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METEORITIC MATERIAL ON THE MOON*

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Abstract. 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% 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 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.

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*This review is based in part on two earlier papers by the authors (Anders et al., 1973; Morgan et al., 1974).

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 cast-offs of a larger body. They were internally undifferentiated, had radii less than 100 km, contained between ~15% and ~40% iron, and struck the Moon at velocities generally less than 8 km/sec. 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 ~80±40 basin-forming objects, totaling $\sim 2 \times 10^{-3}$ $M_{☽}$, fell on the Moon after crustal differentiation ~4.5 AE ago, and that only one such body, of $\sim 5 \times 10^{-5}$ $M_{☽}$, 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 7 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.

1. INTRODUCTION

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

(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 bombardment" that produced the highland craters and mare basins (Urey, 1960; Hartmann, 1966): in ancient breccias and highlands regolith.

The amount of meteoritic material had been estimated from crater scaling laws and observed fluxes of interplanetary matter (Öpik, 1969). 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 now 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 which were abundant in meteorites but were expected to be rare in lunar surface rocks (Keays et al., 1970; Ganapathy et al., 1970, 1973, 1974; Laul et al., 1971; Morgan et al., 1972a,b, 1974; Krähenbühl et al., 1973). 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 (Barker and Anders, 1968; Hanappe et al., 1968). 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 first part of this paper reviews the micrometeorite component, a well-explored and essentially closed subject. The second, major part discusses a less finished but more exciting topic: the ancient meteoritic component. The final part reviews the scanty information on the crater-forming component.

2. 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 4 mare sites are shown in Fig. 1. They have been normalized to Cl 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 of high surface exposure age, from inter-crater areas, 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 (Morgan _et al_., 1972a). Soil breccias, not plotted here, are essentially similar to soils (Ganapathy _et al_., 1970).

2.1. Composition

Soils from all 4 sites show essentially the same picture: siderophiles enriched to 1.5 to 2% Cl 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 4 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. See Laul et al., 1971; Morgan et al., 1972b; Baedecker et al., 1972; Chou et al., 1974).

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 systematic depletion of volatiles relative to siderophiles, and thus were most consistent with C1 chondrites (Ganapathy et al., 1970). However, now that more data (and better indigenous corrections) are available, a hint of such depletion is discernible. In the three Apollo samples, 7 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 (Anders et al., 1973). Still, it appears that the dominant component has C1 composition.

2.2. 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 4 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 sizable contribution from an ancient meteoritic component (Anders et al., 1973). Accordingly, we have given a "best estimate" of the net amount of C1 component. From the latter, we have calculated the average influx rate at each site, as in Ganapathy et al. (1970).

The most uncertain factor in this calculation is the mean hickness of the regolith, which has been estimated to be 4.6 m at all 4 sites (Oberbeck and Quaide, 1968). The mean influx rate for the three Apollo sites is 2.4×10^{-9} g $cm^{-2}yr^{-1}$.* It agrees rather well with pre-Apollo estimates by Whipple (1967a) and Öpik (1969): 1.3×10^{-8} g $cm^{-2}yr^{-1}$ (total) and 1.05×10^{-8} g $cm^{-2}yr^{-1}$ (micrometeorites only).

At low approach velocities, the meteor impact rate should vary strongly with selenographic position (Wiesel, 1971). From the graph given by Wiesel, the following relative fluxes would be expected at the 4 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/sec, far below the actual mean velocity of meteors.

2.3. 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 3-4% of the siderophile elements in the soil (recalculated from Ganapathy *et al.*, 1970, with the latest abundance data and solar wind flux). Crater-forming objects provide a somewhat larger fraction, perhaps 5 to 20%

*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 μm vs <1000 μm) and hence presumably enriched in meteoritic material. Contamination seems to have been more severe than in the Apollo soils (Laul *et al.*, 1972), 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 (1971) estimates it as 0.5-1 m, but suggests that it is similar to that in Oceanus Procellarum, which he gives as 1-3 m, rather than the 4.6 m cited by Oberbeck and Quaide (1968).

(Öpik, 1969; Ganapathy et al., 1970). This estimate is rather uncertain, because it depends on a host of poorly known quantities: projectile velocity distribution, crater scaling laws, mixing efficiency of projectile and target material as a function of throwout 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 Sec. 7). 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 (1971, 1972) 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} vs 2.4×10^{-9} g $cm^{-2}yr^{-1}$. A lower value (by a factor of 4 to 6) was obtained from lunar microcraters (Hartung et al., 1972; Dohnanyi, 1972), 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 (Öpik, 1956; Whipple, 1967a,b; Dohnanyi, 1972). Apparently comets have a composition close to that of C1 chondrites, as proposed by Herbig (1961), Anders (1963), Whipple (1968), and others. The present characterization is based entirely on trace elements, but is also supported by spectroscopic studies of Millman (1972), showing that 9 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 (Brownlee et al., 1972). 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 (DuFresne and Anders, 1962), and contain solar-wind gases suggestive of irradiation in a regolith (Jeffery and Anders, 1970). Comets probably 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 (Anders, 1971a, 1974).

Interestingly, Johnson and Fanale (1973), Chapman and Morrison (1973), and Gaffey and McCord (1974) have found that C1 and C2 chondrites resemble some asteroids in albedo and spectral reflectivity. Thus it seems that asteroids are a possible source of C1 chondrites.

3. THE ANCIENT METEORITIC COMPONENT

Highland soils show a markedly different pattern, as first seen at Apollo 14 (Ganapathy et al., 1972), and later at 4 other sites (see the review by Anders et al., 1973, as well as Wlotzka et al., 1973; Baedecker et al., 1973). 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. Fig. 4 shows an alkali-poor and an alkali-rich highland breccia (black circles and black squares), each matched up with a crystalline rock of similar bulk composition and Rb, Cs, U content (open symbols). Most of the 16 elements have comparable abundances in the breccia and its crystalline counterpart, except for the first 5, 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 (Kimura et al., 1974). It appears that these abundances represent true indigenous levels. On the other hand, the more common, high abundances around 1-10 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 (Wlotzka et al., 1972; Ganapathy et al., 1974), which comprise 0.1-1% of highland breccias and impact melts (Dickey, 1970; Vinogradov, 1972). A suspension of metal droplets in a silicate melt is dynamically unstable on time scales comparable to the freezing time of basaltic flows (Fish et al., 1960; Provost and Bottinga, 1972).

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.

3.1. Classification

The 6 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, while Ni and Au condense almost concurrently with iron, slightly before and after, respectively (Grossman, 1972 and unpublished data; Larimer, 1967 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, 1971 and earlier papers; Baedecker, 1971; Scott, 1972).

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 (Morgan et al., 1972a; Ganapathy et al., 1973). The trends show up more clearly on ternary plots. Figs. 6 and 7 show results for 74 highland samples from 5 sites. The data are normalized to Cl chondrite abundances (Krähenbühl et al., 1973b), to prevent the plots from being dominated by the element of highest absolute abundance. Corrections have been applied for indigenous contributions (Morgan et al., 1974). They are typically <1% for Ir, Au, and Re, and 1 to 30% 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 limited ourselves to rocks and to lithic fragments from coarse soils. Agglutinates, magnetic separates, soil breccias, and glasses from coarse soils were excluded.

Approximately 6 groups seem to be present, as indicated by the dashed lines (Fig. 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 exceptions are Group 4, and a few samples of sporadically high indigenous Sb or Ge content.

The definition of these groups involves some subjectivity, and we do not claim that the present 6 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.

3.2. Comparison with Meteorites

The ancient lunar meteoritic bodies show little resemblance to present-day meteorites (Figs. 8-10). 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 Figs. 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 5 samples were analyzed for all 3 elements in the same laboratory (Krähenbühl _et al_., 1973b; Fouché and Smales, 1967a,b). For most other classes, data were few and from different sources.

3.3. Basins or Craters?

Granted that the ancient meteoritic material dates from the early intense bombardment, does it come mainly from a few large basins or from a multitude of smaller craters? The clustering into 6 groups alone does not prove that only 6 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 (1971), using a single size distribution law (Baldwin, 1964), estimated that 56% of the highland ejecta will be contributed by craters (actually basins) larger than 412 km in diameter, and an additional 25% by craters between 206 and 412 km. Short and Forman (1972) 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%, 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 30-60%, probably close to Öpik's 81%.

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 (1972) 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 (Stöffler et al., 1974). 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 on the Moon thus will fly 6 times farther than on the Earth. Indeed, several rocks of deepseated origin have been found on the lunar surface: a troctolite from 15-40 km depth (Gooley et al., 1974) and a number of dunite clasts, presumably from below the 65 km crust (e.g. Albee et al., 1974).

Secondary Craters? Oberbeck et al. (1974) 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 4- or 7-fold 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 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, and 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 layer in core 12028; Laul et al., 1971). Greater mixing depths will be attained at the sites of secondary craters, but because these craters amount 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 (Morgan et al., 1974). 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, Taylor et al., 1973).

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 80-90% 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 (Morgan et al., 1974), and Figs. 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 Fig. 6: all but 8 of the 74 points fall within the six groups.

4. ASSIGNMENT TO BASINS

4.1. 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. (1973). We have recalculated their data, using the basin coordinates and age sequence of Hartmann and Wood (1971) rather than Stuart-Alexander and Howard (1970), and including the Luna 20 site (Table 2).

4.2. Pre-Basin Overlay?

In principle, these trends can be blurred by two-stage transport, i.e. re-ejection 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 pre-basin surface (Morgan et al., 1974). It turns out that the old overlay comprises only some 10-200 m, or 1-5% of the new ejecta, hardly a significant fraction.

Highland craters, on the other hand, contribute ~1 km of overlay (Short and Forman, 1972), 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 Fig. 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 example, 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.

4.3. Tentative Assignments

Imbrium. Group 1 (Fig. 6) has all 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 S. 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 deepseated 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 ten 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, which 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 S. Massif (Schmitt, 1973) and hence must represent one of the younger basins. With Imbrium already assigned, the main possibilities are Nectaris or Crisium. If it came from Nectaris, then Group 3 should be very common at Apollo 16 (Table 2); yet only 2 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 4 of the 7 samples in this group.

Nectaris. Either Group 5 or 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 (Ganapathy et al., 1974). 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 (AFGIT, 1973; Hodges et al., 1973). The latter contain no meteoritic component and have therefore been interpreted as deep ejecta from the Nectaris basin (Krähenbühl et al., 1973a; Ganapathy et al., 1974). 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 (Vinogradov, 1972; Crozaz et al., 1973), 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 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 (Wilhelms and McCauley, 1971). 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 6 groups (note the dispersal of its members in Fig. 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.

Orientale. We also do not have a strong candidate for Orientale material. Early estimates (Hodges et al., 1973; Chao et al., 1973) suggested that some tens of meters of Orientale material might be present at Apollo 16 and other sites, but the calculations of McGetchin et al. (1973) suggest much smaller thicknesses, 1-4 meters (Table 2). Moreover, because of the great ejection distances, such material probably fragmented on impact and became dispersed throughout the local regolith (Oberbeck et al., 1974). Two, highly speculative candidates are a subgroup of Group 1, distinguished by a high Re/Ir ratio (R group of Ganapathy et al., 1973) or some samples of very low Ir/Au ratio (Ganapathy et al., 1974).

Summary. Table 3 summarizes our tentative assignments, first for the age sequence of Hartmann and Wood (1971) used above, and then for the sequence of Stuart-Alexander and Howard (1970): 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 (Morgan et al., 1974). 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 matrix, 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 (1973) proposed that the tan-gray* breccias are younger than the blue-gray breccias, having intruded them in partially molten state. Head (1974) suggested that the Taurus-Littrow area was tectonically reactivated by the Imbrium event.

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

5. ORIGIN OF BASIN-FORMING OBJECTS

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

5.1. 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 cast-offs 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 (Wise, 1963; O'Keefe, 1970, 1972), condensates or volatilization residues from a hot Earth (Ringwood, 1970), or fragments of a differentiated proto-Moon disrupted during capture (Urey and Macdonald, 1971; Öpik, 1972; Smith, 1974; Wood and Mitler, 1974).

5.2. Internal Structure

The ubiquity of metal in highland breccias suggests that the basin-forming bodies were undifferentiated, 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 degree, to produce the distribution in Fig. 5.

Cooling rates of iron meteorites (Goldstein and Short, 1967) support this conclusion. Fricker et al. (1970) 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, Baldwin, 1963; R = 68 km, Urey, 1968).

5.3. 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 (Nininger, 1956). 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 each other in chondrites (Larimer and Anders, 1970), it is reasonable to assume that Au_P/Fe_P equalled 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% and "terrestrial" at 36% Fe. They bracket all known chondrite classes, which range from 18 to 35% Fe.

About 19% of the highland breccias in Fig. 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% 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%, close to the value of 5.3% 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%) are shown. Those for terrestrial iron content (36%) 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.

<u>Momentum</u>: $M/\mu = 5.67 \times 10^{-5}\ kw$ (Öpik, 1958, 1961)

<u>Energy</u>: $M/\mu = 1.58 \times 10^{-10}\ w^{2.117}$ (Gault, 1973)

The <u>k</u> in Öpik's equation is a velocity-dependent parameter, varying from 2 to 4.7 in the range 0 to 35 km/sec.

The two relations are plotted in Fig. 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, 6 of the 12 points fall below lunar escape velocity (2.4 km/sec), 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%. But even an iron content as high as 36% (open circles) gives quite low velocities: less than

8 km/sec in 9 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 3 cases above 8 km/sec).

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 against the background of the ancient component (Sec. 7). It seems difficult to escape the conclusion that most of the ancient projectiles had <u>systematically lower velocities</u> than the present crater-forming population (~15 km/sec for asteroidal material; more for cometary material). Only Group 6 comes close to the present-day range.

5.4. 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 5 siderophile elements Ir, Re, Au, Sb, and Ge, 8 of the remaining elements measured by us also are in part meteoritic. Fig. 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.

We have derived the abundance patterns of the 6 groups in this manner, using 3-4 samples of high siderophile element content from each group (Fig. 15). The patterns were very consistent for the first 6 elements; less so for the last 4, 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 (Case et al., 1973; Krähenbühl et al., 1973b; Anders, 1968). (3) In all groups except 6, highly volatile Te and Bi are less abundant than the preceding 4, moderately volatile elements. This trend is also observed in ordinary chondrites (Larimer and Anders, 1967; Laul et al., 1973; Larimer, 1973), 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 which 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, and hence the abundance pattern is poorly defined. (4) Group 3, which plots closest to C1 chondrites in Figs. 8-9, 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 (1974). None of the 6 groups are 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 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

(Larimer and Anders, 1970; Anders, 1971b; Grossman, 1972; Grossman and Clark, 1973), 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.

6. ORIGIN OF BASIN-FORMING OBJECTS

6.1. 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 Myr.

A second, more ambiguous, clue is the clustering of highland rock ages between 3.8 and 4.0 AE (Podosek et al., 1973,and references cited therein). It is not yet clear whether this clustering implies a genuine cataclysm, i.e. a peak in the bombardment rate (Tera et al., 1973, 1974), or merely resetting of a continuum of older ages by the Imbrium impact. In terms of the cataclysm hypothesis, all basins formed within 100-200 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, running up to ~4.5 AE, as the actual impact dates of basins (Schaeffer and Husain, 1974; Kirsten and Horn, 1974).

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? Nunes and Tatsumoto, 1973), and thus fixes a point on the bombardment curve of the Moon. The crust, comprising 0.1 $M_☽$, probably contains no more than 2% of meteoritic material on the average, or 0.002 $M_☽$ (Baldwin, 1971, arrived at a figure of 0.003 $M_☽$ from crater counts and an extrapolation of meteorite fluxes. His latest value (private communication, 1974), is 0.002 $M_{☽}$.] Another point on the bombardment curve is fixed by the Imbrium impact 3.9 AE ago. Only the Orientale body, of estimated mass 5×10^{-5} $M_{☽}$, was yet to fall after that time. These two points are shown in the left-hand portion of Fig. 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 (Hartmann and Wood, 1971). This is an attempt to allow for additional discoveries (El Baz, 1973; Scott, 1974).

It is not certain that the flux in this interval was exponential. However, if we make this assumption (Hartmann, 1972), we can estimate the probable formation times of the basins from their relative age. The horizontal bars in Fig. 17 correspond to the age sequence of Hartmann and Wood (1971), omitting basins of ≤300 km 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 7 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 landing sites on the nearside. This fact, rather than a special cataclysm, may be responsible for the scarcity of ages in this interval.

6.2. Origins

Four origins may be considered for the basin-forming objects (Hartmann and Wood, 1971; Morgan et al., 1972a).

(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 4 types of bodies, moonlets in Earth orbit (Ruskol, 1962, 1971, 1972) 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 (1965) and Wetherill (1968) gave a half-life of only ~30 Myr (after the initial, rapid sweepup of some 90% 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 $t_{\frac{1}{2}} \approx 80$ Myr, 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).

7. 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 (Morgan et al., 1972a). 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% C1 equivalent for an impact velocity of 15 km/sec (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 they 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 Morgan et al., 1973 for references, and Wasson and Baedecker, 1972, 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. (1973) 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/sec.

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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REFERENCES

Albee A.L., Chodos A.A., Dymek R.F., Gancarz A.J., Goldman D.S., Papanastassiou D.A., and Wasserburg G.J. (1974) Dunite from the lunar highlands: Petrography, deformation history, Rb-Sr age. In Lunar Science V, 3-5, Lunar Science Institute, Houston.

Anders E. (1963) On the origin of carbonaceous chondrites. Ann. N.Y. Acad. Sci. **108**, 514-533.

Anders E. (1968) Chemical processes in the early solar system, as inferred from meteorites. Acc. Chem. Res. **1**, 289-298.

Anders E. (1971a) Interrelations of meteorites, asteroids, and comets. In Physical Studies of Minor Planets, ed. T. Gehrels, NASA SP-267, U.S. Government Printing Office, Washington, D.C., 429-446.

Anders E. (1971b) Meteorites and the early solar system. Ann. Rev. Astron. Astrophys. **9**, 1-34.

Anders E. (1974) Do stony meteorites come from comets? Submitted to Icarus.

Anders E., Ganapathy R., Krähenbühl U., and Morgan J.W. (1973) Meteoritic material on the Moon. The Moon **8**, 3-24.

Apollo Field Geology Investigation Team (1973) Apollo 16 exploration of Descartes: A geologic summary. Science **179**, 62-68.

Arnold J.R. (1965) The origin of meteorites as small bodies.- III. General considerations. Astrophys. J. **141**, 1548-1556.

Baedecker P.A. (1971) Iridium (77). In Handbook of Elemental Abundances in Meteorites, ed. B. Mason, Gordon and Breach, New York, 463-472.

Baedecker P.A., Chou C.-L., and Wasson J.T. (1972) The extralunar component in lunar soils and breccias. Geochim. Cosmochim. Acta Suppl. **3**, 1343-1359.

Baedecker P.A., Chou C.-L., Grudewicz E.B., and Wasson J.T. (1973) Volatile and siderophilic trace elements in Apollo 15 samples: Geochemical implications and characterization of the long-lived and short-lived extralunar materials. Geochim. Cosmochim. Acta Suppl. **4**, 1177-1195.

Baldwin R.B. (1963) The Measure of the Moon, University of Chicago Press, Chicago, 488 pp.

Baldwin R.B. (1964) Lunar crater counts. Astron. J. 69, 377-392.

Baldwin R.B. (1971) On the history of lunar impact cratering: The absolute time scale and the origin of planetesimals. Icarus 14, 36-52.

Barker J.L., Jr. and Anders E. (1968) Accretion rate of cosmic matter from iridium and osmium contents of deep-sea sediments. Geochim. Cosmochim. Acta 32, 627-645.

Brownlee D.E., Hodge P.W., and Hörz F. (1973) Information from lunar microcraters pertaining to interplanetary grains. Meteoritics 8, 18.

Case D.R., Laul J.C., Pelly I.Z., Wechter M.A., Schmidt-Bleek F., and Lipschutz M.E. (1973) Abundance patterns of thirteen trace elements in primitive carbonaceous and unequilibrated ordinary chondrites. Geochim. Cosmochim. Acta 37, 19-33.

Chao E.C.T., Soderblom L.A., Boyce J.M., Wilhelms D.E., and Hodges C.A. (1973) Lunar light plains deposits (Cayley Formation) - A reinterpretation of origin. In Lunar Science IV, Lunar Sci. Institute, Houston, 127-128.

Chapman C.R. and Morrison D. (1974) The minor planets: Sizes and mineralogy. Sky and Telescope, February, 92-95.

Chou C.-L., Baedecker P.A., Bild R.W., Robinson K.L., and Wasson J.T. (1974) Volatile elements in lunar soils. In Lunar Science V, Lunar Science Institute, Houston, 115-117.

Crozaz G., Walker R., and Zimmerman D. (1973) Fossil track and thermoluminescence studies of Luna 20 material. Geochim. Cosmochim. Acta 37, 825-830.

Dence M.R. and Plant A.G. (1972) Analysis of Fra Mauro samples and the origin of the Imbrium Basin. Geochim. Cosmochim. Acta, Suppl. 3, 379-399.

Dickey J.S., Jr. (1970) Nickel-iron in lunar anorthosites. Earth Planet. Sci. Lett. 8, 387-392.

Dohnanyi J.S. (1971) Flux of micrometeoroids: Lunar sample analyses compared with flux model. Science 173, 558.

Dohnanyi J.S. (1972) Interplanetary objects in review: Statistics of their masses and dynamics. Icarus 17, 1-48.

DuFresne E.R. and Anders E. (1962) On the chemical evolution of the carbonaceous chondrites. Geochim. Cosmochim. Acta 26, 1085-1114.

Fish R.A., Goles G.G., and Anders E. (1960) The record in the meteorites - III. On the development of meteorites in asteroidal bodies. Astrophys. J. 132, 243-258.

Fouché K.F. and Smales A.A. (1967a) The distribution of trace elements in chondritic meteorites - I. Gallium, germanium and indium. Chem. Geol. 2, 5-33.

Fouché K.F. and Smales A.A. (1967b) The distribution of trace elements in chondritic meteorites - II. Antimony, arsenic, gold, palladium, and rhenium. Chem. Geol. 2, 105-134.

Fricker P.E., Goldstein J.I., and Summers A.L. (1970) Cooling rates and thermal histories of iron and stony-iron meteorites. Geochim. Cosmochim. Acta 34, 475-491.

Gaffey M.J. and McCord T.B. (1974) The composition of asteroid surfaces. Presented at Am. Astron. Soc., Div. Planet. Sci., Ann. Mtg., Palo Alto, April 1-6.

Ganapathy R., Keays R.R., Laul J.C., and Anders E. (1970) Trace elements in Apollo 11 lunar rocks: Implications for meteorite influx and origin of Moon. Geochim. Cosmochim. Acta, Suppl. 1, 1117-1142.

Ganapathy R., Laul J.C., Morgan J.W., and Anders E. (1972) Moon: Possible nature of the body that produced the Imbrian Basin, from the composition of Apollo 14 samples. Science 175, 55-59.

Ganapathy R., Morgan J.W., Krähenbühl U., and Anders E. (1973) Ancient meteoritic components in lunar highland rocks: Clues from trace elements in Apollo 15 and 16 samples. Geochim. Cosmochim. Acta, Suppl. 4, 1239-1261.

Ganapathy R. and Anders E. (1974) Bulk compositions of the Moon and Earth, estimated from meteorites. Geochim. Cosmochim. Acta, Suppl. 5, in press.

Ganapathy R., Morgan J.W., Higuchi H., Anders E., and Anderson A.T. (1974) Meteoritic and volatile elements in Apollo 16 rocks in separated phases from 14306. Geochim. Cosmochim. Acta, Suppl. 5, in press.

Gault D.E. (1973) Displaced mass, depth, diameter, and effects of oblique trajectories for impact craters formed in dense crystalline rocks. The Moon 6, 32-44.

Goldstein J.I. and Short J.M. (1967) The iron meteorites, their thermal history, and parent bodies. Geochim. Cosmochim. Acta 31, 1733-1770.

Gooley R., Brett R., Warner J., and Smyth J.R. (1974) Sample 76535, a deep lunar crustal rock. Geochim. Cosmochim. Acta 38, in press.

Grossman L. (1972) Condensation in the primitive solar nebula. Geochim. Cosmochim. Acta 36, 597-619.

Grossman L. and Clark S.P., Jr. (1973) High-temperature condensates in chondrites and the environment in which they formed. Geochim. Cosmochim. Acta 37, 635-649.

Hanappe F., Vosters M., Picciotto E., and Deutsch S. (1968) Chimie des neiges antarctiques et taux de deposition de matiere extraterrestre - II. Earth Planet. Sci. Lett. 4, 487-496.

Hartmann W.K. (1966) Early lunar cratering. Icarus 5, 406-418.

Hartmann W.K. (1972) Paleocratering of the Moon: Review of post-Apollo data. Astrophys. Space Sci. 17, 48-64

Hartmann W.K. and Wood C.A. (1971) Moon: Origin and evolution of multi-ring basins. The Moon 3, 3-78.

Hartung J.B., Hörz F., and Gault D.E. (1972) Lunar microcraters and interplanetary dust. Geochim. Cosmochim. Acta, Suppl. 3, 2735-2753.

Head J.W. (1974) Morphology and structure of the Taurus-Littrow highlands (Apollo 17): Evidence for their origin and evolution. The Moon 9, 355-395.

Herbig G.H. (1961) Comments during discussion. Proc. Lunar and Planetary Colloquium 2 [4] 64.

Hodges C.A., Muehlberger W.R., and Ulrich G.E. (1973) Geologic setting of Apollo 16. Geochim. Cosmochim. Acta, Suppl. 4, 1-25.

Jeffery P.M. and Anders E. (1970) Primordial noble gases in separated meteoritic minerals - I. Geochim. Cosmochim. Acta 34, 1175-1198.

Johnson T.V. and Fanale F.P. (1973) Optical properties of carbonaceous chondrites and their relationship to asteroids. J. Geophys. Res. 78, 8507-8518.

Keays R.R., Ganapathy R., Laul J.C., Anders E., Herzog G.F., and Jeffery P.M. (1970) Trace elements and radioactivity in lunar rocks: Implications for meteorite infall, solar-wind flux, and formation conditions of Moon. Science 167, 490-493.

Kimura K., Lewis R.S., and Anders E. (1974) Distribution of gold and rhenium between nickel-iron and silicate melts: Implications for the abundance of siderophile elements on the Earth and Moon. Geochim. Cosmochim. Acta 38, 683-701.

Kirsten T. and Horn P. (1974) ^{39}Ar-^{40}Ar-chronology of the Taurus-Littrow region II: A 4.28 b.y. old troctolite and ages of basalts and highland breccias. In Lunar Science V, Lunar Science Institute, Houston, 419-421.

Krähenbühl U., Ganapathy R., Morgan J.W., and Anders E. (1973a) Volatile elements in Apollo 16 samples: Implications for highland volcanism and accretion history of the Moon. Geochim. Cosmochim. Acta, Suppl. 4, 1325-1348.

Krähenbühl U., Morgan J.W., Ganapathy R., and Anders E. (1973b) Abundance of 17 trace elements in carbonaceous chondrites. Geochim. Cosmochim. Acta 37, 1353-1370.

Larimer J.W. (1967) Chemical fractionations in meteorites - I. Condensation of the elements. Geochim. Cosmochim. Acta 31, 1215-1238.

Larimer J.W. (1973) Chemical fractionations in meteorites - VII. Cosmothermometry and cosmobarometry. Geochim. Cosmochim. Acta 37, 1603-1623.

Larimer J.W. and Anders E. (1967) Chemical fractionations in meteorites - II. Abundance patterns and their interpretation. Geochim. Cosmochim. Acta 31, 1239-1270.

Larimer J.W. and Anders E. (1970) Chemical fractionations in meteorites - III. Major element fractionations in chondrites. Geochim. Cosmochim. Acta 34, 367-388.

Laul J.C., Morgan J.W., Ganapathy R., and Anders E. (1971) Meteoritic material in lunar samples: Characterization from trace elements. Geochim. Cosmochim. Acta, Suppl. 2, 1139-1158.

Laul J.C., Ganapathy R., Morgan J.W., and Anders E. (1972) Meteoritic and non-meteoritic trace elements in Luna 16 samples. Earth Planet. Sci. Lett. 13, 450-454.

Laul J.C., Ganapathy R., Anders E., and Morgan J.W. (1973) Chemical fractionations in meteorites - VI. Accretion temperatures of H-, LL-, and E-chondrites, from abundances of volatile trace elements. Geochim. Cosmochim. Acta 37, 329-357.

Mason B. (editor) (1971) Elemental Abundances in Meteorites. Gordon and Breach, New York.

McGetchin T.R., Settle M., and Head J.W. (1973) Radial thickness variation in impact crater ejecta: Implications for lunar basin deposits. Earth Planet. Sci. Lett. 20, 226-236.

Millman P.M. (1972) Cometary meteoroids. In Nobel Symposium 21: From Plasma to Planet, ed., A. Elvius. Almqvist and Wiksell, Stockholm, 157-168.

Morgan J.W., Krähenbühl U., Ganapathy R., and Anders E. (1972a) Trace elements in Apollo 15 samples: Implications for meteorite influx and volatile depletion on the Moon. Geochim. Cosmochim. Acta, Suppl. 3, 1361-1376,

Morgan J.W., Laul J.C., Krähenbühl U., Ganapathy R., and Anders E. (1972b) Major impacts on the Moon: Characterization from trace elements in Apollo 12 and 14 samples. Geochim. Cosmochim. Acta, Suppl. 3, 1377-1395.

Morgan J.W., Ganapathy R., Laul J.C., and Anders E. (1973) Lunar crater Copernicus: Search for debris of impacting body at Apollo 12 site. Geochim. Cosmochim. Acta 37, 141-154.

Morgan J.W., Ganapathy R., Higuchi H., Krähenbühl U., and Anders E. (1974) Lunar basins: Tentative characterization of projectiles, from meteoritic elements in Apollo 17 boulders. Geochim. Cosmochim. Acta, Suppl. 5, in press.

Nininger H.H. (1956) Arizona's Meteorite Crater: Past, Present, Future. American Meteorite Museum, Sedona, Arizona, 232 pp.

Nunes P.D. and Tatsumoto M. (1973) Excess lead in "Rusty Rock" 66095 and implications for an early lunar differentiation. Science 182, 916-920.

Oberbeck V.R. and Quaide W.L. (1968) Genetic implications of lunar regolith thickness variations. Icarus 9, 446-465.

Oberbeck V.R., Hörz F., Morrison R.H., Quaide W.L., and Gault D.E. (1974) Effects of formation of large craters and basins on emplacement of smooth plains material. In Lunar Science V, Lunar Science Institute, Houston, 568-570.

O'Keefe J.A. (1970) The origin of the Moon. J. Geophys. Res. 75, 6565-6574.

O'Keefe J.A. (1972) The origin of the Moon: Theories involving joint formation with the Earth. Astrophys. Space Sci. 16, 201-211.

Öpik E.J. (1956) Interplanetary dust and terrestrial accretion of meteoric matter. Irish Astron. J. 4, 84-135.

Öpik E.J. (1958) Meteorite impact on solid surface. Irish Astron. J. 5, 14-33.

Öpik E.J. (1961) Notes on the theory of impact craters. In Proc. Geophys. Lab.-Lawrence Radiation Lab. Cratering Symp., Vol. 2, Paper S. UCRL Report 6438, 1-28.

Öpik E.J. (1969) The Moon's surface. Ann. Rev. Astron. Astrophys. 7, 473-526.

Öpik E.J. (1971) Cratering and the Moon's surface. Advan. Astron. Astrophys. 8, 107-337, ed. Z. Kopal. Academic Press, New York.

Öpik E.J. (1972) Comments on lunar origin. Irish Astron. J. 10, 190-238.

Podosek F.A., Huneke J.C., Gancarz A.J., and Wasserburg G.J. (1973) The age and petrography of two Luna 20 fragments and inferences for widespread lunar metamorphism. Geochim. Cosmochim. Acta 37, 887-904.

Provost A. and Bottinga Y. (1972) Rates of solidification of Apollo 11 basalt and Hawaiian tholeiite. Earth Planet. Sci. Lett. 15, 325-337.

Ringwood A.E. (1970) Origin of the Moon: The precipitation hypothesis. Earth Planet. Sci. Lett. 8, 131-140.

Ruskol E.L. (1962) The origin of the Moon. In The Moon, eds., Z, Kopal and Z. Mikhailov. Academic Press, New York, 149-155.

Ruskol E.L. (1971) On the origin of the Moon - III. Some aspects of the dynamics of the circumterrestrial swarm. Astron. J. 48, 819-829.

Ruskol E.L. (1972) On the initial distance of the Moon forming in the circumterrestrial swarm. In The Moon, eds., S.K. Runcorn and H.C. Urey. D. Reidel, Dordrecht, 402-404.

Schaeffer O.A. and Husain L. (1974) Chronology of lunar basin formation and ages of lunar anorthositic rocks. In Lunar Science V., Lunar Science Institute, Houston, 663-665.

Schmitt H.H. (1973) Apollo 17 report on the valley of Taurus-Littrow. Science 182, 681-690.

Scott D.H. (1974) The geologic significance of some lunar gravity anomalies. In Lunar Science V, 693-694, LSI.

Scott E. (1972) Chemical fractionation in iron meteorites and its interpretation. Geochim. Cosmochim. Acta 36, 1205-1236.

Short N.M. and Forman M.L. (1972) Thickness of impact crater ejecta on the lunar surface. Mod. Geol. 3, 69-91.

Smith J.V. (1974) Origin of Moon by disintegrative capture with chemical differentiation followed by sequential accretion. In Lunar Science V, Lunar Science Institute, Houston, 718-720.

Stöffler D., Dence M.R., Abadian M., and Graup G. (1974) Ejecta formations and pre-impact stratigraphy of lunar and terrestrial craters: Possible implications for the ancient lunar crust. In Lunar Science V, Lunar Science Institute, Houston, 746-748.

Stuart-Alexander D.E. and Howard K.A. (1970) Lunar maria and circular basins - A review. Icarus 12, 440-456.

Taylor L.A., Mao H.K., and Bell P.M. (1973) "Rust" in the Apollo 16 rocks. Geochim. Cosmochim. Acta, Suppl. 4, 829-839.

Tera F., Papanastassiou D.A., and Wasserburg G.J. (1973) A lunar cataclysm at ~3.95 AE and the structure of the lunar crust. In Lunar Science IV, Lunar Science Institute, Houston, 723-725.

Tera F., Papanastassiou D.A., and Wasserburg G.J. (1974) The lunar time scale and a summary of isotopic evidence for a terminal lunar cataclysm. In Lunar Science V, Lunar Science Institute, Houston, 792-794.

Urey H.C. (1960) The duration of intense bombardment processes of the Moon. Astrophys.J. 132, 502-503.

Urey H.C. (1968) Mascons and the history of the Moon. Science 162, 1408-1410.

Urey H.C. and MacDonald G.J.F. (1971) Origin and history of the Moon. In Physics and Astronomy of the Moon, ed. Z. Kopal. Academic Press, New York, 213-289.

Vinogradov A.P. (1971) Preliminary data on lunar ground brought to Earth by automatic probe "Luna 16". Geochim. Cosmochim. Acta, Suppl. 2, 1-16.

Vinogradov A.P. (1973) Preliminary data on lunar soil collected by the Luna 20 unmanned spacecraft. Geokhimiya, 763-774, 1972. English translation in Geochim. Cosmochim. Acta 37, 721-729.

Wasson J.T. and Schaudy R. (1971) The chemical classification of iron meteorites - V. Groups IIIC and IIID and other irons with germanium concentrations between 1 and 25 ppm. Icarus 14, 59-70.

Wasson J.T. and Baedecker P.A. (1972) Provenance of Apollo 12 KREEP. Geochim. Cosmochim. Acta, Suppl. 3, 1315-1326.

Wetherill G.W. (1968) Dynamical studies of asteroidal and cometary orbits and their relation to the origin of meteorites. In Origin and Distribution of the Elements, ed., L.H. Ahrens. Pergamon Press, Oxford, 423-443.

Whipple F.L. (1967a) The meteoritic environment of the Moon. Proc. Roy. Soc. 296, 304-315.

Whipple F.L. (1967b) On maintaining the meteoritic complex. In The Zodiacal Light and the Interplanetary Medium, NASA SP-150, 409-426.

Whipple F.L. (1968) Origins of meteoritic material. In Physics and Dynamics of Meteors, eds., L. Kresák and P.M. Millman. D. Reidel, Dordrecht, 481-485.

Wiesel W. (1971) The meteorite flux at the lunar surface. Icarus 15, 373-383.

Wilhelms D.E. and McCauley J.F. (1971) Geologic map of the near side of the Moon. In Geologic Atlas of the Moon, #I-703. U.S.Geological Survey, Washington, D.C.

Wise D.U. (1963) An origin of the Moon by rotational fission during formation of the Earth's core. J. Geophys. Res. 68, 1547-1554.

Wlotzka F., Jagoutz E., Spettel B., Baddenhausen H., Balacescu A., and Wänke H. (1972) On lunar metallic particles and their contribution to the trace element content of Apollo 14 and 15 soils. Geochim. Cosmochim. Acta, Suppl. 3, 1077-1084.

Wlotzka F., Spettel B., and Wänke H. (1973) On the composition of metal from Apollo 16 fines and the meteoritic component. Geochim. Cosmochim. Acta, Suppl. 4, 1483-1491.

Wood J.A. and Mitler H.E. (1974) Origin of the Moon by a modified capture mechanism, or half a loaf is better than a whole one. In Lunar Science V, Lunar Science Institute, Houston, 851-853.

Table 1. Meteoritic Components in Mare Soils

(percent Cl material or equivalent)

		Siderophiles				Volatiles									
		Ir	Re	Au	Ni	Sb	Ge	Br	Bi	Mean Sid.	Mean Volat.	Best Estimate Cl-comp.	Regolith 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?
Cl Chondrites (abundance in ppb)		514	35.2	152	10300	138	31200	4810	110						

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.*, 1972a, for references.

Cl chondrites: From Krähenbühl *et al.* (1973) except Br (Goles *et al.*, 1967).

Table 2. Ejecta Depth in Meters[*]

Contributing Basin	Crater Density[†]	Apollo 11	Apollo 12	Apollo 14	Apollo 15	Apollo 16	Apollo 17	Luna 16	Luna 20
Orientale	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

[*] Calculated according to McGetchin *et al*. (1973).

[†] 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 (Hartmann and Wood, 1971).

Table 3. Tentative Basin Assignments

Group	Ir/Au	Ge	Mare Basin*	
			HW	SH
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

*HW = Basin age sequence of Hartmann and Wood (1971)

SH = Basin age sequence of Stuart-Alexander and Howard (1970)

Table 4. Target/Projectile Mass Ratio

M/μ based on*	M/μ Value†					
	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 ‡	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

*For a "lunar" iron content of the projectile, i.e. 9 weight percent. For a "terrestrial" iron content of 36%, the M/μ values will be 4 times larger.

†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% highland samples with lower siderophile element contents.

‡See Morgan et al. (1974) for references.

FIGURE CAPTIONS

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. (From Anders et al., 1973).

Abundance pattern is flat, with siderophiles and volatiles almost equally abundant. Apparently the meteoritic component has a primitive composition (cf. Fig. 2). Data mainly from this laboratory. (See Morgan et al., 1972a, for references.)

Figure 2. Primitive meteorites (left) contain siderophiles and volatiles in comparable abundance. Fractionated meteorites (right) are depleted in volatiles. From Anders et al. (1973). Data mainly from Mason (1971).

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. (From Anders et al., 1973).

Figure 4. Highland breccias (solid symbols) are strongly enriched in the first 5, 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.

Figure 6. Six distinct types of ancient meteoritic component seem to be present, differing in their proportions of Ir, Au, and Ge. 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.

Figures 8,9. Ancient lunar meteoritic components show little resemblance to known chondrite classes.

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

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

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

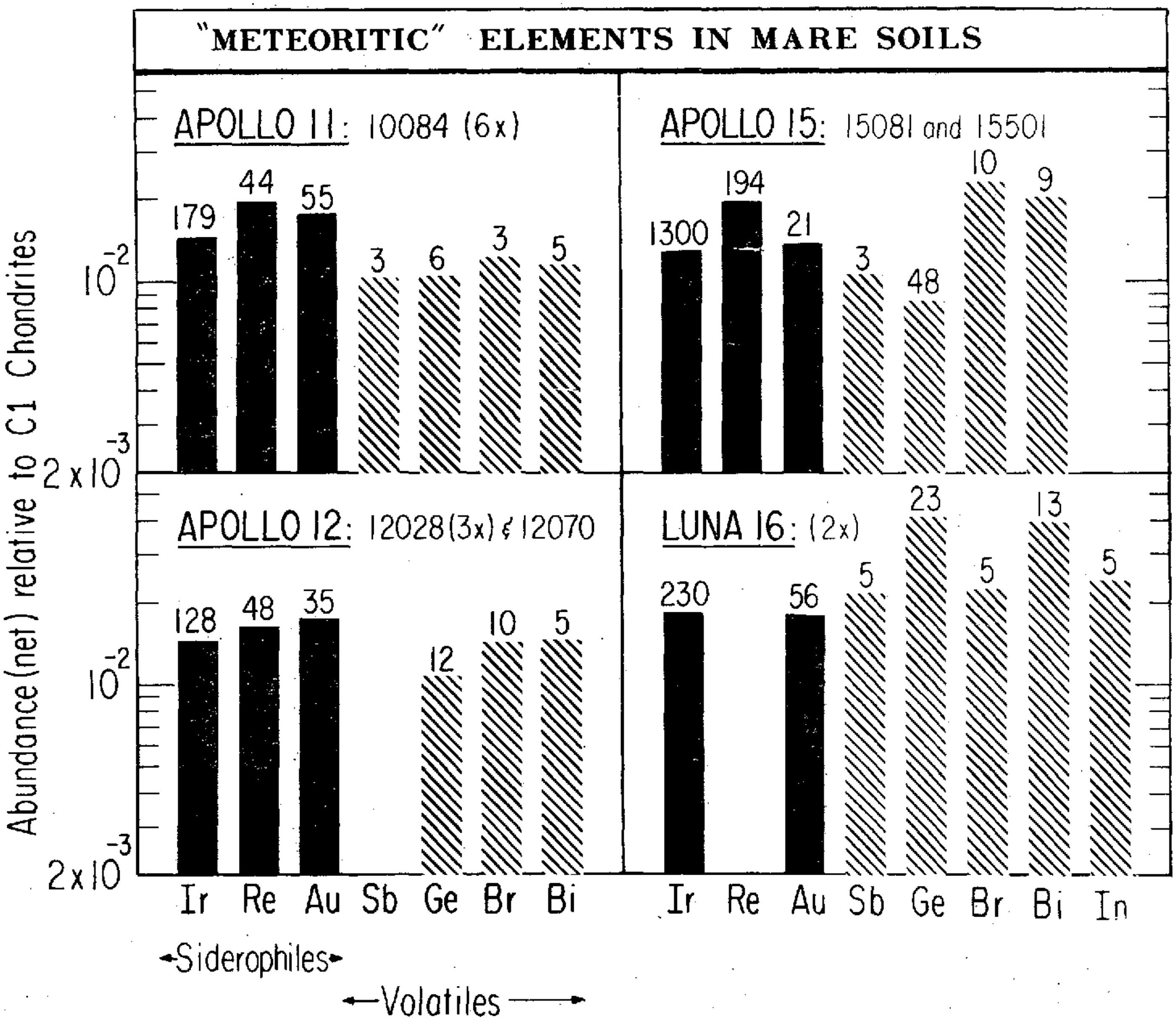
Figure 13. Nominal impact velocity of basin-forming objects, estimated from cratering relations of Gault and Öpik. The two sets of points represent extreme values of iron content of the projectiles. Except for #6, these bodies seem to have had impact velocities well below the mean geocentric velocity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

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

Figure 15. Abundance patterns of 6 ancient meteoritic groups, corrected for indigenous contribution.

Figure 16. Abundance patterns of bulk Earth and Moon, according to model of Ganapathy and Anders (1974). Compare with Fig. 15. Groups 1 and 2 are complementary to Earth and Moon, being poorer in refractories (Ir, Re) and richer in volatiles (Ge, Sb, etc.).

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^{+80}_{-40} basin-forming objects) and the population surviving after the Imbrium impact 3.9 AE ago (Orientale, $\sim 5 \times 10^{-5}$ $M_{☽}$). 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 7 basins formed in this interval lie on the farside or east limb.



"METEORITIC" ELEMENTS IN MARE SOILS
APOLLO 11: 10084 (6x)
179
44
55
3
6
3
5
APOLLO 15: 15081 and 15501
1300
194
21
3
48
10
9
APOLLO 12: 12028(3x) & 12070
128
48
35
12
10
5
LUNA 16: (2x)
230
56
5
23
5
13
5
Abundance (net) relative to C1 Chondrites
10^{-2}
2×10^{-3}
Ir Re Au Sb Ge Br Bi
Ir Re Au Sb Ge Br Bi In
Siderophiles
Volatiles

Fig. 1

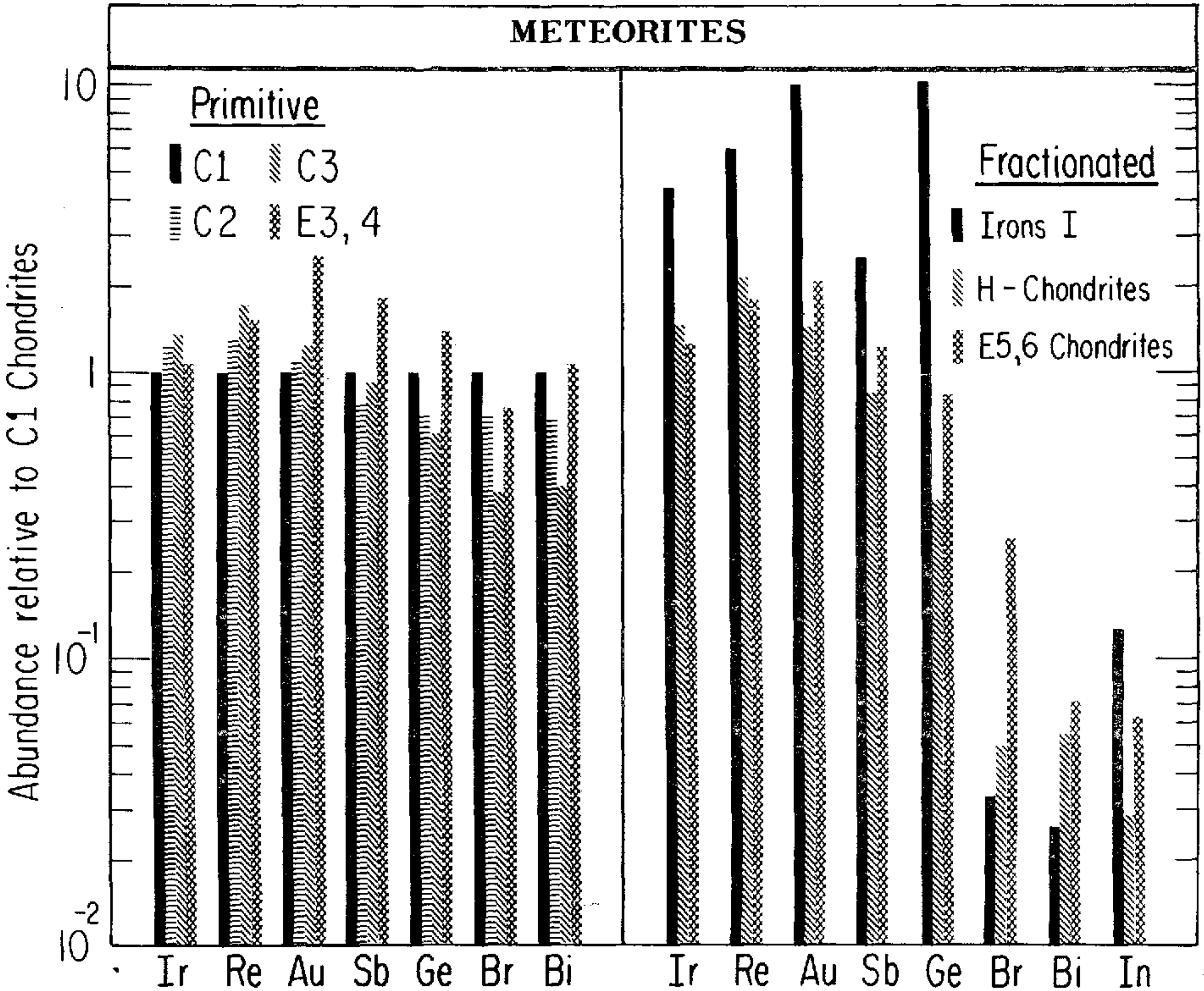

METEORITES
Primitive
C1
C3
C2
E3, 4
Fractionated
Irons I
H - Chondrites
E5,6 Chondrites
Abundance relative to C1 Chondrites
10
1
10^{-1}
10^{-2}
Ir
Re
Au
Sb
Ge
Br
Bi
Ir
Re
Au
Sb
Ge
Br
Bi
In

Fig.2

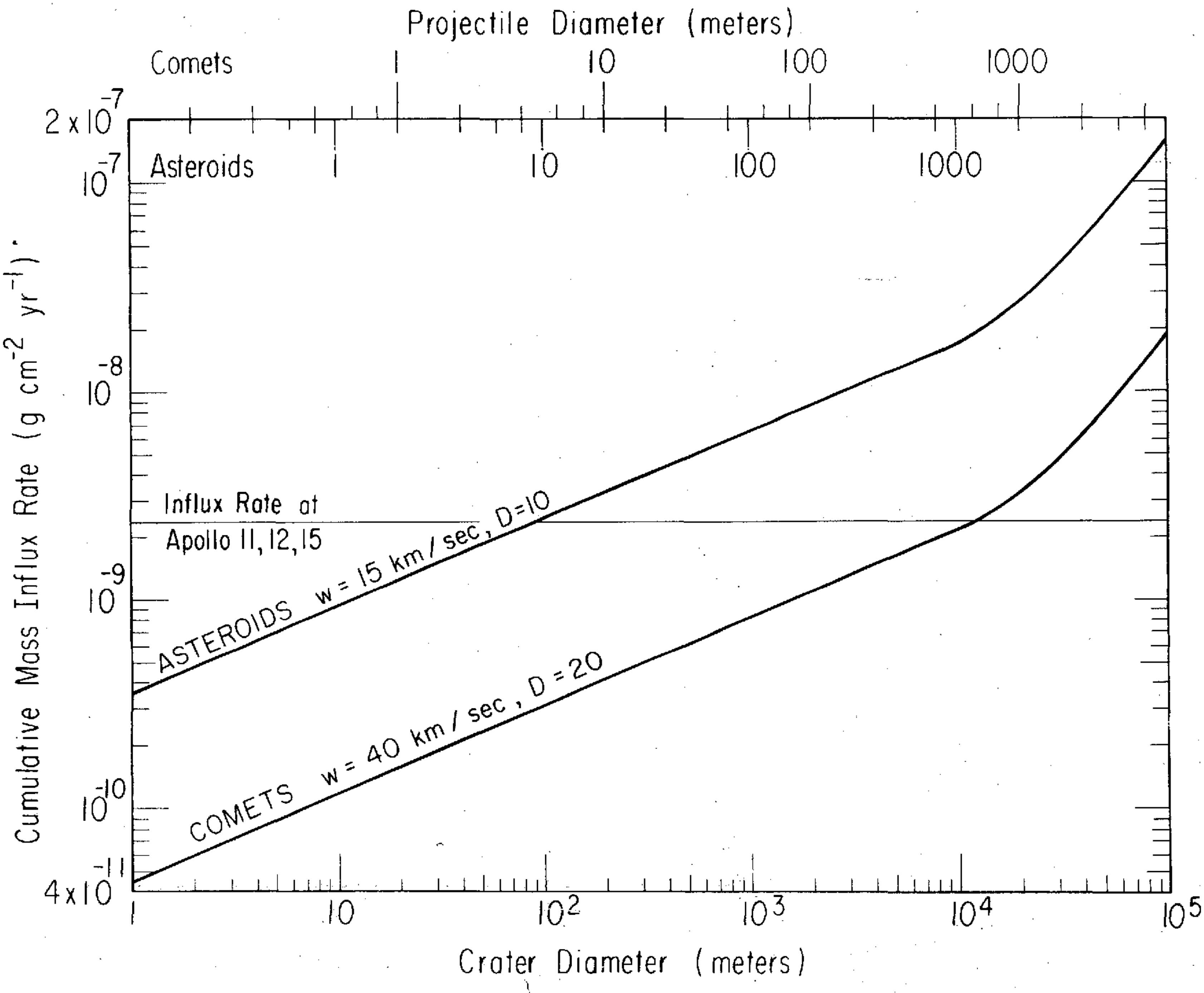
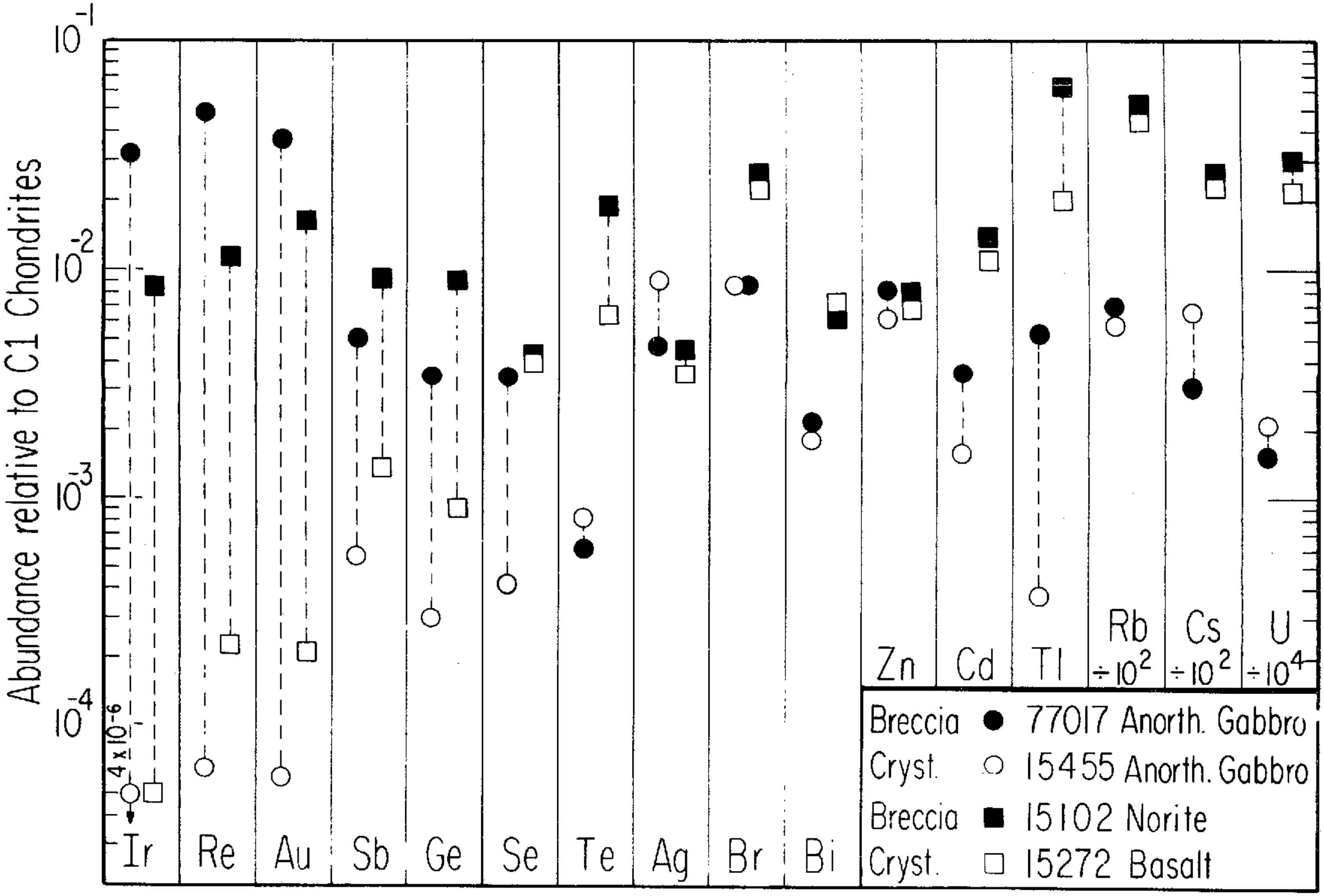

Projectile Diameter (meters)
Comets
1
10
100
1000
2 x 10^-7
10^-7
Asteroids
1
10
100
1000
10^-8
10^-9
10^-10
4 x 10^-11
Cumulative Mass Influx Rate (g cm^-2 yr^-1)
Influx Rate at
Apollo 11, 12, 15
ASTEROIDS w = 15 km / sec, D=10
COMETS w = 40 km / sec, D = 20
1
10
10^2
10^3
10^4
10^5
Crater Diameter (meters)

Fig.3



Abundance relative to C1 Chondrites
10^{-1}
10^{-2}
10^{-3}
10^{-4}
4×10^{-6}
Ir
Re
Au
Sb
Ge
Se
Te
Ag
Br
Bi
Zn
Cd
Tl
Rb ÷10²
Cs ÷10²
U ÷10⁴
Breccia ● 77017 Anorth. Gabbro
Cryst. ○ 15455 Anorth. Gabbro
Breccia ■ 15102 Norite
Cryst. □ 15272 Basalt

Fig.4

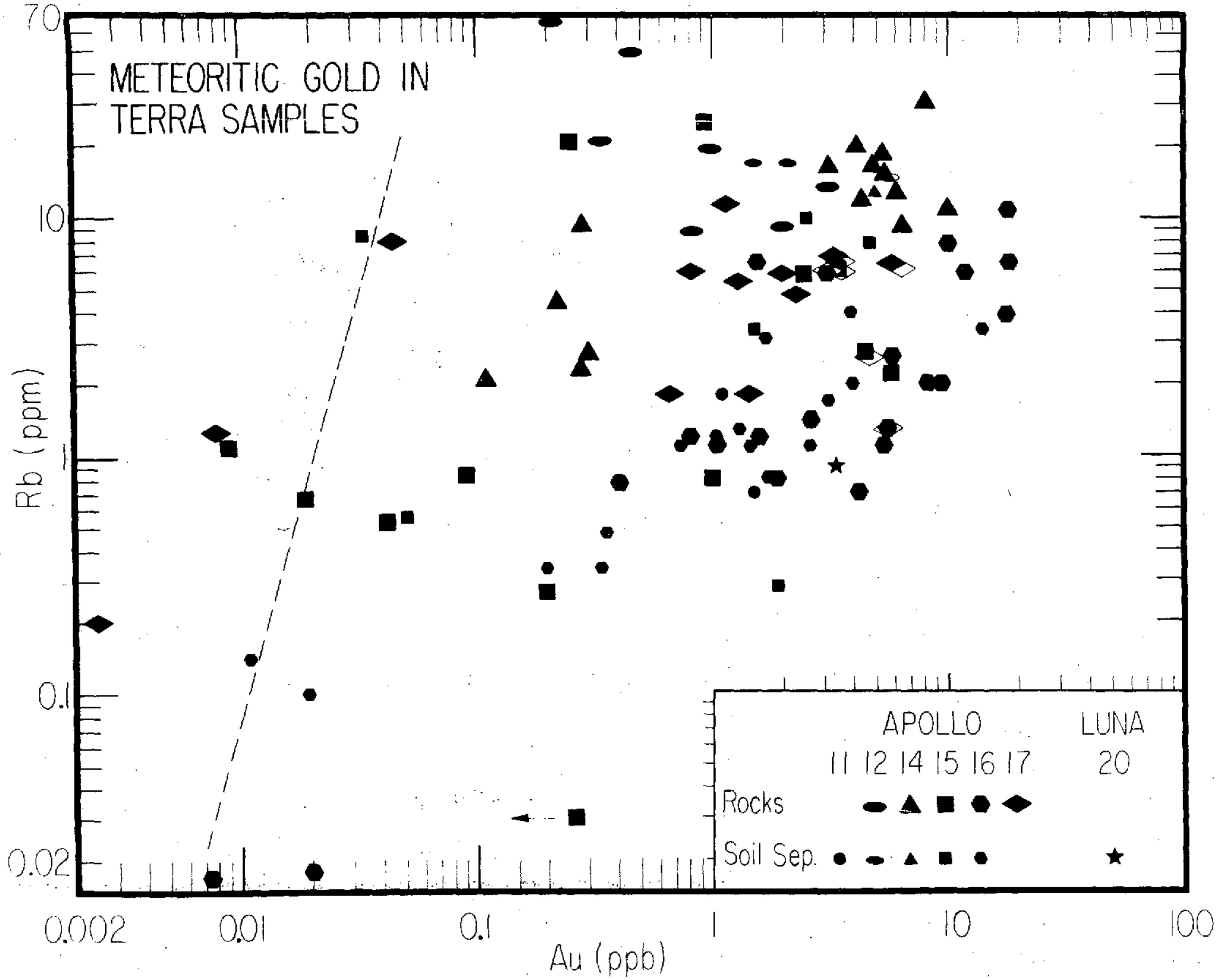

METEORITIC GOLD IN
TERRA SAMPLES
70
10
1
0.1
0.02
Rb (ppm)
0.002
0.01
0.1
1
10
100
Au (ppb)
APOLLO
LUNA
11 12 14 15 16 17
20
Rocks
Soil Sep.

Fig. 25

METEORITIC METAL IN LUNAR HIGHLAND ROCKS

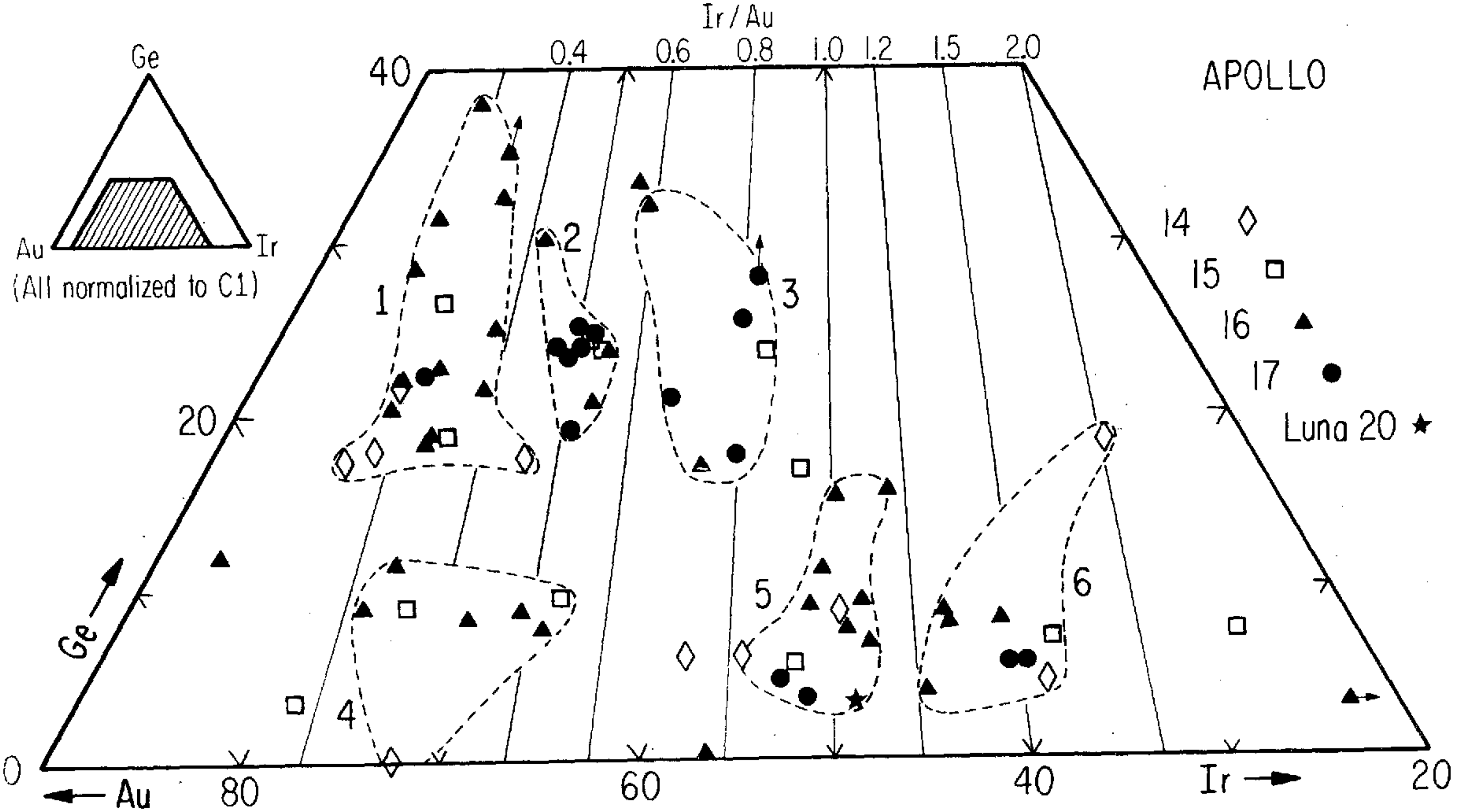


Fig. 36

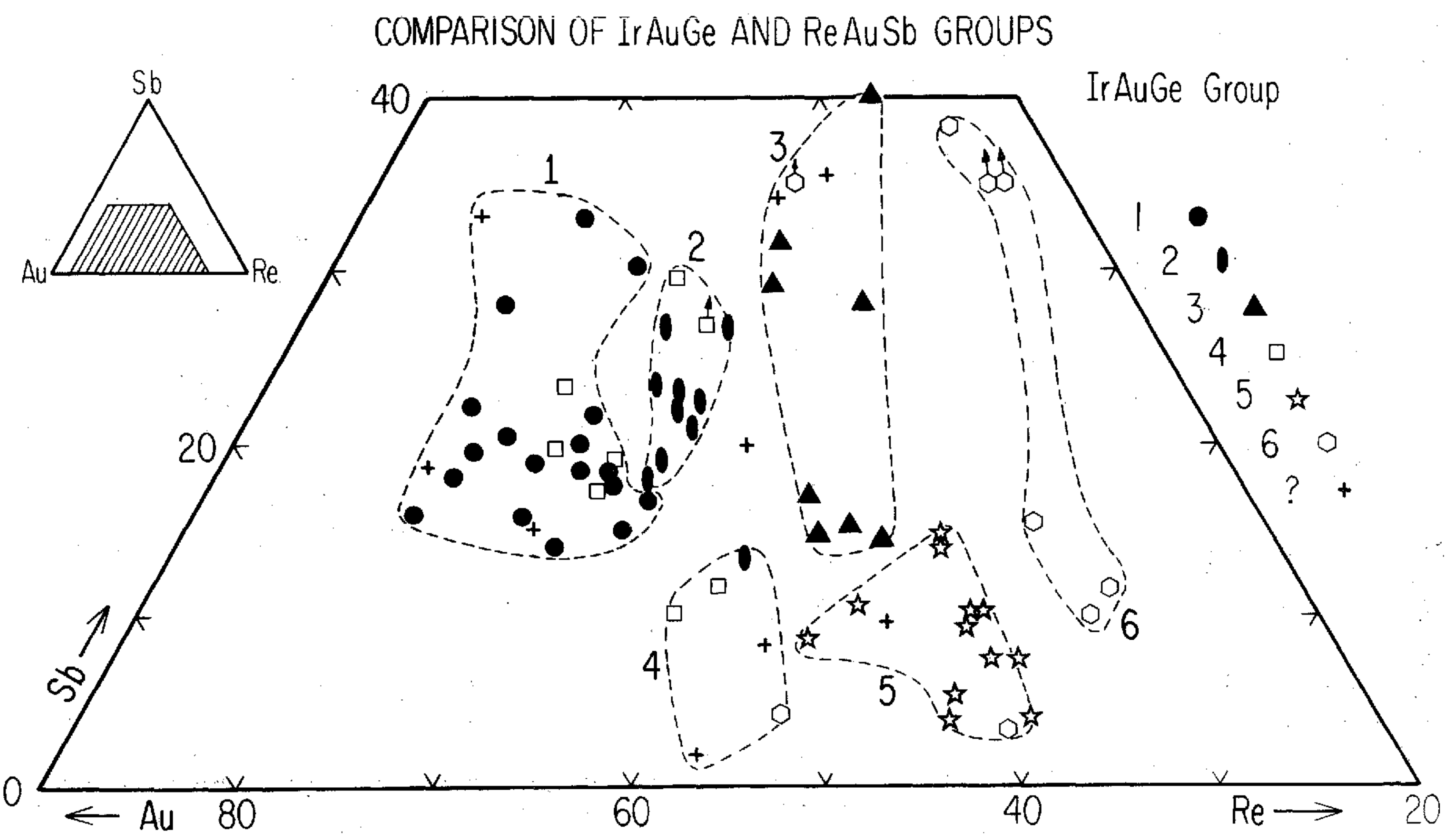

COMPARISON OF IrAuGe AND ReAuSb GROUPS
Sb
Au
Re
40
20
0
Sb
Au
80
60
40
Re
20
1
2
3
4
5
6
IrAuGe Group
1
2
3
4
5
6
?

Fig. 47

Lunar Meteoritic Groups vs. Chondrites

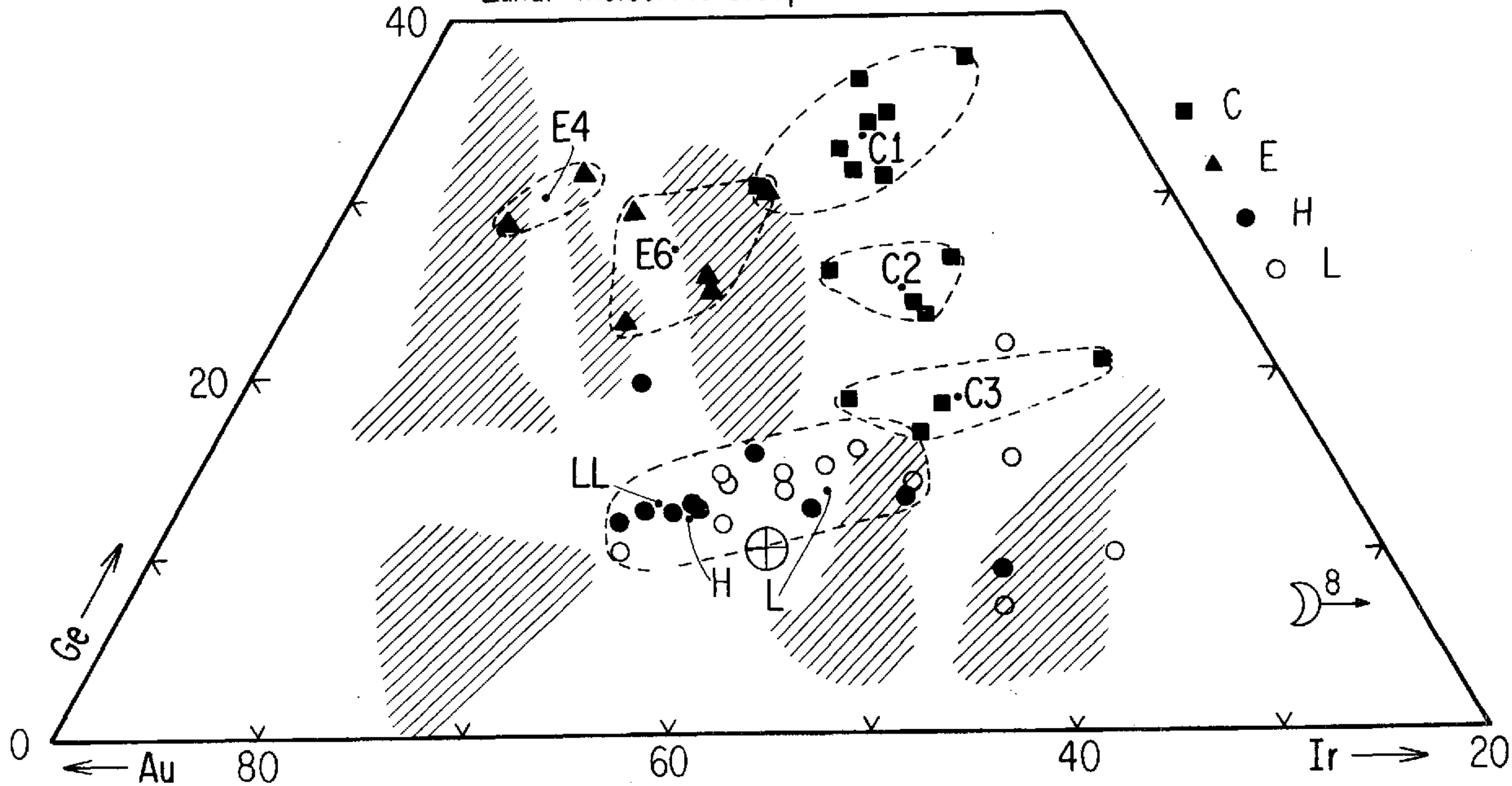


Fig. 58

Lunar Meteoritic Groups vs. Chondrites

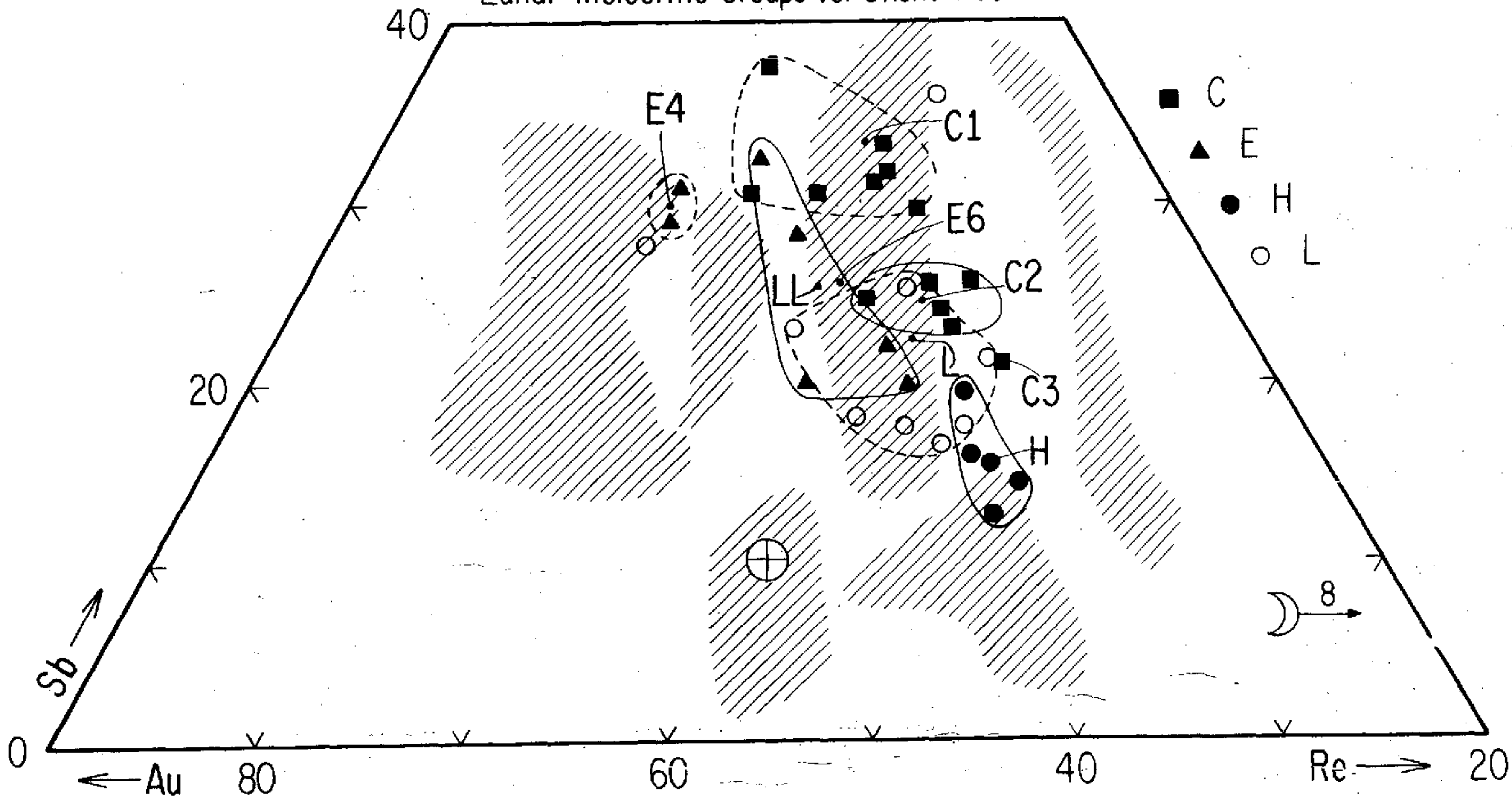


Fig.~~8~~ 9

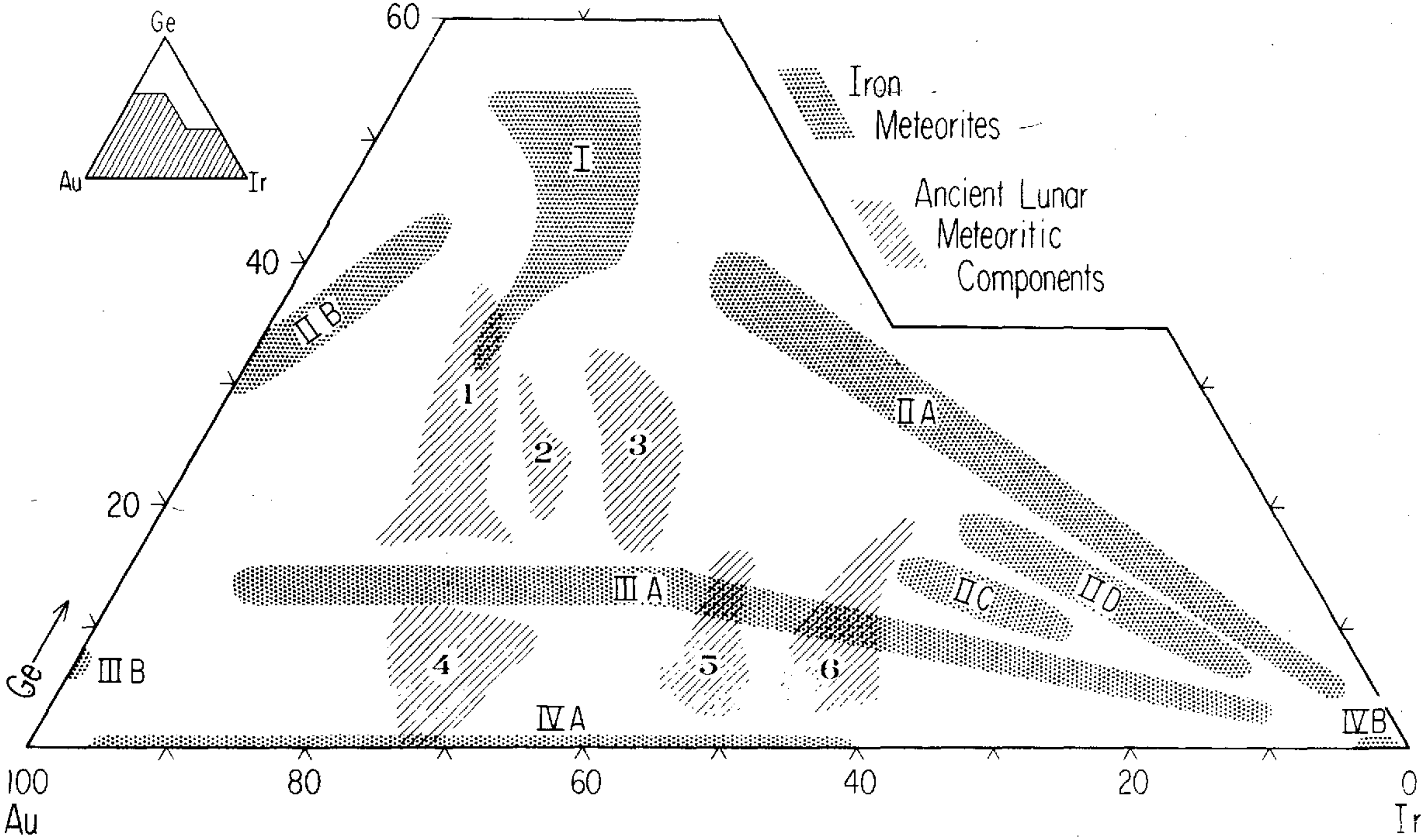

Ge
Au
Ir
60
40
20
Iron Meteorites
Ancient Lunar Meteoritic Components
I
II B
II A
II C
II D
III A
III B
IV A
IV B
1
2
3
4
5
6
Ge
100
80
60
40
20
0
Au
Ir

Fig.10

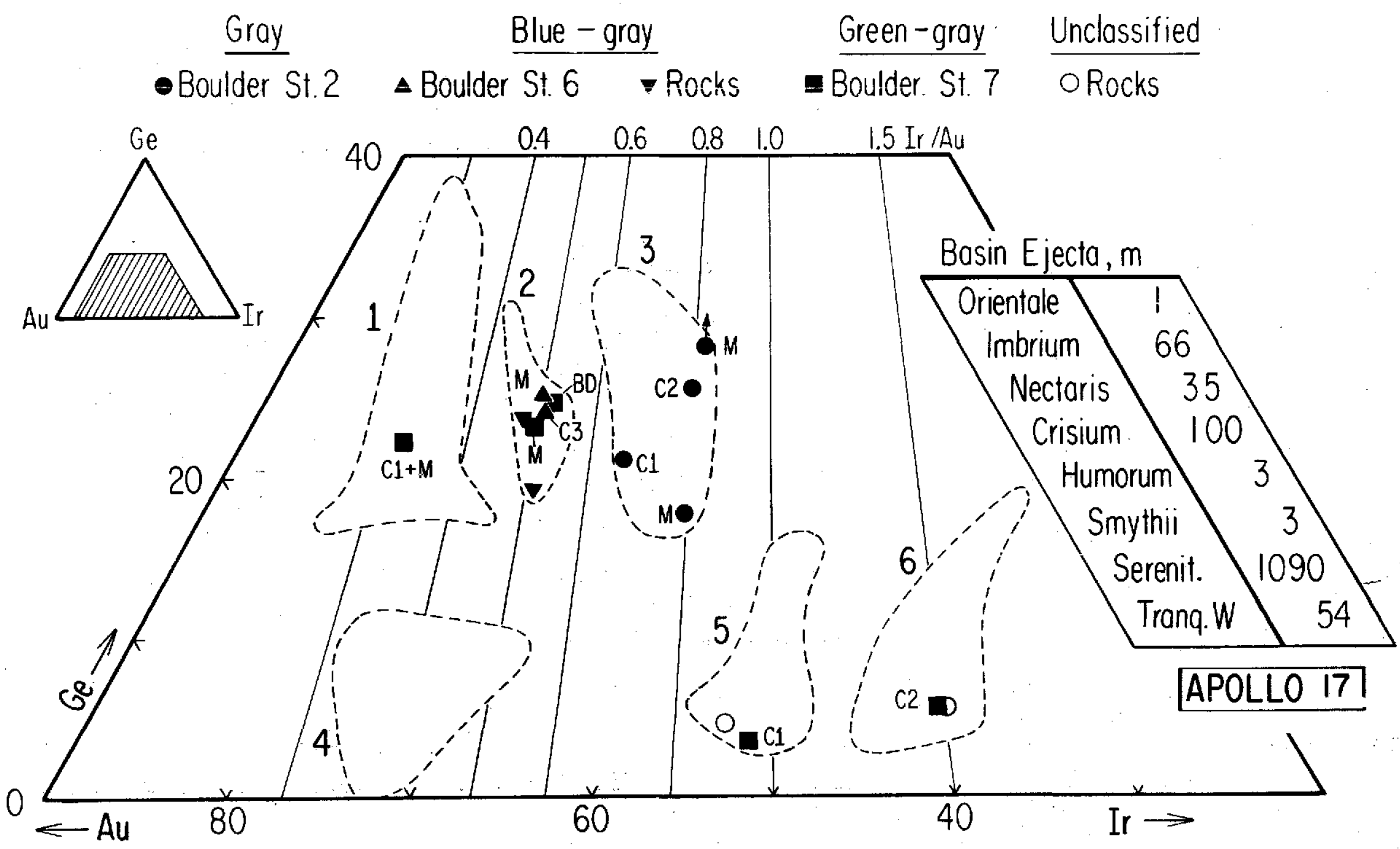
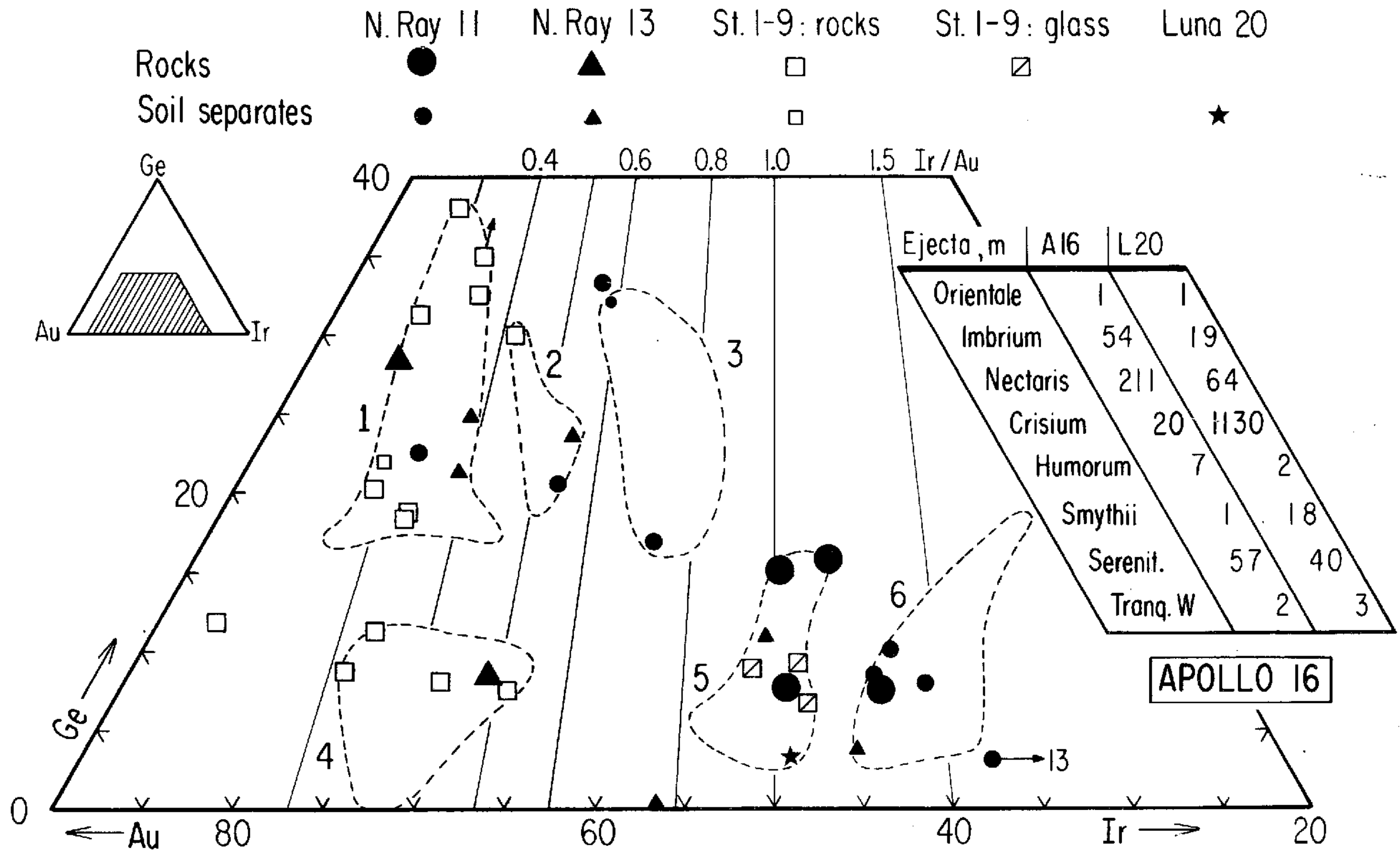
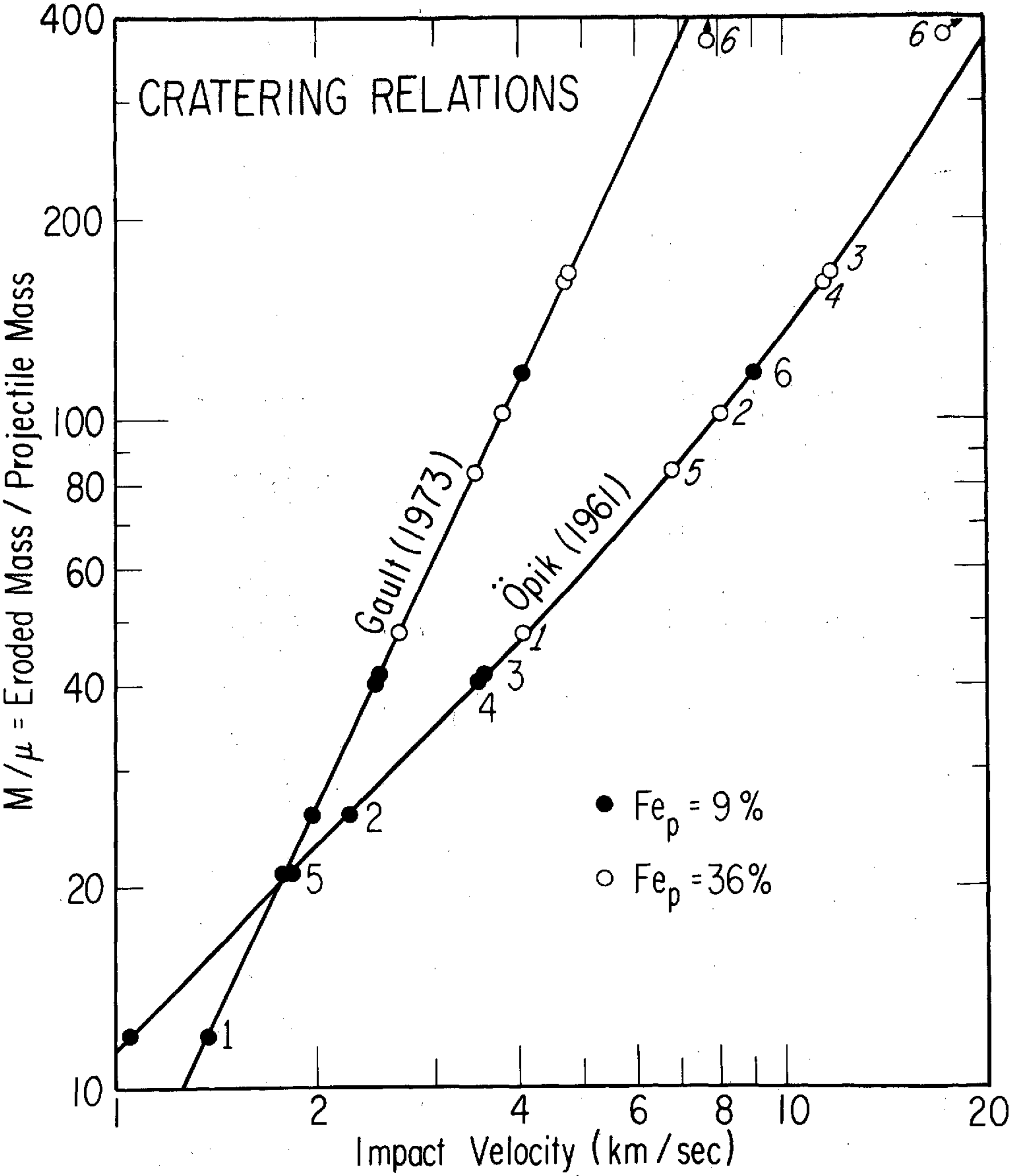

Gray
Blue - gray
Green - gray
Unclassified
● Boulder St. 2
▲ Boulder St. 6
▼ Rocks
■ Boulder St. 7
○ Rocks
Ge
Au
Ir
0.4
0.6
0.8
1.0
1.5 Ir /Au
40
20
0
1
2
3
4
5
6
C1+M
M
BD
C3
M
M
C2
C1
M
C1
C2
Basin Ejecta, m
Orientale 1
Imbrium 66
Nectaris 35
Crisium 100
Humorum 3
Smythii 3
Serenit. 1090
Tranq. W 54
APOLLO 17
Ge
Au
80
60
40
Ir

Fig. 11



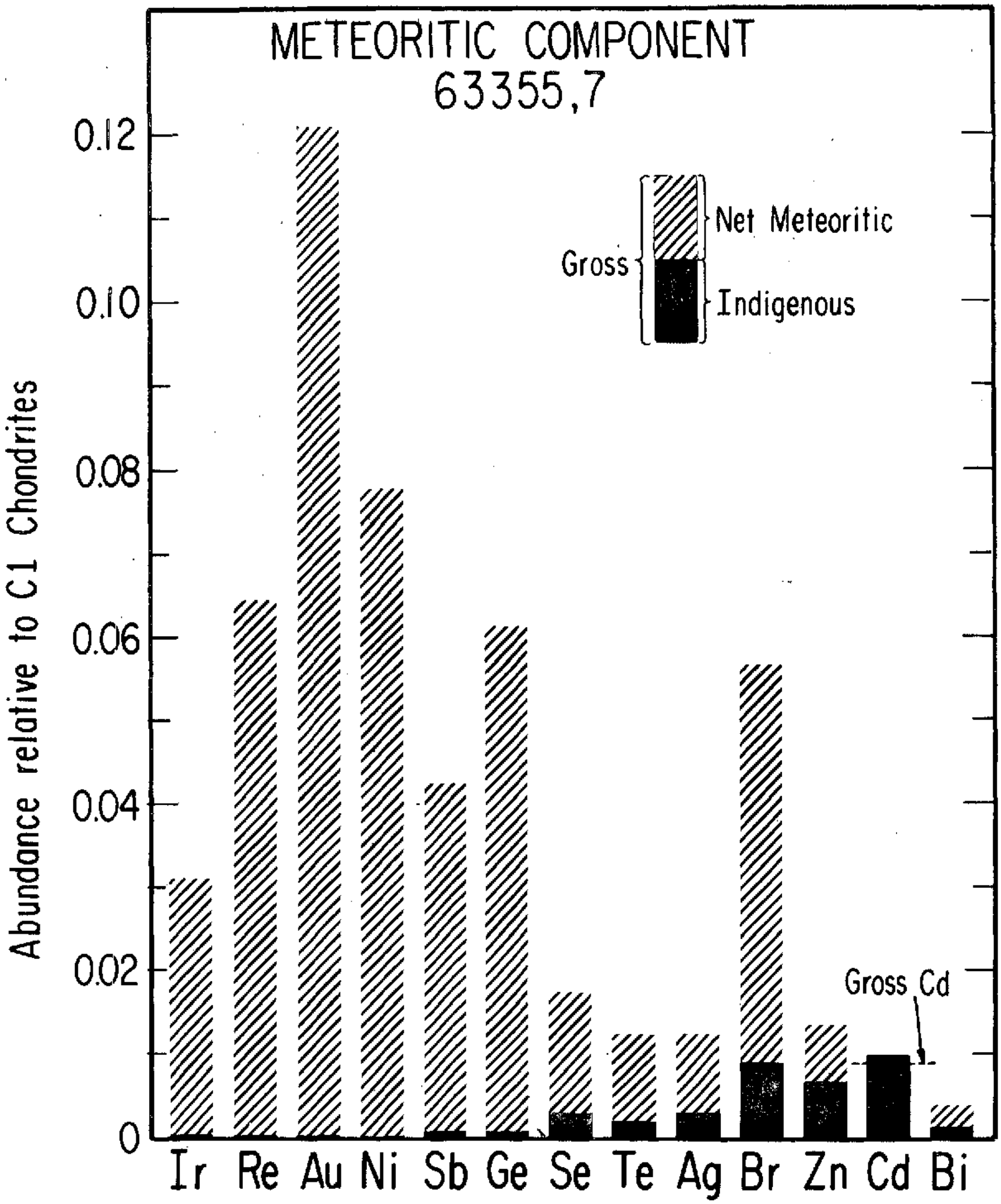
N. Ray 11
N. Ray 13
St. 1-9: rocks
St. 1-9: glass
Luna 20
Rocks
Soil separates
Ge
Au
Ir
40
0.4
0.6
0.8
1.0
1.5
Ir/Au
Ejecta, m
A16
L20
Orientale 1 1
Imbrium 54 19
Nectaris 211 64
Crisium 20 1130
Humorum 7 2
Smythii 1 18
Serenit. 57 40
Tranq. W 2 3
1
2
3
4
5
6
20
0
Au
80
60
40
Ir
20
13
APOLLO 16

Fig. 12



CRATERING RELATIONS
M / μ = Eroded Mass / Projectile Mass
Impact Velocity (km / sec)
Gault (1973)
Öpik (1961)
Fe_p = 9 %
Fe_p = 36 %
400
200
100
80
60
40
20
10
1
2
4
6
8
10
20

Fig. 13



METEORITIC COMPONENT
63355,7
Net Meteoritic
Gross
Indigenous
Gross Cd
Abundance relative to C1 Chondrites
0.12
0.10
0.08
0.06
0.04
0.02
0
Ir
Re
Au
Ni
Sb
Ge
Se
Te
Ag
Br
Zn
Cd
Bi

Fig. 14

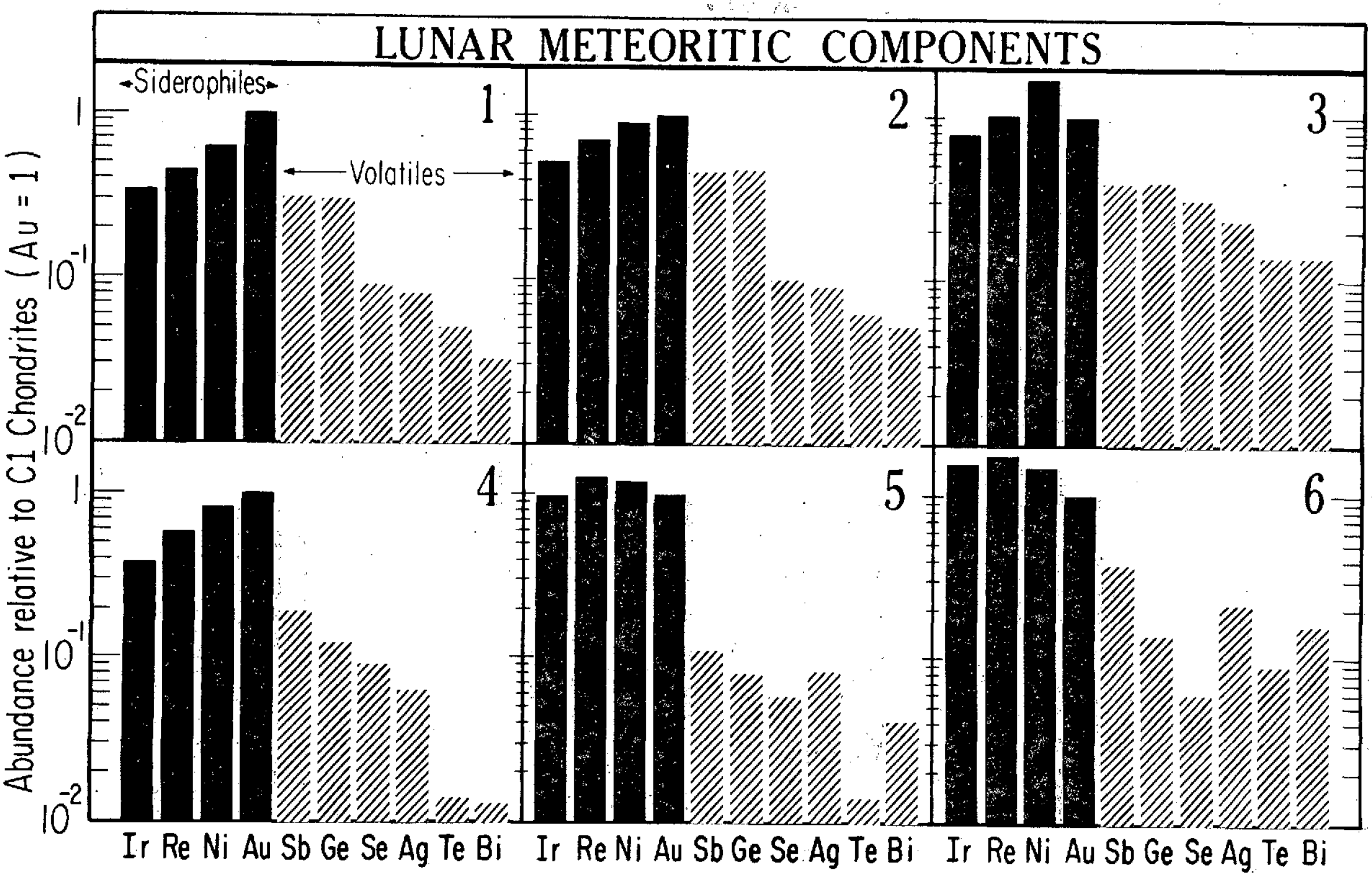

LUNAR METEORITIC COMPONENTS
Siderophiles
Volatiles
Abundance relative to C1 Chondrites (Au = 1)
1
2
3
4
5
6
Ir Re Ni Au Sb Ge Se Ag Te Bi

Fig.15

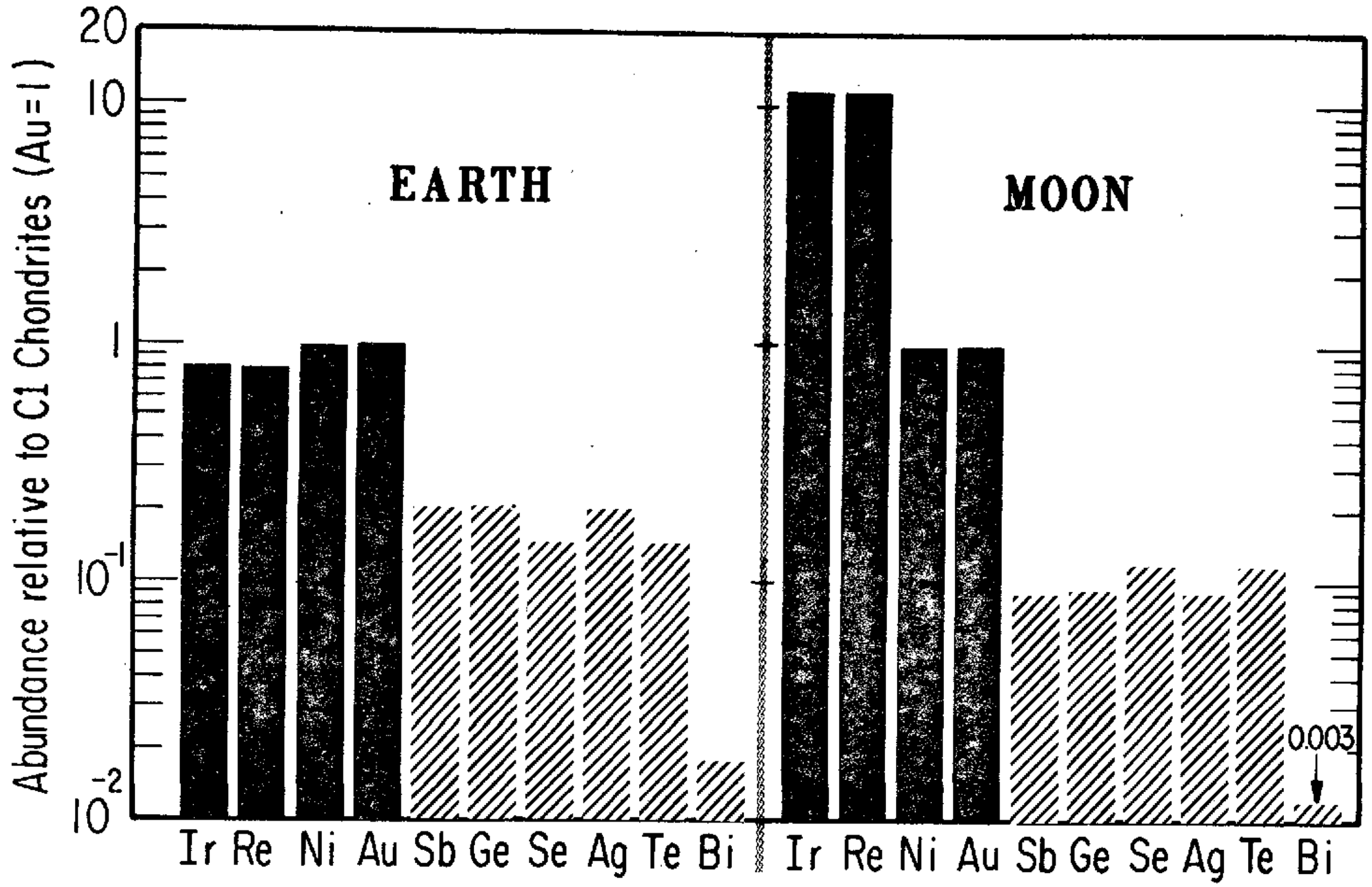
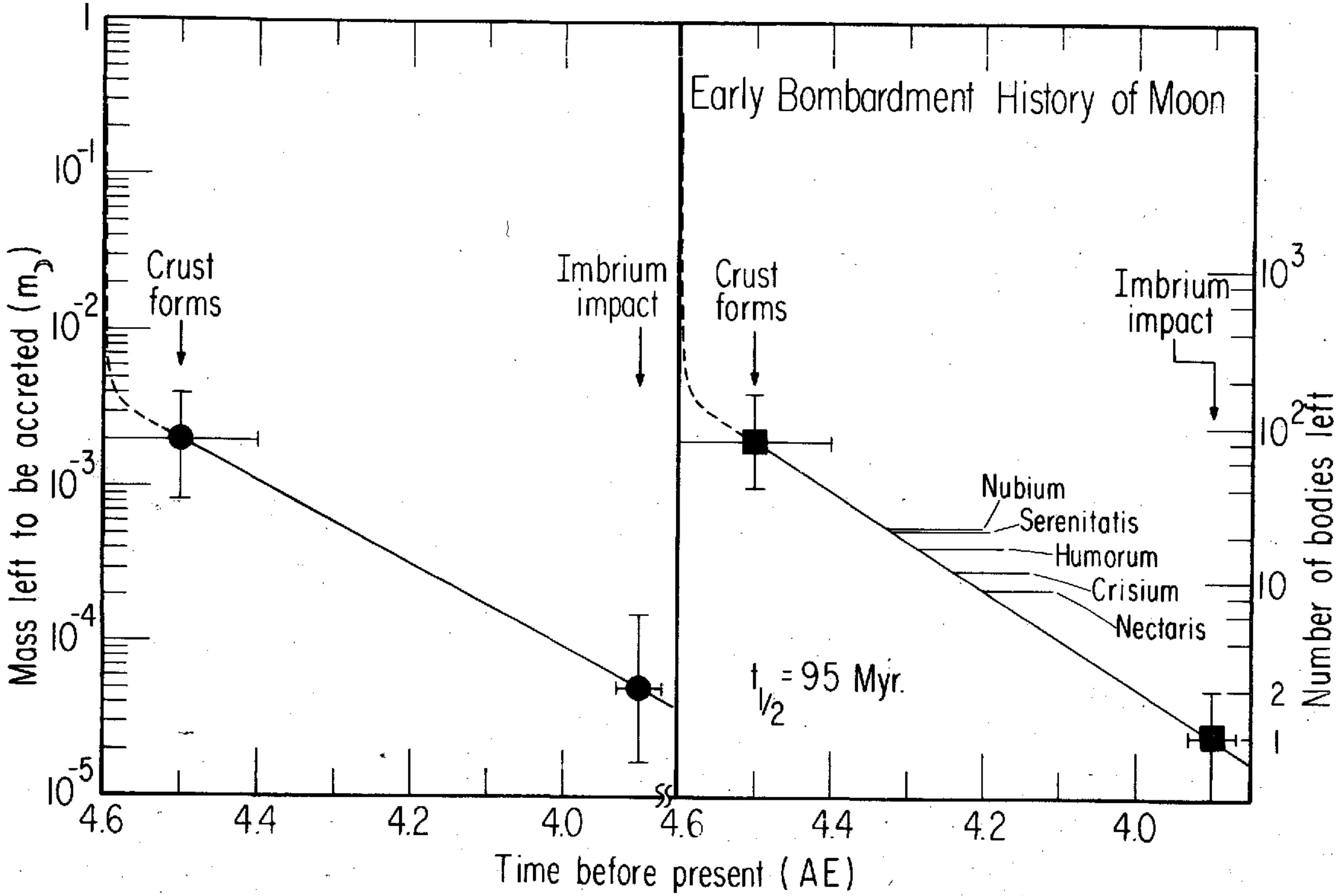

Abundance relative to C1 Chondrites (Au=1)
20
10
1
10^{-1}
10^{-2}
EARTH
MOON
0.003
Ir Re Ni Au Sb Ge Se Ag Te Bi
Ir Re Ni Au Sb Ge Se Ag Te Bi

Fig.16



Early Bombardment History of Moon
Mass left to be accreted ($m_☽$)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Crust forms
Imbrium impact
Crust forms
Imbrium impact
Nubium
Serenitatis
Humorum
Crisium
Nectaris
$t_{1/2}$ = 95 Myr.
10^3
10^2
10
2
1
Number of bodies left
4.6
4.4
4.2
4.0
4.6
4.4
4.2
4.0
Time before present (AE)

Fig.17