In the course of the investigation of ^{18}O variations in dissolved oxygen in seawater (*9*), it became apparent that the dissolved oxygen was enriched in ^{18}O relative to atmospheric oxygen (*5*). This result was not unexpected, since Klots and Benson (*10*) had previously reported this effect in the solution of oxygen and nitrogen in distilled water. We report here measurements of the solubility fractionation in seawater (average salinity 34.6 per mil).

Seawater was collected in 1-liter reagent bottles, poisoned with $HgCl_2$, and stripped of its dissolved gases with CO_2. Air was then bubbled into the bottles of deoxygenated water in order to equilibrate the water with oxygen. The equilibrations were carried out at several temperatures, and the air was sampled periodically for isotopic analysis. The air samples all had $\delta^{18}O$ values within $\pm$ 0.05 per mil of the mean value for atmospheric oxygen. After equilibration, the dissolved oxygen was stripped from the solution into a vacuum line. The stripping gas (CO_2) was removed by a trap maintained at liquid-nitrogen temperature that was shown to trap only the condensable gases. The oxygen and nitrogen are then adsorbed onto a type 5A molecular sieve (*11*), and the oxygen is converted to CO_2 for isotopic analysis as described above.

Isotopic fractionation effects are reported in terms of the isotopic fractionation factor α, defined as $\alpha = R_{aq}/R_{gas}$, where the subscripts aq and gas refer to the aqueous phase and the gas phase, respectively. The single-stage enrichment in per mil, ε, is given by $(\alpha - 1) \times 1000$. The measured $\delta^{18}O$ values for the dissolved oxygen and the calculated enrichment factors relative to atmospheric oxygen are given in Table 2. Figure 1 shows the enrichment factors for solution in sea water and the earlier measurements by Klots and Benson (*10*) for distilled water. The linear least squares fit was calculated for the four points measured in this work, excluding the measurement at 18°C, and yielded for the temperature variation of the enrichment factor:

$$\varepsilon(\text{per mil}) = 0.85 - 0.010\, t\ (°C)$$

Klots and Benson's extrapolated value at 0°C is 0.80 ± 0.15 per mil, in excellent agreement with the regression value found here of 0.85 ± 0.05 per mil.

Within the above precision, there is no salinity dependence of the solubility of ^{18}O relative to ^{16}O (salting-out effect). Weiss (*12*) has similarly detected no salinity effect on the solubility of ^3He relative to ^4He. In both cases, the heavier isotope ^{18}O or ^4He is the more soluble.

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References and Notes

1. M. Dole, G. A. Lane, D. P. Rudd, D. A. Zaukelies, *Geochim. Cosmochim. Acta* **6**, 65 (1954).
2. G. A. Lane, thesis, Northwestern University (1955).
3. The delta (δ) units are defined by: $\delta = [(R/R_{std}) - 1] \times 1000$, where R is the ratio $^{18}O : {}^{16}O$ in a sample, and R_{std} is the ratio in the standard.
4. The acronym SMOW stands for the defined standard mean ocean water isotopic standard [H. Craig, *Science* **133**, 1833 (1961)], which is very close to the true oceanic mean. Samples of SMOW are provided by the International Atomic Energy Agency, Vienna.
5. P. M. Kroopnick, thesis, University of California, San Diego (1971).
6. H. Craig, *Geochim. Cosmochim. Acta* **12**, 133 (1957).
7. Water samples, such as SMOW, are analyzed by equilibrating CO_2 with the water and analyzing the CO_2. Thus, atmospheric O_2 is analyzed relative to CO_2 in isotopic equilibrium with liquid SMOW, and the isotopic fractionation factor for CO_2 and water is required to express the results relative to SMOW.
8. Y. Bottinga and H. Craig, *Earth Planet. Sci. Lett.* **5**, 285 (1969). J. O'Neil and S. Epstein [*J. Geophys. Res.* **71**, 4955 (1966)] reported a value of 1.0407 from their study, and Bottinga and Craig averaged all data from the two laboratories to obtain a factor of 1.04075. However, O'Neil (personal communication) now believes his value may be as large as 1.0412. The Bottinga and Craig value has been adopted here. Other measurements of this factor are reviewed by Bottinga and Craig.
9. H. Craig and P. M. Kroopnick, *Trans. Amer. Geophys. Union* **51**, 325 (1970); P. M. Kroopnick and H. Craig, *ibid.* **52**, 255 (1971) (abstracts).
10. C. E. Klots and B. B. Benson, *J. Chem. Phys.* **38**, 890 (1961).
11. Details of this procedure are given by Kroopnick (*5*). No detectable isotopic fractionation occurs during the adsorption and desorption of oxygen gas on type 5A molecular sieve. The molecular sieve material was obtained from the Linde Division, Union Carbide Corporation, New York.
12. R. Weiss, *Science* **168**, 247 (1970).
13. Supported by grants from the National Science Foundation and the Office of Naval Research to the Isotope Laboratory of the Scripps Institution of Oceanography. We thank Mrs. K. Podvin for performing the mass spectrometer analyses and Dr. J. O'Neill for extensive discussions on the conversion process and the fractionation factor.

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Moon: Possible Nature of the Body That Produced the Imbrian Basin, from the Composition of Apollo 14 Samples

Abstract. Soils from the Apollo 14 site contain nearly three times as much meteoritic material as soils from the Apollo 11, Apollo 12, and Luna 16 sites. Part of this material consists of the ubiquitous micrometeorite component, of primitive (carbonaceous–chondrite-like) composition. The remainder, seen most conspicuously in coarse glass and norite fragments, has a decidedly fractionated composition, with volatile elements less than one-tenth as abundant as siderophiles. This material seems to be debris of the Cyprus-sized planetesimal that produced the Imbrian basin. Compositionally this planetesimal has no exact counterpart among known meteorite classes, though group IVA irons come close. It also resembles the initial composition of the earth as postulated by the two-component model. Apparently the Imbrian planetesimal was an Earth satellite swept up by the moon during tidal recession or capture, or an asteroid deflected by Mars into terrestrial space.*

Lunar surface rocks are strikingly depleted in siderophile elements (such as Au, Ir, Ni, and Re) and volatile elements (such as Ag, Bi, Br, Sb, and Te). This has made it possible to recognize even a small meteoritic component in those lunar materials that were affected by meteorite impacts: soils, breccias, and glasses (*1, 2*). Both the amount and type of meteoritic material can be estimated from the abundance pattern (usually normalized to cosmic or to Cl chondrite abundances). When the pattern shows siderophile and volatile elements in comparable abundance, a "primitive" meteorite is indicated (for example, carbonaceous chondrites). When volatiles are less abundant than siderophiles, a "fractionated" meteorite is indicated (ordinary chondrites, irons).

We have analyzed eight Apollo 14 samples by our radiochemical neutron activation procedure (*1*), modified to include two more elements, Re and Sb (Table 1). The first two of these samples were bulk soils, collected at two locations. The next five were petrographically distinct separates, handpicked by J. A. Wood and U. B. Marvin from the 1- to 2-mm fraction of four soils. They were cleaned ultrasonically in double-distilled acetone to remove adhering

Table 1. Abundances of trace elements in Apollo 14 samples, expressed in parts per billion.

Sample, number of fragments	Ir	Re	Au	Sb	Ag	Se	Te	Br	Bi	In	Zn	Cd	Tl	Rb	Cs	Sample weight (mg)
14163,57*, bulk soil	12.7	1.00	5.4	5.7	17.5	340	70	490	1.6	72	31,000	140	32	16,000	680	141;83
14259,20, comprehensive soil	18.4	1.30	6.6		27	350	50		1.8	34	22,000	83	18	15,400	620	122
14154,02-3†, magnetic, 29 fragments	11.9	0.99	10.0	2.4	10	270	110	310	1.5	26	23,000	78	20	13,200	580	32
14258,36-5‡, ropy glass, 12 fragments	13.1	0.91	5.1	0.87	2.5	120	30	70	0.49	5.9	5,600	20	5.2	4,100	180	27
14154,02-7†, dark norite, 13 fragments	8.9	0.92	4.8	2.2	1.4	130	≤40	270	0.63		2,900	48	33	16,500	740	40
14151,12-7§, dark norite, 14 fragments	6.6	0.63	3.1	2.9	0.94	130	30	220	0.62		2,400	36	30	16,400	710	35
14146,02-9‖, light norite, 8 fragments	4.9	0.43	5.4	1.7	1.2	91	≤70	150	≤0.6	10.6	1,800	14	9.9	15,200	620	31
14053, igneous rock	0.017	0.007	0.11	0.64	0.60	140	15	50	0.29	15.0	2,100	20	1.4	2,100	91	156

* Mean of two analyses except Sb, Te, Br, and In, which are based on single determinations. † Trench, middle layer. ‡ Comprehensive soil. § Trench, bottom layer. ‖ Trench, surface layer.

powder. The last sample, 14053, represents one of the two crystalline rocks returned by the Apollo 14 mission.

In order to obtain the net meteoritic component, the indigenous lunar contribution must be subtracted from the gross abundances in Table 1. For Apollo 11 and 12 we used the average of the crystalline rocks for this purpose, because their bulk composition closely resembled that of the soil (*1*, *2*). This is not feasible for Apollo 14, because neither of the two crystalline rocks truly represents the nonmeteoritic part of the soil. Rock 14053 differs markedly from average soils in a variety of nonmeteoritic elements, being poorer in K, Rb, Cs, Al, rare earths, Ba, U, Th, and Zr, but richer in Fe, Cr, Sc, and V (Table 1) (*3*). Rock 14310 has about the right bulk chemistry (*3*), but, though classified as igneous, it contains meteoritic elements in the same abundance as a typical breccia (*4*). We suspect that it is remelted soil or breccia, not a pristine sample of Fra Mauro source rock.

We shall therefore try to characterize the meteoritic component from the gross abundances, without making any correction for the lunar component. This is reasonably safe for the siderophile elements Ir, Re, and Au, which are depleted in all lunar rocks investigated to date, even 14053, by about two orders of magnitude relative to soils. The fact that the Ir:Re and Ir:Au ratios in the Apollo 14 samples are nearly constant and virtually identical to the cosmic ratios (*5*) seems to justify the assumption that these elements are largely of meteoritic origin (*6*). Volatile elements, on the other hand, show less extreme and more variable depletions in Apollo 11 and Apollo 12 rocks compared to soils. Meteoritic components estimated from gross abundances therefore represent only upper limits. Like all upper limits, they are interesting only if unexpectedly low.

For comparison with meteorites, it is useful to normalize the data twofold: first to cosmic abundances, then to a single reference element, such as Au. These normalized abundances indicate the depletion of each element below its cosmic level, relative to Au. [Gold is a suitable reference standard because its condensation temperature in a cosmic gas is close to that of a major element, Fe (*7*); empirically, one finds little fractionation of Au and Fe in iron meteorites and chondrites (*8*).]

Table 2 gives normalized abundances for seven lunar samples and nine meteorite classes (*9*). Only those eight elements are included for which the lunar contribution is expected to be small. They represent all three major cosmochemical groups (*7*): refractories (Ir and Re), siderophiles (Au), and volatiles (Sb, Se, Te, Zn, Ag, and Bi). We shall be concerned mainly with the first eight elements, as the last, Bi, is very volatile and varies too much in abundance in some meteorite classes to serve as a diagnostic element.

The two bulk soils and the magnetic separate are richer in volatiles than the other four lunar samples. We attribute this to admixture of micrometeorites of primitive (approximately Cl chondrite) composition. Such a primitive component has been found in all lunar soils that have had long surface exposures (*1*, *2*, *10*). The glass and norites, on the other hand, contain a more fractionated component, with lower abundances of volatiles.

Where does this meteoritic component come from? Certainly not from the local craters. All the samples were collected well outside the ejecta blankets of these craters, according to the geologic map of the site (*3*). The bulk soil and the trench samples were collected near Triplet North crater, about 2.7 and 1.5 crater radii away; the comprehensive soil was taken about 3.8 crater radii from Doublet South crater. All were at least 5.3 crater radii from Cone crater. Our work on Apollo 12 samples shows that at these distances the local component is no longer prominent, being swamped by micrometeorites and ray material from distant, large craters. Moreover, siderophile meteoritic elements (Ir, Re, Au, and Ni) are two to three times more abundant in Apollo 14 soils and breccias than in all the other lunar soils investigated to date, including Luna 16 (*1*, *2*, *10*). The amount of meteoritic material in crater ejecta is inversely proportional to the impact velocity, and thus one might suppose that the Apollo 14 craters were made by slow projectiles. It is unlikely, however, that the required low impact velocity (or concentration of meteoritic material in part of the ejecta) was achieved in all ten impacts at the Apollo 14 site, but never at the Apollo 11 and Apollo 12 and Luna 16 sites. More probably, this meteoritic component is common to the Fra Mauro formation at the Apollo 14 site, and possibly elsewhere. In that case it represents debris of the planetesimal that produced the Imbrian basin.

It is of great interest to establish the

Table 2. Elemental abundances in meteorites (*9*) and lunar samples relative to "cosmic" abundances and normalized to Au.

Material	Ir	Re	Sb	Se	Te	Zn	Ag	Bi
Meteorites								
C1	1.07	0.96	0.97	1.02	0.88	1.20	1.07	0.99
C2	1.12	1.07	0.60	0.55	0.45	0.40	0.37	0.44
C3,4	1.24	1.23	0.58	0.39	0.22	0.28	0.52	0.27
H	1.14	1.33	0.42	0.25	0.23	0.098	0.15	0.026
L	0.96	1.05	0.43	0.39	0.28	0.15	0.35	0.029
LL	0.70	0.83	0.40	0.39	0.39	0.17	0.32	0.067
E4	0.47	0.52	0.54	0.40	0.33	0.55	0.37	0.35
E5,6	0.67	0.76	0.46	0.35	0.093	0.029	0.13	0.028
Irons, type IVA	0.08–1.1	0.11–2.2	0.003–0.017	< 0.0002	< 0.003	< 0.7	< 0.002 – 0.03	< 0.002
Lunar samples								
14163,57, bulk	0.78	0.71	0.90	0.45	0.59	2.3	1.3	0.34
14259,20, comprehensive	0.93	0.76		0.38	0.34	1.4	1.6	0.32
14154,02-3, magnetic	0.40	0.38	0.21	0.19	0.50	0.93	0.39	0.17
14258,36-5, ropy glass	0.86	0.69	0.15	0.17	0.27	0.45	0.19	0.11
14154,02-7, dark norite	0.62	0.74	0.39	0.19	≤0.38	0.24	0.11	0.15
14151,12-7, dark norite	0.71	0.78	0.80	0.30	0.44	0.31	0.12	0.23
14146,02-9, light norite	0.30	0.31	0.27	0.12	≤0.59	0.14	0.085	0.13

chemical nature of the Imbrian planetesimal, thought to be one of the building blocks of the earth or the moon (*11*). Let us see whether it resembles any of the major classes of meteorites.

The high content of Ir, Re, and Au points to meteorites rich in siderophile elements: chondrites, irons, or stony irons. We can at once eliminate six meteorite classes: C1, C2, C3,4, L, LL, and E4 chondrites. All are consistently richer in Ag and Se than are the Apollo 14 samples. Most are also richer in Ir, Re, and Sb. Inasmuch as the Apollo 14 values are upper limits (not having been corrected for an indigenous contribution) values lower than the meteoritic ones are significant.

The choice thus narrows to the remaining three meteorite classes: H or E5,6 chondrites and irons of group IVA. [Other classes of irons can be excluded, being too high in either Ir or Ge or both (*4*).] Neither H nor E chondrites fit very well. The H chondrites have suitably low abundances of Ag, but are too rich in Ir, Re, Sb, and Se. To eliminate this discrepancy, one might assume that some 40 percent of the Au in Apollo 14 samples is indigenous, but this seems rather unlikely (*6*). Class E chondrites of types 5 and 6 have the right Ir and Re abundances, but are too rich in Se and perhaps Sb.

This leaves IVA irons as the prime candidates. Their Ir and Re abundances vary more widely than those of chondrites and overlap the range for Apollo 14 samples. Their volatile abundances are variable but generally lower than those of Apollo 14 samples. Since the latter contain an indigenous lunar component, the agreement may be better than indicated by the data in Table 2.

Alternatively, material similar to IVA irons but less depleted in volatiles would also fit. The existence of such material is not postulated wholly ad hoc, because meteorites seem to have undergone at least four cosmochemical fractionations in the solar nebula, each of which is capable of producing a continuum of compositions (*7*). The known meteorite classes represent but a few points in this continuum.

Data on additional Apollo 14 samples (*4*) confirm these trends, as they show equal or even greater depletions. It appears that the Imbrian planetesimal was depleted in refractory metals to 30 to 90 percent, and in volatiles to less than 10 percent of their cosmic abundance relative to Au.

It seems very unlikely that the Imbrian planetesimal consisted wholly of iron. Cyprus-sized iron objects, as required for the Imbrian impact, are probably made by differentiation of bodies of chondritic composition, containing perhaps 10 to 30 percent metal. To obtain a pure iron meteorite, the remaining 70 to 90 percent material must be neatly spalled away. This seems improbable. Indeed, after 4.6 billion years of fragmentation, few if any asteroids with iron surfaces have been found in spectral reflectivity surveys (*12*). Probably the Imbrian planetesimal consisted mostly of silicate, with metal contained either in a single core or (by analogy with the IVA parent body) in isolated pockets dispersed throughout the body (*13*). Among the known classes of stony meteorites, the eucrites have some of the characteristics expected for this stony phase: low volatile content and low Ir : Au ratios (*6*).

It is interesting to compare the inferred composition of the Imbrian planetesimal with estimates for the earth and moon as a whole. No information exists on refractory metals, but the volatile contents of the earth and moon have been estimated as 11 and 2 percent of cosmic abundance, relative to Si (*2, 6*). For comparison with our value for the Imbrian planetesimal, we recalculate these numbers to Au by using Urey's Fe : Si ratios of 1.0 and 0.3 for the earth and moon (*14*) and assuming cosmic Au : Fe ratios in both bodies. The corrected volatile contents for the earth and moon that are 10 and 6 percent, relative to Au. Both values are consistent with that for the Imbrian planetesimal, less than 10 percent. Thus, we cannot tell from the volatile content whether the Imbrian planetesimal was of earthlike or moonlike composition.

A further clue comes from the amount of meteoritic material in Apollo 14 soil. Let us define μ as the mass of meteoritic material in soil and M as the mass of crushed lunar rock in soil. The mean Au content of the four soils in Table 2 is 4.6 parts per billion. The mass fraction of meteoritic material in the soil, $\mu/(M+\mu)$, then equals $4.6 \times 10^{-9}/(\mathrm{Au} : \mathrm{Fe})_{\mathrm{IP}}\mathrm{Fe}_{\mathrm{IP}}$, where $(\mathrm{Au} : \mathrm{Fe})_{\mathrm{IP}}$ and $\mathrm{Fe}_{\mathrm{IP}}$ are the mass ratio of Au : Fe and the mass fraction of Fe in the Imbrian planetesimal. Let us assume that $(\mathrm{Au} : \mathrm{Fe})_{\mathrm{IP}}$ equaled the cosmic ratio, 7.9×10^{-7}, and that $\mathrm{Fe}_{\mathrm{IP}}$ equaled the terrestrial, lunar, cosmic, or IVA iron bulk Fe content [36, 13, 28, and 92 percent; (*15*)]. This leads to values for $\mu/(M+\mu)$ of 1.61×10^{-2}, 4.46×10^{-2}, 2.07×10^{-2}, and 0.63×10^{-2} for the four cases.

These values may be examined in the light of cratering theory. From Öpik's cratering relation (*16*), the velocity w is related to the ratio of eroded mass to projectile mass, M/μ

$$M/\mu = kw(\rho/s)^{\frac{1}{2}}$$

where s is the crushing strength of the target rock, ρ is its density, and k is a velocity-dependent parameter varying between 2 and 5. If we make the admittedly risky assumption that the amount of meteoritic matrial in Apollo 14 soil equals the average μ/M for the entire impact, we can solve for w. With $s = 9 \times 10^8$ dyne/cm^2 and $\rho = 3.3$ g/cm^3, we obtain $w = 4.9$, 1.8, 3.9, and 12 km/sec for "terrestrial," "lunar," "cosmic," and "iron meteorite" Fe contents of the projectile. The second value is unreasonable, being less than the lunar escape velocity of 2.38 km/sec. This is not quite enough to rule out a "lunar" composition, because the amount of meteoritic material at the Apollo 14 site may not be typical of the entire impact. Still, the relative constancy of the meteoritic component in a variety of materials (light norite, dark norite, and ropy glass) suggests that our values are not grossly unrepresentative. At the very least it can be said that the present data suggest an iron-rich projectile.

In view of our arguments against a pure iron body, the fourth value (12 km/sec) applies to the possibility that the ejecta at the Apollo 14 site were excavated by a purely metallic portion of the Imbrian object. Sampling Imbrian ejecta at other landing sites should tell whether this is a realistic possibility.

Urey has maintained for a number of years that the Imbrian planetesimal had a low impact velocity, 2.4 to 6 km/sec (*11, 17*). Our first three estimates certainly agree with his view. Using Öpik's (*16*) crater scaling law and $w = 4.9$ km/sec, we obtain the mass of the planetesimal as 1.5×10^{22} g, close to Urey's and MacDonald's (*11*) estimates from other scaling laws. The diameter, for a density of 4 g/cm^3, is 190 km.

It is puzzling, of course, that a body with so low a selenocentric velocity survived for approximately 700 million years before being captured. The date of the Imbrian object. Samplings of Rb/Sr and $^{40}Ar/^{39}Ar$ ages, is less than 3.89 billion years (*18*), about 700 million years after the formation of the solar system. Four origins may be considered for the Imbrian object.

1) It may have been one of the last survivors of an Earth-crossing population of planetesimals. This is unlikely, because the survival fraction of such a population after 700 million years is only about 6×10^{-4} according to unpublished Monte Carlo calculations by Mellick and Anders (*19*) and less according to other authors (*20*). The selenocentric velocities of the longer-lived members of this population would be typically 12 km/sec, owing to acceleration during close approaches to the earth (*20*). This is consistent with our fourth estimate, involving a differentiated body with extended metallic regions, but not with the first three.

2) It may have been an interplanetary object whose orbit barely grazed that of the earth. Öpik (*21*) has shown that a large fraction of such objects, in orbits of low eccentricity, could survive indefinitely between the inner planets; only those trespassing into the space swept by the planets would be eliminated by collisions. However, if the Imbrian planetesimal was a member of such a population, evenly distributed between the earth and Mars, other members of similar size should have survived to this day. No such objects have ever been found in asteroid searches, although they would be among the easiest to observe.

3) It may have been an asteroid initially in a Mars-crossing orbit, later perturbed into an Earth-crossing orbit. The elimination of asteroids by this process roughly follows an exponential law, with mean lives ranging from a few hundred million to a few billion years, depending on the initial orbital elements (*19*). The shorter of these lifetimes agrees with the date of the Imbrian collision, and the chemical similarity to IVA irons (of presumably asteroidal origin) also supports this possibility. Williams (*22*) has noted that the distribution of asteroid perihelions shows an abrupt drop in the region swept by Mars, which suggests that a large fraction of initially Mars-crossing asteroids have been eliminated in the course of time.

4) The Imbrian planetesimal may have been an Earth satellite, swept up by the moon during tidal recession or capture. This possibility, favored by Urey (*11*) and Öpik (*16*), readily accounts for the low velocity and long collision lifetime.

The ages of lunar basins may provide a crucial test between alternatives 3 and 4. According to 4, the lunar basins should be isochronous within much less than 10^8 years, the time scale of tidal recession (*23*), whereas according to 3 the age differences would be much larger. Crater counts by Hartmann and Wood (*24*) suggest substantial differences in relative age, but these cannot be converted to absolute ages until ejecta from another basin are dated by radiometric methods.

The present data allow only a partial chemical characterization of the Imbrian planetesimal. Nonetheless, three conclusions can be drawn.

1) The Imbrian planetesimal contained approximately its cosmic complement of siderophile elements. It had not experienced a "planetary" segregation of metal and silicate, which typically depletes siderophile elements by factors of 10^{-3} to 10^{-4} (*2, 6*). Hence it cannot represent material spun off the earth after core formation (*25*), a condensate or volatilization residue from a hot earth (*26*), or a fragment of a differentiated protomoon disrupted during capture (*11*). If its Fe content deviated at all from cosmic, this must be attributed to a "nebular" metal-silicate fractionation (*7, 27*), by analogy with meteorites and planets (*6, 7, 27, 28*). This process, presumably based on the ferromagnetism of metal grains, has fractionated metal from silicate by factors of up to 3 in the inner solar system.

2) Refractory metals (Ir, Re) were depleted by 10 to 70 percent. This raises the possibility that refractory oxides (such as CaO and Al_2O_3) were likewise depleted, because these elements tend to correlate in cosmochemical fractionation processes. However, no direct evidence on this point is available from the Apollo 14 samples, because lunar surface rocks themselves are enriched in refractory oxides.

3) Volatile elements were depleted to less than one-tenth of their cosmic abundance, as in the eucrites and the earth and moon as a whole. In terms of the two-component model of planet formation (*7, 27*), the Imbrian planetesimal thus contained less than 10 percent of low-temperature, volatile-rich material; the remainder consisting of high-temperature, volatile-poor material.

If the Apollo 14 rocks indeed contain debris of the Imbrian planetesimal at an abundance of several percent, a search for such material by petrographic methods may be worthwhile. Particularly if the impact velocity was low, some material may have survived relatively unaltered, with only moderate shock damage. Petrographers should be on the lookout for xenoliths of "meteoritic" mineralogy.

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References and Notes

1. R. R. Keays, R. Ganapathy, J. C. Laul, E. Anders, G. F. Herzog, P. M. Jeffery, *Science* **167**, 490 (1970); R. Ganapathy, R. R. Keays, J. C. Laul, E. Anders, in "Proceedings of the Apollo 11 Lunar Science Conference," *Geochim. Cosmochim. Acta* (Suppl. 1) **2**, 1117 (1970); R. Ganapathy, R. R. Keays, E. Anders, *Science* **170**, 533 (1970).
2. E. Anders, R. Ganapathy, R. R. Keays, J. C. Laul, J. W. Morgan, in "Proceedings of the Second Lunar Science Conference," *Geochim. Cosmochim. Acta* (Suppl. 2) **2**, 1021 (1971); J. C. Laul, J. W. Morgan, R. Ganapathy, E. Anders, *ibid.*, p. 1139.
3. Lunar Sample Preliminary Examination Team, *Science* **173**, 681 (1971); R. E. Eggleton and T. W. Offield, in *Geologic Atlas of the Moon, Fra Mauro Region–Apollo 14, Map I-708* (U.S. Geological Survey, Washington, D.C., 1971).
4. J. W. Morgan, J. C. Laul, U. Krähenbühl, R. Ganapathy, E. Anders, in preparation.
5. A. G. W. Cameron, in *Origin and Distribution of the Elements*, L. H. Ahrens, Ed. (Pergamon, Oxford, 1968), p. 125. In place of Cameron's values for Ag and Ir, based on older data, we have used the most recent abundances of these elements in Cl chondrites [0.95 and 0.62 atom per 10^6 Si atoms; (*13*)].
6. As emphasized by a referee, we cannot be absolutely sure that this is true. Perhaps the Ir, Re, and Au in Apollo 14 soil are indigenous and were depleted only by a factor of about 10^{-2} in the initial metal-silicate segregation on the moon that produced the pre-Imbrian crust. This seems rather unlikely because Ca-rich achondrites, representative of metal-silicate segregation on bodies smaller than the moon, typically are depleted in Ir by more extreme factors, 10^{-3} to 10^{-4} (J. C. Laul, R. R. Keays, R. Ganapathy, E. Anders, J. W. Morgan, *Geochim. Cosmochim. Acta*, in press). Lunar and terrestrial basalts show still greater depletions, by factors of 10^{-4} to 10^{-5}.
7. E. Anders, *Annu. Rev. Astron. Astrophys.* **9**, 1 (1971); *Accounts Chem. Res.* **1**, 289 (1968); J. W. Larimer and E. Anders, *Geochim. Cosmochim. Acta* **31**, 1239 (1967); *ibid.* **34**, 367 (1970).
8. J. C. Cobb, *J. Geophys. Res.* **72**, 1329 (1967); J. H. Crocket, R. R. Keays, S. Hsieh, *Geochim. Cosmochim. Acta* **31**, 1615 (1967); W. D. Ehmann, P. A. Baedecker, D. M. McKown, *ibid.* **34**, 493 (1970); E. Goldberg, A. Uchiyama, H. Brown, *ibid.* **2**, 1 (1951); K. F. Fouché and A. A. Smales, *Chem. Geol.* **2**, 105 (1967).
9. B. Mason, Ed., *Elemental Abundances in Meteorites*, in press.
10. A. P. Vinogradov, in "Proceedings of the Second Lunar Science Conference," *Geochim. Cosmochim. Acta* (Suppl. 2) **1**, 1 (1971); J. C. Laul, R. Ganapathy, J. W. Morgan, E. Anders, *Earth Planet. Sci. Lett.*, in press.
11. H. C. Urey, *The Planets* (Yale Univ. Press, New Haven, Conn., 1952); ——— and G. J. F. MacDonald, in *The Moon*, Z. Kopal, Ed. (Academic Press, New York, ed. 2, 1971); H. C. Urey, in *The Smithsonian Report for 1960* (Smithsonian Institution, Washington, D.C., 1961), pp. 251–265.
12. C. R. Chapman, in *Physical Studies of Minor Planets*, T. Gehrels, Ed. (NASA SP-267, National Aeronautics and Space Administration, Washington, D.C., in press).
13. P. E. Fricker, J. I. Goldstein, A. L. Summers, *Geochim. Cosmochim. Acta* **34**, 475 (1970).
14. H. C. Urey, *Quart. J. Roy. Astron. Soc.* **8**, 23 (1967).
15. D. L. Anderson, C. Sammis, T. Jordan, *Science* **171**, 1103 (1971).
16. E. J. Öpik, *Ann. Rev. Astron. Astrophys.* **7**, 473 (1969).
17. H. C. Urey, *Science* **162**, 1408 (1968).
18. J. F. Sutter, L. Husain, O. A. Schaeffer, *Earth Planet. Sci. Lett.* **11**, 249 (1971); L. Husain, J. F. Sutter, O. A. Schaeffer, *Science* **173**, 1235 (1971); G. Turner, J. C. Huneke, S. A. Podosek, G. J. Wasserburg, *Earth Planet. Sci. Lett.* **12**, 19 (1971); D. A. Papanastassiou and G. J. Wasserburg, *ibid.*, p. 36.
19. P. J. Mellick and E. Anders, unpublished work.
20. J. R. Arnold, *Astrophys. J.* **141**, 1536 (1965); G. W. Wetherill, in *Origin and Distribution of the Elements*, L. H. Ahrens, Ed. (Pergamon, Oxford, 1968), pp. 423–443.
21. E. J. Öpik, *Proc. Roy. Irish Acad. Sect. A* **54**, 165 (1951).
22. J. G. Williams, in *Physical Studies of Minor Planets*, T. Gehrels, Ed. (NASA SP-267, National Aeronautics and Space Administration, Washington, D.C., in press).
23. G. J. F. MacDonald, *Rev. Geophys.* **2**, 467 (1964).
24. W. K. Hartmann and C. A. Wood, *Moon*, in press.
25. D. U. Wise, *J. Geophys. Res.* **68**, 1547 (1963); J. A. O'Keefe, *ibid.* **74**, 2758 (1969); *ibid.* **75**, 6565 (1970).
26. A. E. Ringwood, *Geochim. Cosmochim. Acta* **30**, 41 (1966); *J. Geophys. Res.* **75**, 6453 (1970).
27. J. A. Wood, *Nature* **194**, 127 (1962).
28. H. C. Urey, *Astrophys. J.* (Suppl.) **1**, 147 (1954).
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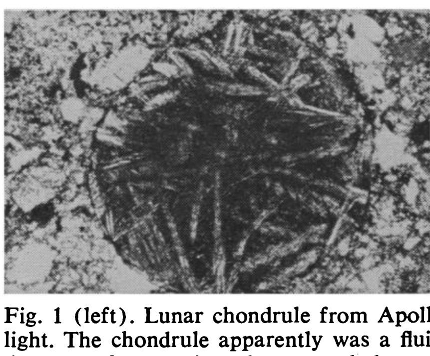
Chondrules in Apollo 14 Samples: Implications for the Origin of Chondritic Meteorites

Abstract. *Chondrules have been observed in several breccia samples returned by the Apollo 14 mission. These lunar chondrules are believed to have formed during a large impact event, perhaps the one that formed the Imbrian Basin. This suggests that some meteoritic chondrules are also formed by impact processes such as crystallization after shock melting and abrasion and diffusion in base-surge and fall-back deposits generated by impacts on planetary surfaces.*

Glass spherules, some of which are partially devitrified, have been observed in samples from Apollo 11 and 12 by previous investigators of lunar samples (*1, 2, 3,* and others). However, few of these spherules, if any, have the textures that are typical of most meteoritic chondrules. In some of the Apollo 14 breccias there are abundant spherical and rounded bodies with radiating lath-like crystals, brown turbid glass, aggregates of grains, and many of the typical textures of meteoritic chondrules (Figs. 1, 2, and 3). Lunar chondrules have been reported by Butler *et al.* (*4*), Kurat *et al.* (*5*), Fredriksson *et al.* (*6*), and von Engelhardt *et al.* (*7*).

Abundant chondrules and chondrule-like bodies have been observed in lunar samples 14313, 14318, and 14301, and



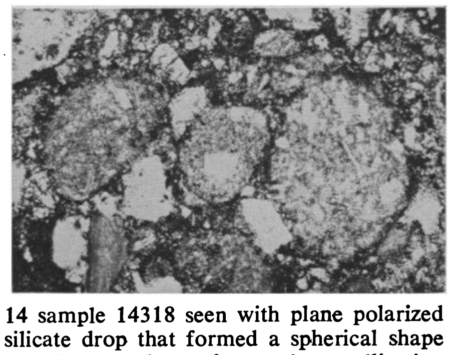


Fig. 1 (left). Lunar chondrule from Apollo 14 sample 14318 seen with plane polarized light. The chondrule apparently was a fluid silicate drop that formed a spherical shape due to surface tension, then crystals began to nucleate at the surface and crystallization proceeded into the body of the sphere. This texture is typical of many meteoritic chondrules. The chondrule is 0.5 mm in diameter and composed chiefly of pyroxene, plagioclase, and brown turbid glass. Fig. 2 (right). Three lunar chondrules in Apollo 14 sample 14313 seen in plane polarized light. These chondrules do not appear to have been fluid drops, but instead appear to be rounded rock fragments of both breccias and igneous rocks. These fragments may have been rounded by abrasion in the movement of the base-surge deposits from the Imbrian impact. The length of the field of view is 0.8 mm.