JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. E1, PAGES 1691–1701, JANUARY 25, 1998

Concentrations of radioactive elements in lunar materials

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Abstract. As an aid to interpreting data obtained remotely on the distribution of radioactive elements on the lunar surface, average concentrations of K, U, and Th as well as Al, Fe, and Ti in different types of lunar rocks and soils are tabulated. The U/Th ratio in representative samples of lunar rocks and regolith is constant at 0.27; K/Th ratios are more variable because K and Th are carried by different mineral phases. In nonmare regoliths at the Apollo sites, the main carriers of radioactive elements are mafic (i.e., 6–8% Fe) impact-melt breccias created at the time of basin formation and products derived therefrom.

1. Introduction

The Lunar Prospector mission is expected to return the first global data for the distribution of radioactivity on the surface of the Moon; in addition, data for some or most of the major rock-forming elements will also be obtained [*Feldman et al.*, 1996]. As an aid to interpretation of data obtained from the mission, I have compiled a database of the average concentrations of K, Th, and U in lunar materials as obtained from laboratory analysis of samples; for reference, data for Al, Ti, and Fe are also provided. Although other compilations of elemental concentrations in lunar materials exist [e.g., *Taylor*, 1975, 1982; *BVSP*, 1981; *Heiken et al.*, 1991], such databases were not compiled with the explicit intent of providing self-consistent data for the radioactive elements. The compilation of Table 1 also differs from others in containing a greater variety of compositionally and geographically distinct lithologies than previous compilations in order to show the variation within nominal classes of lithologies (e.g., impact-melt breccias).

2. Methods and Data

The values in Table 1 are averages calculated from data obtained from many sources, a few of which are previous compilations. Most available data for Th and U in lunar samples were obtained by instrumental neutron activation analysis (INAA), a technique that is not highly precise for these elements, particularly at low concentrations. For example, in a routine analysis of an Apollo 16 soil sample (typically, 2.2 μg/g Th and 0.6 μg/g U) in this laboratory, we determine Th to 3% and U to 10% (1σ). For a few lunar samples, Th and U data have been obtained either by mass-spectrometric isotope dilution (MSID) [e.g., *Unruh and Tatsumoto*, 1978], which is highly precise, or by nondestructive gamma ray spectrometry [e.g., *O'Kelley et al.*, 1970; *Keith et al.*, 1972], which has the advantage that large (whole-rock) sample masses were used. Potassium has been determined by a variety of techniques (X ray fluorescence spectroscopy, atomic absorption spectroscopy, INAA, MSID, and electron microprobe analysis of glass).

Paper number 97JE03267.
0148-0227/98/97JE-03267$09.00

For some elements in some lithologies, data are few or lacking. This is particularly true for rare materials (e.g., Luna 16 samples, quartz monzodiorite). For some types of lunar materials, the range in reported concentrations of radioactive elements among different samples exceeds a factor of 2. Such variation occurs in part because analytical uncertainties are relatively large at low concentrations and there may be systematic differences among laboratories. The major cause, however, is sampling error, which is aggravated by the following factors. (1) Masses of lunar samples allocated by NASA for analysis are small; thus masses of analyzed subsamples are typically of the order of 10–100 mg; these subsamples are usually not splits of a larger mass of pulverized sample, as is typical in analysis of terrestrial rocks. (2) Th and U are carried largely in zircon, (3) concentrations of Th and U in lunar zircons are high (7–843 μg/g Th and 46–1069 μg/g U [*Meyer et al.*, 1996; *Wopenka et al.*, 1996]), and (4) the number of zircons in any given analyzed subsample is small. Thus absolute concentrations of Th and U in a sample depend largely on the number of zircons it contains, and any two 100-mg samples probably contain different numbers. For these various reasons, averages presented here are based on as many individual analyses as possible. The listed uncertainties (95% confidence limits, stN^{-2}, where t is the Student's t-factor at $N-1$ degrees of freedom) reflect both the number of analyses (N) and the variance of the values averaged (s^2).

3. KREEP

Approximately 98–99% of the lunar surface crust consists of the minerals plagioclase feldspar, pyroxene (several varieties), olivine, and ilmenite, as well as glass derived from impact melting of rocks bearing these minerals. During formation of the major minerals by crystallization from high-temperature magmas, the radioactive elements K, Th, and U are "incompatible" in that, as large ions, they are not readily accepted into the crystal structure of the minerals which leads to their concentration in the residual liquid phase as crystallization progresses. Only after a large fraction of the system has crystallized do the concentrations of the radioactive elements in the liquid become sufficiently high that K-, Th-, and U-rich accessory minerals form. On Earth, K-feldspar (e.g., orthoclase) is a major rock-forming mineral because the concentration of K in the Earth is sufficiently high. On the Moon, the concentration of K (and other alkali elements) is so low that K-feldspar only occurs in highly evolved rocks, most

Table 1. Average Concentrations of Al, Ti, Fe, and Radioactive Elements in Lunar Materials, With 95% Confidence Limits

	Al, %	Ti, %	Fe, %	K, µg/g	Th, µg/g	U, µg/g	References
Highly Evolved Igneous Rocks							
Alkali anorthosite	16.5 ± 0.8	0.13 ± 0.10	1.5 ± 0.8	2200 ± 600	4.8 ± 3.3	1.1 ± 0.8	J3, L9, M3, S4, W14, W15, W16, W17, W18
Apollo 17 KREEP basalt	7.2 ± 0.4	0.76 ± 0.07	11.5 ± 0.4	2100 (*N*=1)	5.7 ± 0.5	1.39 ± 0.13	B5, J3, S1
Apollo 16 alkali gabbronorite (67975)	9. ± 5.	1.4 ± 1.3	9. ± 3.	9000 ± 7000	8. ± 11.	3. ± 3.	J7
Apollo 15 KREEP basalt	8.4 ± 1.8	1.2 ± 0.1	7.6 ± 0.2	4900 ± 400	11.0 ± 0.8	3.1 ± 0.2	C1, H2, H3, K3, M7, R2, W13, WU
Granite and felsite	6.1 ± 1.5	0.6 ± 0.3	6. ± 3.	35000 ± 11000	36. ± 13.	11. ± 5.	B4, B6, J3, M6, R10, S5, W16, W17
Quartz monzodiorite	6.5 ± 0.8	1.5 ± 0.3	11.0 ± 0.9	14000 ± 3000	40. ± 12.	10. ± 3.	J3, L16, M3, N4, S7
Mafic, KREEP-Rich, Impact-Melt Breccias							
Apollo 15 group D	9.2 ± 0.7	0.92 ± 0.09	7.4 ± 0.4	1400 ± 200	3.4 ± 0.6	0.9 ± 0.3	L16, R9, R11
Apollo 16 group 2DB	11.6 ± 0.4	0.56 ± 0.09	6.2 ± 0.2	1590 ± 110	4.30 ± 0.12	1.14 ± 0.05	K4 and sources therein
Apollo 17 poikilitic	9.6 ± 0.3	0.90 ± 0.04	7.0 ± 0.2	1800 ± 200	4.99 ± 0.08	1.36 ± 0.03	J5, WU
Apollo 17 aphanitic	11.0 ± 1.3	0.47 ± 0.14	6.4 ± 0.3	1500 ± 500	5.2 ± 0.3	1.43 ± 0.10	J5, WU
Apollo 15 group C	9.8 ± 1.3	0.57 ± 0.09	6.3 ± 0.7	2000 ± 400	5.7 ± 0.6	1.7 ± 0.3	L10, L16, R11, R12
Apollo 15 group B	8.8 ± 0.5	0.69 ± 0.09	7.8 ± 0.4	2600 ± 600	7.4 ± 0.8	2.1 ± 0.2	D2, L16, L10, R11
Apollo 16 group 1M	9.0 ± 0.2	0.80 ± 0.02	7.5 ± 0.6	3600 ± 300	8.2 ± 0.8	2.2 ± 0.2	K4 and sources therein
Apollo 17 high-Th	9.1 ± 0.7	1.0 ± 0.2	7.4 ± 0.3	2700 ± 700	8.5 ± 0.8	2.3 ± 0.2	J5, WU
Apollo 16 group1F	10.2 ± 0.5	0.71 ± 0.03	6.5 ± 0.3	2900 ± 300	8.8 ± 0.6	2.24 ± 0.11	K4 and sources therein
Apollo 15 group A	8.6 ± 0.8	1.1 ± 0.2	8.0 ± 0.7	7000 ± 3000	14.5 ± 3.8	4.0 ± 1.0	L16, R11, R12
Apollo 16 ultra-KREEPy	10.2 ± 0.6	1.3 ± 0.7	7.4 ± 0.8	3900 ± 5100	16. ± 8.	5. ± 3.	L15
Apollo 14	8.8 ± 0.3	0.99 ± 0.09	8.3 ± 0.3	5300 ± 1000	17.6 ± 2.0	4.8 ± 0.6	H1, J3, R6, S3, W4, W21
Mare Basalts							
Apollo 15 green glass (15426)	4.04 ± 0.06	0.21 ± 0.02	15.6 ± 0.4	~200 (*N*=2)	0.16 ± 0.13	~0.02 ± (*N*=1)	BV, M9, T1
Apollo 17 very-low-Ti	5.7 ± 0.4	0.5 ± 0.3	13.0 ± 1.3	120 ± 30	0.3 ± 0.2	0.13 ± 0.10	J5, W19
Luna 24 very-low-Ti	6.3 ± 0.3	0.71 ± 0.06	16.6 ± 0.6	220 ± 140	0.3 ± 0.4	0.1 (*N*=1)	B2, B7, L6, M1, U1
Apollo 14 aluminous group 5	6.25 ± 0.19	1.6 ± 0.4	13.6 ± 1.0	530 ± 320	0.37 ± 0.11	n.a.	D1
Apollo 17 high-Ti	4.68 ± 0.05	7.39 ± 0.08	14.80 ± 0.11	464 ± 20	0.4 ± 0.3	0.13 ± 0.09	BV, D3, L3, L5, M7, N2, R3, R7, W7, W9, W10
Asuka-881757	5.3 ± 0.2	1.45 ± 0.1	17.5 ± 0.3	300 ± 30	0.45 ± 0.04	0.2 ± 0.4	J4, W12
Apollo 15 olivine normative	4.64 ± 0.08	1.37 ± 0.06	17.3 ± 0.2	370 ± 20	0.47 ± 0.03	0.136 ± 0.007	C5, H4, K2, M8, O3, R2, T3
Apollo 17 orange glass (74220)	3.43 ± 0.15	5.28 ± 0.09	17.30 ± 0.15	640 ± 90	0.52 ± 0.14	0.16 ± 0.02	D3, K8, K13, N6, N7, P4, R13, WU
Apollo 15 quartz normative	5.0 ± 0.2	1.15 ± 0.07	15.7 ± 0.3	480 ± 40	0.55 ± 0.05	0.149 ± 0.013	C5, H4, K2, M8, O3, R2, T3
Apollo 12 ilmenite	5.0 ± 0.6	2.7 ± 0.3	16.5 ± 0.5	510 ± 30	0.75 ± 0.09	0.23 ± 0.02	N3, O2, R4, R8, W3
Yamato-793169	6.0 ± 0.4	1.3 ± 0.1	16.3 ± 0.4	480 ± 70	0.75 (*N*=2)	0.13 (*N*=1)	J4, W12
Apollo 12 olivine	4.4 ± 0.3	1.66 ± 0.08	16.3 ± 0.2	450 ± 40	0.78 ± 0.06	0.229 ± 0.015	C3, G2, N3, O2, R4, R8, W3
Apollo 11 low K	5.6 ± 0.2	6.2 ± 0.3	14.8 ± 0.4	550 ± 80	0.81 ± 0.15	0.23 ± 0.03	B3, C2, O1, R5, S9, T1
Apollo 14 aluminous groups 3 and 4	6.5 ± 0.3	1.7 ± 0.6	13.1 ± 0.7	640 ± 140	0.8 ± 0.3	n.a.	D1
Apollo 12 pigeonite	5.2 ± 0.2	2.1 ± 0.2	15.4 ± 0.2	570 ± 80	1.03 ± 0.11	0.29 ± 0.03	G2, N3, O2, R4, R8, W3

Table 1. (continued)

	Al, %	Ti, %	Fe, %	K, µg/g	Th, µg/g	U, µg/g	References
			Mare Basalts (continued)				
Luna 16 aluminous	7.16 ± 0.17	2.9 ± 0.3	14.5 ± 0.5	1400 ± 300	1.6 ± 0.7	0.24 (*N*=2)	A1, K10, M2, P2, V1
Apollo 14 aluminous group 2	6.53 ± 0.15	1.24 ± 0.05	13.0 ± 0.4	1090 ± 110	2.1 ± 0.4	n.a.	D1
Apollo 14 aluminous group 1	6.69 ± 0.16	1.34 ± 0.03	12.6 ± 0.4	1310 ± 80	2.32 ± 0.13	n.a.	D1
Apollo 11 high-K	4.35 ± 0.14	6.7 ± 0.3	15.3 ± 0.3	2440 ± 100	2.9 ± 0.3	0.80 ± 0.04	B3, C2, O1, R5, S9, T1, W2
			Ferroan Anorthosite (99% Plagioclase)				
Sample 15415	18.8 ± 0.3	0.012 ± 0.013	0.163 ± 0.013	130 ± 20	0.019 ± 0.012	0.003 ± 0.002	sources in R9
			Feldspathic Breccias				
Apollo 16 ferroan granulitic breccia	16.7 ± 1.6	0.19 ± 0.08	2.5 ± 1.7	430 ± 210	0.18 ± 0.07	0.05 ± 0.02	L11, L13, S6, W18
Apollo 16 impact-melt breccia, group 4	16.5 ± 0.3	0.22 ± 0.03	2.29 ± 0.12	400 ± 70	0.37 ± 0.10	0.11 ± 0.03	K4 and sources therein
Apollo 17 ferroan granulitic breccia	13.7 ± 0.2	0.27 ± 0.10	4.7 ± 0.4	500 ± 130	0.64 ± 0.17	0.15 ± 0.07	H3, J5, L2, L5, L11, W8
Apollo 17 magnesian granulitic breccia	14.2 ± 0.5	0.16 ± 0.09	3.7 ± 0.5	700 ± 500	0.7 ± 0.5	0.23 ± 0.15	B6, H3, J5
Apollo 16 magnesian granulitic breccia	14.0 ± 0.3	0.16 ± 0.03	3.9 ± 0.3	750 ± 150	0.8 ± 0.2	0.25 ± 0.09	L11, L12, L14, S6, W8
Apollo 16 impact-melt breccia, group 3	15.2 ± 0.5	0.20 ± 0.03	3.29 ± 0.12	650 ± 110	1.17 ± 0.04	0.31 ± 0.02	K4 and sources therein
			Mare Regoliths				
Luna 24	6.2 ± 0.2	0.63 ± 0.04	15.4 ± 0.3	210 ± 20	0.36 ± 0.05	0.11 ± 0.03	B7, J6, K11, L7, L17, M1, N5
Apollo 17, most Fe rich (stations 1 and 5)	5.8 ± 0.3	6.0 ± 0.5	13.8 ± 0.2	660 ± 10	0.7 ± 0.2	0.2 ± 0.2	K8, R7, R13
Luna 16	8.28 ± 0.17	2.06 ± 0.07	12.6 ± 0.3	880 ± 70	1.17 ± 0.13	0.31 ± 0.06	G1, H1, J2, K10, L7, P2, T4, V1
Apollo 15, most Fe rich (station 9a)	5.5 ± 0.3	1.11 ± 0.14	15.5 ± 0.4	800 ± 110	1.5 ± 0.3	0.44 ± 0.16	A2, B9, K3, L4, W4, W5, W22
Apollo 11	7.2 ± 0.2	4.46 ± 0.11	12.3 ± 0.2	1120 ± 30	1.94 ± 0.11	0.59 ± 0.13	C2, H1, L1, O1, R5, S9, T1, W2, WU
Apollo 12, most Fe rich (12037 and 12060)	5.7 (*N*=1)	1.5 (*N*=1)	14.6 ± 0.8	1700 (*N*=1)	3.6 ± 0.8	0.9 ± 0.3	W3, WU
Apollo 12, most Th rich (12032 and 12033)	7.4 ± 0.3	1.55 ± 0.11	11.5 ± 0.4	3400 ± 400	9.7 ± 1.3	2.7 ± 0.3	C3, C4, C6, L1, M4, O2, T2, W1, W20, WU
			Highlands Regoliths				
Yamato-86032	15.2 ± 0.4	0.11 ± 0.02	3.32 ± 0.18	160 ± 50	0.21 ± 0.02	0.05 ± 0.01	sources in K6
ALHA81005	13.6 ± 0.3	0.16 ± 0.02	4.25 ± 0.09	190 ± 60	0.28 ± 0.06	0.10 ± 0.04	B8, K1, K9, L8, P1, W11
MAC88105	14.9 ± 0.9	0.14 ± 0.01	3.33 ± 0.10	230 ± 40	0.39 ± 0.03	0.10 ± 0.01	sources in K6
QUE93069	15.2 (*N*=2)	0.14 (*N*=2)	3.40 ± 0.08	250 (*N*=2)	0.52 (*N*=2)	0.14 (*N*=2)	K12, S8
Apollo 16, North Ray crater	15.1 ± 0.6	0.26 ± 0.04	3.22 ± 0.18	670 ± 210	1.0 ± 0.3	0.31 ± 0.10	K5 and sources therein
Luna 20	12.0 ± 0.3	0.30 ± 0.02	5.7 ± 0.2	590 ± 70	1.2 ± 0.3	0.34 ± 0.09	B1, J1, K7, L2, L7, M5, N1, R1, V2
Apollo 16, Cayley plains	14.10 ± 0.11	0.358 ± 0.013	4.30 ± 0.07	980 ± 40	2.22 ± 0.07	0.59 ± 0.02	K6 and sources therein
Apollo 17, most Fe poor (stations 2 and 3)	11.0 ± 0.2	0.92 ± 0.06	6.68 ± 0.07	1330 ± 40	3.0 ± 0.3	0.76 ± 0.06	K8, L5, R7, R13, W6
Apollo 15, most Fe poor (station 2)	9.27 ± 0.14	0.79 ± 0.02	8.96 ± 0.11	1560 ± 40	3.5 (*N*=2)	0.9 (*N*=2)	C5, K2, K3, WU
Apollo 14	9.24 ± 0.06	1.05 ± 0.03	8.08 ± 0.09	4500 ± 130	12.7 ± 0.2	3.50 ± 0.10	H1, P3, R6, S2, S3, W21, WU

Within each class, items are listed in order of increasing Th concentration; n.a., not analyzed.

References: A1, *Albee et al.* [1972]; A2, *Apollo 15 PET* [1972]; B1, *Bansal et al.* [1972]; B2, *Barsukov et al.* [1977]; B3, *Beaty et al.* [1979]; B4, *Blanchard and Budahn* [1979]; B5, *Blanchard et al.* [1975]; B6, *Blanchard et al.* [1977]; B7, *Blanchard et al.* [1978]; B8, *Boynton and Hill* [1983]; B9, *Brunfelt et al.* [1972]; BV, *BVSP* [1981]; C1, *Church et al.* [1972]; C2, *Compston et al.* [1970]; C3, *Compston et al.* [1971]; C4, *Cuttitta et al.* [1971]; C5, *Cuttitta et al.* [1973]; C6, *Cliff et al.* [1971]; D1, *Dickinson et al.* [1985]; D2, *Drake et al.* [1973]; D3, *Duncan et al.* [1974]; G1, *Gillum et*

Table 1. (continued)

al. [1972]; G2, *Goles et al.* [1971]; H1, *Hubbard et al.* [1972]; H2, *Hubbard et al.* [1973]; H3, *Hubbard et al.* [1974]; H4, *Helmke et al.* [1973]; J1, *Jérome and Philipott* [1973]; J2, *Jérome et al.* [1972]; J3, *Jolliff et al.* [1991]; J4, *Jolliff et al.* [1993]; J5, *Jolliff et al.* [1996]; J6, *Jovanovic et al.* [1978]; J7, *James et al.* [1987]; K1, *Kallemeyn and Warren* [1983]; K2, *Keith et al.* [1972]; K3, *Korotev* [1987]; K4, *Korotev* [1994]; K5, *Korotev* [1996]; K6, *Korotev* [1997]; K7, *Korotev and Haskin* [1988]; K8, *Korotev and Kremser* [1992]; K9, *Korotev et al.* [1983]; K10, *Korotev et al.* [1988]; K11, *Korotev et al.* [1990]; K12, *Korotev et al.* [1996]; K13, *Keith et al.* [1974]; L1, *Laul and Papike* [1980]; L2, *Laul and Schmitt* [1973]; L3, *Laul and Schmitt* [1975a]; L4, *Laul et al.* [1972]; L5, *Laul et al.* [1974]; L6, *Laul et al.* [1978]; L7, *Laul et al.* [1981]; L8, *Laul et al.* [1983]; L9, *Laul* [1986]; L10, *Laul et al.* [1988]; L11, *Lindstrom and Lindstrom* [1986]; L12, *Lindstrom and Salpas* [1981]; L13, *Lindstrom and Salpas* [1983]; L14, *Lindstrom et al.* [1977]; L15, *Lindstrom* [1984]; L16, *Lindstrom et al.* [1988]; L17, *Lunatic Asylum* [1978]; M1, *Ma et al.* [1978a]; M2, *Ma et al.* [1979]; M3, *Marvin et al.* [1991]; M4, *Maxwell and Wiik* [1971]; M5, *Morgan et al.* [1973]; M6, *Morris et al.* [1990]; M7, *Murali et al.* [1977]; M8, *Ma et al.* [1978b]; M9, *Ma et al.* [1981]; N1, *Nava and Philpotts* [1973]; N2, *Neal et al.* [1990]; N3, *Neal et al.* [1994]; N4, *Nyquist et al.* [1977]; N5, *Nyquist et al.* [1978]; N6, *Nava* [1974]; N7, *Nunes et al.* [1974]; O1, *O'Kelley et al.* [1970]; O2, *O'Kelley et al.* [1971]; O3, *O'Kelley et al.* [1972]; P1, *Palme et al.* [1983]; P2, *Philpotts et al.* [1971]; P3, *Philpotts et al.* [1972]; P4, *Philpotts et al.* [1974]; R1, *Reed and Jovanovic* [1973]; R2, *Rhodes and Hubbard* [1973]; R3, *Rhodes et al.* [1976]; R4, *Rhodes et al.* [1977]; R5, *Rose et al.* [1970]; R6, *Rose et al.* [1972]; R7, *Rose et al.* [1974]; R8, *Rosholt and Tatsumoto* [1971]; R9, *Ryder* [1985]; R10, *Ryder and Martinez* [1991]; R11, *Ryder and Spudis* [1987]; R12, *Ryder et al.* [1988]; R13, *Rhodes et al.* [1974]; S1, *Salpas et al.* [1987]; S2, *Schnetzler and Nava* [1971]; S3, *Scoon* [1972]; S4, *Shervais et al.* [1984]; S5, *Shih et al.* [1993]; S6, *Stöffler et al.* [1985]; S7, *Taylor et al.* [1980]; S8, *Spettel et al.* [1995]; S9, *Silver* [1970]; T1, *Tatsumoto* [1970]; T2, *Tatsumoto et al.* [1971]; T3, *Tatsumoto et al.* [1972]; T4, *Tera and Wasserburg* [1972]; WU, unpublished data, this laboratory; U1, *Unruh and Tatsumoto* [1978]; V1, *Vinogradov* [1971]; V2, *Vinogradov* [1973]; W1, *Wakita and Schmitt* [1971]; W2, *Wänke et al.* [1970]; W3, *Wänke et al.* [1971]; W4, *Wänke et al.* [1972]; W5, *Wänke et al.* [1973]; W6, *Wänke et al.* [1974]; W7, *Wänke et al.* [1975]; W8, *Wänke et al.* [1976]; W9, *Warner et al.* [1975]; W10, *Warner et al.* [1979]; W11, *Warren and Kallemeyn* [1991]; W12, *Warren and Kallemeyn* [1993]; W13, *Warren and Wasson* [1978]; W14, *Warren and Wasson* [1980]; W15, *Warren et al.* [1981]; W16, *Warren et al.* [1983]; W17, *Warren et al.* [1987]; W18, *Warren et al.* [1990]; W19, *Wentworth et al.* [1979]; W20, *Willis et al.* [1971]; W21, *Willis et al.* [1972]; W22, *Woodcock and Pillinger* [1978].

notably granite. The exceedingly low concentrations of the three elements in ferroan anorthosite (~99% plagioclase; Figure 1) attest to their incompatibility with anorthitic plagioclase, the major mineral of the lunar crust (75–85% by mass).

Concentrations of Th and U in lunar rocks range over about 3 orders of magnitude, and it is clear from inspection of Figure 1 that U/Th ratios are constant over the entire range. Similar behavior is observed among any pair of incompatible lithophile elements. The constancy of interelement ratios for incompatible elements among nearly all lunar rocks that are rich in incompatible elements is taken as one argument that formation of the lunar crust proceeded from crystallization of a global ocean of magma [e.g., *Warren*, 1985] that eventually resulted in a single reservoir, the final dregs of magma ocean crystallization, that was highly enriched in incompatible elements and trapped beneath the feldspathic crust [*Warren and Wasson*, 1979]. The term KREEP was invoked early as a descriptor for a small rock and some glass fragments found in the Apollo 12 regolith that were surprisingly rich in K, REE (rare earth elements), P, and other incompatible elements such as Th and U [*Hubbard et al.*, 1971]. The term is now loosely identified with the magma ocean residuum (*ur*-KREEP of *Warren and Wasson* [1979]), products derived from it, and any material with high abundances of incompatible elements. In practice, KREEP (as a noun) is not well defined and it is not always clear from context whether the term refers to a residual liquid, an igneous rock, a polymict breccia, a composition, or some conceptual chemical component. Nevertheless, most polymict and some igneous rocks from the Apollo missions appear to contain some type of KREEP component, and it is the variation in the relative abundance of that component among polymict samples that is largely responsible for the strong correlations of Figure 1.

Rocks and soils plotting at the low-Th end of the trends, however, may not contain any KREEP component in the sense that they may not contain a component of high-Th material specifically derived from the final stages of crustal differentiation by impact mixing (for polymict samples) or by assimilation (for igneous rocks). Nevertheless, on the Th-U plot, low-Th samples fall along the KREEP mixing trend because, given that lunar rocks are all composed predominantly of the same few minerals (plagioclase, pyroxene, olivine, and ilmenite), there is no mechanism for fractionating Th from U during igneous processes, except at the extreme stages of differentiation. Thus for U, materials deviating from the trend of Figure 1 at low Th concentrations probably reflect analytical uncertainty. For K, in contrast, the greater degree of scatter on the K-Th plot is in part an effect of igneous fractionation because the two elements are carried by different mineral phases, feldspar and zircon. The positive K intercept (~150 μg/g) reflects that potassium is more compatible with major rock-forming minerals than is Th, i.e., during crystallization, potassium is reluctantly accepted by plagioclase feldspar, a major mineral phase in all the rocks of the figure.

For Th-rich igneous melts at the extreme stages of differentiation, Th fractionates from U by formation of zircon and other accessory minerals, e.g., baddeleyite, zirconolite, zirkelite, whitlockite, monazite, and yttrobetafite. The U/Th ratio of any single such mineral grain may deviate substantially from the average of Figure 1 (0.27), depending upon the identity of mineral and when it crystallized [e.g., *Meyer et al.*, 1996]. However, the constancy of the ratio in bulk-rock analyses indicates that no significant spatial segregation of Th from U occurs, even among small volumes corresponding to 10–100 mg of analyzed sample. Lunar igneous systems are almost entirely solidified by the time Th-rich accessory minerals form, hindering segregation, and there is no mechanism (e.g., hydrothermal fluids) to redistribute the elements after solidification.

4. Classes of Lunar Materials

4.1. Rocks

The data of Table 1 are divided into several classes or categories of materials. Rocks in the category "highly evolved igneous rocks" all have high concentrations of radioactive elements because they crystallized from liquids from which a large volume of material had already crystallized. The class includes the two known types of KREEP basalt, i.e., lithologies of KREEP composition that are believed to be of igneous origin. Plutonic igneous rocks include alkali anorthosites (mostly from Apollo 12 and 14), alkali gabbronorite (from Apollo 16), granite (also called felsite), and related quartz monzodiorite and quartz monzogabbro. Alkali anorthosites are rare but are the most potassium rich of lunar an-

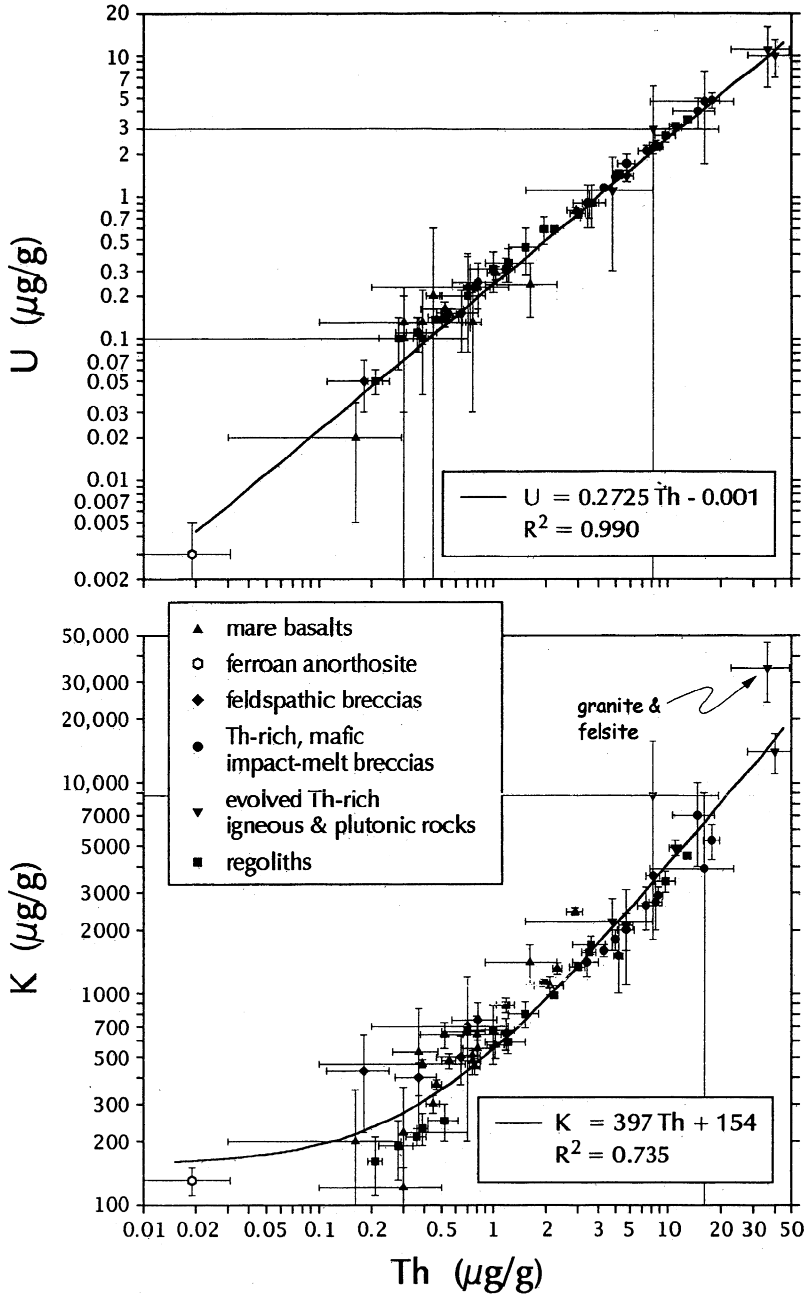

Figure 1. Variation in concentrations of U and K with Th in lunar materials; each point represents one of the line items of Table 1, and the error bars represent the listed uncertainties (for those few data where no uncertainty is given in Table 1, a conservative value was estimated). In both plots, the diagonal line (the K-Th line is straight on linear axes) represents a linear least squares fit to the data where each concentration value is weighted according to its uncertainty (method of *York* [1969]). The Th-U line passes through the origin, within error.

orthosites. Granite is the only known lunar rock with a high abundance of potassium feldspar, which accounts for its anomalous enrichment in K with respect to Th (Figure 1). Because evolved plutonic rocks are typically coarse grained and samples usually occur only as small clasts in breccias or in the regolith, concentrations of incompatible elements are highly variable from sample to sample. For example, Th concentrations range from 18 to 66 µg/g ($N = 10$) among the granite and felsite samples upon which the mean of Table 1 is based. Highly evolved igneous rocks are rare in the lunar sample collection and, except for KREEP basalt [*Spudis and Hawke*, 1986], there is no reason to expect that any extensive area of the lunar surface is dominated by such rocks.

The most common, Th-rich, nonmare rocks of the Apollo collection are not KREEP basalts, but mafic impact-melt breccias ("Fra Mauro basalts," "LKFM," etc.). Such breccias (and their reworked derivatives, e.g., glassy breccias and agglutinates) constitute 29% of the regolith of the Cayley Plains at the Apollo 16 site [*Korotev*, 1997], more than 50% of the light mantle deposit at Apollo 17 [*Jolliff et al.*, 1996], and probably a significant fraction of the Apennine Front at Apollo 15. Because they are considerably more abundant than KREEP basalts, mafic melt breccias are the principal carriers of the radioactive elements in highlands regoliths from the Apollo landing sites. They are also the most mafic (Fe rich) of the common nonmare lithologies in the regolith (Figure 2). Most mafic impact-melt breccias are probably products of basin-forming impacts, and it is generally believed that the high concentrations and KREEP-like relative abundances of incompatible elements in the breccias occur because some type of igneous KREEP material occurred in the target area of the impacts [*Ryder and Wood*, 1977; *Spudis and Davis*, 1986], i.e., the breccias are physical mixtures that include some igneous KREEP component. At the Apollo 15, 16, and 17 sites, different compositionally and petrographically distinct groups of mafic melt breccias are recognized [*Spudis and Ryder*, 1981; *Ryder and Spudis*, 1987; *Korotev*, 1994, *Jolliff et al.*, 1996], and these various groups are each tabulated separately in Table 1. The unusually high uncertainties for K, Th, and U in the rare "ultra-KREEPy" Apollo 16 melt breccias [*Lindstrom*, 1984] result because the melt breccia contains clasts of K- and Th-rich alkali gabbronorite, only seven small (3–32 mg) samples of the breccia have been analyzed, and concentrations of the elements were consequently highly variable among the samples.

Data for most known types of mare basalt are listed in Table 1. Included are data for the Apollo 15 green and Apollo 17 orange pyroclastic glasses and two lunar meteorites, Asuka-881757 and

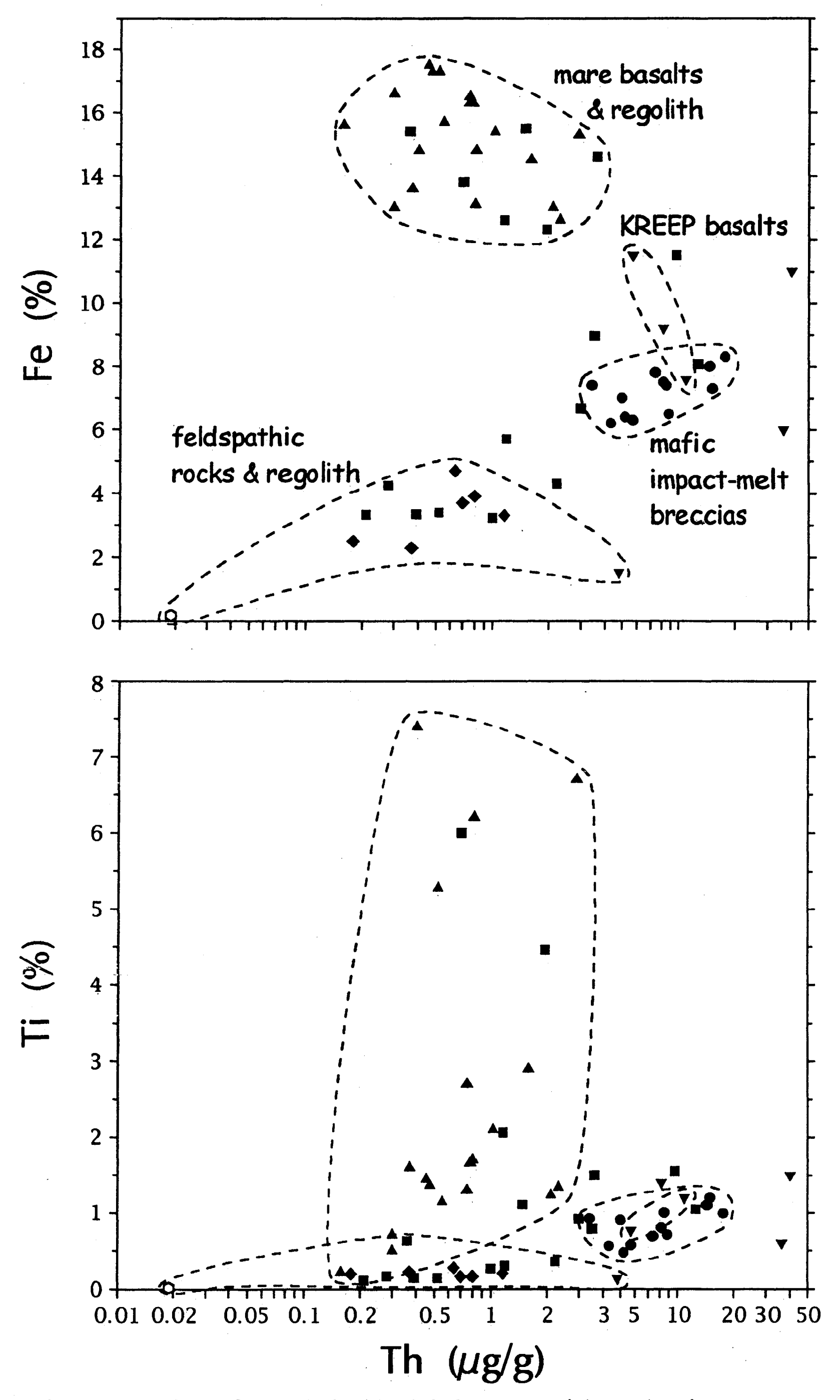

Figure 2. Variation in concentrations of Fe and Ti with Th in lunar materials; each point represents one of the line items of Table 1. See Figure 1 for symbol key.

Yamato-793169, which are coarse-grained, low-Ti basalts that were ejected from an unknown impact site on the Moon. Several types of mare basalt (Apollo 11 high-K basalt, Luna 16 aluminous basalt, Apollo 17 orange glass) appear to be significantly enriched in K with respect to Th (Figure 1). Although the aluminous Apollo 14 samples [*Dickinson et al.*, 1985] (all of which occur only as small clasts in breccias and in the regolith) are usually classified as "mare basalts," it is not known with certainty that they are actually extrusive volcanic rocks derived from a visible maria. The Prospector mission will provide an opportunity to seek a potential source region for such basalts, although the search will be complicated because the maria are contaminated by aluminous highlands material (below). Most Apollo mare basalts have low to medium concentrations of radioactive elements. Only the aluminous Apollo 14 basalts and the anomalous Apollo 11 high-K basalts have moderately high concentrations, although there is evidence in the data from the Apollo orbiting gamma ray experiments that some young flows in Mare Imbrium [*Schaber*, 1973] are also rich in Th [*Etchegaray-Ramirez et al.*, 1983].

The "feldspathic breccias" of Table 1 include granulitic and impact-melt breccias with compositions corresponding to noritic and troctolitic anorthosites. Such rocks (sometimes misleadingly called gabbroic anorthosites) are among the most common of the highly feldspathic crystalline rocks in the highlands. Among granulitic breccias, there is a dichotomy in Mg/Fe ratio [*Lindstrom and Lindstrom*, 1986]. Ferroan breccias have Mg' (mole percent Mg/[Mg+Fe]) of 61 ± 5, whereas magnesian breccias have Mg' of 75 ± 2. Highly feldspathic breccias consistently have low concentrations of radioactive elements; among all feldspathic rocks, only the rare alkali anorthosites discussed above have high concentrations of radioactive elements. Some feldspathic rocks have moderate levels of radioactive elements, but these are usually complex breccias consisting of feldspathic, low-Th components like anorthosite and granulitic breccias mixed with mafic, high-Th, impact-melt breccia (e.g., the feldspathic fragmental breccias of Apollo 16 [*Lindstrom and Salpas*, 1983; *Stöffler et al.*, 1985]).

At the Apollo 16 site samples of ferroan anorthosite consisting of ~99% plagioclase are common, although it is likely that this is an artifact of sampling and that typical massive ferroan anorthosite contains a higher proportion of mafic minerals (e.g., 8% by mass [*Warren*, 1990]). Ferroan anorthosite has the lowest concentrations of Th and U among lunar rocks and, as a consequence, precise data are scarce. The best data are from the first large sample studied, Apollo 15 sample 15415, and the data of Table 1 are based on that sample. Samples of ferroan anorthosite that are more mafic than 15415 tend to have higher concentrations of Th and U. The ferroan granulitic breccias and group-4 impact-melt breccia of Apollo 16 (~88% plagioclase, i.e., ~12% mafic minerals), which probably consist largely of brecciated ferroan anorthosite, provide an upper limit (Table 1).

Table 1 does not contain data for mafic, Th-poor plutonic rocks such as norite, troctolite, and dunite, in part because of an inadequate database and also because it is not clear that our few samples of such rocks are adequately representative with respect to K, U, and Th. For the only well-studied dunite sample, 74215–7, concentrations of radioactive elements are very low, as we would expect for a rock composed almost entirely of olivine. The concentration of K is about 25 µg/g [*Laul and Schmitt*, 1975b] and U is in the 3–6 ng/g range [*Higuchi and Morgan*, 1975]. Troctolite and norite samples from Apollo 15 and 17 are believed to have assimilated some type of KREEP component during the processes that led to their formation [*Norman and Ryder*, 1980; *Warren*, 1985]. As a consequence, they contain higher concentrations of KREEP-related elements than we would expect for cumulate, mafic rocks. Apollo 17 norites, for example, average about 1.8 µg/g Th and 0.5 µg/g U [*Warren and Wasson*, 1978]. Any norites and troctolites that might occur distant from the Imbrium basin may contain substantially lower concentrations of radioactive elements.

4.2. Regolith

Regolith samples most closely represent material seen from orbit. Data presented here are for <1-mm fines from the Apollo missions and <0.25-mm fines from the Russian Luna missions. For Apollo 11, Apollo 14, and the three Luna missions, all soil samples from each mission are very similar to each other in composition and the average of Table 1 represents a "site mean" based on available data for all samples (for each of the Luna missions, however, only a single core sample was taken, so any lateral variation in regolith composition would not have been observed). For Apollo 12 and the more geologically complex sites, Apollo 15, 16, and 17, regolith composition varies with sample location. For these sites, two averages representing the compositional extremes are listed. The Apollo 15 and 17 missions visited sites at the interface between the maria and highlands. For these two sites, the most Fe-poor and Fe-rich extremes in soil composition are presented. The most Fe-rich extremes occur at station 9a at Apollo 15 and stations 1 and 5 at Apollo 17; these soils consist mainly of comminuted mare basalt and provide estimates of the composition of the local mare regolith at points distant from the mare-highlands interface. The most Fe-poor extremes occur at station 2 on the Apennine Front at Apollo 15 and stations 2, 2a, and 3 on the light mantle deposit near the South Massif at Apollo 17; these soils contain little mare material and provide estimates of the composition of local highlands regolith at points distant from the mare-highlands interface.

Note that all soils from the maria are poorer in Fe and richer in Al than the corresponding mare basalts, reflecting the presence of highland material in the soil. At the Apollo 11 site, for example, mass balance for Fe requires that ~25% of the regolith is highland material [e.g., *Rhodes*, 1976]. The nonmare components of Apollo 12 soils include one or more with KREEP and alkali-rich compositions. Samples collected near Surveyor crater on the Apollo 12 mission have the lowest abundance of nonmare components (~30% [*Korotev and Rockow*, 1995]), whereas those collected to the east of the crater are dominated by the Th-rich, nonmare components [*Hubbard et al.*, 1971; *Wänke et al.*, 1971; *Korotev and Rockow*, 1995]. The two extreme compositions are given in Table 1. Among mare regolith samples collected in the interior of a maria, those from Luna 24 appear least contaminated with highlands material.

The Cayley plains at (and to the west of) the Apollo 16 site are represented by the mature soils from the central and southern part of the site [*Korotev*, 1997]. The regolith of the Cayley plains, like the nonmare regoliths of Apollo 15 and 17, is atypical of the lunar highlands because of the high proportion of Th-rich, mafic impact-melt breccias. Soils collected on the ejecta deposit of North Ray crater at the Apollo 16 site contain a lower proportion of mafic impact-melt breccia and are consequently poorer in Fe and Th than the soils of the Cayley plains [*Korotev*, 1996]. The North Ray crater soils most likely represent surface material to the east of the Apollo 16 site [*Stöffler et al.*, 1985], more distant from the Imbrium basin.

The first four listings under "highland regoliths" are feldspathic lunar meteorites that are regolith or fragmental breccias from unknown locations, although they probably derive from three or four different "blast off" sites [*Warren*, 1994]. Because the regoliths represented by the feldspathic lunar meteorites contain little or no component of the mafic impact-melt breccia, the meteorites all have low concentrations of Fe and radioactive elements compared to nonmare regoliths from the Apollo sites and to regions near the Imbrium basin as detected by the Apollo orbiting gamma ray experiments [*Metzger et al.*, 1977]. These differences are taken as evidence that the meteorites derive from locations distant from the Apollo sites and thus best represent, among lunar samples, typical lunar surface highlands [*Palme et al.*, 1991; *Korotev et al.*, 1996]. Data for Apollo regolith breccias and fragmental breccias are not tabulated because such breccias are similar in composition to the soils.

5. Remote Sensing

Lunar rock types cannot be distinguished on the basis of radioactivity alone, but additional data for at least some major elements can help resolve the ambiguities (Figure 2). The surface of the Moon is covered by regolith, and regolith dominated (>90%) by a single lithology is rare even among the small samples collected by the Apollo astronauts. Thus, on the size scale obtainable from orbit, all "samples" will be mixtures of several rock types.

A significant and tantalizing result of the Apollo orbiting gamma ray experiments, which covered less than 20% of the lunar surface, was that KREEP was concentrated in the vicinity of Mare Imbrium and Oceanus Procellarum [*Metzger et al.*, 1977]. Thus, even if the lithologies that carry the KREEP signature cannot be identified unambiguously from orbit, a global map of lunar radioactivity will allow us to test hypotheses suggested by the Apollo data. The most important tests will address whether KREEP was of global or localized occurrence prior to basin formation. If KREEP was globally distributed at depth, as is envisioned by simple magma ocean scenarios [e.g., *Heiken et al.*, 1991, Figures 2.5b and d], then Th enrichments should occur in the continuous ejecta deposits of some large basin other than Imbrium. If, instead, KREEP was not global in occurrence and the Imbrium impactor happened to strike that anomalous region of the crust where KREEP was concentrated, then the present distribution of radioactivity on the surface of the Moon is largely dominated by the original shape of that region and the distribution of Imbrium ejecta [*Haskin*, 1998].

Acknowledgments. This work was supported by the National Aeronautics and Space Administration through grant NAGW-3343. Helpful comments by B. L. Jolliff and L. A. Haskin and reviews by G. J. Taylor and M. J. Drake improved the manuscript.

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(Received August 11, 1997; revised November 6, 1997; accepted November 11, 1997.)