Abundance of Major Elements

Lunar Rock Compositions and Some Interpretations

Abstract. *Samples of igneous "gabbro," "basalt," and lunar regolith have compositions fundamentally different from all meteorites and terrestrial basalts. The lunar rocks are anhydrous and without ferric iron. Amounts of titanium as high as 7 weight percent suggest either extreme fractionation of lunar rocks or an unexpected solar abundance of titanium. The differences in compositions of the known, more "primitive" rocks in the planetary system indicate the complexities inherent in defining the solar abundances of elements and the initial compositions of the earth and moon.*

This report discusses some of the results, limitations, and interpretations of studies of the textures, mineralogy, and chemical composition of lunar samples "gabbro" 10044, gabbroic "basalt" 10057, and the dust (regolith) 10084,28 (*1*). The chemical data (Table 1) were obtained by gravimetric, photometric, and flame photometric techniques. Amounts of alumina were adjusted on the basis of x-ray fluorescent analyses for Cr and Mn in the R_2O_3 group (Table 1).

Analyses of Apollo 11 samples pose problems as difficult as interpretations of the data. The difficulties in our analytical studies resulted from limitations in size of the samples (4 g), time, and the large amounts of titanium.

Interpretations must be made in ignorance of the interrelations of the lunar rock complexes from which the samples came. Our interpretations are based largely upon, and biased by, our understanding of properties and origins of the more "primitive" terrestrial basalts and gabbros, as well as meteorites, especially the "basaltic" achondritic meteorites (*2*).

The three lunar samples consist largely of the minerals pyroxene, ilmenite, and plagioclase. The pyroxene is a pale pink to beige titaniferous augite, and the plagioclase is bytownite. These same minerals with somewhat analogous diabasic textures are common in terrestrial mafic igneous rocks. One major difference is in the proportions of the minerals. The pyroxene is most abundant. It surrounds and interlocks with the plagioclase in diabasic (ophitic) texture. In terrestrial basalts and gabbros, plagioclase commonly equals or exceeds pyroxene in abundance and forms a crystal mesh that envelops the pyroxene. The second striking difference is the abundance of ilmenite in the lunar samples, a reflection of the large concentrations of titanium and iron. Actually TiO_2 is three to five times more abundant in the lunar samples than in the most titaniferous achondritic meteorite, Angra dos Reis (TiO_2, 2.39).

The lunar rocks also are anhydrous and without Fe^{+3} (Table 1). The vesicular (scoriaceous) texture of lunar "basalt" 10057 indicates that this rock originally contained volatiles, but if water or hydroxyl were components of the volatiles, they were expelled. This vesiculation and degassing of the rock would be possible only if the basaltic melt cooled at or very near a dry lunar surface, presumably in a near vacuum.

All terrestrial basalts—and many meteorites—contain some ferric iron and combined water and have formed under higher fluid pressures. In terrestrial basalts both ferric iron and combined water commonly approach or exceed 1 weight percent (Table 2). The most titaniferous terrestrial basalts common to oceanic and many continental volcanoes are also most enriched in K, Na, ferric iron, and combined water (Table 2 and Fig. 1). These are the alkali-olivine basalts that many petrologists

Table 1. Chemical compositions (weight percent) of Apollo 11 regolith and two rocks. Analyst, C. G. Engel. Al_2O_3 values corrected after x-ray fluorescence analyses for Mn and Cr by J. S. Wahlberg (U.S. Geological Survey, Denver, Colorado).

	10044 Gabbro	10057 Vesicular diabase (basalt)	10084,28 Regolith (dust)
SiO_2	42.01	39.79	41.50
TiO_2	8.81	11.44	7.50
Al_2O_3	11.67	10.84	14.31
Fe_2O_3	.00*	.00 ?	.06 ?
FeO	17.98	19.35	15.62
MnO	.24	.20	.22
MgO	6.25	7.65	7.95
CaO	12.18	10.08	11.84
Na_2O	.48	.54	.48
K_2O	.11	.32	.16
H_2O^+	.00	.00	.00
H_2O^-	.00	.01	.01
P_2O_5	.08	.17	.10
Total	99.81	100.39	99.75

* Actual value, —0.08.

Table 2. Compositions (weight percent) of lunar gabbro, average basaltic achondrite, and common terrestrial basalts. The H_2O^+ content in terrestrial oceanic tholeiitic basalt and alkali-olivine basalt due in part to secondary alteration.

	Apollo 11 gabbro 10044	Basaltic achondrite	Oceanic tholeiitic basalt	Alkali-olivine basalt
SiO_2	42.01	48.51	50.01	48.01
TiO_2	8.81	.48	1.37	2.92
Al_2O_3	11.67	13.04	16.18	15.97
Fe_2O_3	.00	1.11 ?	2.32	3.87
FeO	17.98	15.90	7.07	7.56
MgO	6.25	7.87	7.71	5.26
CaO	12.18	11.00	11.33	9.04
Na_2O	.48	.50 ?	2.79	3.73
K_2O	.11	.08 ?	.22	1.89
H_2O^+	.00	.07	.87	1.33
P_2O_5	.08	.19	.13	.42

infer are derived from depths of 50 to 500 km in the earth's mantle. A minority contain from 4 to 7 percent TiO_2, but invariably other major elements such as Si, Al, and P also exceed lunar concentrations (Table 1). Other compositional differences are even more striking. Many alkali-olivine basalts have appreciable ferric iron, combined water or hydroxyl, high Ba, U, Th, Pb, Zr, Th/U, low K/Rb, and, relative to meteorites, more fractionated abundance distribution patterns of rare earths (*2*).

The far-more-abundant tholeiitic basalts of the ocean crust, ridges, and rises actually appear to be the most "primitive" terrestrial basalts. They show many interesting similarities in composition with basaltic achondrite meteorites and have abundance distribution patterns of rare earths like those of many meteorites (*2*, *3*). Compared to the lunar samples (Table 2) the oceanic tholeiitic basalts contain approximately the same amounts of Mg, Ca, K, P, U, Th, Y, and Yb, but far less Fe, Ti, Ba, and Zr, and higher concentrations of Si, Al, and Na. Curiously, the one major element ratio common to the most "primitive" terrestrial basalts and meteorites is Al/Ca (0.9–1). But in the lunar "basalt" and "gabbro" this ratio is 0.8 and 0.7, respectively. In many ultramafic lavas extruded from the earth's mantle Al/Ca is as low as 0.6.

Variations in ratios such as Al/Ca, Si/Mg, and Na/K and in amounts of Ti and P seem to emphasize the probability that a variety of igneous processes have fractionated all known planetary rocks. The three major igneous processes are (i) partial melting, (ii) fractional crystallization, and (iii) distillation and volatile transfer (*2*). The effects of widely varying pressures, temperatures, and gravity also are obvious.

Hence, if the earth and moon (and meteorites?) have a common, closely related source and origin, several generalizations follow: (i) available earth rocks are too highly differentiated (fractionated) from their initial source rocks to offer major insights into initial earth, or earth-moon, compositions and processes; (ii) the moon is a rock complex with quite divergent rock types; (iii) lunar and meteoritic matter are products of intermediate and divergent environments and processes in planetary evolution; and (iv) solar and cosmic abundances of elements are more uncertain than ever. Perhaps the most provoking questions are whether current studies of the moon will provide important insights into early earth history, the origin of meteorites, and tektites.

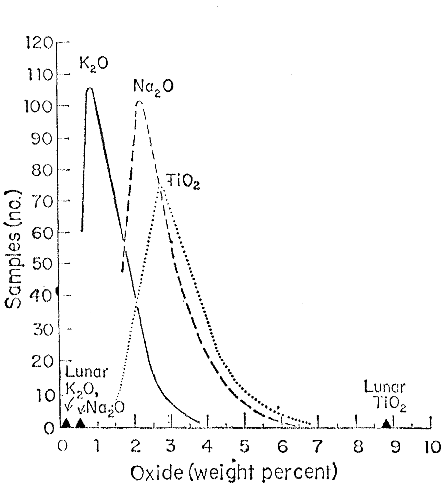

Fig. 1. Frequency distribution of the oxides K_2O, Na_2O, and TiO_2 in alkali-olivine basalts of the oceans. Values for the lunar "gabbro" are plotted as closed triangles on the horizontal coordinate.

A. E. J. ENGEL
Scripps Institution of Oceanography, University of California, San Diego,
CELESTE G. ENGEL
U.S. Geological Survey, Scripps Institution of Oceanography

References and Notes

1. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
2. A. E. J. Engel, C. G. Engel, R. G. Havens, *Bull. Geol. Soc. Amer.* **76**, 719 (1965); P. W. Gast, *Basalts: A Treatise on Rocks of Basaltic Composition* (Interscience, New York, 1967), vol. 1, p. 325; A. E. J. Engel and C. G. Engel, *The Sea* (Interscience, New York, in press), vol. 4.
3. L. A. Haskin, F. A. Frey, R. A. Schmitt, R. H. Smith, *Phys. Chem. Earth* **7**, 167 (1966).
4. Supported by NASA grant NAS 9-7894.

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Oxygen, Silicon, and Aluminum in Lunar Samples by 14 MeV Neutron Activation

Abstract. *Abundances of oxygen, silicon, and aluminum in 27 lunar rocks and* c *aliquants of lunar soil have been determined by 14 MeV neutron activation. Mean abundances and standard deviations of individual abundances (in weight percent) within each type are: type A (2 rocks), 38.5 ± 1.2 oxygen, 18.9 ± 0.8 silicon, and 4.0 ± 0.4 aluminum; type B (7 rocks), 39.4 ± 1.0 oxygen, 18.7 ± 0.8 silicon, and 5.0 ± 0.6 aluminum; type C (18 rocks), 41.1 ± 1.0 oxygen, 19.7 ± 0.7 silicon, and 6.6 ± 0.5 aluminum; soil (3 aliquants), 40.8 ± 1.2 oxygen, 20.2 ± 0.2 silicon, and 7.2 ± 0.1 aluminum. Oxygen abundances are lower than those in most common terrestrial rocks and are comparable to those found in certain types of stony meteorites. From these results the lunar soil is most similar to the type C lunar rocks.*

The elements oxygen, silicon, and aluminum make up over 60 percent by weight of common terrestrial igneous rocks. The abundances of these major elements may be determined precisely and accurately by means of 14 MeV neutron-activation analysis. In addition, the technique is rapid and essentially nondestructive.

All lunar samples and comparator standards were packaged in heat-sealed polyethylene vials under a dry nitrogen atmosphere (*1*). Samples and standards were irradiated at fluxes of 10^8 to 10^9 neutrons cm^{-2} sec^{-1} provided by a Kaman Nuclear A-1250 14 MeV neutron generator. A single sample transfer system employing nitrogen for the propellent gas was used (*2*). Samples and comparator standards were irradiated separately, and radioactivities were counted sequentially. Corrections for variations in the neutron flux were made by use of a BF_3 neutron monitor. Comparator standards for oxygen and silicon were powders and chunks derived from a piece of pure optical lens quartz. Independent standards of primary standard grade $K_2Cr_2O_7$ were also used for oxygen. Standards for aluminum were NBS 91 standard opal glass and NBS 70a standard feldspar. Samples of USGS standard rock BCR-1 and several basalts furnished by NASA were analyzed simultaneously with the lunar samples (*3*).

The nuclear reactions involved are: $^{28}Si(n,p)^{28}Al$, $^{16}O(n,p)^{16}N$, and $^{27}Al(n,p)^{27}Mg$. Corrections for primary interference reactions and gamma-ray spectral interferences have been considered and applied where required. The most important corrections were applied in the determination of aluminum where the $^{30}Si(n,\alpha)^{27}Mg$ reaction is a primary interference reaction and the $^{56}Fe(n,p)^{56}Mn$ reaction provides a spectral interference. No corrections were applied for the primary interference reactions $^{31}P(n,\alpha)^{28}Al$ in the determination of silicon and $^{19}F(n,\alpha)^{16}N$ in the determination of oxygen. The target nuclides are likely to have relatively low abundances in lunar rocks based on preliminary analyses, but data presented