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Chemical Composition of Lunar Meteorites and the Lunar Crust

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Abstract—The paper presents the first analyses of major and trace elements in 19 lunar meteorites newly found in Oman. These and literature data were used to assay the composition of highland, mare, and transitional (highland–mare interface) regions of the lunar surface. The databank used in the research comprises data on 44 meteorites weighing 11 kg in total, which likely represent 26 individual falls. Our data demonstrate that the lunar highland crust should be richer in Ca and Al but poorer in mafic and incompatible elements than it was thought based on studying lunar samples and the first orbital data. The Ir concentration in the highland crust and the analysis of lunar crater population suggest that most lunar impactites were formed by a single major impact event, which predetermined the geochemical characteristics of these rocks. Lunar mare regions should be dominated by low-Ti basalts, which are, however, enriched in LREEs compared to those sampled by lunar missions. The typical material of mare–highland interface zones can contain KREEP and magnesian VLT basalts. The composition of the lunar highland crust deduced from the chemistry of lunar meteorites does not contradict the model of the lunar magma ocean, but the average composition of lunar mare meteorites is inconsistent with this concept and suggests assimilation of KREEP material by basaltic magmas. The newly obtained evaluations of the composition of the highland crust confirm that the Moon can be enriched in refractory elements and depleted in volatile and siderophile elements.

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INTRODUCTION

The composition of the lunar crust and the pristine lunar material provides record of the processes that formed it and, hence, contains information on the origin and evolution of the Earth's satellite (see, for example, Taylor, 1982). The understanding of these processes is crucial for the reconstruction of the early evolutionary stages of the Earth, whose traces are practically completely obliterated by younger geological processes. Information on the crustal material of the Moon is currently based mostly on data of remote sensing and on the results obtained on lunar samples collected by the Apollo and Luna missions. Remote sensing data cover the virtually whole surface of the Moon but are characterized by a low accuracy and provide information on the distribution of only some chemical elements (see, for example, Gillis et al., 2004). Lunar rock samples brought to the Earth were examined with the application of a broad spectrum of laboratory analytical techniques and were the main source of principally important factual data on the Moon. However, these samples were collected only on the near side of the Moon and only within territories that were of the greatest interest from the geological standpoint and were suitable for the landing of spacecrafts.

Estimates of the composition of the lunar crust available from the literature are based on various approaches and assumptions. For example, the composition of the crust obtained by Turkevich (1973) is a simple average of the chemical compositions of regolith samples collected at 12 landing sites. The estimates of the composition of the crust before the intense bombardment presented in (Stöffler et al., 1985; Korotev, 1996, 1997) are based on the chemistries of Apollo 16 samples and the geological analysis of the Apollo 16 landing site. The now most popular composition of the lunar highland crust was proposed by Taylor (1982), who assumed concentrations of SiO_2 (45 wt %) and Na_2O (0.45 wt %) equal to the typical concentrations of these components in highland rocks. The MgO and Al_2O_3 contents were taken from orbital data (the latter is calculated from the measured Al/Si ratio). The FeO concentration was found from the MgO/FeO ratio of highland rocks, and the CaO concentration was calculated by difference to 100 wt %. The concentrations of trace and incompatible elements and

K were estimated from their correlations with Th in lunar samples and orbital data on the Th concentrations in surface lunar rocks. The Cr, V, and Sc contents were obtained from the Fe/Cr, Cr/V, and Cr/Sc ratios of highland rocks.

Lunar meteorites are a new type of lunar samples accessible for laboratory examination. These are rock fragments that were ejected from the Moon by impact events and reached the Earth's surface. The first lunar meteorite Y 791197 was found in the ice of Antarctica by the 20th Japanese Antarctic Expedition in November 1979. Because of its apparent similarity with some chondrites, this sample has long been left unexamined, and the first lunar meteorite is considered to be the ALHA 81005 meteorite found in 1982 in Antarctica (Takeda et al., 1986). The number of lunar meteorites found on the Earth as of yet is fairly significant. A random sampling of the Moon's surface by impacts implies that lunar meteorites are representative samples of lunar rocks (from both its near and the far side) and thus can be utilized to assay the composition of the lunar crust. This approach was first proposed in (Palme et al., 1991) immediately after the first finds of lunar meteorites in Antarctica and was recently applied in (Korotev et al., 2003), in which data on eleven lunar meteorites of highland origin were summarized. Numerous lunar meteorites found over the past years in desert areas throughout the world provide possibilities for the further development of this approach. Our research was aimed at evaluation of the composition of the lunar crustal material with the use of this approach and data on lunar meteorites recently found in Oman and described in the literature.

METHODOLOGY

The evaluation of the lunar crust composition on the basis of the chemistry of lunar meteorites should be valid if the number of lunar meteorite finds of is proportional to the number of their falls on the Earth and the number of the impact events that ejected these meteorites, with the random distribution of these events over the Moon's surface is considered undoubted (see, for example, Bazilevskii et al., 1983; Melosh, 1989). Then the abundances of certain rock types in the lunar crust should correspond to the proportions of the respective meteorite types. An analogous methodology, which was justified by Chayes (1956), is applied in determining the modal composition of rocks with the use of point counters. However, because of the fragmentation of meteoritic bodies, the number of meteorite falls is always smaller than the number of meteorite finds, i.e., many meteorite finds are paired (fragments of the same fall). At the same time, one impact event can eject a number of rock fragments (launch pairing), which would reach the Earth at different times and should be regarded as different falls. This violates the direct dependence between the number of impacts on the lunar surface that eject lunar meteorites and the number of their falls onto the Earth. It is difficult to define pairing, particularly the launch pairing. Some approaches to solve this problem were proposed in (Nishiizumi et al., 1996; Thalmann et al., 1996; Eugster and Polnau, 1996; Nazarov et al., 2003; and others) and made it possible to group finds into individual falls, which are used to average the chemical composition. However, the uncertainties of this grouping can produce shifted mean values of element concentrations.

An alternative approach can be based on the assumption that the mass ratios of various types of lunar crustal rocks are proportional to the mass ratios of the corresponding lunar meteorites. This means that a fragment of larger size could be more probably ejected from a petrographic province of greater area or that the greater number of impact events in the territory of this province should have produced a greater mass of lunar meteorites. It is assumed in this approach that the composition of the lunar crust corresponds to the weighted mean composition of lunar meteorites (with regard for their masses), which eliminates the problem of pairing. However, this approach is more sensitive to the statistical volume of the population, because random variations in the masses of meteorites can be significant (the distribution of the masses is of lognormal character), which diminishes the accuracy and can result in a shift of the estimated averages. In this sense, for example, the greatest lunar meteorite Kalahari 002 (13.5 kg) can be regarded as found "prematurely", because it differs from the general distribution of lunar meteorites by mass. An analogous problem may be encountered when the modal composition of rocks is determined by linear counters and, consequently, can yield undistorted estimates only when the statistics is high enough (Chayes, 1956). In our research we utilized both approaches, which were regarded as independent.

The statistical volume of the population of lunar meteorites is still not very significant and includes 84 registered lunar meteorites with a total mass of 26.8 kg. Nevertheless, this is much greater than the amount collected by the -Luna- missions (close to 300 g), although is lesser that the mass of the -Apollo- samples (380 kg). It was demonstrated that the lunar meteorites were ejected from the Moon at <10 Ma (Nishiizumi et al., 1996; Thalmann et al., 1996) by small impact events producing craters of <10 km in diameter (Semenova et al., 1992, 1993; Warren, 1994; Nazarov et al., 2003). The maximum depth of excavation for a 10 km crater is about 1 km (Melosh, 1989). Thus, the population of lunar meteorites characterizes the state of the lunar crust over the past 10 Ma to a depth of less than 1 km. For comparison, the orbital estimates of the chemical composition pertain to a regolith layer of a few dozen centimeters thick (Taylor, 1982).

The limited character of the lunar meteorite population in terms of statistical volume and "sampling" depth of the lunar crust is compensated by their compositional representativeness. Lunar meteorites can be classified into three groups (see, for example, Korotev et al., 2003): (1) highland feldspathic, (2) mare basaltic, and (3) mixed. The latter group includes meteorites containing both highland and mare and/or KREEP material. Most lunar meteorites, particularly highland ones, are impact breccias, which were formed by mixing of various types of lunar rocks during impact processes. Compared to magmatic rocks, whose clasts are present in the breccias, the latter are thought to represent better mineral and chemical compositions of a lunar terrain from which they were ejected. Lunar meteorites contain practically all rock types known in Apollo and Luna samples, including such rare components as monzodiorites (Semenova et al., 1992, 1993), granites, picrite glasses, and spinel cataclasites (Demidova et al., 2003a, 2003b). The find of the latter rocks is of principal importance, because they indicate that lunar meteorites contain a deep-seated component of the lunar highland crust that was ejected to its surface levels as a result of the intense bombardment at approximately 4 Ga. It is thus reasonable to believe that the compositional parameters of lunar meteorites characterize the lunar crustal composition not worse than samples collected on the Moon.

A significant problem is the weathering of meteorites in deserts, a process that modifies the concentrations of some elements in them (for example, the concentrations of Ba, Sr, Sb, As, U, and others) compared to the initial lunar concentrations (see, for example, Nazarov et al., 2003). However, the initial concentrations of these elements can be estimated using correlations between their concentrations and the contents of other elements (whose concentrations are not modified during weathering) that were reliably established for lunar samples.

SAMPLES AND METHODS

Lunar meteorites from Oman. As of now, more than 40 lunar meteorites (3782 g in total mass) were found in Oman, mostly in its Dhofar province. These finds are thought (Nazarov et al., 2003) to represent seven individual falls of lunar meteorites: (1) Dho 025, 301, 304, and 308; (2) Dho 081 and 280; (3) Dho 0.26; (4) Dho 302, 303, 305, 306, 307, 309, 310, and 311; (5) Dho 489; (6) Dho 490; and (7) Dho 287. All of these meteorite groups differ in chemical composition, mineralogy, and degree of their weathering and originate from highland terrains, except Dho 287, which is a mare basalt.

The recently found Dho 730 and Dho 731 meteorites most probably belong to group 4, because they were found in the vicinity of the meteorites of this group and have similar chemistry, mineralogy, and lithology (Nazarov et al., 2004). It is worth mentioning, however, that this group possibly comprises more than one fall. For example, Dho 302 and Dho 305 show certain geochemical differences (Nazarov et al., 2002, 2003a, 2003b; Demidova et al., 2003c), and Dho 303 differs from all other meteorites of this group in concentrations of noble gases and can represent still another fall (Shukolyukov et al., 2004). Nevertheless, the unpaired character of these meteorites is not proved, and they are regarded as fragments of a single meteor shower.

The Dho 733 and Dho 925 meteorites, which were also recently found in Oman, can be ascribed to other independent falls. The former meteorite is a highland granulitic breccia (Russell et al., 2003) and differs from other lunar highland meteorites, which are mostly impact-melt breccias (Lindstrom et al., 1985; Greshake et al., 2001; Nazarov et al., 2002, 2004; Demidova et al., 2003b, 2003c). The Dho 925 meteorite as well as Dho 960 and Dho 961 paired with it (Demidova et al., 2005) are enriched in very low-Ti basalt (VLT) material, and we classify them as mixed meteorites.

Thus, at least nine independent falls can be now recognized in Dhofar, Oman. Our data on the chemical composition of the Dhofar lunar meteorites are summarized in Table 1, and the weighted mean compositions of paired finds are listed in Table 2.

Methods. Slices of ~1 g mass were sawn from the Dho 025, Dho 026, Dho 280, and Dho 287 meteorites. These slices were then crushed to a powder in an agate mortar, and the powders were analyzed for Si, Ti, Al, Cr, Fe, Mn, Mg, and Ca by conventional XRF and ICP-AES techniques. Alkalis were determined by atomic absorption in separate portions of the material. Dho 280 was analyzed only by XRF. Trace element concentrations were determined in 20-mg aliquots by INAA.

The concentrations of trace elements in the small Dho 301, Dho 311, Dho 730, Dho 731, Dho 733, and Dho 925 meteorites were determined by INAA in 20 mg fragments. As estimates for the bulk compositions of these meteorites (except Dho 733), we assumed the composition of the impact melt matrix determined in thin sections by an electron microprobe with a beam defocused to 7–10 μm at an accelerating voltage of 15 kV and a beam current of 10 nA. The composition of the impact melt matrix was determined for each meteorite as an average of a few dozen analyses. The Fe content of the matrices determined by this way is in good agreement with the Fe concentrations measured by INAA in 20-mg fragments. This means that matrix compositions closely approximate the bulk compositions of the meteorites. The composition of the Dho 733 granulitic breccia was calculated from the its modal composition and the average compositions of its mineral phases.

Data on the compositions of other lunar meteorites were compiled from (Koeberl et al., 1990, 1991, 1993, 1996; Lindstrom et al., 1990, 1991a, 1991b, 1995; Palme et al., 1983, 1991; Warren and Kallemeyn, 1987, 1989, 1991, 1993; Yanai, 1990; Hill and Boynton, 2003; Hill et al., 1991; Korotev et al., 1996, 2003, 2004; Semenova et al., 2000; Zipfel et al., 1998; Delaney, 1989; Dreibus et al., 1996; Jolliff et al., 1991, 1998, 2003;

Table 1. Chemical composition of lunar meteorites from Dhofar, Oman

Component	Dho 025	Dho 026	Dho 280	Dho 301	Dho 302	Dho 303	Dho 304	Dho 305	Dho 306	Dho 307
SiO_2	43.9	44.3	44.4	44.1	44.5	44.0	45.0	43.9	44.0	43.8
TiO_2	0.30	0.22	0.19	0.36	0.27	0.15	0.34	0.16	0.15	0.09
Al_2O_3	26.7	29.6	30.7	28.6	28.1	29.7	25.3	28.5	27.2	30.8
Cr_2O_3	0.10	0.08	0.04	0.10	0.09	0.06	0.17	0.10	0.12	0.09
FeO	4.98	4.06	3.40	4.27	4.02	3.20	5.71	3.69	4.00	2.58
MnO	0.08	0.06	0.05	0.07	0.06	0.06	0.12	0.07	0.05	0.05
MgO	6.53	3.92	2.53	4.83	4.84	4.97	7.09	6.08	7.55	4.06
CaO	16.1	17.0	18.2	16.5	16.5	16.9	14.8	15.9	15.5	17.3
Na_2O	0.28	0.24	0.39	0.39	0.41	0.34	0.37	0.36	0.33	0.36
K_2O	0.07	0.08	0.02	0.04	0.09	0.01	0.04	0.02	0.04	0.01
P_2O_5	0.08	0.05	0.06	0.07	0.12	0.03	0.07	0.04	0.07	0.02
H_2O	0.27	0.57	0.05	–	–	–	–	–	–	–
Total	99.3	100.2	100.1	99.3	99.0	99.4	99.0	99.2	99.0	99.2
Sc	10.2	8.0	5.6	9.97	5.91	5.42	9.3	7.2	5.8	5.6
Cr	674	497	287	651	492	460	591	522	675	450
Co	16.5	14.0	9.1	13.6	18.5	12.5	18.1	14.3	14.4	10.8
Ni	200	170	170	260	190	60	200	60	230	30
Sr*	2010	175	220	1710	995	530	3120	1280	920	290
Zr	62	27	25	27	23	25	65	44	24	30
Ba*	340	30	25	375	265	315	2302	1390	690	100
La	3.6	2.9	1.6	3.68	2.36	1.04	4.1	0.73	1.13	1.2
Ce	8.6	6.6	3.3	8.4	5	2.19	9.0	1.7	2.38	2.4
Nd	5.2	3.8	2.0	4.6	2.8	1.12	4.7	1.3	1.29	1.2
Sm	1.5	1.1	0.60	1.28	0.8	0.33	1.3	0.46	0.38	0.37
Eu	1.3	1.1	0.80	0.74	0.9	0.81	0.74	0.94	0.72	0.83
Tb	0.35	0.25	0.14	0.24	0.18	0.066	0.30	0.11	0.087	0.08
Yb	1.2	0.85	0.47	0.63	0.65	0.19	1.1	0.35	0.34	0.28
Lu	0.21	0.15	0.08	0.099	0.11	0.033	0.18	0.06	0.059	0.05
Hf	1.3	0.86	0.49	0.79	0.8	0.24	0.79	0.67	0.36	0.28
Ta	0.1	0.24	0.35	–	–	–	–	0.39	–	0.31
Ir	7.2	6.3	9.9	5.6	5.1	9.3	20	10.3	5.9	–
Au	3	9	5	4	–	1	13	3	5	6
Th	0.8	0.36	0.33	0.66	0.43	0.59	0.50	0.15	0.28	0.15
U*	0.27	0.2	–	–	–	0.54	–	–	0.34	0.52

Table 1. (Contd.)

Component	Dho 308	Dho 309	Dho 310	Dho 311	Dho 730	Dho 731	Dho 733	Dho 925	Dho 950
SiO_2		44.3	43.6	44.1	43.7	43.4	45.5	45.4	43.9
TiO_2		–	0.12	0.13	0.17	0.14	0.33	0.27	0.05
Al_2O_3		29.1	29.2	29.9	27.6	28.2	28.5	22.0	33.1
Cr_2O_3		0.10	0.05	0.08	0.09	0.08	0.08	0.20	0.02
FeO	5.41**	3.09	2.84	3.17	4.13	3.52	3.08	8.77	1.08
MnO		–	0.05	0.05	0.06	0.06	0.05	0.11	0.02
MgO		6.15	5.79	5.08	6.90	6.55	5.47	8.02	1.77
CaO		16.1	16.6	16.8	15.9	16.1	16.2	13.7	18.6
Na_2O	0.47**	0.34**	0.36**	0.34	0.35	0.36	0.71	0.35	0.37
K_2O		–	0.01	0.01	0.02	0.02	0.03	0.06	0.01
P_2O_5		–	–	0.05	0.05	0.06	–	–	0.004
H_2O		–	–	–	–	–	–	–	
Total		99.2	98.6	99.7	99.0	98.5	100.0	98.7	98.9
Sc	10.3	5.3	5.2	5.3	6.5	5.9	6.0	24.8	–
Cr	632	650	340	373	525	480	300	1302	–
Co	22	13.4	34.3	10.5	14.8	14.9	12.2	36.6	–
Ni	130	90	140	70	120	100	47	170	–
Sr*	5680	440	370	590	380	1000	212	630	–
Zr	115	28	85	43	38	17	20	90	–
Ba*	1140	120	180	330	110	440	297	105	–
La	4.0	0.84	0.74	0.67	0.91	0.51	1.2	3.0	–
Ce	9.7	1.9	1.72	1.6	2.1	1.5	3.0	6.5	–
Nd	6.0	1.2	1.13	1.0	1.3	1.4	2.6	3.7	–
Sm	1.8	0.39	0.37	0.35	0.42	0.52	0.97	1.4	–
Eu	1.0	0.57	0.77	0.88	0.96	1.4	2.5	0.49	–
Tb	0.39	0.08	0.097	0.07	0.11	0.11	0.17	0.36	–
Yb	1.2	0.26	0.43	0.19	0.42	0.31	0.42	1.61	–
Lu	0.18	0.043	0.077	0.033	0.074	0.049	0.065	0.30	–
Hf	1.4	0.18	0.51	0.55	0.30	0.19	0.77	0.72	–
Ta	0.44	0.27	0.36	0.32	–	0.43	0.28	1.1	–
Ir	26	16.9	9.0	6.3	11.9	5.7	1.3	22.6	–
Au	9	5	4	12	2	11	43	8	–
Th	1.7	0.055	1.0	0.32	0.46	0.38	0.60	0.93	–
U*	1	0.52	0.54	0.2	0.66	0.78	0.72	1.14	–

Note: Major elements are given in wt %, Au and Ir are in ppb, others are in ppm. Dashes mean that the component was not analyzed.
* Added in the course of weathering.
** INAA data.

Fagan et al., 2002, 2003; Thalmann et al., 1996; Spettel et al., 1995; Yanai and Kojima, 1991; Bischoff et al., 1987, 1998; Kaiden and Kojima, 2002; Warren and Bridges, 2004; Anand et al., 2003, 2004; Taylor et al., 2001, 2004; Zeigler et al., 2004; Warren et al., 2001; Greshake et al., 2001). These data were averaged for each meteorite. When data on paired meteorites were considered (if data on the composition of each fragment were available), the average composition of the fragments was calculated with regard for the masses of individual samples. The NWA 773 meteorite consisted of two roughly equal parts: olivine gabbro and polymict regolith breccia (Fagan et al., 2003). The composition of this meteorite as a whole was calculated as the weighted mean for the two parts. The Dho 287 meteorite (Anand et al., 2003) also consisted of two parts: low-

Table 2. Chemical composition of lunar highland meteorites

Meteorite	ALHA 81005	DaG 262	DaG 400	NWA 482	QUE 93069[1]	Y 791197	Y 82192[2]	MAC 88104[3]	PCA 02007	Dho 026[4]
Mass, g	31.4	513	1425	1015	24.5	52.4	712	724	22.4	709
SiO_2	45.7	44.3	43.9	43.9	44.9	44.3	44.5	45.0	41.6	44.3
TiO_2	0.26	0.22	0.20	0.16	0.31	0.34	0.16	0.24	0.28	0.22
Al_2O_3	25.7	27.2	28.9	29.4	28.4	26.5	28.7	28.3	27.7	29.6
Cr_2O_3	0.13	0.10	0.12	0.09	0.09	0.13	0.10	0.09	0.16	0.07
FeO	5.39	4.40	3.58	3.78	4.38	6.14	4.35	4.28	6.53	4.06
MnO	0.08	0.07	0.05	0.05	0.06	0.09	0.05	0.06	0.09	0.06
MgO	8.05	5.21	4.52	4.28	4.43	5.97	5.25	4.05	7.05	3.92
CaO	15.0	16.5	17.9	17.8	16.5	15.5	16.1	16.7	16.3	17.0
Na_2O	0.30	0.35	0.33	0.38	0.36	0.32	0.44	0.34	0.36	0.24
K_2O	0.02	0.05	0.08	0.04	0.03	0.02	0.02	0.03	0.04	0.08
P_2O_5	–	0.06	0.16	0.04	–	0.31	0.05	0.05	0.06	0.05
Total	100.7	98.5	99.8	99.9	99.4	99.7	99.7	99.1	100.2	99.6
Sc	9.1	7.9	5.7	6.9	7.6	12.4	8.0	8.6	11.8	8.6
V	24	26	–	–	–	30	26	34	51	–
Co	21.4	22	13.9	13.2	23.2	16.8	14.4	15.0	29.8	16.0
Ni	199	270	123	144	324	177	127	151	354	170
Ga	2.7	4.2	3.8*	3.9*	3.9	3.3	4.0	3.6	3.9	3.7
Rb	1.5	–	2	4	1.3	6	9.6	0.9	0.82	–
Sr	138	245	229	171	156	146	161	150	152	187
Zr	26	34	28	21	44	31	29	36	40	27
Ba	26	240	198	30	45	29	26	32	35	43
La	1.85	2.44	2.22	1.52	3.51	2.16	1.24	2.58	2.67	3.00
Ce	4.65	7.25	5.52	3.99	9.01	5.05	3.21	6.39	7.69	7.65
Nd	3.05	3.85	3.30	2.50	5.25	3.19	1.99	3.79	5.28	4.70
Sm	0.87	1.15	0.89	0.79	1.57	1.04	0.59	1.16	1.89	1.30
Eu	0.68	0.73	0.72	0.75	0.82	0.74	0.97	0.79	0.90	1.00
Gd	1.4	1.2	–	–	1.9	1.6	1.1	1.3	2.1	–
Tb	0.19	0.24	0.18	0.16	0.34	0.23	0.15	0.24	0.40	0.31
Dy	1.24	1.75	–	–	2.16	1.54	1.1	1.56	2.1	–
Ho	0.28	0.3	–	–	0.45	0.28	0.21	0.33	0.45	0.41
Yb	0.77	0.91	0.69	0.63	1.23	0.99	0.58	0.99	1.29	0.98
Lu	0.12	0.13	0.10	0.09	0.18	0.14	0.08	0.15	0.20	0.16
Hf	0.67	0.85	0.63	0.58	1.18	0.88	0.45	0.86	1.33	0.92
Ta	0.08	0.11	0.12	0.07	0.17	0.09	0.06	0.10	0.24	0.32
W	–	–	2	0.6	0.15	0.8	0.3	0.2	0.2	–
Ir	6.5	12	4.1	5.3	15.6	6.3	4.1	7.3	13.1*	6.3
Au	2.2	4.4	26	3.4	4.9	3.5	1.5	2.8	–	6.7
Th	0.28	0.43	0.30	0.24	0.60	0.31	0.20	0.38	0.40	0.43
U	0.08	0.21	0.29	0.08	0.16	0.10	0.06	0.10	0.10**	0.20

Table 2. (Contd.)

Meteorite	Dho 025[5]	Dho 081[6]	Dho 733	Dho 302	Weighted mean	σ	Simple mean	σ	Combined mean	σ
Mass, g	772	425	98	367[7]						
SiO_2	43.9	44.7	45.5	43.9	44.2	0.1	44.3	0.3	44.2	0.2
TiO_2	0.30	0.16	0.33	0.14	0.21	0.01	0.24	0.02	0.22	0.01
Al_2O_3	26.7	30.9	28.5	28.9	28.7	0.3	28.2	0.4	28.5	0.2
Cr_2O_3	0.10	0.05	0.08	0.07	0.09	0.01	0.10	0.01	0.09	0.01
FeO	4.98	3.26	3.08	3.34	4.03	0.16	4.40	0.28	4.12	0.17
MnO	0.08	0.05	0.05	0.06	0.06	0.003	0.06	0.004	0.06	0.002
MgO	6.52	2.56	5.47	5.86	4.72	0.28	5.22	0.38	4.90	0.24
CaO	16.1	17.5	16.2	16.3	17.0	0.2	16.5	0.2	16.8	0.1
Na_2O	0.28	0.44	0.71	0.35	0.35	0.02	0.37	0.03	0.36	0.02
K_2O	0.06	0.03	0.03	0.02	0.05	0.01	0.04	0.01	0.05	0.01
P_2O_5	0.08	0.06	-	0.04	0.08	0.02	0.09	0.02	0.08	0.01
Total	99.0	99.6	100.0	99.0	99.6		99.7		99.5	
Sc	10.1	5.5	6.0	5.6	7.5	0.4	8.1	0.6	7.7	0.4
V	–	–	–	–	29	2	32	4	30	2
Co	16.3	9.4	12.2	13.6	14.9	0.8	16.9	1.4	15.4	0.8
Ni	148	136	47	90	148	12	176	23	154	13
Ga	3.1	2.4	3.7*	3.8*	3.7	1.3	3.6	0.8	3.6	0.8
Rb	5	–	–	–	3.9	1.0	3.5	1.0	3.7	0.7
Sr	2020	228	212	532	155***	3	150***	3	152***	2
Zr	57	25	20	37	32	3	32	3	32	2
Ba	225	23	297	284	29***	2	32***	3	30***	2
La	3.31	1.53	1.20	0.84	2.15	0.20	2.15	0.22	2.15	0.15
Ce	8.38	3.34	3.00	1.90	5.46	0.53	5.50	0.60	5.48	0.40
Nd	5.09	1.96	2.6	1.20	3.29	0.31	3.41	0.35	3.34	0.23
Sm	1.51	0.61	0.97	0.39	0.97	0.09	1.05	0.11	1.00	0.07
Eu	1.00	0.76	2.50	0.82	0.85	0.06	0.94	0.12	0.87	0.07
Gd	–	–	–	–	1.2	0.1	1.5	0.1	1.3	0.1
Tb	0.33	0.14	0.17	0.09	0.21	0.02	0.23	0.02	0.22	0.01
Dy	–	–	–	–	1.5	0.1	1.6	0.1	1.5	0.1
Ho	0.44	–	–	–	0.34	0.03	0.35	0.03	0.34	0.02
Yb	1.22	0.49	0.42	0.32	0.78	0.07	0.82	0.08	0.80	0.05
Lu	0.19	0.08	0.07	0.05	0.12	0.01	0.12	0.01	0.12	0.01
Hf	1.16	0.47	0.77	0.29	0.71	0.07	0.79	0.08	0.74	0.05
Ta	0.18	0.25	0.26	0.29	0.15	0.02	0.17	0.02	0.16	0.01
W	0.7	–	–	–	0.9	0.3	0.6	0.2	0.7	0.2
Ir	5.9	7.9	1.3*	11.8	6.3	0.8	7.7	1.1	6.7	0.7
Au	5.3	5.1	43	4.4	3.2****	0.5	4.0****	0.5	3.6****	0.4
Th	0.61	0.28	0.60	0.27	0.35	0.03	0.38	0.04	0.36	0.02
U	0.22	0.07	0.72	0.55	0.08***	0.01	0.10***	0.02	0.08***	0.01

Note: Major elements are given in wt %, Au and Ir are in ppb, other elements are in ppm. σ is the standard error of the averages. Dashes mean that the component was not analyzed.

* Calculated by Ni–Ir and Al–Ga regression lines.

** Calculated from the Th/U ratio equal to 3.8.

*** Average for Antarctic meteorites only.

**** Exclusive of DaG 400 and Dho 733.

[1] Including QUE 94269 (3.1 g).

[2] Including Y 82193 (27 g) and Y 86032 (648 g).

[3] Including MAC 88105 (663 g).

[4] Including Dho 457–468 (561 g in total mass).

[5] Including Dho 301, 304, and 308 (21 g in total mass).

[6] Including Dho 081 (174 g).

[7] Including Dho 303, 305, 306, 307, 309, 310, 311, 730, 731, and 950 (363 g in total mass).

Ti mare basalt (95%) and regolith breccia (5%). Inasmuch as the composition of the breccia was not known, the calculations proceeded from the basalt composition alone and, correspondingly, the mass of the basaltic portion of the meteorite.

There are no data on the Ir and Ga contents in some meteorites, and the concentrations of these elements were evaluated from the Ni–Ir and Al–Ga regressions. The regression lines were drawn taking into account the standard errors of the mean concentrations of each element (Alekseev, 2000). The average concentrations of Ba and Sr (elements that are introduced into lunar meteorites during their terrestrial weathering) were calculated only for Antarctic finds. Lunar meteorites on whose composition only unsystematic and fragmentary information was available were not utilized in this research. We processed data on 44 meteorites with a total mass of 11.07 kg, 26 of these meteorites can be regarded as independent falls according to literature data. The names of these meteorites and their types were approved and registered by the Meteoritical Society. The results are summarized in Tables 2–4, in which paired meteorites are combined under common first numbers of their finds with the specification of their total mass. For example, the Dho 025, Dho 301, Dho 304, and Dho 308 paired meteorites are listed under a common name of Dho 025, and their total mass is quoted.

Tables 2–4 also list the average compositions of highland, mare, and mixed meteorites. These compositions were calculated in two manners: (1) by the simple averaging by number of all falls and (2) by weighted mean averaging by mass of each meteorite. The compositions calculated by these two methods are very close for highland and mixed meteorites and slightly different for mare meteorites, which include LAP 02205 and its other fragments with a total mass of 1782 g, which is more than half of the overall mass of all mare meteorites. Combining the averages calculated by the two methods allowed us to obtain the most realistic estimates of the mean compositions of highland, mare, and mixed lunar meteorites (Tables 2–4).

RESULTS

Highland meteorites. This population includes 14 meteorites (Table 2), which account for 62% by mass and 54% by the number of falls of all lunar meteorites in our selection. The textures of highland meteorites are similar to those of Apollo 16 and Luna 20 highland rocks. These meteorites are breccias with impact-melt or granulitic matrices or regolith breccias. The clast population of these breccias is dominated by various breccias, anorthosite–norite–troctolite and gabbro–anorthosite rocks, and fragments of plagioclase, pyroxene, and olivine.

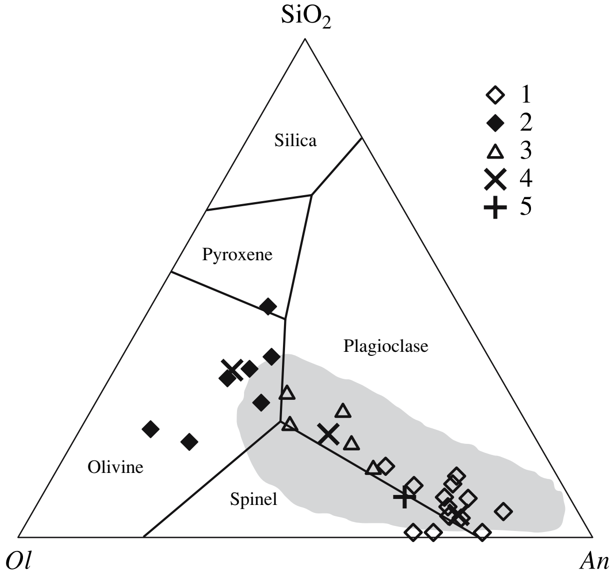

Fig. 1. Normative compositions (mol %) of lunar meteorites in an olivine (Fo_{70})–anorthite–silica diagram (see, for example, Prinz et al., 1973).

(1, 2, 3) Highland, mare, and mixed meteorites, respectively; (4) average compositions of these meteorites; (5) composition of the lunar highland crust (Taylor, 1982). The diagram also shows the composition of the Apollo 16 and Luna 20 lunar highland rocks.

In composition highland meteorites correspond to noritic and troctolitic anorthosites (Fig. 1). In contrast to Apollo 16 and Luna 20 highland breccias, whose composition varies from anorthosite to norite, troctolite, and VHA basalt (see, for example, Prinz et al., 1973), and to the pristine magmatic rocks represented by ferroan anorthosites (FAN) and the rocks of the high-Mg group (HMS), highland meteorites are characterized by a very narrow scatter of their major and trace element concentrations s (Table 2) at MG# ranging from 60 to 76 mol % and plagioclase composition $An_{94–97}$, as is typical mostly of ferroan anorthosites (Fig. 2). Only the Dho 733 meteorite has MG# and plagioclase compositions corresponding to those of HMS rocks. Lunar highland breccias have MG# and plagioclase composition intermediate between FAN and HMS rocks, although these breccias were not produced by the mixing of these rocks (see, for example, Ryder, 1979).

Similar to lunar highland rocks, lunar highland meteorites show the positive Eu anomaly (Fig. 3), but their REE and other incompatible element concentrations s are lower than those in Apollo 16 and Luna 20 regolith and impact breccias but definitely higher than those in ferroan anorthosites (Figs. 3, 4). The concentrations of incompatible and compatible elements, for example, Sc (Fig. 4) in highland meteorites are close to those in some HMS rocks and granulitic breccias corresponding to norite anorthosites in composition. However, incompatible and compatible elements, for example, Sc and Sm (Fig. 4), of highland meteorites are pos-

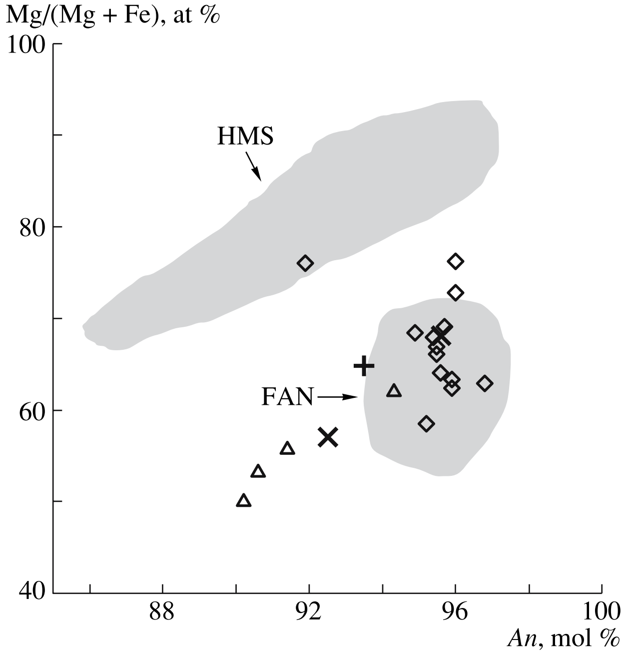

Fig. 2. MG values of normative mafic silicates and the composition of normative plagioclase in highland and mixed meteorites.

See Fig. 1 for symbol explanations. The diagram also shows the compositional fields of plagioclase and mafic silicates in ferroan anorthosites (FAN) and the Mg-rich rocks of the HMS series (Warren and Wasson, 1979).

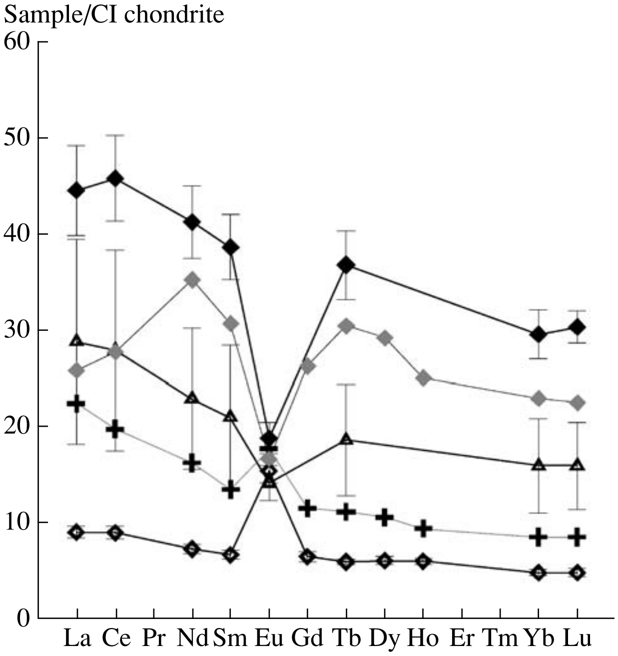

Fig. 3. Averaged REE patterns for lunar meteorites, lunar crust (see Fig. 1 for symbol explanations) and low-Ti mare basalt 12009 (gray diamonds). Data on the basalt and the lunar crust were compiled from (Taylor, 1982). The diagram also shows the errors of the mean values.

itively correlated, which is atypical of HMS rocks and granulitic breccias.

Some highland rocks are thought to contain the material of mare and KREEP basalts. For example, elevated concentrations of Sc, Cr, and Ti in Y 791197 (Lindstrom et al., 1985) and PCA 02007 (Taylor et al., 2004) are believed to indicate an admixture of a mare component, which is confirmed by petrographic evidence. The PCA 02007 meteorite also shows higher concentrations of such incompatible elements as Zr, Hf, and Th (compared to those in other highland meteorites), which suggest an admixture of KREEP material. However, the content of KREEP and mare basalt material in highland meteorites is insignificant and does not appreciably affect the geochemistry of these rocks.

Similar to impact breccias and regoliths of lunar highlands, lunar highland meteorites have elevated concentrations of siderophile elements compared to those in highland magmatic rocks and mare basalts (Figs. 5, 6). The Ni and Co proportions in all of these rocks are chondritic and suggest background Co concentrations of about ~10 ppm in highland rocks. The Ir/Ni ratio is also very close to the chondritic one, particularly in highland meteorites but is possibly slightly lower in highland breccias and regoliths (Fig. 6). The high Au concentrations in DaG 400 and Dho 733 (Table 2) are most probably explained by terrestrial contamination. In other meteorites, Au is strongly correlated with other siderophile elements. The Au/Ir ratio is, however, notably higher than the chondritic one (Table 2) similar to that in lunar highland breccias (see, for example, Korotev, 1997). It is interesting that all lunar highland impact rocks, including lunar meteorites, show positive correlations between siderophile elements and incompatible lithophile elements, such as La, Sm, and Hf (Fig. 7). Lunar magmatic rocks (mare basalts and HMS rocks) are characterized by the opposite tendency, which is consistent with current concepts concerning the geochemistry of these elements in magmatic processes.

Mare meteorites. This population comprises seven meteorites (Table 3), which accounts for 27% of the falls and 32% of the mass of all lunar meteorites considered here. Most of the mare meteorites consist of basalts (dolerites), but some of the meteorites are basaltic regolith breccias (see, for example, Demidova et al., 2003a).

The meteorites of the mare population strongly vary in composition, but all of them are low-Ti basalts, except the NWA 773 and EET 87521 meteorites, whose Ti concentrations correspond to those in VLT basalts (Fig. 8).

As most lunar low-Ti basalts, mare meteorites are mainly olivine-normative (Fig. 1). The Al_2O_3 concentrations in mare meteorites mostly range from 7 to 11 wt %, as is also typical of lunar low-Ti basalts. The highest Al_2O_3 contents (12–13 wt %) were reported in

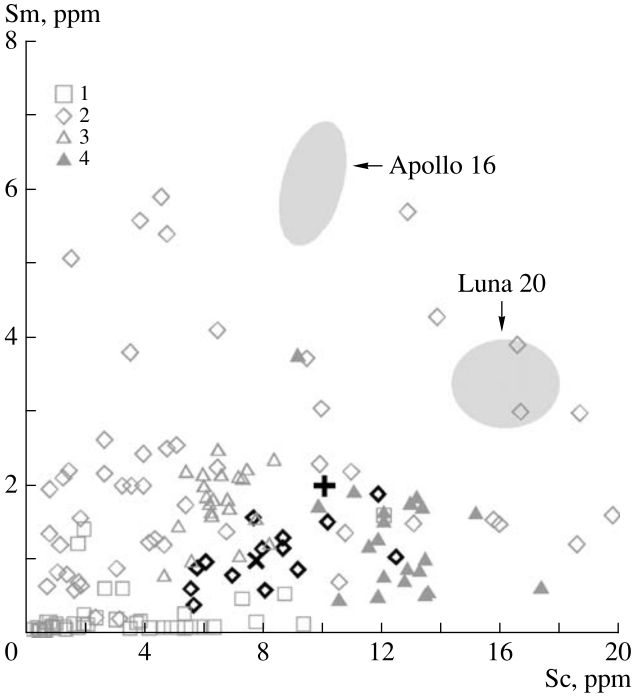

Fig. 4. Sc and Sm concentrations in highland meteorites and some lunar highland rocks.

(1) Ferroan anorthosites; (2) rocks of the magnesian series; (3) magnesian granulitic breccias; (4) ferroan granulitic breccias. See Fig. 1 for other symbol explanations. The diagram also shows the composition fields of the Apollo 16 and Luna 20 regoliths (Korotev, 1997). Data on lunar rock samples were compiled from numerous literature sources.

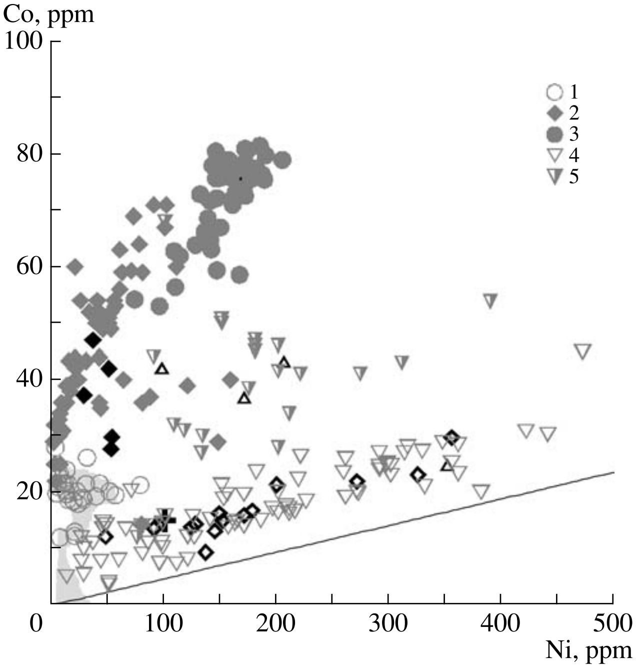

Fig. 5. Ni and Co concentrations in lunar meteorites and lunar rocks.

(1) High-Ti basalts; (2) low-Ti basalts, including VLT basalts and Luna 16 basalts; (3) Apollo 15 green glasses; (4) highland regolith and impact breccias; (5) mare regolith. See Fig. 1 for other symbol explanations. The diagram also shows the composition field of FAN and HMS rocks, which is located close to the origin of coordinates. The line corresponds to the chondritic Co/Ni ratio.

EET 87521 and Y 793169. Similar high Al concentrations were observed only in some VLT basalts of Luna 24, Apollo 12 and 15 and in Apollo 14 high-Al and high-K basalts (Rhodes and Hubbard, 1973; Neal et al., 1988). The variations in the Na and K concentrations of mare basalts are insignificant, but the Dho 287 meteorite, which is enriched in the KREEP component, has the highest Na_2O content (0.53 wt %) among all meteorites and high concentrations of K_2O and REE (Table 3).

The concentrations of incompatible and compatible elements in mare meteorites are characteristic of lunar low-Ti basalts (Figs. 5, 7, 8), although it should be mentioned that Y 793169 and Asuka 881757 are noted for high Sc contents, which are characteristic of high-Ti, but not low-Ti, lunar rocks (Fig. 8). All mare meteorites display the negative Eu anomaly, which is a typical feature of lunar mare rocks (Fig. 3). At the same time, all mare meteorites except Y 793169 and Asuka 881757 are obviously enriched in LREE, whereas typical mare lunar basalts are depleted in these elements (Figs. 3, 9).

Similarities between mare meteorites and mare lunar rocks are also seen in their Ni and Co concentrations (Fig. 5). At the same time, the Ir (Fig. 6) and Au concentrations in mare meteorites (0.2–1.6 and 0.2–4 ppb, respectively) are generally higher than those in lunar mare basalts, which pertains to both the basalts and the basaltic breccias. The contents of all siderophile elements are in mare meteorites notably lower than in the highland rocks and lunar regolith samples collected by the Apollo and Luna missions (Figs. 5, 6).

Mixed meteorites. This population includes five lunar meteorites, which account for 19% of the number of lunar meteorite falls and 6% of their total mass (Table 4). The QUE 94281 and Y 793274 meteorites show certain similarities in mineralogy, petrography, and chemical composition (Arai and Warren, 1999; Lindstrom et al., 1996; Dreibus et al., 1996; Arai et al., 1996), which led some researchers to hypothesize that these meteorite could be simultaneously ejected from a single source on the Moon (Warren and Arai, 1997; Arai and Warren, 1999). However, these meteorites are characterized by different concentrations of noble gases (Eugster and Polnau, 1996) and have different ejection ages from the Moon (Nishiizumi et al., 1996). Because of this, here we treat these two meteorites as different falls. Paired finds of Dho 925, Dho 960, and Dho 961, which are breccias, have chemical and petrographic characteristics similar to those of Y 983885 and could be launch paired (Demidova et al., 2005). However, because there are no data on their exposure age, we still cannot accept this idea and, thus, regard these

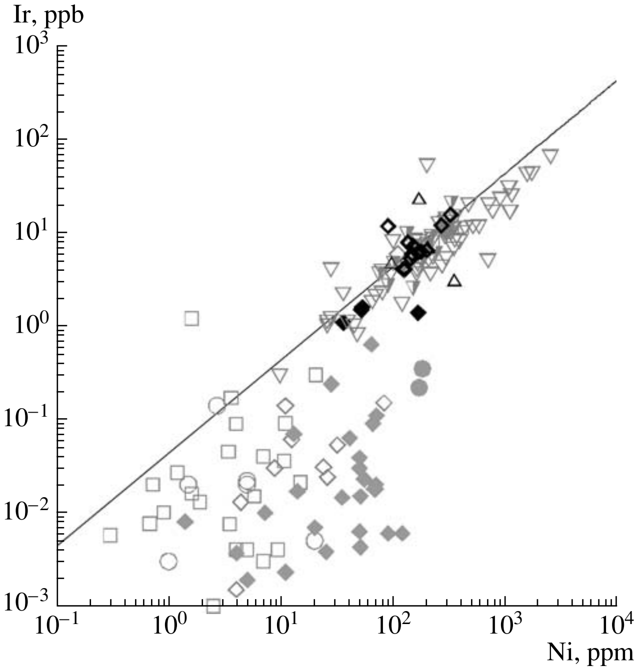

Fig. 6. Ni and Ir concentrations in lunar meteorites and lunar rocks.

See Figs. 1, 4, and 5 for symbol explanations. The line corresponds to the chondritic Ir/Ni ratio.

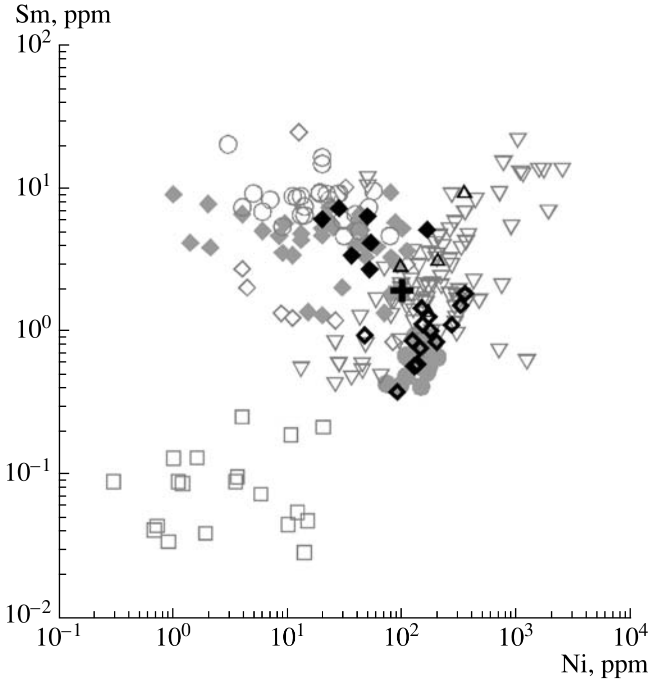

Fig. 7. Ni and Sm concentrations in lunar meteorites and lunar rocks.

See Figs. 1, 4, and 5 for symbol explanations.

meteorites as different falls. The recently found the SaU 169 lunar meteorite (Lorenzetti et al., 2003) definitely belongs to the same group. It is extremely strongly enriched in the KREEP component (its Th concentration is as high as 8.4 ppm), but regretfully, no complete data on its chemical composition are still published, and this led us to leave this unique meteorite beyond the scope of our consideration.

All mixed meteorites are impact or regolith breccias containing various proportions of highland, mare, and KREEP material. The bulk composition of these rocks corresponds to anorthositic norite or high-Al basalt (Table 4), i.e., they plot within the compositional field of lunar highland rocks (Fig. 1). However, compared to pristine highland FAN and HMS rocks, mixed meteorites contain more sodic plagioclase and more ferrous mafic silicates (Fig. 2). The mare material of mixed meteorites likely consists almost exclusively of VLT basalts (Hill and Boynton, 2003; Jolliff et al., 1998; Arai et al., 2004; Lindstrom et al., 1991b; Demidova et al., 2005). These basalts are, however, characterized by higher MG# than the Luna 24 VLT basalts and are closer to the Apollo 17 VLT basalts.

The concentrations of lithophile elements in mixed meteorites are intermediate between those in mare and highland meteorites (Figs. 3, 7, 8). The proportions and concentrations of REE in these meteorites significantly vary (Table 4, Fig. 3). Four meteorites of this population have a negative Eu anomaly, which is weakly pronounced in QUE 94281, Y 793274, and Y 981031 and is more significant in Calcalong Creek. The Dho 925 meteorite notably differs from other meteorites of this population. This meteorite is characterized by relatively low REE concentrations, comparable to those in highland meteorites, and the absence of an Eu anomaly. All mixed meteorites are enriched in LREE (Fig. 9).

The concentrations of siderophile elements in mixed meteorites are relatively high. In three of these meteorites, Co concentrations are equal to those in mare regolith, i.e., are higher than in highland meteorites (Fig. 5). This suggests that the meteorites contain relatively much Co of lunar (mare) origin. The Ir/Ni ratio in mixed meteorites is close to the chondritic one (Fig. 6). The Dho 925 and Y 983885 meteorites bear the highest Ir concentrations (22.6 and 22 ppb, respectively) among lunar meteorites.

DISCUSSION

Composition of the lunar crust. Geological data suggest that the lunar crust is dominated by highland rocks, and the percentage of mare basalts does not exceed 1% (Head and Wilson, 1992). The abundance of KREEP material remains unknown but is thought to be relatively low. Hence, the average composition of highland lunar meteorites provides an estimate for the average bulk composition of the lunar crust, in any event, the ancient crust with an age of >4 Ga, before the extensive eruptions of nonmare and mare basalts. The average compositions of these meteorites, which were evalu-

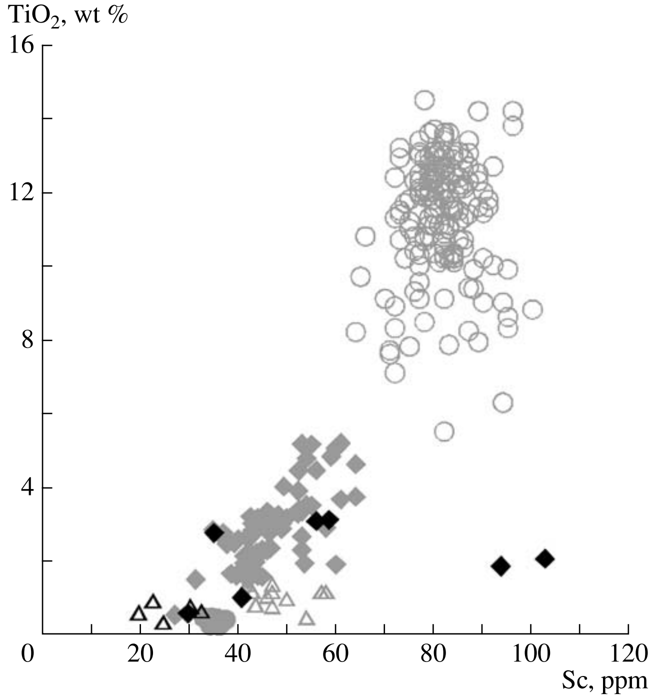

Fig. 8. Sc and Ti concentrations in mare and mixed meteorites and mare basalts.

Open circles are VLT basalts, other symbols are as in Figs. 1 and 5.

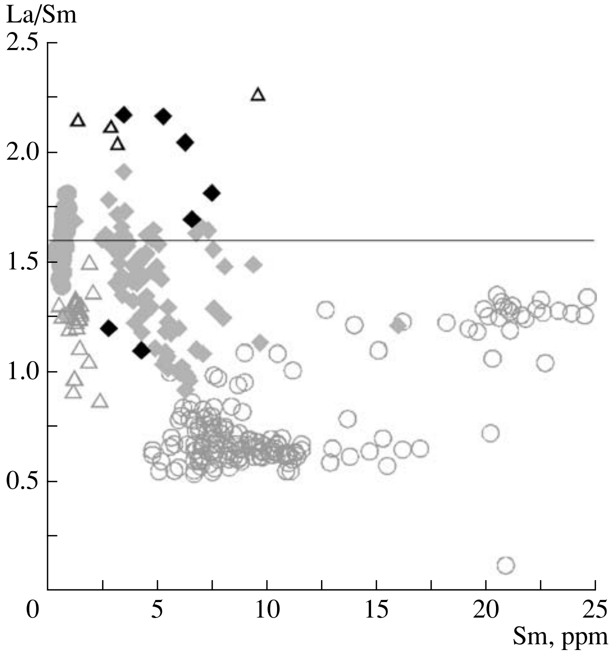

Fig. 9. La/Sm ratio and Sm concentration in mare and mixed meteorites and mare basalt.

The line shows the chondritic La/Sm ratio. See Figs. 1, 5, and 8 for symbol explanations.

ated by us and in (Korotev et al., 2003) (Tables 2, 5) are in good agreement. Compared to the most popular estimate of the highland crust composition (Taylor and Jakes, 1974; Taylor, 1982), whose major-element concentrations are comparable to those in the average composition of the lunar regolith (Table 5), the "meteoritic" estimate shows higher concentrations of Ca and Al (i.e., plagioclase) at lower concentrations of Fe, Mg, and incompatible elements. It should be mentioned that the first orbital evaluations of the Th concentration (Table 5) in highland lunar terrains that were assumed for calculations in (Taylor and Jakes, 1974; Taylor, 1982) were likely overestimated. According to the latest orbital data (provided by the Lunar Prospector and Clementine orbiters), the average Th concentration in the predominant highlands of the far side is 0.4 ppm at the FeO mean concentration of 4.4 wt % (Gillis et al., 2004). These values are consistent with meteoritic data (Tables 2, 5). Thus, the average composition of highland meteorites seems to representatively reflect the composition of the highland material, which is predominant in the lunar crust. The regolith of lunar highlands contains an admixture of the mare component, and its average composition (Table 5) most likely provides a distorted estimate for the composition of the highland crust.

Although the percentage of mare basalts in the lunar crust is likely insignificant, their chemistry is principally important for understanding the differentiation processes of the lunar material. The average chemical composition of mare meteorites (Table 3) implies that the mare territories of the Moon are dominated by low-Ti basalts, which contain 2.3 ± 0.3 wt % TiO_2 on average and are enriched in LREE, in contrast to known lunar mare rocks. High-Ti basalts typical of Apollo 11 and Apollo 17 samples should be spread not as widely. This conclusion is consistent with the results of orbital studies, which indicate that lunar maria are dominated by basalts containing 2–4 wt % TiO_2 (Giguere et al., 2000). However, according to the orbital data (Gillis et al., 2004), the FeO concentration in lunar maria should be systematically lower (<21 wt %) than it follows from the chemistry of mare meteorites (Table 3).

The average composition of mixed meteorites resembles that of low-K Fra Mauro breccias (LKFM) widespread among Apollo 14 samples (Vaniman and Papike, 1980) but differs from them in lower Ti and REE concentrations. It is reasonable to suggest that the population of mixed meteorites characterizes the composition of the mare–highland interface. A distinctive feature of these transitional zones is the presence of magnesian KREEP and VLT basalts. This means that the formation age of the breccias in these areas is younger than the age of highland breccias.

The averaging of geochemical data over all lunar meteorites makes it possible to obtain an average estimate for the composition of the lunar surface (Table 5) to a depth of less than 1 km (see above). The FeO content in this composition is close to the results of orbital

Table 3. Chemical composition of lunar mare meteorites

Meteorite	Asuka 881757	EET 87521[1]	NWA 773	NWA 032[2]	Y 793169	LAP 02205[3]	Dho 287A	Weighted mean	σ	Simple mean	σ	Combined mean	σ
Mass, g	442	84	633	456	6.1	1782	146.3						
SiO_2	46.2	47.9	44.7	44.7	44.8	47.6	43.2	46.4	0.6	45.6	0.6	46.0	0.4
TiO_2	2.06	1.00	0.57	3.08	1.86	3.12	2.76	2.46	0.40	2.06	0.38	2.25	0.28
Al_2O_3	10.7	13.0	6.79	8.74	12.0	9.67	8.35	9.20	0.55	9.89	0.82	9.41	0.5
Cr_2O_3	0.26	0.21	0.36	0.40	0.22	0.31	0.65	0.34	0.03	0.34	0.06	0.34	0.03
FeO	23.3	18.6	18.8	22.6	22.6	20.6	22.1	20.9	0.6	21.2	0.7	21.0	0.47
MnO	0.30	0.24	0.26	0.33	0.25	0.26	0.29	0.28	0.01	0.28	0.01	0.28	0.01
MgO	6.36	7.38	20.0	8.45	5.75	5.72	13.2	9.04	2.19	9.55	2.00	9.32	1.48
CaO	11.9	11.3	7.90	10.9	12.6	10.8	8.74	10.3	0.5	10.6	0.64	10.4	0.41
Na_2O	0.30	0.38	0.17	0.36	0.32	0.39	0.53	0.34	0.04	0.35	0.04	0.34	0.03
K_2O	0.04	0.05	0.09	0.11	0.08	0.09	0.19	0.09	0.01	0.09	0.02	0.09	0.01
P_2O_5	–	–	0.08	–	0.29	0.11	0.21	0.11	0.02	0.17	0.05	0.12	0.03
Total	101.4	100.1	99.7	99.6	100.8	98.6	100.2	99.4		100.1		99.5	
Sc	102.6	40.8	29.8	56.0	93.6	58.6	35.2	57.3	8.4	59.5	10.7	58.1	6.8
Co	27.8	47.0	75.3	42.0	29.9	37.3	42.3	43.9	6.2	43.1	6.0	43.5	4.3
Ni	52	36	166	50	53	28	20	58	21	58	17	58	13
Ga	2.8	5.1	3.7	–	3.5	–	–	3.4	0.4	3.7	0.5	3.5	0.3
Rb	2.5	4.0	1.5	–	3.0	–	–	2.1	0.4	2.8	0.5	2.3	0.4
Sr	115	110	60	142	78	129	530	125***	4	108***	11	123***	7
Zr	45	133	173	175	60	206	60	168	23	122	25	147	18
Ba	27	80	153	242	34	157	200	129***	30	74***	30	101***	24
La	3.4	7.6	11.5	11.2	4.7	13.6	12.9	11.5	1.4	9.3	1.5	10.5	1.1
Ce	10.0	19.4	30.4	29.7	14.7	36.5	30.3	30.6	3.5	24.4	3.7	27.7	2.7
Nd	8.3	11.9	18.5	21.0	11.9	25.0	20.4	20.7	2.3	16.7	2.3	18.7	1.7
Sm	2.8	3.5	5.3	6.6	4.3	7.5	6.3	6.3	0.7	5.2	0.6	5.7	0.5
Eu	0.97	0.91	0.46	1.10	1.31	1.36	1.18	1.10	0.14	1.04	0.12	1.06	0.09
Tb	0.75	0.76	1.09	1.56	1.02	1.92	1.22	1.52	0.18	1.19	0.16	1.34	0.13
Yb	3.29	2.88	3.96	5.79	4.60	6.54	3.35	5.36	0.56	4.34	0.52	4.81	0.41
Lu	0.51	0.43	0.56	0.80	0.66	0.90	0.51	0.75	0.02	0.62	0.06	0.74	0.04
Hf	2.2	2.6	4.3	5.0	3.0	5.4	2.6	4.6	0.5	3.6	0.5	4.1	0.4
Ta	0.27	0.30	0.49	0.62	0.31		0.71	0.48	0.07	0.45	0.08	0.47	0.05
Ir	1.5	1.1	1.4	1.4*	1.6	0.5*	0.2*	0.9	0.4	1.1	0.3	1.0	0.2
Au	0.2	0.7	1.4	4.0	1.1	–	–	1.8	0.7	1.5	0.7	1.7	0.5
Th	0.40	0.90	1.77	1.90	0.68	2.33	0.90	1.84	0.27	1.27	0.27	1.56	0.21
U	0.14	0.23	0.47	0.45	0.09	0.55	0.24**	0.45	0.02	0.31	0.07	0.44	0.04

Note: Major elements are given in wt %, Au and Ir are in ppb, other elements are in ppm. Dashes mean that the component was not analyzed. σ is the standard error of the averages.

* Calculated by Ni–Ir regression line.

** Calculated from the Th/U ratio equal to 3.8.

*** Average for Antarctic meteorites only.

[1] Including EET 96008 (53 g).

[2] Including NWA 479 (156 g).

[3] Including LAP 02224, 02226, and 02436 (556 g in total mass).

Table 4. Chemical composition of lunar mixed meteorites

Meteorite	Calcolong Creek	QUE 94281	Y 793274[1]	Y 983885	Dho 925[2]	Weighted mean	σ	Simple mean	σ	Combined mean	σ
Mass, g	19	23	195	290	106						
SiO_2	47.2	46.1	47.3	45.6	45.4	46.2	0.5	46.3	0.4	46.3	0.3
TiO_2	0.85	0.70	0.58	0.53	0.27	0.52	0.06	0.59	0.10	0.54	0.06
Al_2O_3	20.7	16.4	15.4	22.1	22.0	19.7	1.5	19.3	1.4	19.5	1.0
Cr_2O_3	0.19	0.27	0.27	0.21	0.20	0.23	0.02	0.23	0.02	0.23	0.01
FeO	10.9	13.8	14.3	9.41	8.77	11.0	1.2	11.4	1.1	11.2	0.8
MnO	0.14	0.19	0.14	0.12	0.11	0.13	0.01	0.14	0.01	0.13	0.01
MgO	6.13	9.68	9.12	7.98	8.02	8.34	0.34	8.18	0.61	8.30	0.35
CaO	16.1	12.5	12.2	14.0	13.7	13.4	0.5	13.7	0.7	13.5	0.43
Na_2O	0.49	0.39	0.41	–	0.35	0.40	0.02	0.41	0.03	0.40	0.02
K_2O	0.24	0.09	0.08	–	0.06	0.08	0.02	0.12	0.04	0.09	0.02
P_2O_5	–	–	0.08	–	–	–					
Total	102.9	100.0	99.9	99.9	98.9	100.1		100.5		100.2	
Sc	22.7	30.4	32.6	19.8	24.8	25.0	2.8	26.1	2.4	25.6	1.8
V	59	99	83	–	–	83	6	81	11	82	6
Co	24.6	42.9	41.8	–	36.6	39.3	2.5	36.5	4.2	38.6	2.5
Ni	350	205	97	–	170	141	37	206	53	162	35
Ga	4.7	4.5	4.4	–	2.1*	3.7	0.8	3.9	1.2	3.8	0.7
Sr	149	120	110	–	630	114***	8	126***	12	118***	8
Zr	354	92	89	–	90	104	35	156	66	115	39
Ba	257	75	80	–	105	94***	34	137***	60	104***	36
La	21.7	6.5	6.1	–	3.0	6.0	2.3	9.3	4.2	6.8	2.5
Ce	54.1	18.1	15.2	–	6.5	14.8	6.0	23.5	10.5	16.9	6.3
Nd	29.5	10.1	10.4	–	3.7	9.4	3.3	13.4	5.6	10.4	3.3
Sm	9.6	3.2	2.9	–	1.4	2.8	1.0	4.3	1.8	3.1	1.1
Eu	1.27	0.83	0.86	–	0.49	0.76	0.12	0.86	0.16	0.80	0.10
Tb	1.94	0.66	0.62	–	0.36	0.61	0.20	0.89	0.35	0.68	0.21
Yb	7.5	2.4	2.4	–	1.6	2.4	0.7	3.5	1.3	2.6	0.8
Lu	1.10	0.35	0.33	–	0.30	0.36	0.10	0.52	0.19	0.39	0.11
Hf	7.7	2.4	2.4	–	0.72	2.2	0.9	3.3	1.5	2.5	0.9
Ta	–	0.31	0.29	–	1.1	0.55	0.27	0.57	0.27	0.56	0.20
Ir	3.0	6.8	4.6	22	22.6	15.6	4.2	11.8	4.3	13.7	3.1
Au	3.0	2.1	2.8	–	8.0	4.4	1.4	4.0	1.4	4.2	1.0
Th	4.55	1.01	0.88	–	0.93	1.1	0.5	1.8	0.9	1.3	0.5
U	1.18	0.28	0.23	–	0.24**	0.29	0.12	0.48	0.23	0.33	0.14

Note: Major elements are given in wt %, Au and Ir are in ppb, other elements are in ppm. Dashes mean that the component was not analyzed. σ is the standard error of the averages.

* Calculated by Al–Ga regression line.

** Calculated from the Th/U ratio equal to 3.8.

*** Exclusive of Dho 925, 960, and 961.

[1] Including Y 981031 (186 g).

[2] Including Dho 960, 961 (57 g in total mass).

Table 5. Estimated chemical composition of lunar highland crust

Component	Highland crust				Highland surface	Upper crust	Primary highland crust			Highland crust	Moon's surface
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
SiO_2	45	44.9	45.5	–	44.7	44.9	–	–	–	44.2	45.0 (0.2)
TiO_2	0.56	0.56	0.6	0.3	0.22	0.22	0.30	0.39	0.25	0.22	0.86 (0.13)
Al_2O_3	24.6	24.6	24.0	26.1	28.2	28.5	31.4	29.9	31.4	28.5	21.7 (0.9)
Cr_2O_3	0.1	–	–	0.1	0.096	0.092	0.04	0.05	0.05	0.09	0.18 (0.02)
FeO	6.6	6.6	5.9	5.2	4.4	4.0	2.64	3.39	2.49	4.12	10.1 (0.8)
MnO	–	–	–	0.1	0.063	0.060	–	–	–	0.06	0.13 (0.01)
MgO	6.8	8.6	7.5	6.1	5.4	5.3	3.34	3.57	3.02	4.90	6.69 (0.51)
CaO	15.8	14.2	15.9	15.4	16.3	16.4	17.6	16.8	17.4	16.8	14.5 (0.3)
Na_2O	0.45	–	0.6	0.33	0.35	0.34	0.48	0.54	0.43	0.36	0.36 (0.01)
K_2O	0.075	0.072	–	0.024	0.027	0.026	–	–	–	0.05	0.07 (0.01)
P_2O_5	–	–	–	0.024	0.027	0.023	–	–	–	0.08	–
MG#	64.7	69.9	69.4	67.6	69	70	69.3	65.3	68.4	67.8	54.2 (5.1)
Sc	10	–	–	–	8.0	8.0	4.5	6.55	4.5	7.7	25 (3)
Co	15	–	–	18	17	10	6.8	6.4	7.7	15.4	27 (2)
Ni	100	–	–	152	185	~16	32	37	56	154	128 (12)
Ga	–	–	–	3	–	–	–	–	–	3.6	3.7 (0.5)
Sr	120	200	–	138	150	151	–	–	–	152	140 (3)
Zr	63	105	–	29	35	35	–	–	–	32	80 (10)
Ba	66	110	–	28	33	33	32	42	40	30	64 (10)
La	5.3	8.8	–	1.98	2.3	2.4	1.89	1.83	2.31	2.15	5.4 (0.7)
Ce	12	21.6	–	5.48	6.0	6.0	–	–	–	5.48	14.0 (1.7)
Nd	7.4	12.4	–	3.08	3.6	3.7	–	–	–	3.34	9.1 (1.1)
Sm	2	3.26	–	0.99	1.1	1.1	0.80	0.80	1.08	1.00	2.8 (0.3)
Eu	1	1.7	–	0.75	0.78	0.79	1.05	1.14	0.98	0.87	0.93 (0.05)
Tb	0.41	0.59	–	0.22	0.23	0.23	–	–	–	0.22	0.63 (0.07)
Yb	1.4	2.25	–	0.92	0.89	0.90	0.60	0.90	0.88	0.80	2.3 (0.3)
Lu	0.21	0.35	–	0.13	0.13	0.13	0.11	0.13	0.14	0.12	0.33 (0.03)
Hf	1.4	2.3	–	0.73	0.8	0.8	–	–	–	0.74	2.0 (0.2)
Ir	–	–	–	6	7.5	=0	–	–	–	6.7	5.6 (0.7)
Au	–	–	–	2	2.8	~0.6	–	–	–	9.0	3.0 (0.3)
Th	0.9	1.5	–	0.24	0.37	0.38	0.26	0.29	0.43	0.36	0.88 (0.13)
U	0.24	0.4	–	–	–	–	–	–	–	0.08	0.21 (0.03)

Note: Major elements are given in wt %, Au and Ir are in ppb, others are in ppm, MG# = Mg/(Mg + Fe), mol %.
[1] Compilation of orbital and geochemical data from (Taylor, 1982); [2] compilation of orbital and geochemical data from (Taylor and Jakes, 1974); [3] average regolith composition for 12 landing sites (Turkevich, 1973); [4] average of lunar meteorites (Palme et al., 1991); [5] average of lunar meteorites (Korotev et al., 2003); [6] average of lunar meteorites minus the meteoritic component (Korotev et al., 2003); [7] according to the composition of the Apollo 16 ancient breccias (Korotev, 1996); [8] according to the composition of the Apollo 16 feldspathic breccias (Korotev, 1996); [9] according to the chemistry of Apollo 16 samples (Korotev, 1997); [10] our data (Table 2); [11] our data (falls and masses)—combined mean for all lunar meteorites (in parentheses—standard error of the averages).

measurements, which yielded a mean FeO concentration at the surface equal to 8.6 wt % (Gillis et al., 2004). The average Th concentration (1.6 ppm) according to orbital data is higher, and the modal value (0.6 ppm) is lower, than in our estimate. It is interesting that the concentrations of incompatible elements, including Th, according to the "meteoritic" evaluation for the lunar surface are close to the estimates for the lunar crust in

(Taylor, 1982), although the former estimate is richer in mafic elements and Fe (Table 5).

Meteoritic bombardment. The composition of highland meteorites is thought (Korotev, 1997) to reflect the composition of the surface crustal rocks of the Moon that were produced before the lunar cataclysm, i.e., a pulse of active meteoritic bombardment at ~4 Ga, a process that formed the lunar impact basins. This interpretation is based on the fact that highland meteorites are depleted in incompatible elements compared to Apollo 16 and Luna 20 highland breccias, which are believed to be ejecta from the impact basins, and on the similarities between the chemical composition of highland meteorites and the inferred material of the primary highland crust (Table 5). It is necessary, however, to stress that highland meteorites (similar to highland breccias) are impactites, are enriched in siderophile elements (Figs. 5, 6), and have the same elevated Au/Ir ratio that suggests that these meteorites were produced by impacts of similar cosmic bodies, and belong to the same Ni–Sm mysterious trend (Fig. 7). Thus, if highland meteorites represent the crustal material of the Moon before the origin of the impact basins, this material was then also reworked by impact processes, and the ancient meteoritic bombardment should be regarded as a long-lasting process.

The average Ir concentration in highland meteorites (Table 2) points to the presence of about 1.3 wt % meteoritic material like CI in the highland crust. If the thickness of lunar highland impactites is 25 km (Taylor, 1982), and their density is 3 g/cm^3 (i.e., their mass is equal to 3×10^{24} g), then the mass of the CI material contained in the lunar crust can be evaluated at 4×10^{22} g. At the duration of meteoritic bombardment of 500 Ma (from 4.5 to 4.0 Ga), the ancient flux of CI material onto the Moon is 0.2 mg/cm^2 per year or 9.3×10^{-4} mm/year, which is several orders of magnitude higher than the recent flux of cosmic material (15 μg/cm^2 per year; Kyte and Wasson, 1986) but is much lesser than the intensity of meteoric precipitation in the Sahara (50 mm/year) and is comparable with the lowest sedimentation rates in the ocean (1 mm/thous. years). At an accretion rate of 10 km/s, the total energy of the ancient meteorite flux to the Moon was approximately 2×10^{27} J, but its power was only 3×10^{-7} W/cm^2, which is much lower that the solar constant (0.14 W/cm^2) and one order of magnitude lower than the Earth's and Moon's heat flows ($2–6 \times 10^{-6}$ W/cm^2). Hence, ancient bombardment as a process that lasted for 500 Ma seems not to have played any significant geological role and could form a thick cover of lunar impactites. These rocks should be formed by a short event.

Indeed, the exponential character of the size distribution of lunar impact craters implies that the bulk of the energy was released when the largest impact structure of a crater population was produced, i.e., within a very short time span. Using equations of crater mechanics (Bazilevskii et al., 1983; Melosh, 1989), it can be demonstrated that the formation of the South Pole–Aitken Basin, the Moon's largest impact basin of 2600 km in diameter, led to the release of approximately 3×10^{27} J energy, i.e., about 85% of all kinetic energy of projectiles that produced lunar impact basins of >300 km in diameter. The mass of the South Pole–Aitken impactor should have been approximately equal to 5×10^{22} g, and the mass of the crater ejecta should have been 6×10^{23} g, i.e., 85% of the mass of all basin-forming impactors and 73% of the mass of all impact basin ejecta. The orders of magnitude of these values are comparable with those of our estimates for the mass of cosmic material (4×10^{22} g) and the mass of impactites (3×10^{24} g) in the lunar crust. Hence, although the lunar highland crust is riddled with impact craters, the physical and chemical consequences of the intense meteoritic bombardment are, in fact, determined by a single most significant impact. This fact explains the correlation between the concentrations of siderophile and incompatible elements in highland lunar meteorites and breccias (Fig. 7), which implies that the formation of the South Pole–Aitken Basin was accompanied by the excavation of KREEP material, which was distributed, together with the projectile material over the lunar surface. Later smaller impact events could only somewhat modify the proportions of the cosmic and KREEP materials in the ejecta of this basin. It is thus reasonable to suggest that the whole complex of lunar highland impactites, including highland meteorites, consists of the crater ejecta of a single basin, located near the South Pole of the Moon, and these ejecta were likely slightly reworked by later impact events. The chemistry of highland meteorites seems to reflect the composition of the predominant material in these ejecta.

Lunar magmatism. Contamination with meteoritic material practically does not modify the concentrations of major elements in lunar highland rocks, with the exceptions of Fe and Mg, whose meteorite contribution is 0.32 wt % FeO and 0.21 wt % MgO (see also Korotev et al., 2003). Thus, the primary highland crust of the Moon should have been slightly more magnesian (68.5 mol %) than the composition presented in Table 2 (67.8 mol %). However, the chemistry of the highland crust is determined by the mixing of some pristine magmatic rocks during impact processes. In addition, impact reworking has notably modified textures of highland rocks. Because of this, the original state of the lunar highland crust remains obscure. The detailed examination of Apollo and Luna samples indicates that the pristine magmatic highland rocks of the Moon belonged to two series: ferroan anorthosites (FAN) and high-Mg rocks (HMS), which were produced by different magmatic events (Warren and Wasson, 1980). However, it was determined that the composition of highland impact breccias cannot be explained by the mixing of these magmatic rocks, and the highland crust should contain, in addition to FAN, some magnesian material (see, for example, Ryder, 1979), which has not been identified petrographically. This magnesian component was thought to be a quenched liquid (Taylor and Bence, 1975), cosmic material (Wänke et al., 1977), and cotectic compositions from which plagioclase could crystallize, such as highland olivine norite HON (Korotev et al., 1980), VHA basalts (Prinz et al., 1979), and the parental magma of the lunar crust PLC (Ringwood, 1977).

FAN fragments are definitely present in highland meteorites and most probably dominate in them (Fig. 2). Magnesian rocks are quite diverse and are mostly fragments of granulites of the composition of troctolite, norite, and troctolitic and noritic anorthosite, which also contain plagioclase of anorthite composition. This diversity of the rocks suggests that the lunar crust composition was not controlled by simple binary mixing. However, assuming the average MG# of the ferroan anorthosites equal to 58 mol % (Fig. 2), their fraction in the average composition of the lunar crust can be estimated as 50–75%, because the MG# of the other rocks with plagioclase of the same composition lies within the range of 70–90 mol %.

The high abundance of anorthosites in the lunar crust provided the basis for the magma ocean model (see, for example, Taylor and Jakes, 1974), which could allegedly explain the whole evolutionary history of lunar magmatism. According to this model, the outer zone of the Moon to a depth of at least 400 km, or even the whole Moon, were completely molten. As the melt crystallized, mafic minerals were accumulated at deep levels and, when the melt became saturated with respect to plagioclase, its flotation produced the feldspathic crust. The residual liquid rich in incompatible elements crystallized immediately beneath the crust, and the subsequent partial melting of this layer resulted in eruptions of KREEP basalts. The generation of mare basalts is explained within the scope of this model by the partial melting of the layer of mafic cumulates after KREEP magmatism. The complementary character of the REE patterns of mare and highland rocks is considered to be reliable evidence for favor of the magma ocean model. An alternative hypothesis is the model of serial magmatism (Walker, 1983), in which it is assumed that the lunar crust has a cotectic composition (15–20 wt % Al_2O_3, i.e., 55% plagioclase), and ferroan anorthosites and other cumulus highland rocks were formed during the differentiation of cotectic magmas near the surface. This model differs from the model of magmatic ocean in maintaining smaller-scale fractionation and does not consider the problem of the genesis of mare basalts.

The average highland crust composition obtained with the use of highland meteorites is even richer in plagioclase and plots farther away from the cotectic compositions than the average composition proposed by Taylor (1982). Thus, the chemistry of lunar meteorites is at variance with the model of serial magmatism and suggests that the highland crust is dominated by cumulate rocks, as also follows from the magma ocean model. However, the average REE pattern of mare meteorites is not complementary to lunar highland rocks (Fig. 3), and, therefore, does not support the model of the lunar magma ocean. The enrichment of LREE (Figs. 3, 9) testifies that the basaltic magmas assimilated KREEP material, which corresponds to the hybridism model proposed in (Ringwood and Kesson, 1976), and petrological data highlight the great diversity of mare basalts and the possible lateral heterogeneity of the lunar mantle (see, for example, Demidova et al., 2003a).

Some constraints on the bulk composition of the Moon. The high Al concentration in the “meteoritic” estimate for the lunar crust composition (Tables 2, 5) is in better agreement with the idea that the Moon is enriched in refractory elements. Indeed, the mass of the lunar crust (at its thickness of 70–73 km) is close to 10% of the total Moon’s mass (Taylor, 1982), and hence, the contribution of crustal Al_2O_3 to the bulk Moon’s composition can be estimated to be 2.86 wt %. This is slightly higher than the Al_2O_3 concentration in the volatile-free basis of CI chondrites (2.44 wt %) (Taylor, 1982) and suggests that the Moon could be enriched in refractory elements, because Al should be present definitely in the lunar mantle (Taylor, 1982). However, the concentrations of refractory incompatible elements (for example, La and Th) in the “meteoritic” estimate are lower than in the composition in (Taylor, 1982), and hence, their contribution to the bulk composition of the Moon (Table 5) does not exceed their concentrations in the volatile-free basis of CI chondrites. Moreover, it is now thought that the lunar crust can have a lesser thickness (not more than 44 km; Wieczorek, 2003; Chenet et al., 2002), and then evidence for the Moon enriched in refractory elements based on the lunar crust chemistry becomes not so convincing. The fact that the ratios of elements characterized by similar geochemical behaviors but different volatilities (for example, K/U and Ga/Al) are in the lunar crust lower than in chondrites also cannot be unambiguously explained, because volatiles could also be lost during the lunar crust formation as a result of evaporation processes.

However, the concentrations of incompatible elements in the lunar crust do not directly reflect their concentrations in the initial lunar material and were largely controlled by magmatic fractionation processes. The highland crust (Tables 2, 5) can be provisionally regarded as a mixture of plagioclase and a parental magma from which this plagioclase accumulated. This magma should have had a cotectic composition saturated with respect to, at least, olivine and plagioclase (Fig. 1) and reflected the composition of the source (initial lunar material) from which it was formed. Its composition can be assayed by mathematical modeling of magmatic crystallization (Ariskin et al., 1997). A noteworthy feature of this composition is the absence of an Eu anomaly (Table 6). Assuming 100% extraction of the highland crust (Table 6) from this magma, it can be

Table 6. Compositions of the parental magma of the lunar crust and its source at various degrees of partial melting

Object	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	MG#	Sc	Co	La	Ce	Nd	Sm	Eu	Yb	Lu
Lunar crust	44.2	0.22	28.5	4.12	0.06	4.90	16.8	0.36	67.8	7.7	15.4	2.15	5.48	3.34	1.00	0.87	0.80	0.12
Parental magma	46.0	0.66	17.5	10.1	0.17	10.3	14.4	0.46	64.5	21.3	36.4	4.67	12.9	8.41	2.60	0.90	2.33	0.35
Source at 17% melting	41.0	0.11	3.0	13.6	0.03	39.6	2.5	0.08	83.8	3.6	6.1	0.75	2.20	1.43	0.44	0.15	0.39	0.06
Source at 35% melting	42.1	0.23	6.1	12.9	0.06	33.3	5.1	0.16	82.2	7.5	12.7	1.60	4.53	2.94	0.91	0.32	0.82	0.12
Moon's composition	43.4	0.30	6.0	13.0*	0.15	32.0	4.5	0.09	84.2**	19	–	0.90	2.34	1.74	0.57	0.21	0.61	0.09
volatile-free basis of CI chondrites	33.43	0.11	2.44	34.97	0.35	23.38	1.95	1.06	54.4	7.8	765	0.37	0.96	0.71	0.23	0.09	0.25	0.04

Note: Major elements are given in wt %, Au and Ir are in ppb, others are in ppm, MG# = Mg/(Mg + Fe), mol %.
* 10.7 wt % FeO in the lunar mantle (Taylor, 1982).
** Value for the lunar mantle (Taylor, 1982).
Composition of the moon and CI chondrites (Taylor, 1982). No corrections for meteoritic Co in the lunar crust were made, and hence, the concentrations of endogenic lunar Co in our estimates should be lower than the listed values.

easily demonstrated that the mass of the parent magma should have been approximately equal to 17% of the Moon's mass. It can be then hypothesized that this melt was produced by the fractionation of the whole Moon, for example, as a result of 17% partial melting. This enables us to assay the composition of the source, corresponding to the composition of the Moon as a whole, by adding needed amounts of olivine (of composition that yields the chemistry of the parental magma at the 17% melting of the source) to the cotectic magma. Of course, this calculated composition (Table 6) corresponds to the minimum evaluation of the incompatible element concentrations s and demonstrates that the lunar material could be enriched in refractory elements (REEs) and depleted in volatiles (Na) and siderophile elements (Co) relative to CI chondrites. If the parental magma of the highland crust was generated by the partial melting of only part of the Moon, then the contents of incompatible elements in the source should have been higher. For example, the partial melting only of the upper 400-km shell of the Moon (which corresponds to the presumed depth of the magma ocean) yields 35% melting and a composition of the initial material close to the estimated bulk composition of the Moon in (Taylor, 19982), which was obtained based on the synthesis of geochemical and geophysical data. It should be stressed that the Sc/La, Ti/La, La/Al, and La/Yb ratios in our estimates are not equal to the chondritic ones (Table 6). The strong depletion of Sc and the high La/Yb ratio of the cotectic magma relative to the chondritic proportions suggest that the derivation of this magma was associated with the retainment of pyroxene and, perhaps, also garnet in the source if the pristine lunar material had a chondritic composition, as was assumed in (Taylor, 1982). This equilibrium is possible under a high pressure, and hence, it is reasonable to suggest that the parental highland magma was derived from deep zones of the Moon.

CONCLUSIONS

Lunar meteorites representatively characterize the composition of the lunar crustal material. Estimates of the average composition of the lunar crust based on the number of falls and masses of lunar meteorites lead to similar results, which suggests the validity of these evaluations. Furthermore, these estimates for the Fe, Ti, and Th concentrations are comparable with the orbital data recently obtained by the Lunar Prospector and Clementine spacecrafts.

The lunar highland crust should definitely be richer in plagioclase and poorer in incompatible elements than it was thought previously based on studying lunar rock samples delivered to the Earth. This crust is dominated by ferroan anorthosites (50–75%) and contains magnesian material. The average composition of mare areas of the Moon's surface corresponds to low-Ti basalts. High-Ti basalts seem to be spread not as widely. A typical feature of mare meteorites is their enrichment in LREE, which is not the case with the mare basalt samples delivered by the Apollo and Luna missions. The population of mixed meteorites reflects the composition of the mare–highland interface and suggests that these areas can be characterized by the presence of KREEP and VLT basalts.

The composition of the lunar highland crust deduced from the chemistry of lunar meteorites is not cotectic and is consistent with the concept of the magma ocean. However, the REE fractionation of mare meteorites is in conflict with this concept and suggests a significant role of the assimilation of the KREEP component by the magmas of mare basalts.

The petrography of highland meteorites and their concentrations of siderophile elements are consistent with the hypothesis of heavy meteoritic bombardment late during the formation of the highland crust. However, the correlations of siderophile and lithophile incompatible elements, as well as the size distribution of lunar impact basins, imply that the overwhelming majority of lunar impactites was produced by a single largest impact event, which originally determined their geochemical characteristics.

Geochemical data on lunar meteorites confirm that the primary lunar material can be enriched in refractory elements and depleted in volatile and siderophile elements relative to chondrites. It is reasonable to suggest that the lunar crust was produced by the profound differentiation of lunar interiors.

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