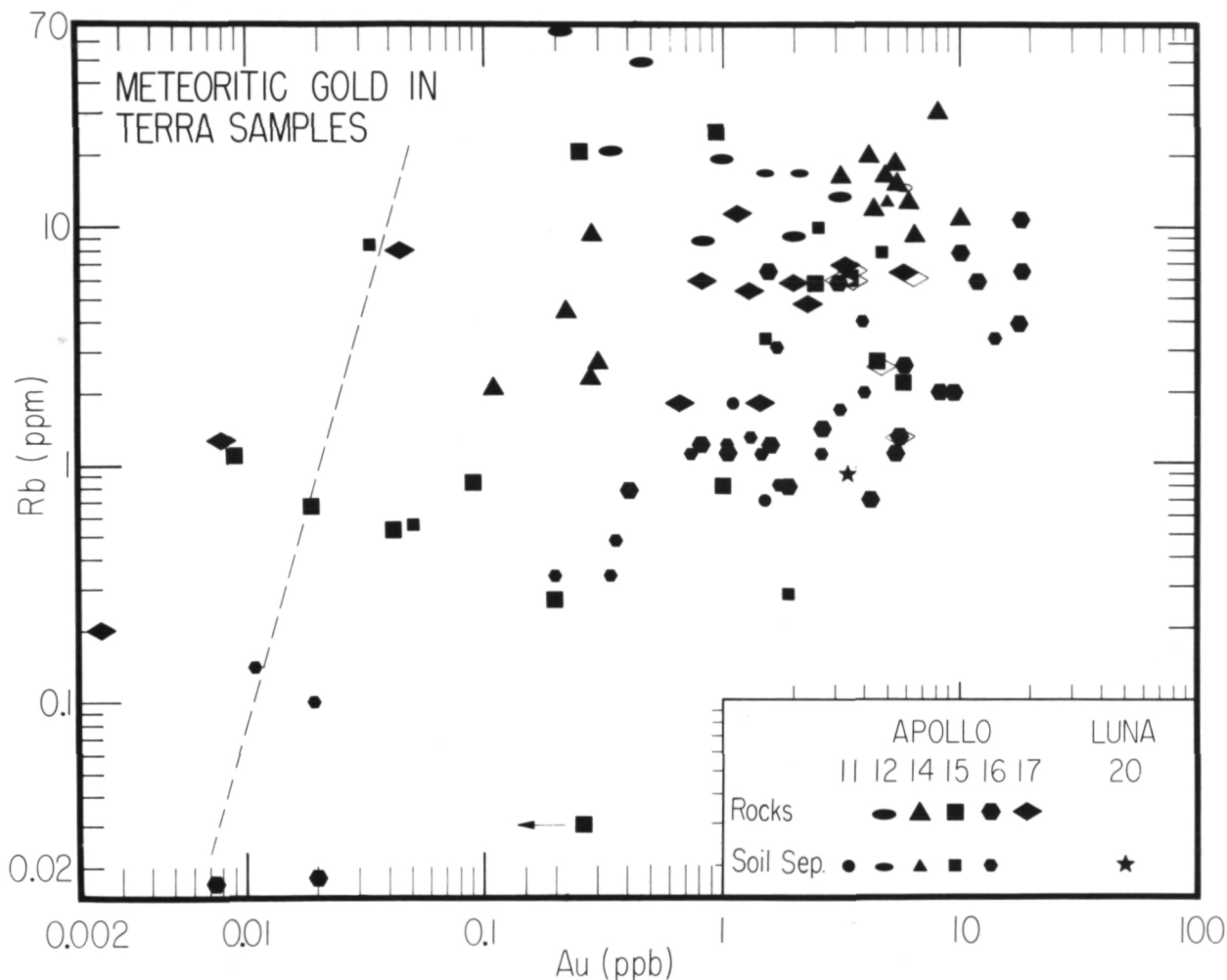


Figure 5.—Most highland samples are enriched in meteoritic gold above indigenous levels (approximated by dashed line). Enrichment is nearly independent of Rb content and rock type. Only anorthosites of < 0.2 ppm Rb tend to be free of meteoritic gold. Perhaps they come from deeper crustal levels not penetrated by meteoritic projectiles.

metal droplets in a silicate melt is dynamically unstable on time scales comparable to the freezing time of basaltic flows (refs. 49 and 50).

For these reasons, it appears that high siderophile abundances in highland rocks are diagnostic of a meteoritic component. Because this component occurs in breccias that have remained closed systems for at least 3.9 AE, it can properly be called an ancient meteoritic component.

CLASSIFICATION

The six diagnostic elements differ greatly in condensation temperature from a solar gas. Re and Ir condense a few hundred degrees above iron, Sb and Ge condense a few hundred degrees below iron, and Ni and Au condense almost concurrently with iron, slightly before and after, respectively, (Grossman, ref. 51 and unpublished data, and ref. 52 Larimer, and unpublished data).

Presumably for this reason these elements show large abundance variations in meteorites, which have been used as the basis for classification (Wasson and Schaudy, ref. 53 and earlier papers, and refs. 54 and 55).

Similar variations in Ir/Au and Ge/Au ratios have been seen in lunar samples, suggesting the presence of more than one kind of meteoritic component (refs. 8 and 11). The trends show up more clearly on ternary plots. Figures 6 and 7 show results for 74 highland samples from five sites. The data are normalized to C1 chondrite abundances (ref. 13) to prevent the plots from being dominated by the element of highest absolute abundance. Corrections have been applied for indigenous contributions (ref. 2). They are typically less than 1 percent for Ir, Au, and Re, and 1 to 30 percent for Ge and Sb. Because the corrections become larger at lower abundances, we used only samples of >0.2 ppb Au. In order to avoid samples

of mixed parentage, we used only rocks and lithic fragments from coarse soils. Agglutinates, magnetic separates, soil breccias, and glasses from coarse soils were excluded.

Approximately six groups seem to be present, as indicated by the dashed lines in figure 6. The elongated shape of the groups reflects the fact that Ge and Sb are less reliable indicator elements than are Ir, Re, and Au. Their indigenous contributions are larger and more variable, and their volatility makes them more prone to metamorphic redistribution. Consequently we used Ir/Au and Re/Au ratios as our prime criteria in defining the groups.

The reality of these groups is supported by the mutual consistency of the two plots (each of which has a volatile element at the apex and a refractory element in the right corner). Most points belonging to a given IrAuGe group fall in a similarly situated, compact cluster on the ReAuSb plot. The principal

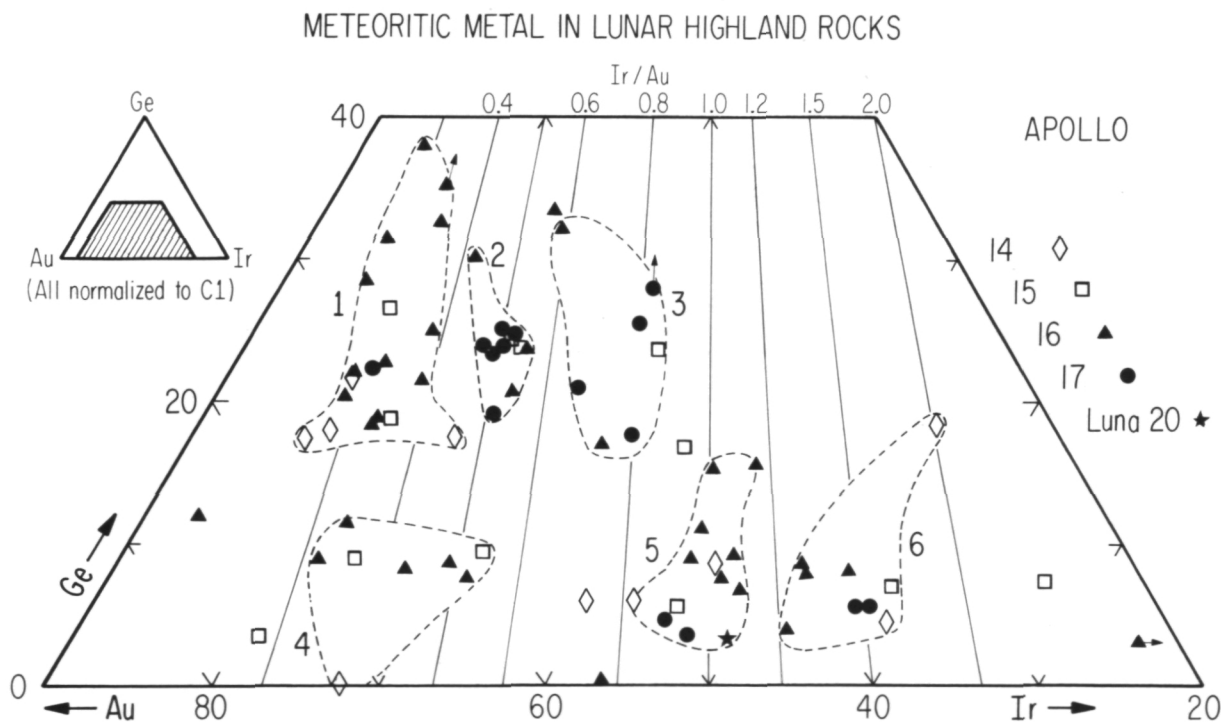


Figure 6.—Six distinct types of ancient meteoritic component differing in their proportions of Ir, Au, and Ge, seem to be present. Both the clustering of the points and their uneven geographic distribution suggest that this material is derived mainly from a few large objects—probably the projectiles that excavated the mare basins.

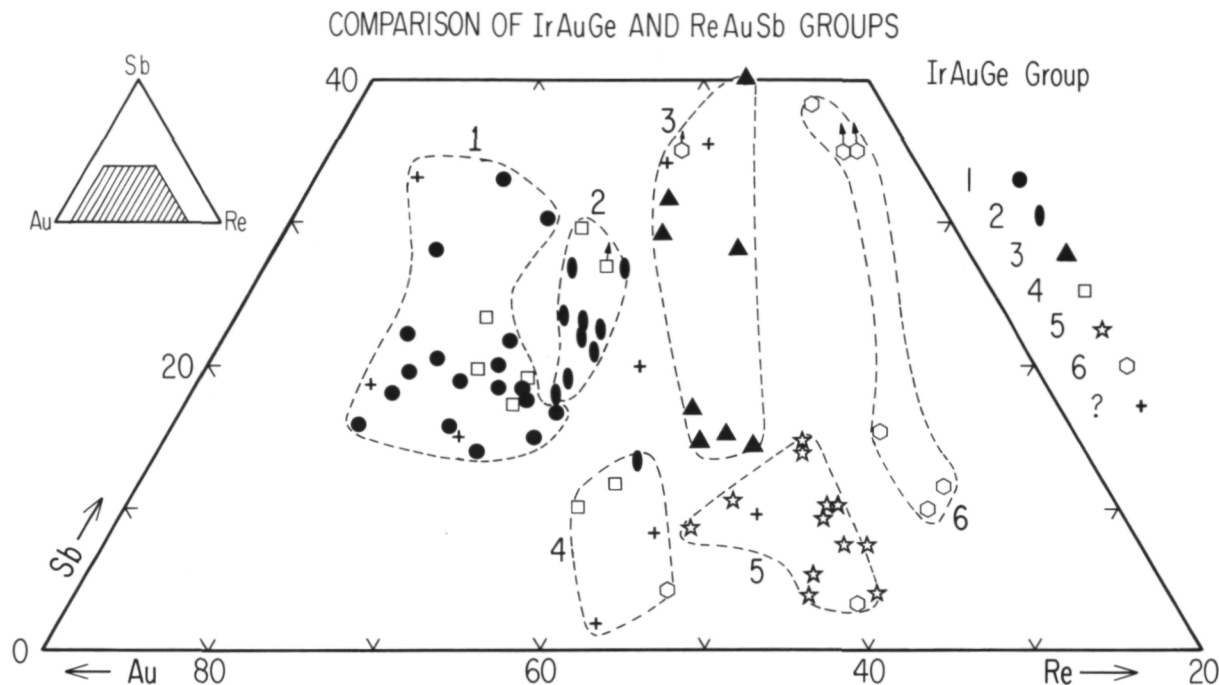


Figure 7.—Six analogous groupings may be recognized on the basis of Re, Au, and Sb content. Most of the points belonging to a given IrAuGe group fall in a similarly situated cluster on an ReAuSb plot. The principal exception is Group 4 which is largely dispersed on this plot.

exceptions are group 4 and a few samples of sporadically high indigenous Sb or Ge.

The definition of these groups involves some subjectivity, and we do not claim that the present six groups are final. In general, we have tried to be conservative, creating as few groups as possible. The separation between some of the groups is not as sharp as one might like, e.g., 1 and 2 or 5 and 6. However, in both cases there were reasons not to combine them. Group 2 contains a compact cluster of Apollo 17 samples which would stand out as a distinctive subgroup in a combined group 1 + 2. Groups 5 and 6 also contained distinctive subsets of samples; moreover, if combined, these two groups would cover a wider range in Ir/Au ratio than any other.

COMPARISON WITH METEORITES

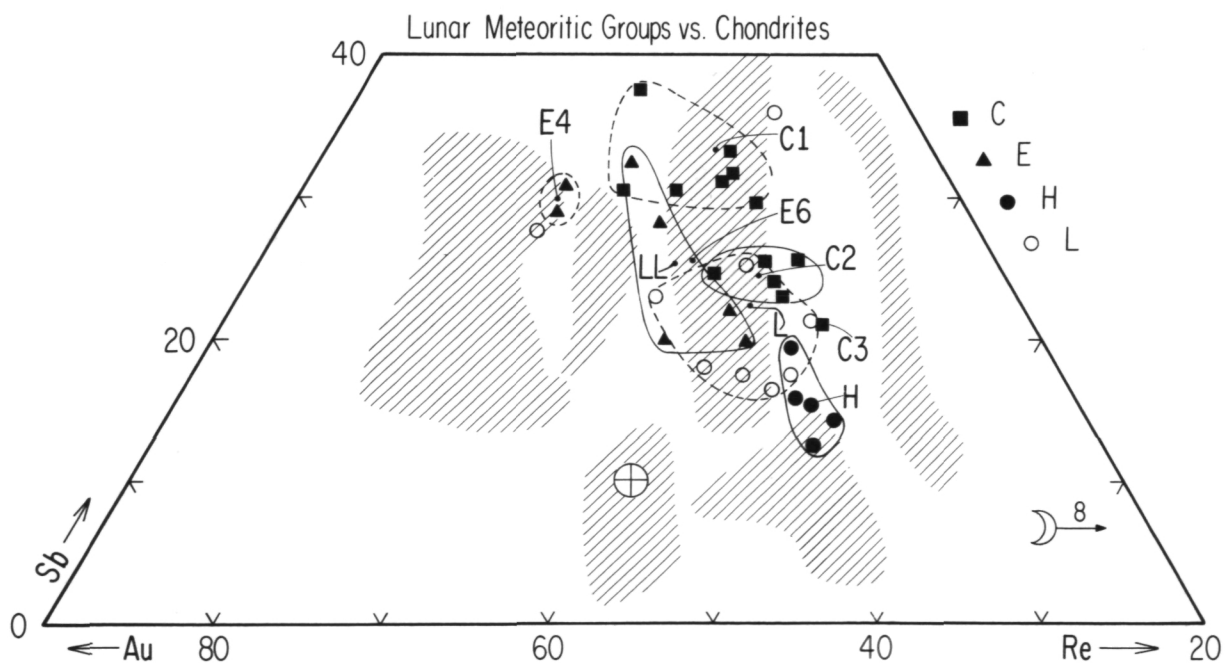
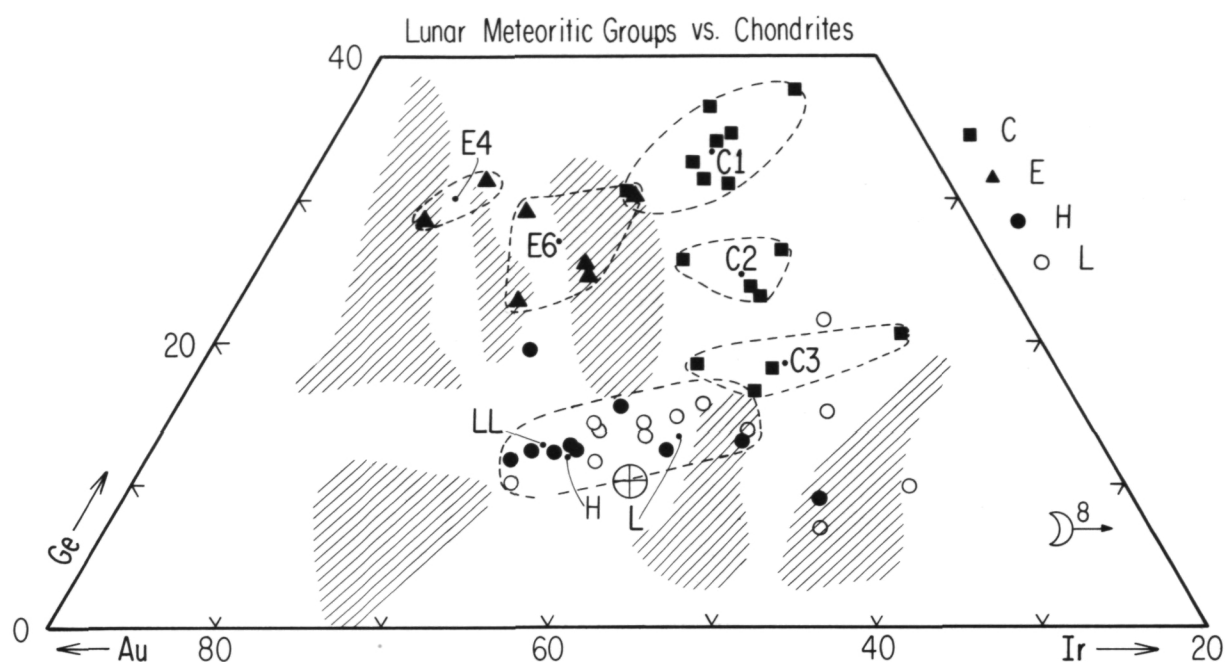
The ancient lunar meteoritic bodies show little resemblance to present-day meteorites

(figs. 8 through 10). Most meteorite groups avoid the lunar fields. Only a few (E4, E6, H-chondrites, and I and IIIA irons) show as much as a marginal overlap. It appears that the ancient meteoritic bodies represent a distinct population, different from present-day meteorites.

One interesting point that emerges from figures 8 and 9 is that the chondrite groups are not much more compact than the lunar meteorite groups. Probably the best indication of the "natural width" of a chondrite group comes from C1 chondrites (figs. 8 and 9) and H, L chondrites (fig. 9), where at least five samples were analyzed for all three elements in the same laboratory (refs. 13, 56, and 57). For most other classes, data were few and from different sources.

BASINS OR CRATERS?

Granted that the ancient meteoritic material dates from the early intense bombard-



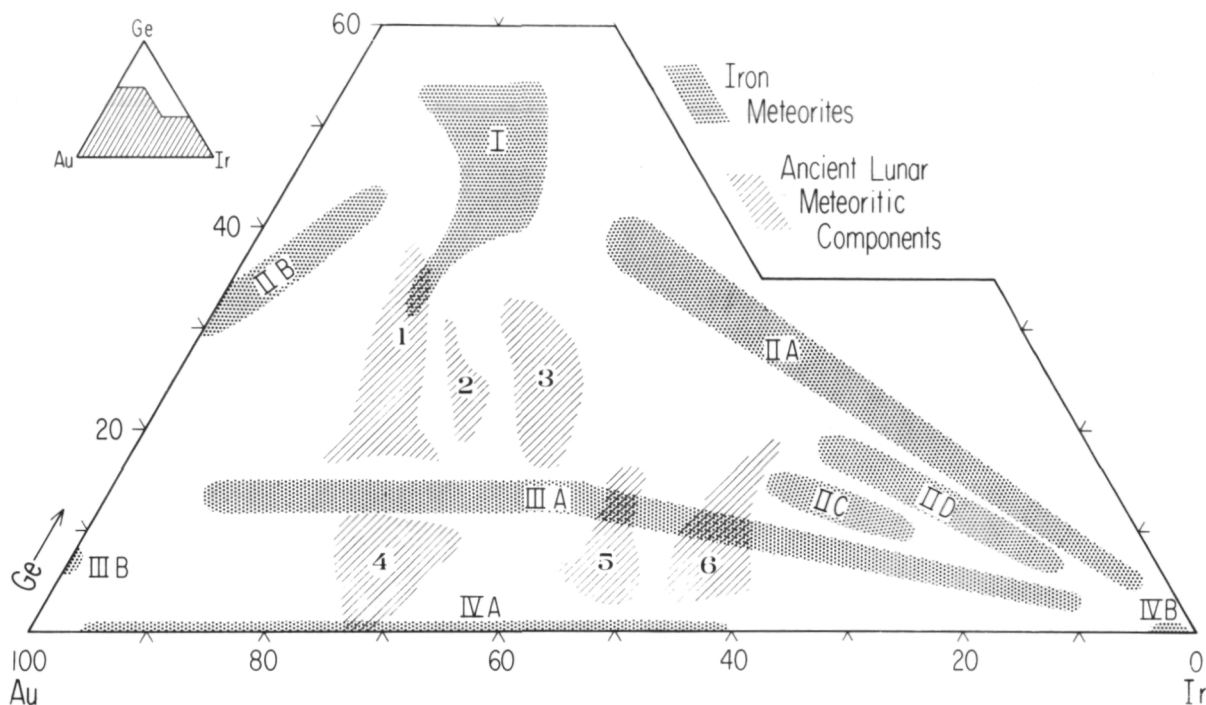


Figure 10.—Ancient lunar meteoritic components do not resemble iron meteorites.

ment, does it come mainly from a few large basins or from a multitude of smaller craters? The clustering into six groups alone does not prove that only six bodies were involved. Six families of crater-forming bodies, each with hundreds of members, would lead to the same result. A more conclusive argument comes from the size distribution of lunar craters and basins.

Contribution of Basins

Various authors have estimated the amount of ejecta in the lunar highlands and their results consistently show that the largest objects will contribute the lion's share. This is a consequence of the small slope of the size distribution function. Öpik (ref. 58), using a single size distribution law (ref. 59), estimated that 56 percent of the highland ejecta will be contributed by craters (actually basins) larger than 412 km in diameter, and an additional 25 percent by craters between 206 and 412 km. Short and Forman

(ref. 60) determined the crater contribution separately by integrating the size distribution function to 400 km and then adding the basins individually. Their results indicate a basin contribution of 30 to 60 percent, depending on the degree of slumping assumed. However, Short and Forman used a relation for the crater depth/diameter ratio which gave preposterously small volumes for the larger basins—comparable to the projectile volume. Thus, the basin contribution is likely to be substantially higher than 30 to 60 percent, probably close to Öpik's 81 percent.

Shallow Ejecta Only?

Even though the basins may account for most of the ejecta, it does not necessarily follow that their projectile debris will dominate at distant sites. Dence and Plant (ref. 61) pointed out that the pre-Imbrian surface was covered with mixed ejecta from many highland craters and argued, by analogy

with Ries Crater "bunte Breccia," that this surface layer contributed the bulk of the ejecta at Fra Mauro and other distant sites. Because of its shallow origin and gentle shock history, it would not contain any Imbrium projectile debris. Deeper, more heavily shocked material analogous to suevite would be found only at closer range, e.g., at the Apollo 15 site. Other authors have also used the Ries analogy to argue for a shallow origin and short range of lunar crater ejecta (ref. 62). However, these arguments neglect the difference in gravity between Earth and Moon. The range R of a fragment ejected with velocity v at an angle β is given by

$$R = (v^2/g) 2 \sin \beta \cos \beta$$

where g is the acceleration due to gravity. Other things being equal, a fragment will thus fly six times farther on the Moon than on the Earth. Indeed, several rocks of deep-seated origin have been found on the lunar surface: a troctolite from a depth of 15 to 40 km (ref. 63) and a number of dunite clasts, presumably from below the 65-km crust (e.g., ref. 64).

Secondary Craters?

Oberbeck et al. (ref. 65) have raised a different objection. They note that any basin ejecta reaching Apollo landing sites would strike at high enough velocities to excavate a secondary crater of several times their own mass. Thus Imbrium or Orientale material reaching the Apollo 16 site would be diluted from four to seven times with local rock. They therefore contend that the ancient meteoritic component is derived mainly from many small local craters, not a few large distant basins.

Oberbeck's mechanism certainly applies to large blocks tens or hundreds of meters in diameter. But observed mass distribution functions and the scarcity of secondary craters (a few percent of the lunar surface) show that such blocks comprise only a minor part of the distant ejecta. Moreover, their very size precludes any admixture of projectile debris. The great bulk of the distant

ejecta seems to have been of from millimeter to decimeter size, judging from both the grain and clast size of lunar breccias and the uniform dispersion of the metal on a millimeter scale.

Now, when the first 10 cm of 100 m of such fine-grained basin ejecta arrive at a given site, they will indeed mix with the local regolith, to a depth on the order of the diameter of the largest fragments, i.e., ~ 10 cm. Successive 10-cm layers will mix not with pristine local regolith, but with material containing progressively larger amounts of basin ejecta. So, before as much as a meter of material has been deposited, the process has turned into orderly sedimentation, without appreciable mixing. The situation is analogous to that in the mare regolith, where lateral deposition greatly predominates over vertical mixing. A spectacular demonstration is the integrity of coarse-grained, Bi- and Cd-rich layers in core 12028 (ref. 10). Greater mixing depths will be attained at the sites of secondary craters, but because these craters account for only a minor part of the ejecta, the resulting polymict breccias will not be very common.

This is confirmed by trace element and electron microprobe data. Thirteen out of fourteen breccias studied at Chicago contain only one kind of meteoritic metal (ref. 2). The Co and Ni contents of metal grains in a given breccia also tend to cluster strongly, at least in cases where the Ni content is low enough for all the metal to be present as kamacite (see, for example, ref. 66).

Finally, we must stress the truism that local impacts can never become dominant over basins if basins contribute the major part of the ejecta. At best, local impacts can mobilize and remobilize older basin ejecta. But if basins contribute 80 to 90 percent of the projectile debris on the Moon, they will dominate the meteoritic component in second-, third-, and n th-generation breccias. The only secular trend of such repeated mixing will be eventual homogenization of the metal. Data on breccias (ref. 2) and figures 6 and 7 show that very little such homogenization has taken place.

Thus it seems safe to conclude that the ancient meteoritic debris comes mainly from a few large events superimposed on a continuum of smaller events. This is consistent with the clustering of the points in figure 6: all but eight of the 74 points fall within the six groups.

Assignment to Basins

EJECTA THICKNESS

We can try to assign the groups to individual basins by comparing their frequency of occurrence at each landing site (fig. 6) with expected contributions of ejecta from each basin, according to McGetchin et al. (ref. 67). We have recalculated their data using the basin coordinates and age sequence of Hartmann and Wood (ref. 68), rather than Stuart-Alexander and Howard (ref. 69), and including the Luna 20 site (table 2).

PREBASIN OVERLAY?

In principle, these trends can be blurred by two-stage transport, i.e., reejection of older ejecta during formation of a basin. To assess the importance of this effect, we have calculated the average overlay thickness at the center of each prebasin surface (ref. 2). It turns out that the old overlay comprises only some 10 to 200 m, or 1 to 5 percent, of the new ejecta, hardly a significant fraction.

Highland craters, on the other hand, contribute ~ 1 km of overlay (ref. 60), and thus may pose a more serious problem. A large crater contribution could manifest itself in two ways, depending on whether or not the crater-forming population was chemically distinct from the basin-forming population. If it was, it would fill the continuum between the groups in figure 6. If it was not, it would merely blur the geographic trends, all groups being equally common at all landing sites. Neither of these is the case: note, for ex-

ample, the scarcity of Apollo 17 samples in groups 1 and 4 and their dominance in groups 2 and 3. We thus conclude that the crater contribution was small compared to the basin contribution. Let us therefore try to assign each group to an individual basin.

TENTATIVE ASSIGNMENTS

Imbrium

Group 1 (fig. 6) has all the attributes expected for an Imbrian origin, according to table 2. It is prominent at all sites except Luna 20 which is the most distant from the Imbrium basin and Apollo 17 which is partly shielded by South Massif from Imbrian ejecta. It seems to comprise the topmost stratigraphic unit everywhere, judging from its prominence in intercrater areas and lower abundance on crater rims (Cone Crater at Apollo 14, North Ray Crater at Apollo 16), where deep-seated material is expected to dominate.

Serenitatis

According to table 2, material from this basin should be dominant at Apollo 17. This clue leads us to group 2, six of whose 10 members come from Apollo 17. Not only is this the largest grouping of Apollo 17 samples, but it also includes all samples of the oldest breccia type at this site, the blue-gray breccias (fig. 11). Two of them come from the Station 6 boulder that originated 1600 m below the crest of North Massif. This suggests a position fairly low in the stratigraphic sequence: Serenitatis or older (table 2).

Crisium

Group 3 is most likely derived from Crisium. It is represented mainly by the gray, foliated boulder from Station 2 of Apollo 17 (fig. 11), which apparently comes from near the top of South Massif (ref. 70) and, hence, must represent one of the younger basins. With Imbrium already assigned, the main

Table 2.—*Ejecta Depth in Meters* ⁽¹⁾

Contributing Basin	Crater Density ⁽²⁾	Apollo 11	Apollo 12	Apollo 14	Apollo 15	Apollo 16	Apollo 17	Luna 16	Luna 20
Oriente	2.4 ± 0.2	1.1	4	4	1.9	1.3	1.1	0.6	0.6
Imbrium	2.5 ± 0.2	59	133	128	560	54	66	19	19
Nectaris	16 ± 2	232	8	10	13	211	35	78	64
Crisium	17 ± 4	42	4	5	13	20	100	482	1134
Humorum	25 ± 2	4	68	47	5	7	3	1.4	1.8
Smythii	27 ± 7	2	0.4	0.5	0.9	1.4	3	18	18
Serenitatis	28	144	20	26	693	57	1089	47	40
Tranquillitatis W.	30	121	0.7	0.9	4	1.8	54	3	3
Tranquillitatis E.		9	0.2	0.3	1.0	1.9	32	5	6
Nubium	30	3	44	63	2	6	1.1	0.6	0.5
Fecunditatis	30	2	0.1	0.2	0.3	1.1	1.8	258	80
Australe		17	6	6	10	15	15	46	39

NOTES: (1) Calculated according to McGetchin et al. (ref. 67).

(2) Relative to average mare = 1. These crater densities refer to ejecta blanket of flooded basins or to floors of unflooded basins and should be proportional to age (ref. 68).

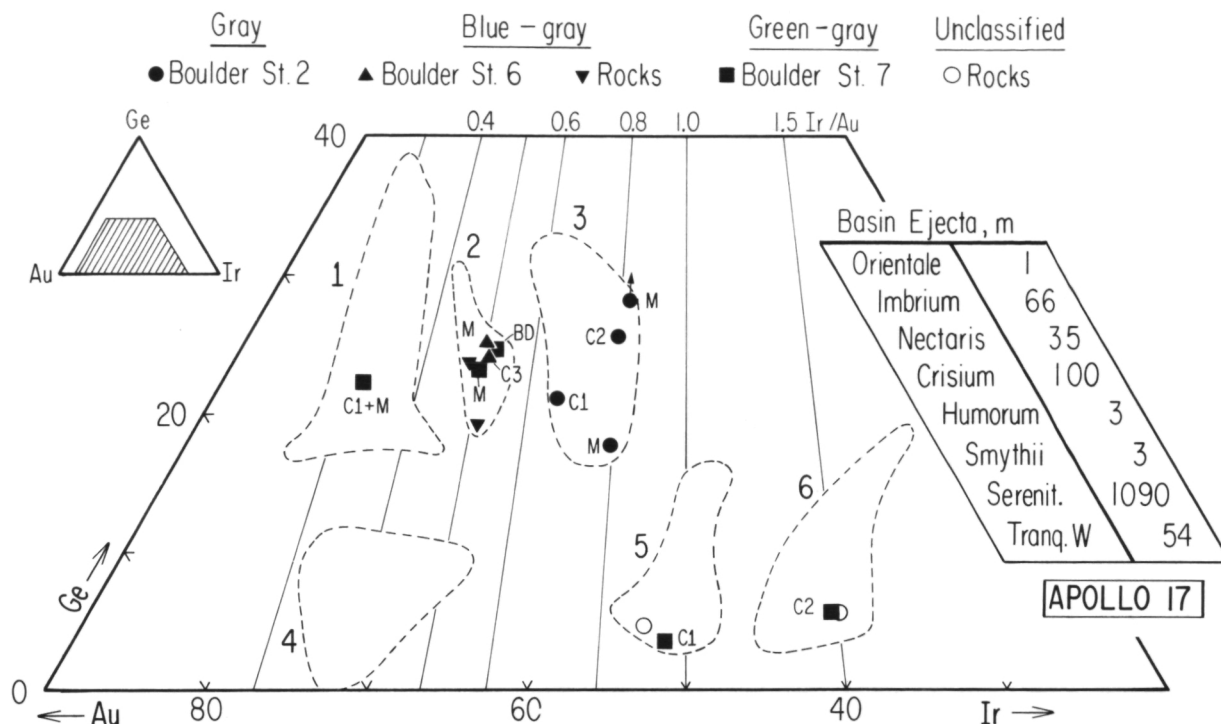


Figure 11.—Distribution of Apollo 17 samples among lunar meteoritic groups. C—clast; M—matrix; BD—black dike.

possibilities are Nectaris or Crisium. If it came from Nectaris, then group 3 should be very common at Apollo 16 (table 2); yet, only two of 37 samples from that site fall in group 3. On the other hand, if it came from Crisium, then group 3 should be more prominent at Apollo 17 than at other sites and, indeed, Apollo 17 accounts for four of the seven samples in this group.

Nectaris

Either group 5 or group 6 may be derived from the Nectaris body. At Apollo 16, both are represented mainly by a distinctive type of alkali-poor, dark-matrix breccia from Stations 11 and 13 near the rim of North Ray Crater (ref. 9). Group 5 also includes three shocked glasses from other stations (fig. 12). The dark-matrix breccias comprise the third stratigraphic unit at that site, being overlain by nearly 300 m of light-matrix breccias and cataclastic anorthosites (refs. 71 and

72). The latter contain no meteoritic component and have therefore been interpreted as deep ejecta from the Nectaris basin (refs. 9 and 73). Thus, groups 5 and 6 must represent basins of Nectarian or older age. We tentatively assign group 5 to the Nectaris body because of its presence at Luna 20 (fig. 12). Both Nectaris and Crisium ejecta should be prominent at that site, but by analogy to the stratigraphy of Apollo 16 all but the bottom portion of the thick Crisium blanket at Luna 20 should consist of deep ejecta, uncontaminated by projectile debris. It must be overlain by a thin blanket of meteorite-bearing Nectaris material. The source crater of Luna 20 soil, Apollonius C (refs. 48 and 74), should have ejected mainly such Nectaris material.

Humorum

Group 6 must be pre-Imbrian in age. It is found mainly in rocks from crater rims

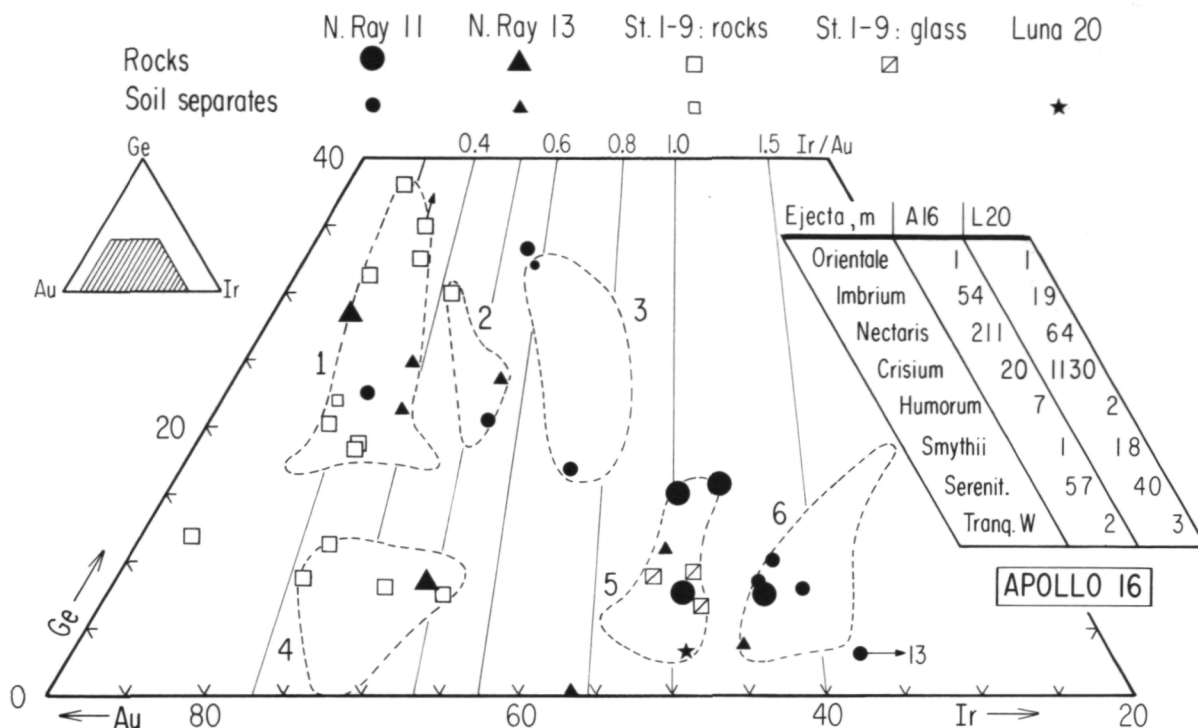


Figure 12.—Distribution of Apollo 16 and Luna 20 samples among lunar meteoritic groups.

which tend to come from lower stratigraphic units: 60017 from Outhouse Rock at North Ray Crater (Apollo 16), and 14063 from one of the White Rocks at Cone Crater (Apollo 14). With Nectaris, Crisium, and Serenitatis already assigned, the principal remaining possibility is the Humorum body. Alternatives are Nubium or the South Imbrium basin at 10°N., 16°W. (ref. 75). Perhaps a further study of Apollo 14 samples will shed some light on this question because material from all three basins should be prominent at that site.

Unassigned

This leaves group 4 unassigned. It is the least well defined of the six groups (note the dispersal of its members in figure 7) and contains a high proportion of impact melts. Perhaps it is not a true group, but merely a chance cluster of samples from groups 1 and 2 that lost some volatiles in impact melting or metamorphism.

Oriente

We also do not have a strong candidate for Oriente material. Early estimates (refs. 72 and 76) suggested that some tens of meters of Oriente material might be present at Apollo 16 and other sites, but the calculations of McGetchin et al. (ref. 67) suggest much smaller thicknesses, 1 to 4 meters (table 2). Moreover, because of the great ejection distances such material probably fragmented on impact and became dispersed throughout the local regolith (ref. 65). Two highly speculative candidates are a subgroup of group 1, distinguished by a high Re/Ir ratio (R group of ref. 8) or some samples of very low Ir/Au ratio (ref. 9).

Summary

Table 3 summarizes our tentative assignments, first for the age sequence of Hartmann and Wood (ref. 68) used above, and

Table 3.—*Tentative Basin Assignments*

Group	Ir/Au	Ge	Mare	
			HW ⁽¹⁾	SH ⁽²⁾
1	0.30–0.40	high	Imbrium	Imbrium
2	0.40–0.55	high	Serenitatis	Serenitatis
3	0.55–0.85	high	Crisium	Nectaris
4	0.30–0.50	low	??	??
5	0.85–1.20	low	Nectaris	Crisium
6	1.50–2.0	low	Humorum or Nubium	Humorum or Nubium

NOTES: (1) HW = Basin age sequence of Hartmann and Wood (ref. 65).

(2) SH = Basin age sequence of Stuart-Alexander and Howard (ref. 66).

then for the sequence of Stuart-Alexander and Howard (ref. 69): Orientale, Imbrium, Crisium, Humorum, Nectaris, Serenitatis, Fecunditatis, and Tranquillitatis W. The latter set, which reverses the assignments of Crisium and Nectaris, is slightly less self-consistent, but not by a decisive margin.

These assignments must be regarded as tentative until they have been thoroughly checked against all available evidence: radiometric ages, petrography, and field geology. In the first round of such tests, only one serious discrepancy has been found (ref. 2). Three clasts from the Apollo 17 Station 7 boulder (fig. 11) fall into groups 1, 5, and 6 assigned to young basins (Imbrium, Nectaris, and Humorum), whereas the matrix falls into group 2 assigned to an older basin (Serenitatis). Under normal circumstances, clasts should be older than matrices, not younger. To resolve this paradox, it may be necessary to assume that the green-gray breccias are Serenitatis material that was remobilized during the Imbrium event, incorporating clasts of Imbrian age or older. Indeed, Schmitt (ref. 70) proposed that the tan-gray³ breccias are younger than the blue-gray breccias, having intruded them in partially molten state. Head (ref. 77) suggested that the Taurus-Littrow area was tectonically reactivated by the Imbrium event.

³ Tan-gray on the lunar surface, green-gray in the laboratory.

Origin of Basin-Forming Objects

Let us try to infer the properties of the basin-forming objects from the clues available.

PRIMARY OR SECONDARY BODIES?

The high siderophile element content of highland breccias (several percent of solar abundance) shows that the basin-forming objects were independently formed primary bodies, not secondary castoffs of a larger body that had undergone a "planetary" segregation of metal and silicate. Such segregation typically depletes siderophiles by factors of 10^{-4} to 10^{-6} . Hence, they cannot represent material spun off the Earth after core formation (refs. 78, 79, and 80), condensates or volatilization residues from a hot Earth (ref. 81), or fragments of a differentiated protomoon disrupted during capture (refs. 82 through 85).

INTERNAL STRUCTURE

The ubiquity of metal in highland breccias suggests that the basin-forming bodies were undifferentiated and chondrite-like, with the metal phase uniformly dispersed throughout. Otherwise, if the metal had segregated into a core, the projectile would have to mix with the target rock to an incredibly uniform de-

gree to produce the distribution in figure 5.

Cooling rates of iron meteorites (ref. 86) support this conclusion. Fricker et al. (ref. 87) have compared the observed cooling rates with thermal models of asteroids and conclude that the IVA irons, with a wide range of cooling rates, came from a 100-km body whose metal phase did not coalesce into a single core, but formed scattered pockets throughout the body. Smaller bodies should be still less completely differentiated. According to published estimates, even the Imbrium body, largest of the basin-forming objects, was smaller than 100 km ($R = 95$ km (ref. 88); $R = 68$ km (ref. 89)).

IMPACT VELOCITY

The consistently high siderophile element content of highland breccias may be a significant clue to the impact velocities of the bodies. According to cratering theory, the ratio of eroded mass, M , to projectile mass, μ , is a function of impact velocity, w . Thus, if the mean value of M/μ is known for a given impact, the velocity can be calculated.

In practice, the true mean value is hard to determine because projectile and target rock do not mix uniformly. At Meteor Crater,

Arizona, rim material and nearby ejecta are very low in meteoritic elements (Morgan et al., unpublished work), while some of the subfloor material is high in Ni (ref. 90). Unless these effects exactly cancel each other, distant ejecta will contain either more or less than their share of projectile material. For large basins, the situation is simpler inasmuch as even rim material (e.g., Apollo 15, 17) typically had flight distances of $\sim 10^2$ km and, thus, must have been strongly shocked and meteorite-bearing. Consequently, all our samples are distant ejecta in the above sense, and so any bias should be the same for all groups. Thus, the M/μ values and the velocities derived therefrom should be reliable at least in a relative sense.

We have estimated M/μ in three ways: from the Au, Ni, and metal content of lunar breccias. To determine M/μ from the mean Au content, Au_B , we need to know the Au content of the projectile, Au_P . This can be estimated via the iron content of the projectile, Fe_P :

$$(M + \mu)/\mu \approx M/\mu = Au_P/Au_B \\ = (Au_P/Fe_P) (Fe_P/Au_B)$$

Because Au and Fe condense together from a solar gas and scarcely fractionate from

Table 4.—Target/Projectile Mass Ratio

M/μ based on ⁽²⁾	M/μ Value ⁽¹⁾					
	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Au	10.1 (23)	25.3 (12)	47.6 (8)	36.2 (4)	21.3 (13)	153 (9)
Ni	12.7 (15)	26.0 (10)	41.8 (6)	58.7 (3)	16.4 (10)	96 (6)
Metal ⁽³⁾	15.5 (9)	25.2 (5)	24.0 (3)	19.9 (2)	33.9 (3)	69 (4)
Weighted Mean	12.0	25.6	41.4	40.0	20.9	117

NOTES: (1) Number of samples is given in parentheses. The observed ratios, all based on samples with >0.2 ppb Au, were divided by 0.81 to allow for 19 percent highland samples with lower siderophile element contents.

(2) For a "lunar" iron content of the projectile, i.e., 9 wt %. For a "terrestrial" iron content of 36 percent, the M/μ values will be four times larger.

(3) See Morgan et al. (ref. 2) for references.

each other in chondrites (ref. 91), it is reasonable to assume that Au_p/Fe_p equaled the C1-chondrite ratio, 8.0×10^{-7} . This leaves only Fe_p to be determined. We have assumed two extreme values: "lunar" at 9-percent Fe and "terrestrial" at 36-percent Fe. They bracket all known chondrite classes, which range from 18- to 35-percent Fe.

About 19 percent of the highland breccias in figure 5 contain no meteoritic material, or too little to characterize. In order to make our M/μ values representative of the whole of the ejecta, we have corrected the mean Au contents of each group for a 19-percent contribution of meteorite-poor material.

A second set of M/μ values was calculated in an analogous manner from the Ni contents, using the Ni/Fe ratio of C1 chondrites, 5.67×10^{-2} . The third set was based on the metal contents of the breccias on the assumption that all the iron in the projectiles was in the metallic state. (This may not be such a bad assumption, because the Ni content of the metal is about 6 percent, close to the value of 5.3 percent expected for completely reduced C1-chondrite material.) The three sets of M/μ values, and a weighted average, are given in table 4. Only the values for "lunar" iron content (9 percent) are shown. Those for terrestrial iron content (36 percent) are a factor of 4 higher.

These M/μ values may be converted to impact velocity by a suitable cratering relation. There still is some controversy whether cratering is governed by the momentum or kinetic energy of the projectile, and we have therefore used both kinds of relation.

Momentum: $M/\mu = 5.67 \times 10^{-5} kW$ (refs. 92 and 93)

Energy: $M/\mu = 1.58 \times 10^{-10} W^{2.117}$ (ref. 94) The k in Öpik's equation is a velocity-dependent parameter, varying from 2 to 4.7 in the range 0 to 35 km/s.

The two relations are plotted in figure 13, along with M/μ values for lunar and terrestrial iron contents (solid and open circles).

The velocities are consistently low; indeed, for a lunar iron content, six of the 12 points fall below lunar escape velocity (2.4 km/s) for either cratering relation. To the extent

that these M/μ values are representative, this would seem to suggest that the projectiles had Fe contents higher than 9 percent. But even an iron content as high as 36 percent (open circles) gives quite low velocities: less than 8 km/s in nine of 12 cases. (In this M/μ range, Öpik's relation predicts much higher velocities than Gault's. It is in fact responsible for all three cases above 8 km/s.)

These velocities may not be accurate in an absolute sense because they are based on uncertain cratering relations and the uncertain assumption that M/μ in the ejecta was the same as for the whole impact. However, these uncertainties cancel out when we compare M/μ in ancient breccias and in ejecta from more recent craters. Although we have looked hard for contributions from recent craters, they are at best barely detectable

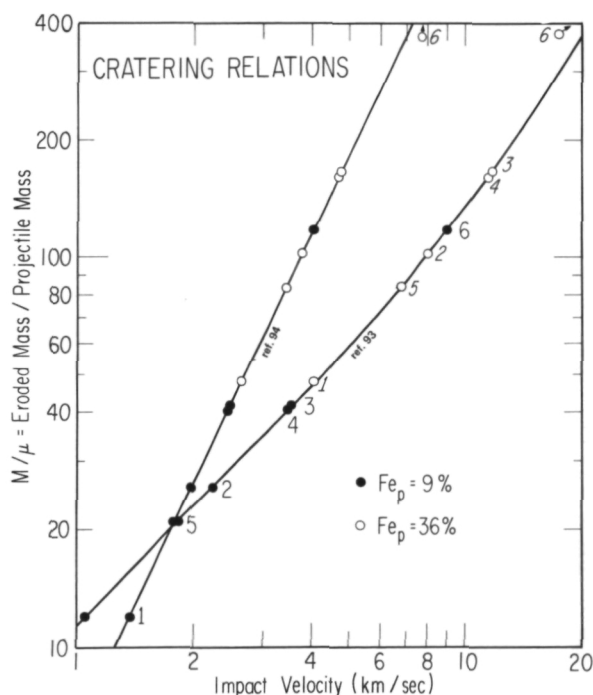


Figure 13.—Nominal impact velocity of basin-forming objects, estimated from cratering relations of Gault and Öpik. The two sets of points represent extreme values of iron content of the projectiles. Except for number 6, these bodies seem to have had impact velocities well below the mean geocentric velocity for present-day meteorites, ~ 15 km/s.

against the background of the ancient component (see p. 684). It seems difficult to escape the conclusion that most of the ancient projectiles had systematically lower velocities than the present crater-forming population (~ 15 km/s for asteroidal material; more for cometary material). Only group 6 comes close to the present-day range.

CHEMICAL COMPOSITION

We can try to characterize the basin-forming bodies more fully, using data on volatile elements. Though we have thus far confined ourselves to the five siderophile elements Ir, Re, Au, Sb, and Ge, eight of the remaining elements measured by us are also in part meteoritic. Figure 14 shows a rather favorable case, with a high content of meteoritic material. The indigenous corrections (black bars) are larger for volatiles than for siderophiles, but remain manageably small for most elements except Br, Zn, and Cd.

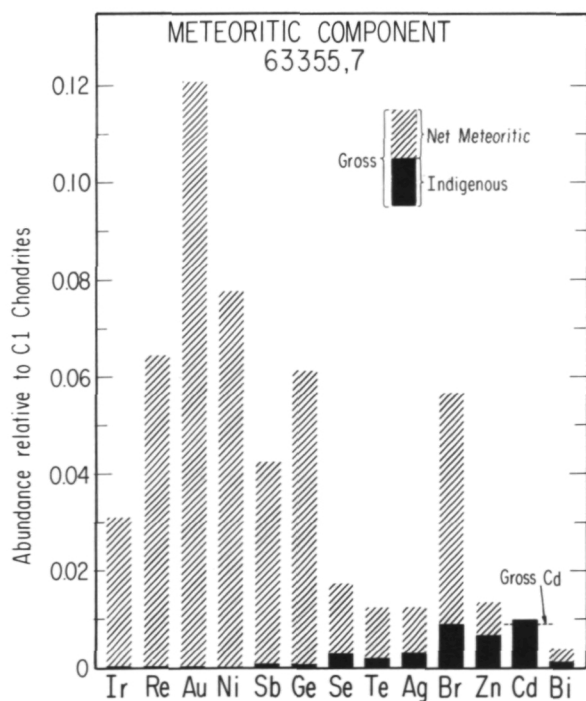


Figure 14.—Even some volatile elements are largely meteoritic in highland samples of high siderophile element abundance.

We have derived the abundance patterns of the six groups in this manner, using three to four samples of high siderophile element content from each group (fig. 15). The patterns were very consistent for the first six elements; less so for the last four, Se to Bi. For those elements, we gave greatest weight to the lowest values.

Several trends are apparent. (1) Groups 1 and 2 have almost identical patterns, except for the higher Au abundance in group 1. (2) In groups 1 to 3, Sb and Ge are equally abundant, while in groups 4 to 6, Ge is less abundant than Sb. Such differences have also been noted between carbonaceous chondrites and ordinary chondrites, where they were attributed to a higher effective temperature of chondrule formation (refs. 13, 95, and 96). (3) In all groups except 6, highly volatile Te and Bi are less abundant than the preceding four, moderately volatile elements. This trend is also observed in ordinary chondrites (refs. 97, 98, and 99), where it has been attributed to accretion in the range of partial condensation of these elements. In terms of this explanation, the flat pattern of group 6 would imply a lower accretion temperature and hence a more distant origin. This is an interesting thought in view of the high M/μ value that implies a high impact velocity (fig. 13) and hence an eccentric orbit. However, as expressed in the high M/μ , the samples of this group have a low content of meteoritic material; hence, the abundance pattern is poorly defined. (4) Group 3, which plots closest to C1 chondrites in figures 8 and 9, is highest in volatiles.

We can extend the comparison to the bulk Earth and Moon (fig. 16), using the compositional model of Ganapathy and Anders (ref. 100). None of the six groups is a perfect match for the Earth or Moon, and perhaps none should be, if these bodies accreted from planetesimals of a range of compositions. The Earth's composition could perhaps be approximated by a combination of groups 3 and 5, or possibly others. The Moon's composition requires a more refractory-rich material than even group 6. Only one sample

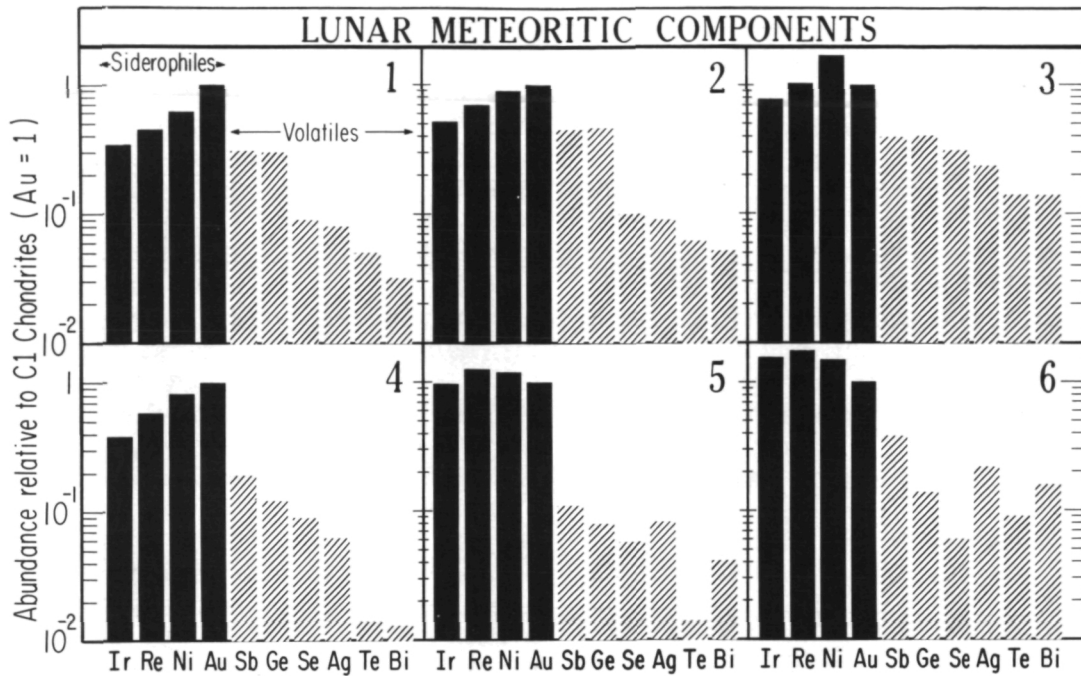


Figure 15.—Abundance patterns of six ancient meteoritic groups, corrected for indigenous contribution.

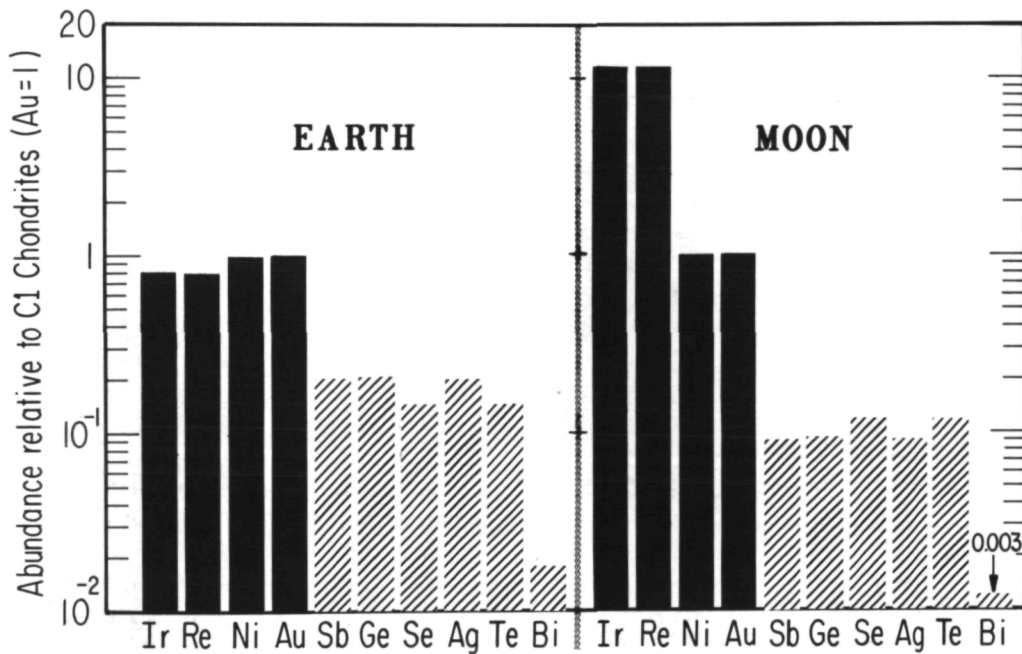


Figure 16.—Abundance patterns of bulk Earth and Moon, according to model of Ganapathy and Anders (ref. 97). Compare with figure 15. Groups 1 and 2 are complementary to Earth and Moon, being poorer in refractories (Ir, Re) and richer in volatiles (Ge, Sb, etc.).

approaching this composition has been found thus far: a breccia fraction from Apollo 16 soil (67602,14-3; off-scale in lower right of fig. 6). However, a mixture of group 5 with an Ir, Re-rich early condensate would give a pretty good match.

Interestingly, groups 1 and 2 are complementary to the Earth and Moon: poorer in refractories (Ir, Re), richer in at least two well-determined volatiles (Sb and Ge). This is consistent with accretion from a cooling nebula (refs. 51, 97, 101, and 102), where refractories concentrate in the large, early-formed bodies, and volatiles in the small, late-formed bodies. This complementarity may signify a genetic link between Earth and Moon on the one hand and basin-forming bodies on the other. In retrospect, it makes sense that the last bodies to fall on the Moon were complementary to it in composition.

Origin of Basin-Forming Objects

CLUES FROM THE BOMBARDMENT HISTORY OF THE MOON

An important clue is the rather young age of the Imbrium basin, 3.9 AE. This is not a statistical fluke, because at least one body (Orientale) fell still later. Apparently the basin-forming objects were stored in orbits of long enough collision lifetime to permit two of them to survive for ≥ 700 m.y.

A second, more ambiguous clue is the clustering of highland rock ages between 3.8 and 4.0 AE (ref. 103, and references cited therein). It is not yet clear whether this clustering implies a genuine cataclysm, i.e., a peak in the bombardment rate (refs. 104 and 105), or merely resetting of a continuum of older ages by the Imbrium impact. In terms of the cataclysm hypothesis, all basins were formed within 100 to 200 Myr of each other; any older ages are due to earlier magmatism or metamorphism unrelated to basin formation. The opposite, "steady bombardment" hypothesis interprets older ages, run-

ning up to ~ 4.5 AE, as the actual impact dates of basins (refs. 106 and 107).

A third clue is the existence of meteorite-free crustal rocks (fig. 5). It limits the amount of meteoritic material that could have fallen on the Moon after crustal differentiation (~ 4.5 AE ago?) (ref. 108), and thus fixes a point on the bombardment curve of the Moon. The crust, comprising $0.1 M_D$, probably contains no more than 2 percent of meteoritic material on the average, or $0.002 M_D$ (Baldwin, ref. 109, arrived at a figure of $0.003 M_D$ from crater counts and an extrapolation of meteorite fluxes. His latest value (private communication, 1974), is $0.002 M_D$.) Another point on the bombardment curve is fixed by the Imbrium impact 3.9 AE ago. Only the Orientale body, of estimated mass $5 \times 10^{-5} M_D$, was yet to fall after that time. These two points are shown in the left-hand portion of figure 17. The right-hand portion shows the same data, but with the number rather than mass of bodies as the ordinate. The number of basin-forming objects 4.5 AE ago is taken as 80^{+80}_{-40} , about twice the number actually known (ref. 68). This is an attempt to allow for additional discoveries (refs. 110 and 111).

It is not certain that the flux in this interval was exponential. However, if we make this assumption (ref. 112), we can estimate the probable formation times of the basins from their relative age. The horizontal bars in figure 17 correspond to the age sequence of Hartmann and Wood (ref. 68), omitting basins of ≤ 300 km in diameter. (The age sequence of Stuart-Alexander and Howard gives fairly similar results, except that Crisium falls at 4.1 AE.)

All of the ages fall between 4.2 and 4.35 AE. The absolute values of these ages should not be taken seriously because they depend critically on the initial number of basin-forming bodies 4.5 AE ago. However, the time gap between 3.9 and 4.2 AE is an interesting and significant feature. It reflects the fact that all seven of the basins formed in the interval between Nectaris and Imbrium lie on the farside or east limb and hence contribute negligible material to the lunar

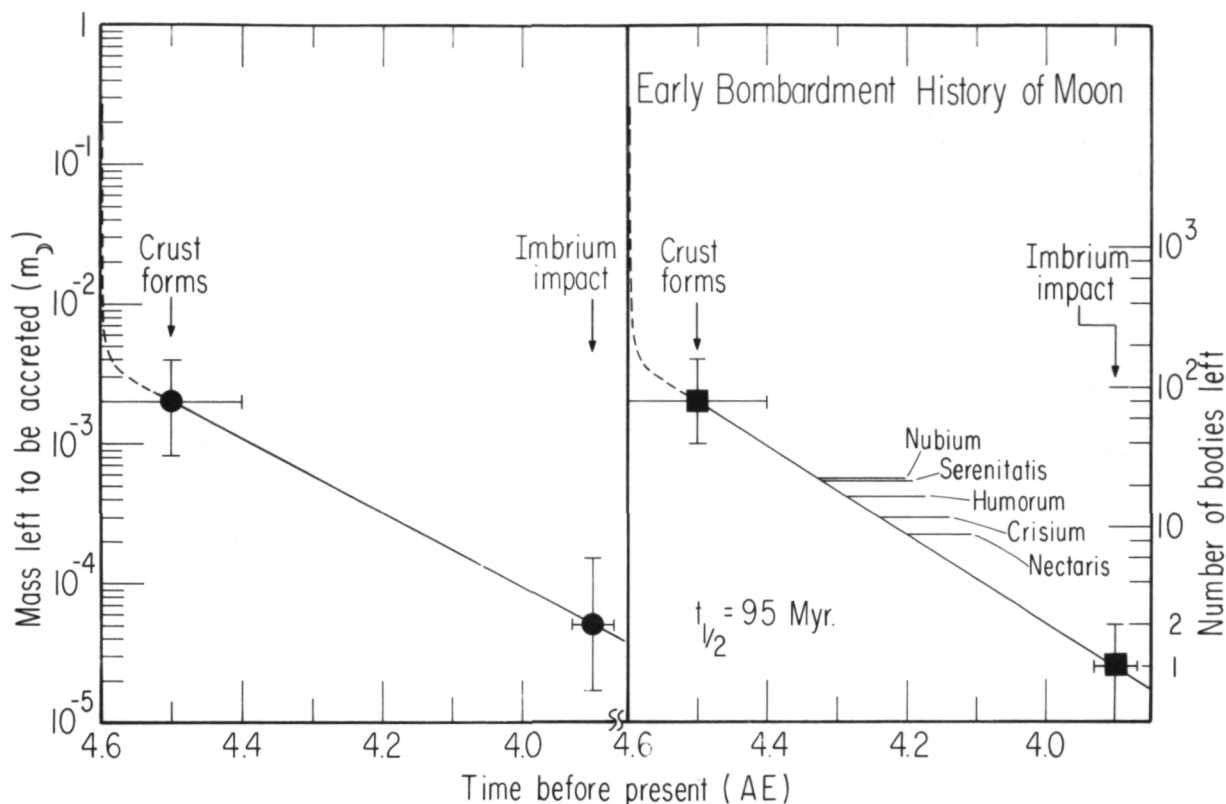


Figure 17.—Two points on the bombardment curve of the Moon are fixed by the mass influx after formation of crust ($\sim 2 \times 10^{-3} M$ or 80_{-40}^{+80} basin-forming objects) and the population surviving after the Imbrium impact 3.9 AE ago (Orientale, $\sim 5 \times 10^{-4} M_{\oplus}$). Horizontal bars at right give expected formation times of major basins. The 300-Myr gap between Nectaris and Imbrium impacts reflects the fact that all seven basins formed in this interval lie on the far side or east limb.

landing sites on the nearside. This fact, rather than a special cataclysm, may be responsible for the scarcity of ages in this interval.

ORIGINS

Four origins may be considered for the basin-forming objects (refs. 68 and 11).

1. Planetesimals in Earth-crossing orbits
2. Planetesimals in Earth-grazing orbits
3. Earth satellites swept up by the Moon during tidal recession or capture
4. Stray asteroids perturbed by Mars or Jupiter into Earth-crossing orbits

Of these four types of bodies, moonlets in Earth orbit (refs. 113, 114, and 115) most readily meet the constraints of survival to

3.9 AE, rapid extinction thereafter, chemical complementarity, and low impact velocity. Planetesimals in Earth-crossing orbits are adequate in most respects, provided their half-life against planetary collision is as long as ~ 100 Myr (fig. 17). The original Monte Carlo calculations by Arnold (ref. 116) and Wetherill (ref. 117) gave a half-life of only ~ 30 Myr (after the initial rapid sweepup of some 90 percent of the bodies). However, the actual lifetime may be longer because secular variations in eccentricity, inclination, and node may put the object out of the Earth's range for part of the time. Unpublished calculations by Mellick and Anders that make some allowance for these effects do in fact give $t_{1/2} \approx 80$ Myr, which is close to the required value.

The other two types of bodies are too long lived to be the main source. However, they may have been a subsidiary source, contributing a few objects of unusual composition or impact velocity (e.g., the group 6 body).

The Crater-Related Component

Of the three meteoritic components mentioned in the introduction, that associated with craters has remained the most elusive. No material definitely attributable to the projectile has been found in soils collected on or near the rims of the following small craters:

Apollo 12: Bench, Surveyor, Head
 Apollo 14: Cone, Doublet, Triplet
 Apollo 15: Elbow
 Apollo 16: North Ray

Only Dune Crater at the Apollo 15 site showed a change in the abundance pattern that could perhaps be attributed to projectile material (ref. 11). However, the data were equally consistent with a mixture of C1 and ancient component.

In principle, the chances of recognizing projectile material were greatest in soils from very young craters (the three Apollo 12 craters and Cone Crater at Apollo 14) which had short surface exposure ages and hence a small C1 component. But these soils all turned out to have a large ancient component which dominated the pattern. To be sure, the expected average amount of projectile material is at most ~ 0.4 -percent C1 equivalent for an impact velocity of 15 km/s (fig. 13). But such amounts should have been detectable in at least the more favorable cases, and so the consistent absence of a crater-related component calls for another explanation. Perhaps the projectiles were chemically inconspicuous (achondrites) or had high velocities. Most likely, however, the crater-rim material contained less than its share of projectile material.

Apart from Dune Crater, the only case where so much as a hint of projectile material has been seen is KREEP glass from

the Apollo 12 site. Most authors believe that this glass represents Copernican ray material (see ref. 118 for references and ref. 119 for a contrary view). The basic pattern in Apollo 12 KREEP looks very much like the group 1 component from Apollo 14 norites, except for a slight, uniform enrichment in Ir, Re, Sb, Se, Zn, Ag, and Bi, relative to Au. Morgan et al. (ref. 118) argue that this enrichment does not represent C1 contamination from recent or post-Imbrian times, but more likely Copernican projectile material. This would imply that the Copernican projectile had a primitive composition (comet?). On the highly tenuous assumption that the amount of projectile material in KREEP glass is representative of the entire Copernican impact, they calculate, from Öpik's cratering equation, an impact velocity of 36 ± 5 km/s.

Clearly, this problem is far from solved. One needs to know how projectile material distributes itself among the ejecta as a function of initial stratigraphy, shock intensity, and throwout distance. With this information (and photogeologic data linking individual soil components to specific craters), it may be possible to make reliable inferences about composition and impact velocities of crater-forming bodies.

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