Surveyor Results and the Composition of the Moon

The results of the alpha-scattering analyses of the top layers of the moon's surface by Turkevich *et al.* (*1*) have provided us with the chemical compositions at the landing sites of Surveyors V, VI, and VII. The results (Table 1) show that the composition is clearly different from that of chondrites and resembles that of terrestrial basalts. In fact, the Surveyor V, VI, and VII results have been interpreted to be basaltic lava flows by Gault *et al.* (*2*). We believe that this is a possible, but not the only possible, interpretation. The Surveyor VII analysis of the Tycho region shows a marked difference from the other two analyses in that the iron content is distinctly less. The iron content of a rock lying on the surface was detectably lower than that of the soil. The analytical data apply only to a very thin top layer (a few microns), and therefore any dust from the lunar surface, thrown around by collisions, might affect the rock analysis. The observations may indicate that the rock is free of iron. Furthermore, the "Fe" peak in the Surveyor analyses also includes neighboring elements and might therefore include small amounts of Ti, Cr, and Mn, thus reducing the necessary Fe content.

Kopal and Rackham (*3*) have suggested an iron-free chemical composition for the throw-out region of another rather recent lunar crater, namely, Kepler. This suggestion was based on completely different arguments. In a sequence of observations during a period of high solar activity they found in the Kepler region a strong short-time luminescence at a wavelength of 6725 Å. As strong luminescence at about 6700 Å had only been observed in the case of the enstatite achondrites, they ascribed a similar material to the Kepler region. Although a number of experiments have been carried out, enstatite achondritic material is found to be the only one to exhibit strong luminescence (*4, 5*).

A possible interpretation is that the soil in the neighborhood of this rock might have acquired its iron from the collisional processes from space that have been going on for a very long period of time. Meteoritic material now arriving at the earth appears to be heavily weighted in favor of iron content. In fact a few collisions of iron meteorites of such size as the Sikhote-Alin meteorite would indicate that probably more metallic iron-nickel is arriving on the earth by mass than all the other elements together. Chirvinskii (*6*) estimates that 74.61 percent of meteoritic matter observed to fall from 1492 to 1950 consists of iron-nickel. In the micrometeorite mass range more iron than stony matter is probably arriving at the earth.

Thus, the soil in the neighborhood of the rock of the Surveyor VII landing may have acquired its iron from space and not from processes on the moon. Shedlovsky and Paisley (*7*) estimate that a maximum of some 200 tons of iron per day are now falling on the earth. If this has been the rate for the last some 10^9 years, about 15 g/cm^2 has fallen on the earth during this time. It seems likely that less iron per square centimeter would fall on the moon, though it would be difficult to be certain of this. If one assumes that this same rate and that "gardening" due to collisions has occurred, some 300 g of soil containing 2 atomic percent of iron could be produced from iron-free material.

Little magnetic effect in the lunar soil was observed by the Surveyors, and if metallic iron-nickel has fallen on the moon in appreciable amounts, this iron must have been oxidized, by water for example. This may not be the correct explanation for all of the iron content, but some contribution from this source of the iron-nickel should have occurred. This effect may also be partially true for the material analyzed by Surveyors V and VI in Mare Tranquillitatis and Sinus Medii, though the most probable explanation for this material is that a partial melting process in the moon's interior produced this basaltic-type material.

Let us now turn to the question of the possible origin of silicate materials such as the enstatite achondrites which are notably free of iron. It appears that in order to produce material of this kind from primitive solar material the iron in its oxidized form must be reduced, that the molten iron must settle in a gravitational field from a molten mass of silicates. In some way the iron sulfide must also be removed. It may have sunk along with the iron, or reduction producing metallic iron and hydrogen sulfide which would escape may also be an alternative process. There appears to be no other way to remove iron from primitive solar material except that it be reduced, melted, and separated in a gravitational field leaving a silicate melt completely free of metallic or oxidized iron. Next, the silicate layer must crystallize with a settling of magnesium metasilicate to

Table 1. Chemical composition of the lunar surface as obtained by Surveyors V, VI, and VII.

	V (atomic %)	VI (atomic %)	VII (atomic %)	VII* (wt %)	VII* (wt %) Oxides
C	3	2	2	1.2	1.2
O	58 ± 5	57 ± 5	58 ± 5	44.6	
Na	2	2	3	3.3	4.4
Mg	3 ± 3	3 ± 3	4 ± 3	4.7	7.7
Al	6.5 ± 2	6.5 ± 2	8 ± 3	10.4	19.4
Si	18.8 ± 3	22 ± 4	18 ± 4	24.3	51.3
"Ca" †		6 ± 2	6 ± 2	11.5	16.0
"Fe" ‡	13 ± 3	5 ± 2	2 ± 1 §		

* The reported mean atomic percentages are used for these calculated percentages, assuming iron is 0. † "Ca" includes Ca, K, and possibly some S; ‡ "Fe" includes Ti, V, Cr, Mn, Fe, Co, Ni. § The undisturbed and disturbed surfaces and a rock agree except that the bare rock contains about 30 percent less iron.

Table 2. Hypothetical mixture consisting of 79 percent of the Norton County–type material and 21 percent of the type viewed by Surveyor VII (without iron), compared with the average of Hainaut and Monte des Fortes (percentages by weight).

	Surveyor VII	Norton County	Mixture	Averages of Hainaut and Monte des Fortes	Suess solar
SiO_2	51.3	56.16	55.15	54.82	55.59
MgO	7.7	42.04	34.83	35.33	34.88
Al_2O_3	19.4	.63	4.57	4.64	3.58
CaO	16.1	.68	3.89	3.00*	2.64
Na_2O	4.4	.13	1.03	1.08	1.46

* This contains an estimated contribution from K_2O.

Table 3. Comparison of the Surveyor VII results (without iron) with a "calculated top layer" of the moon (atomic percent).

	Norton County	Averages of Hainaut and Monte des Fortes	"Calculated top layer"	Surveyor VII
Si	18.95	18.73	18.3	18 ± 4
Mg	21.02	17.98	6.5	4 + 3
Al	0.25	1.87	8.0	8 ± 3
"Ca"	.26	1.10	4.1	6 ± 2
Na	.08	0.71	3.1	< 3
O	59.51	59.63	60.1	58 ± 5
	99.99	100.07	100.1	97

the bottom of the pool. Such settling has occurred on the earth in large molten lava deposits that are considerably insulated, but the separation of minerals is very far from perfect. Thus a long period of settling with very gradual cooling is indicated. Finally a cooling process and a crystallization process of this kind should leave a surface layer consisting of approximately basaltic composition but free of iron. Or, the iron-free melt solidified and was remelted partially with the separation of an iron-free basaltic-type liquid with respect to other elements, that is, alkalies, aluminum, calcium and others.

It is interesting to make some calculations on the assumption that the type of material observed by Surveyor VII has lost all its iron. We shall take the upper limits of carbon and of sodium from this analysis. Table 1 shows the weight percentages calculated in this way, both as elements and oxides. A comparison as to what kind of material would be produced if enstatite achondritic material of the Norton County–type were mixed with Surveyor VII material, on the assumption that no iron is present, is given in Table 2.

We can also compare with the Surveyor VII results a "calculated top layer" obtained from the meteorite data by the use of only the iron-free analyses for silicates. The first and second columns of Table 3 give the atomic percentages of elements in Norton County and the averages of Hainaut and Monte des Fortes. The third column gives the "calculated top layer" which is obtained by subtracting 79 percent Norton County–type material from the latter. These compare favorably with the Surveyor VII results. These calculations show that the material analyzed by Surveyor VII is quite similar to that material that needs to be eliminated from chondritic composition exclusive of iron in order to produce enstatite achondritic material.

A model for the moon has been advanced by Urey (*8*) in which precisely this sort of fractionation is postulated. The postulated layer of the moon's surface is shown in Fig. 1. Another more complicated model which assumes that two layers of liquid could be produced on such an object has also been given.

The model of the moon as a class of objects which formed in the early solar system and of which the larger asteroids are either examples or fragments meets with a difficulty. There the moon is assumed to have formed with the solar composition of the elements and was captured by the earth at the terminal stage of the accumulation of the earth from solid objects. In this case, the moon was about in the neighborhood of the accumulating earth and should have received on its surface a layer of material of approximately the composition of the earth, that is, approximately the composition of the chondritic stone meteorites. For this and other reasons, one of us (Urey) has repeatedly suggested that the chondritic meteorites may come from the moon. However, it now seems improbable that of the three analyses of the surface of the moon, two would agree with that for a rare type of stony meteorite, the basaltic or calcium-rich achondrites, and the third analysis would agree with no type of meteoritic material so far observed, and at the same time that the more numerous chondritic meteorites should come from the moon.

The enstatite achondrites consist essentially of nearly pure $MgSiO_3$ though there are variations among them. At least one-third of them are gas-rich, and in all these cases the enstatite or clinoenstatite crystals are embedded in a grayish matrix also consisting mainly of enstatite. In Pesyanoe, the most gas-rich enstatite achondrite, Müller and Zähringer (*9*) have analyzed both the light and the gray phases and have found important chemical differences. The elements Al, K, Ni, and to a lesser degree also C, Ca, and Ti, are very much enriched in the darker phase. An addition of 7 percent of the type of material observed by Surveyor VII to 93 percent of the lighter phase of Pesyanoe matches quite well the composition of the dark phase (Table 4). The contents of radiogenic Ar^{40}, and therefore of K, are highly variable for different enstatite achondrites and also within the same meteorite (*10*), the gas-rich ones being on the high side. This suggests a mixture with a potassium-bearing phase.

Gases of solar composition + Heat

Ca-rich Fe-poor layer
(Possibly Surveyor VII-type material)

↓

Enstatite achondrites
$MgSiO_3$
No FeO

Metal

FeS

Fig. 1. Possible stratification of the primitive lunar surface.

The presence of large amounts of light rare gases in some of the enstatite achondrites is an important fact bearing on their origin. The evidence that these gases are present in nearly solar proportions, first established for Pesyanoe by Gerling and Levskii (*11*) and then by Zähringer (*12*), and the studies by Eberhardt, Geiss, and Grögler (*13*) on the distribution of the gases within the individual grains of the Khor Temiki meteorite have strongly suggested that this gas component is: (i) a distinct component present only in gas-rich meteorites, and (ii) that it has been implanted directly by a corpuscular radiation of a few Kev, such as the solar wind (*14*). The former conclusion has

Table 4. Comparison of the chemical analyses of the light and dark portions of the Pesyanoe meteorite (*12*) to a mixture of Pesyanoe-light with Surveyor-type material ("Fe includes Fe, Ni, Ti, Cr, Mn).

	Percentages (by weight)					
	Si	Mg	Al	Ca and K	"Fe"	C
93% Pesyanoe-light	25.2	24.0	0.04	0.32	0.3	0.05
7% Surveyor VII	1.6	0.3	.69	.77	.4	.08
Totals	26.8	24.3	.73	1.09	.7	.13
Pesyanoe-dark	27.0	22.5	.8	0.87	1.5	.14

been questioned by Zähringer (*15*). However, Marti (*16*) has shown that the isotopic composition of trapped xenon in Pesyanoe is different from that of trapped primordial xenon in meteorites which again supports the view that two different types of trapped gases do exist.

Mazor and Anders (*17*) suggested an alternative explanation to item (ii), namely, an indirect implantation of the solar wind gases by shock. This alternative is not supported by the distribution of Ar after a shock experiment (*18*). Because this question bears on the origin of enstatite achondrites, more conclusive evidence is required. If the solar-type gases have been implanted directly, then the conclusion seems unavoidable that the individual enstatite grains have been irradiated and then have been recompacted to form the meteorite bodies. If, during the time of irradiation the material is on the surface and is being stirred, a mixture with other material is very likely. This process could have occurred only in the presence of a gravitational field.

Reid and Cohen (*5*) concluded that the mineralogy of the enstatite achondrites is consistent with derivation from a melt of chondritic composition which is allowed to differentiate in a gravitational field under quiescent conditions, so that under highly reducing conditions the higher density metal and sulfide phases will tend to segregate downward. This model is similar to the model for the moon and other primitive objects of the early solar system mentioned above (*8*).

There is, however, one severe objection to an origin of the enstatite achondrites from a larger object such as the moon. A mechanism is required to accelerate lunar rocks to the escape velocity of the moon, and at the same time to prevent the rocks from being heated to the point where the solar-type gases would be lost. Therefore, although enstatite achondritic material might be present on the moon, the meteorites may not come from this place. If so, we would have to look for another place in the solar system where a similar differentiation could have occurred. It is very likely that this meteorite class has been much more abundant in the past than what the present-day sampling would show because the clustering cosmic-ray ages around 45 million years for two-thirds of the enstatite achondrites suggest that the last major breakup took place some 45 million years ago (*10*). The criterion of the cosmic-ray age distribution in a discussion of the origin therefore does not apply for this class. Bogard *et al.* (*19*) have found that the K-Ar age of Norton County is high—4.2 to 4.5 billion years—which is compatible with its Rb-Sr age of 4.7 ± 0.1 billion years. High K-Ar ages have been obtained also for other enstatite achondrites (*20*). The differentiation of these meteorites, therefore, can have occurred only very early in the history of the solar system. Also, Hohenberg (*21*) has recently found by the iodine-xenon (I-Xe) dating method that the enstatite achondrite Shallowater and some chondrites began to retain Xe^{129} simultaneously to within 1 or 2 million years.

The enstatite achondrites have been produced somewhere outside the earth by processes very much like those deduced and described above. Hence any evidence for iron-free materials on the moon or elsewhere is of interest. A substantial gravitational field appears to simplify any models devised for the physical location of the necessary physical processes. There is a suggestion that the moon has some material on its surface which approximates one necessary component, that is, iron-free basalt, and possibly a second one, that is, luminescent enstatite. The enstatite achondrites probably do not come from the moon; but some place with a history similar to the moon would be a probable place of origin. The requirements are: (i) a gravitational field sufficient to allow mixing of fragmented material on its surface and a separation of liquid and solid materials of different composition and (ii) a sufficiently low field to permit breakup and dispersion of material into space.

Note added in proof: We are informed by A. Turkevich that the errors in the "Fe" group abundances obtained for the Surveyor VII "rock" and "soil" analyses may overlap.

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References and Notes

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