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Elemental Abundances of Moon Samples Based on Statistical Distributions of Analytical Data

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Abstract: The successful return of Chang'E-5 (CE5) samples urges the hot topic of the study of the Moon in geochemistry. The elemental data of the analyzed moon samples reported in the literature were collected to determine the elemental abundances in moon samples. Based on 2365 analytical records of moon samples from ten missions of Apollo, Luna, and CE5, elemental abundances of 11 major oxides including Cr_2O_3, 50 trace elements including Ti, P, Mn, Cr, and 15 rare earth elements (REEs) including Y are derived based on statistical distributions of normal, log-normal, and additive log-ratio transformation, respectively. According to the value of 13.5% CaO content, moon samples are classified into two types, as low-Ca and high-Ca samples, whose elemental abundances are also calculated respectively based on the methods used in the total moon samples. With respect to the mid-ocean ridge basalt (MORB) of the Earth, moon samples (including the Moon, low-Ca, and high-Ca samples) are rich in Cr, REEs, Th, U, Pb, Zr, Hf, Cs, Ba, W, and Be and poor in Na, V, Cu, and Zn in terms of their concentrations, and are enriched in Cr and depleted in Na, K, Rb, P, V, Cu, Zn in spider diagrams. The CE5 sample is a low-Ca type of moon sample and is clearly rich in Ti, Fe, Mn, P, Sc, REEs, Th, U, Nb, Ta, Zr, Hf, Sr, Ba, W, and Be and poor in Mg, Al, Cr, and Ni in terms of their concentrations relative to the moon or the low-Ca samples. If compared with the moon sample, the CE5 sample is also clearly rich in K, REE, and P.

Keywords: lunar samples; CE5; low-Ca; high-Ca; spider diagram

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Citation: Hou, Z.; Gong, Q.; Liu, N.; Jiang, B.; Li, J.; Wu, Y.; Huang, J.; Gu, W. Elemental Abundances of Moon Samples Based on Statistical Distributions of Analytical Data. *Appl. Sci.* **2023**, *13*, 360. https://doi.org/10.3390/app13010360

Academic Editors: Dibyendu Sarkar and Andrea L. Rizzo

Received: 30 November 2022
Revised: 22 December 2022
Accepted: 25 December 2022
Published: 27 December 2022

1. Introduction

The successful return of Chang'E-5 (CE5) has marked China as the third country to retrieve moon samples after the United States and the former Soviet Union. Studies on the returned samples have been an interesting and hot topic in geochemistry recently [1–11]. Elemental abundance is a basic topic in geochemistry, such as in the Earth [12–16]; therefore, the elemental composition of CE5 samples and moon samples from the Apollo and Luna missions is very attractive to geochemists.

On the elemental compositions of moon samples, Rose et al. [17–21] proposed the compositions from the Apollo missions. Samples in each Apollo mission were divided into the types of soil and rock, and the average elemental concentrations were used to represent their compositions. However, the analyzed samples or sample count from each mission was mostly less than 30, and items of major oxides, trace elements, and rare earth elements (REEs) were limited, such as 11 major oxides (including Cr_2O_3), 14 trace elements, and 3 REEs (Table 1). In addition, Taylor et al. [22] proposed a set of average elemental compositions in the lunar highland, including 8 major oxides (lack of P_2O_5 and MnO), 16 trace elements, and 14 REEs based on 4 samples from Apollo 17 and 6 samples from Apollo 16 (Table 1). Korotev [23] proposed the compositions of Apollo 16 soils, including 8 major oxides, 12 trace elements, and 8 REEs based on 8 sampling stations with 2~6 samples in each station (Table 1). Warren and Taylor [24] proposed the compositions of mare basalts and highland regolith on the Moon. The compositions of mare basalts include 8 major oxides, 10 trace elements, and 5 REEs derived from the elemental averages of mare basalts from all the Apollo and Luna missions except Apollo 16 and Luna 20. The sample count of the mare basalts is less than 200 from the Apollo missions and less than 20 from the Luna missions. The compositions of highland regolith, including 9 major oxides (lack of P_2O_5), 12 trace elements, and 9 REEs, were derived based on the statistical average of soils from Apollo 16, 2 regolith breccias from Apollo 14, and 7 lunar meteorites (Table 1). Although the elemental data from CE5 samples have been reported recently [1–3,5–7], the elemental compositions or abundances of moon samples are incomplete, which were derived based on only a few analytical samples with limited items (Table 1).

Table 1. Sample counts and element counts of analyzed moon samples.

References	**Rose et al. [17–21]**	**Taylor et al. [22]**	**Korotev [23]**	**Warren and Taylor [24]**	
Samples	**Apollo Missions**	**Lunar Highland**	**Apollo 16 Soils**	**Mare Basalts**	**Highland Regolith**
Counts of samples/records	<30	10	<50	<220	10
Counts of major oxides	11	8	8	8	9
Counts of trace elements	14	16	12	10	12
Counts of rare earth elements	3	14	8	5	9

In this paper, the analytical data reported in the literature on moon samples from Apollo, Luna, and CE5 missions were compiled firstly. Then the elemental abundances of moon samples were derived based on statistical distributions of the analytical data. Thirdly, the moon samples were classified into two types according to their concentrations of CaO, and the elemental abundances of each type were also calculated. Finally, the elemental compositions of CE5 samples were compared with the newly derived elemental abundances of moon samples.

2. Samples and Analytical Methods

2.1. Samples

The exploration and research of the Moon have been launched since 1957 [25]. In 1969, the Apollo 11 mission realized a manned moon landing and retrieved moon samples, which shifted the research on the Moon from theoretical conception to practical analysis [26–31]. Then in 1970, Luna 16 realized an unmanned moon landing sampling [32–34]. In 2020, Chang'E-5 (CE5) brought back moon samples [35]. So far, humans have retrieved moon samples 10 times, including 6 Apollo missions, 3 Luna missions, and the Chang'E-5 mission (Figure 1). The uppermost few meters of the Moon's crust, from which all the moon samples came, is a layer of loose, highly porous regolith or moon soil [24]. Samples from the Apollo missions contain lumps of rocks, breccias, surface soils, and core soils. The Apollo missions brought back a total of 380.95 kg of samples (Table 2), of which rock and breccia samples were picked up by the astronauts on the surface, and soil samples were mainly extracted by the surface scoop and deep drilling core, with a depth of 2 to 3 m. The Luna missions brought back a total of 0.301 kg of samples (Table 2). The sampling method was mechanical core drilling with a depth of 0.2 to 1.6 m. As for the CE5 mission, it brought back a total of 1.731 kg of lunar samples [1–3,5–7]. The sampling methods were mechanical shovel sampling and drilling sampling, but the drilling samples have not been analyzed or reported until now.

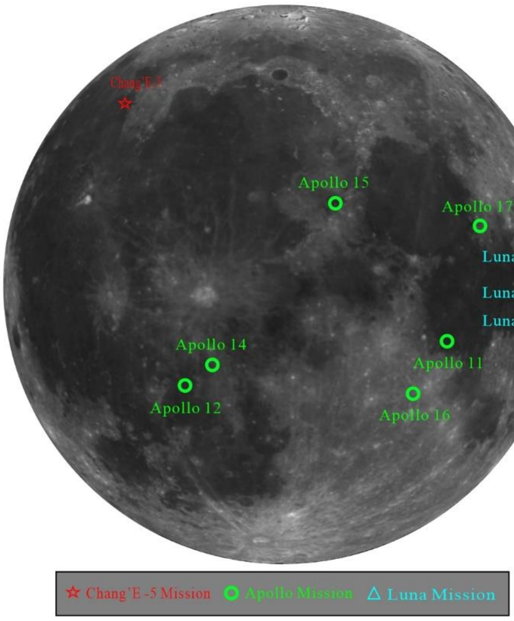

Figure 1. The landing sites of Apollo, Luna, and Chang'E-5 missions.

Table 2. The counts of analyzed records collected in this paper from each mission with other information.

Mission	Longitude	Latitude	Counts of Samples	Weight of Samples (kg)
Apollo 11	23.47297	0.67408	183	21.55
Apollo 12	−23.42157	−3.01239	218	34.30
Apollo 14	−17.47136	−3.6453	272	42.80
Apollo 15	3.63386	26.13222	364	76.70
Apollo 16	15.49812	−8.97301	685	95.20
Apollo 17	30.77168	20.1908	476	110.40
Luna 16	56.3	−0.68	33	0.101
Luna 20	56.5	3.57	34	0.030
Luna 24	62.2	12.75	67	0.170
Chang'E-5	−51.916	43.058	33	1.731
Sum	-	-	2365	382.982

2.2. Analytical Methods

The Apollo samples were first analyzed by the Lunar Sample Preliminary Examination Team of NASA. It reported a few samples' composition data, including major oxides and some trace elements without REEs for each mission [26–31]. Later, other experts and scholars applied to NASA for samples, of which the analytical composition data have been reported one after another [17–21,36,37]. The samples from the Luna missions were first analyzed and tested by the former Soviet Union [32–34]. Then after exchanging with the United States, the composition data was also analyzed and reported [32–34,38–40]. The composition data of CE5 samples have been analyzed and reported only recently [1–3,5–7].

The main analytical methods used to determine the composition data of moon samples are X-ray fluorescence spectrometry (XRF), inductively coupled plasma mass spectrometry (ICP-MS), instrumental neutron activation analysis (INNA), and electron microprobe analysis (EPMA), which can analyze many items such as major oxides, some trace elements, and/or REEs simultaneously [17,36–38]. In addition, other analytical methods such as isotope dilution analyses (IDA), emission spectrography (ES), and radiochemical neutron activation (RCNA) were adopted to analyze the composition of Rb, Sr, Zr, Re, Au, etc. [41–43]. The analytical quality, such as the detection limits, precisions, accuracies, relative errors, and relative standard deviations, were illustrated in the original literature. In general, the relative errors were less than 5% for major oxides and 10% for trace elements, including REEs.

All the analytical data collected in this paper are from moon samples brought back from the Apollo, Luna, and CE5 missions (excluding meteorites found on the Earth) and have been reported in the literature. The analyzed samples are soils, breccias, and rocks, and the counts of analytical samples (or records) in each mission or landing site are listed in Table 2. There are 2365 records of analytical data of moon samples used in this paper in total.

3. Statistical Methods and Results

3.1. Elemental Abundances in Moon Samples

In order to calculate the elemental abundances in moon samples, a total of 2365 records of analytical data were used with equal weight, ignoring the different missions or landing sites, sample types, and analytical methods from the literature.

According to the rule of "The contents of major oxides commonly obey normal distribution", the average of the analytical data excluding outliers was calculated as the abundance for each major oxide here. Firstly, the average (Avg) and standard deviation (Std) of each oxide's data were calculated for all the samples (the count of samples is labeled as n_0). Then, the boundary values of Avg ± 3Std were used to delete the outliers repeatedly until no outlier data were found. Finally, the average of each oxide's data without outliers (the count of samples is labeled as n) was calculated and viewed as its abundance. The abundances of 11 major oxides (including Cr_2O_3) along with counts of samples (n_0 and n) are listed in Table 3, and statistical histograms of major oxides are illustrated in Figure 2. The sum of the 11 major oxides (or Total in Table 2) is 99.10%, which is close to the closure value of 100%.

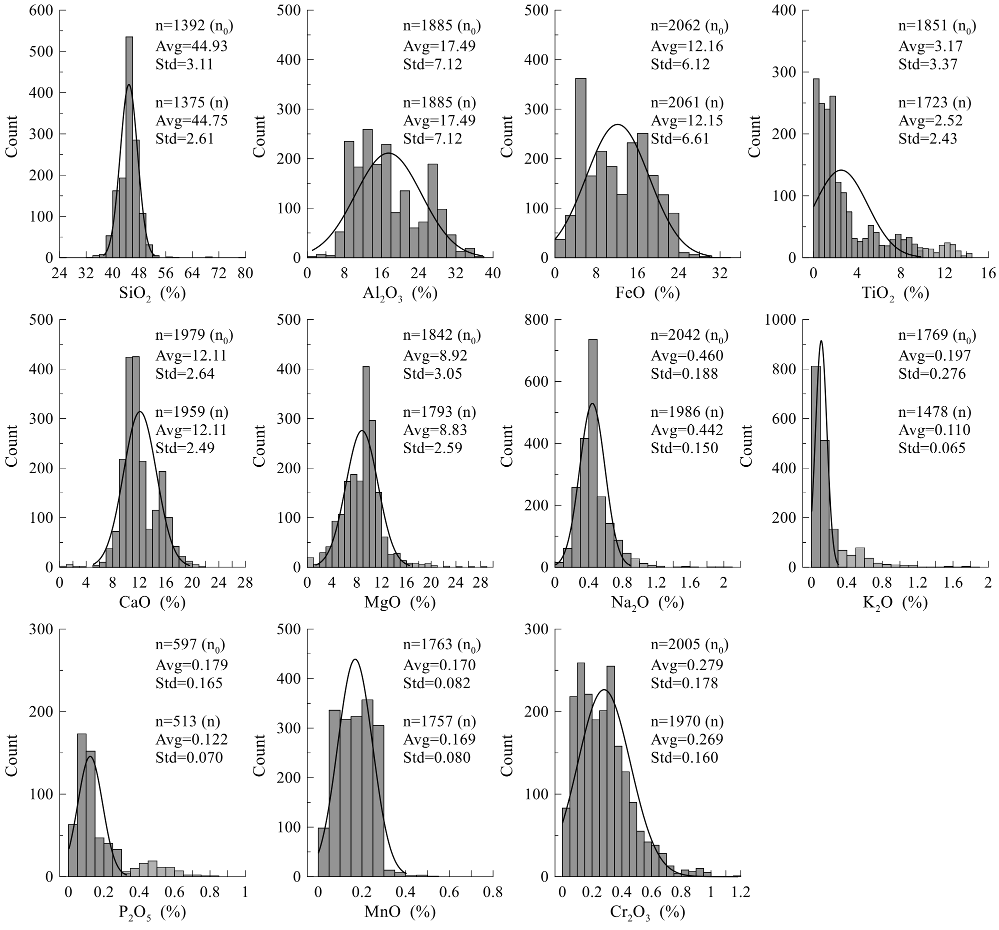

Figure 2. Histograms of major oxides with their counts of samples (n_0 is the count of total analytical data and n is the count of analytical data without outliers). The histogram of K_2O contents is drawn without the three highest values of 5.8, 3.2, and 3.1, and the histogram of P_2O_5 contents is without the two highest values of 1.38 and 1.1.

Table 3. Elemental abundances in moon samples with their counts of samples (n_0 and n).

Oxides/	**Moon**			**Low-Ca**			**High-Ca**			**CE5**
Elements	**Abundance**	**n_0**	**n**	**Abundance**	**n_0**	**n**	**Abundance**	**n_0**	**n**	**Abundance**
SiO_2	44.89	1392	1375	44.78	1029	1015	45	346	327	41.51
Al_2O_3	17.49	1885	1885	14.17	1379	1377	27.66	466	447	10.93
FeO	12.15	2062	2061	14.59	1456	1454	4.98	511	464	22.7
TiO_2	2.52	1851	1723	3.98	1383	1379	0.431	444	419	5.43
CaO	12.11	1979	1959	10.93	1468	1440	15.69	511	493	11.36
MgO	8.83	1842	1793	9.77	1359	1302	5.75	462	461	6.21
Na_2O	0.443	2040	1984	0.449	1452	1422	0.458	509	485	0.434
K_2O	0.11	1769	1478	0.171	1277	1181	0.088	409	393	0.175
P_2O_5	0.123	596	512	0.18	476	461	0.106	120	120	0.248
MnO	0.169	1763	1757	0.194	1347	1341	0.061	362	336	0.285
Cr_2O_3	0.269	2012	1974	0.316	1384	1364	0.095	458	445	0.199
Total	99.1	-	-	99.53	-	-	100.32	-	-	99.49
Ag	5.1	112	112	11.1	38	38	12	1	1	-
As	0.054	79	79	0.057	52	52	0.027	14	14	-
Au	3.91	572	528	4.24	366	347	4.46	87	87	8.8
B	3.88	20	19	3.42	19	18	39	1	1	-
Ba	162	1488	1466	202	962	957	106	307	297	388
Be	1.35	186	185	2.03	86	85	1.06	22	22	2.84
Bi	0.0006	95	93	0.0167	5	5	-	0	0	-
Br	0.076	84	84	0.065	38	38	0.09	9	9	-
Cd	12.4	145	144	59.9	32	32	7.2	21	21	-
Cl	13.5	78	78	12	52	52	22.7	13	13	-
Co	32.2	1675	1608	35.1	1096	1062	25.4	322	322	37.7
Cr	1546	1970	1933	2046	1384	1354	607	429	429	1359
Cs	0.136	583	579	0.242	247	247	0.118	152	152	0.205
Cu	9.45	448	437	9.5	238	229	4.77	83	83	12.2
F	67	48	48	86	37	37	29.2	11	11	-
Ga	4.59	613	574	5.55	384	357	3.42	100	100	5.79
Ge	0.08	181	181	0.087	75	75	0.219	15	15	-
Hf	5.5	1401	1372	6.84	960	954	2.95	248	248	13.8
In	0.0054	159	159	0.0081	40	40	0.0043	14	14	-
Ir	8.1	602	559	8.6	367	359	10.2	116	116	3.61
Li	9.5	347	340	12.3	174	174	6.24	65	65	15.4
Mn	1167	1761	1734	1441	1347	1325	490	341	320	2205
Mo	0.119	89	85	0.239	23	23	0.014	2	2	0.033
Nb	12.2	545	537	15.7	333	332	6.67	96	96	35.6
Ni	213	1413	1323	208	837	806	288	330	329	139
Os	1.67	103	103	15.7	12	12	7.5	1	1	-
P	267	840	840	626	476	476	395	115	115	1080
Pb	1.42	215	211	2.44	81	80	2.08	47	47	1.89
Pd	3.53	136	136	7.3	44	44	2.9	2	2	-
Pt	9.3	13	13	9.4	12	12	9	1	1	-
Rb	2.92	854	845	4.34	447	447	1.97	142	139	5.63
Re	0.167	124	124	0.464	30	30	2.31	2	2	-
Rh	16.7	2	2	16.7	2	2	-	0	0	-
Ru	13.7	29	28	10.1	19	18	23.7	10	10	-
S	819	248	235	881	193	189	592	46	45	-
Sb	0.0054	182	182	0.068	25	25	0.0079	16	16	-
Sc	25.6	1613	1600	36.1	1039	1035	8.3	347	334	63.5
Se	0.068	146	142	0.346	32	32	0.204	7	7	-
Sn	0.497	79	79	0.361	23	23	0.074	21	21	-
Sr	150	1337	1305	148	871	857	165	264	261	309
Ta	0.82	1193	1176	1.08	838	827	0.384	220	219	1.81
Te	0.0053	94	93	0.027	1	1	0.5	1	1	-
Th	1.99	1140	1127	2.36	755	752	1.58	262	255	4.98
Ti	11009	1850	1835	17063	1383	1378	2581	429	408	32526
Tl	0.00324	106	106	0.011	14	14	0.0006	1	1	-
U	0.63	986	959	0.88	589	589	0.465	196	185	1.36
V	64	1077	1070	79	763	751	19.8	188	187	93.1
W	0.207	170	170	0.331	92	92	0.229	12	12	0.54
Zn	13	643	640	18.5	341	340	6.6	92	92	14.5
Zr	222	979	961	288	601	598	134	222	222	523
La	12.3	1553	1532	14.7	1050	1041	8.57	284	249	35.6
Ce	35.1	1429	1407	42.7	946	942	22.5	265	246	97.7
Pr	5	196	195	7.25	87	87	2.9	30	26	12.6
Nd	24.6	1102	1081	31.2	752	740	13.7	159	149	59.7
Sm	7.5	1473	1403	9.48	984	944	3.89	261	248	16.9
Eu	1.35	1499	1443	1.52	1004	997	1.07	269	261	2.58
Gd	9.8	346	335	12.5	143	141	4.67	54	52	19.3
Tb	1.67	1315	1268	2.12	886	851	0.8	255	249	3.28
Dy	10.5	1103	1017	13.3	759	689	5.04	163	152	20.4
Ho	2.36	540	490	3.04	346	302	1.13	74	71	4.14
Er	6.5	375	348	8.4	170	157	3.11	43	40	11.2
Tm	0.9	377	314	1.15	256	208	0.458	45	42	1.48
Yb	5.84	1680	1652	7.39	1126	1121	2.88	303	301	9.75
Lu	0.84	1414	1312	1.07	942	855	0.413	263	245	1.36
Y	60	426	407	73	259	243	31.4	67	64	116

Note: The units of major oxides and trace elements (including REEs) are % and μg/g, respectively, except Ag, Au, Cd, Re, Ru, Rh, Pd, Os, Ir, Pt, which are in ng/g.

According to the rule of "The contents of trace elements commonly obey log-normal distributions", the geometric average of analytical data excluding outliers was calculated as the abundance for each trace element. The elemental abundances of 50 trace elements (including Ti, P, Mn, and Cr), along with their counts of samples (n_0 and n), are also listed in Table 3.

REE pattern is a useful tool for traceability or provenance in geochemistry [44,45], and the key signature is the variation trend of the pattern, which is dependent on REE concentrations. Therefore, the covariation of REE abundances needs to be considered. Here, the additive log-ratio (alr) transformation method [46,47] was adopted to calculate the REE (including Y) abundances, and Yb was selected as the denominator to calculate the ratios for other REEs. Yb was selected as the denominator of the alr transformation method because it not only has the largest count of analyzed samples (n_0 = 1680 and n = 1652) but also obeys the log-normal distribution well relative to the other REEs. According to the geometric average of Yb without outliers, 5.84 μg/g was set as its abundance of moon samples and was used to calculate the abundances of the other REEs (including Y). The abundances of 15 REEs (including Y) with their counts of samples (n_0 and n) are also listed in Table 3.

3.2. Elemental Abundances in Moon Samples with Low-Ca and High-Ca

Although elemental abundances in moon samples were derived based on statistical distributions such as normal, log-normal, and alr-normal distributions, some items clearly deviate from their ideal distributions, such as CaO, FeO, Al_2O_3, TiO_2, P_2O_5, Cr_2O_3, etc., as shown in Figure 2. It is worth mentioning that the distribution of CaO contents is near a bimodal distribution (Figure 2). In order to derive more meaningful elemental abundances, moon samples were classified into two types, as low-Ca and high-Ca samples, based on the CaO content boundary of 13.5% used in this paper.

In the total 2365 analyzed moon samples, there were only 1979 records with valid CaO contents. According to the content boundary of 13.5% CaO, there were 1468 records classified as low-Ca samples and 511 as high-Ca samples. Therefore, moon samples with low Ca were about three-quarters of the total moon samples collected in this paper, and samples with high Ca were about one-quarter.

With respect to the low-Ca moon samples and high-Ca moon samples, we used the same statistical methods as adopted for the total moon samples to calculate the elemental abundances of each type separately. The abundances of each type are also listed in Table 3, along with their counts of samples (n_0 and n).

4. Discussion

4.1. Geochemical Signatures of Elemental Abundances

Based on the elemental abundances of the moon, low-Ca, and high-Ca samples in Table 2, we compared their geochemical signatures with the elemental abundances of carbonaceous chondrite CI [12], primitive mantle [13], bulk oceanic crust [14], mid-ocean ridge basalt (including those of Atlantic, India, and Pacific [14]), continental crust (including total continental crust, lower continental crust, middle continental crust, and upper continental crust [15]), and rocks of China (including acidic rock, intermediate rock, and basic rock of China [16]) and found moon samples are more close to the mid-ocean ridge basalt (MORB) of the Earth. Here, only the comparison results with the MORB were illustrated to derive the geochemical signatures of moon samples.

4.1.1. Major Oxides

According to the illustration method of spider diagrams, the 11 major oxides were first sequenced descending on their abundances of moon samples. Then, moon samples were normalized based on the MORB of the Earth. Finally, the spider diagrams of major oxides of moon samples were derived and illustrated in Figure 3.

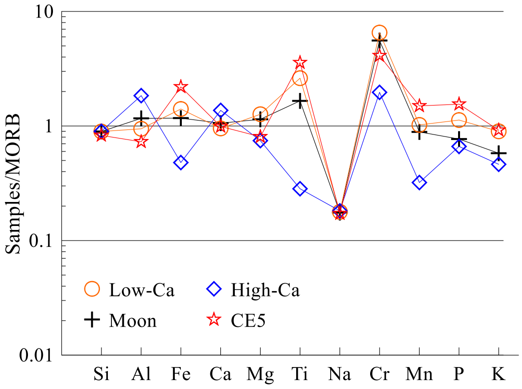

Figure 3. Spider diagrams of major oxides of moon samples normalized based on MORB. Abundances of the MORB are from White and Klein [14]. Elements in the horizontal axis are the abbreviations of their major oxides listed in Table 2.

With respect to the MORB, the moon sample (labeled as Moon in Figure 3) is clearly rich in Cr_2O_3 and TiO_2 and poor in K_2O in terms of their concentrations. The moon sample with low-Ca (labeled as Low-Ca in Figure 3) is also clearly rich in Cr_2O_3 and TiO_2 and poor in K_2O, like the moon sample. While the moon sample with high-Ca (labeled as High-Ca in Figure 3) is clearly rich in Cr_2O_3 and Al_2O_3 and poor in Na_2O, TiO_2, MnO, and FeO in terms of their concentrations. In the three abundances of moon samples, the moon sample with low-Ca is closer to the MORB, except for the clear signature of higher concentrations of Cr_2O_3 and TiO_2 and lower concentrations of K_2O.

With respect to the MORB, the moon samples (including Moon, low-Ca, and high-Ca in Figure 3) are clearly enriched in Cr and depleted in Na in the diagrams. Here, the terms of rich and poor are used for concentrations (comparison between/among samples), and the terms of enriched and depleted are used for diagrams (comparison among elements in the same sample).

4.1.2. REEs

The REE patterns of the three abundances of moon samples (including Moon, low-Ca, and high-Ca) are illustrated in Figure 4.

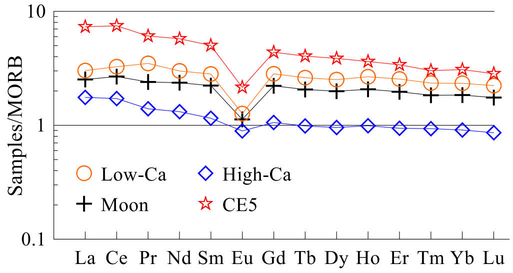

Figure 4. REE patterns of moon samples normalized to the MORB. Abundances of the MORB are from White and Klein [14].

With respect to the MORB, the REE patterns of the Moon and low-Ca samples (Figure 4) are near flat, except for the clear negative Eu anomaly. While the pattern of high-Ca (Figure 4) is tilted right for light REEs and nearly flat for heavy REEs. Therefore, the Moon and low-Ca samples are closer to the MORB than the high-Ca samples in the REE pattern, except for the clear negative Eu anomaly. With respect to the absolute concentrations of REEs, the three abundances of moon samples (including Moon, low-Ca, and high-Ca) are all higher or richer than those of the MORB. The descending sequence of total REE concentrations is (CE5 discussed in the following), low-Ca, Moon, high-Ca, and the MORB (Figure 4).

4.1.3. Trace Elements

Trace elements are illustrated using the spider diagram suggested by Sun and McDonough [48], with 31 elements, including K, P, and Ti. In order to avoid the repetition of REEs, the Ce and Eu were deleted from the spider diagram in which Ce and Eu are following the La and Sm, respectively. Therefore, a total of 29 elements (including K, P, and Ti) were used to draw the spider diagrams of the moon samples, which are illustrated in Figure 5.

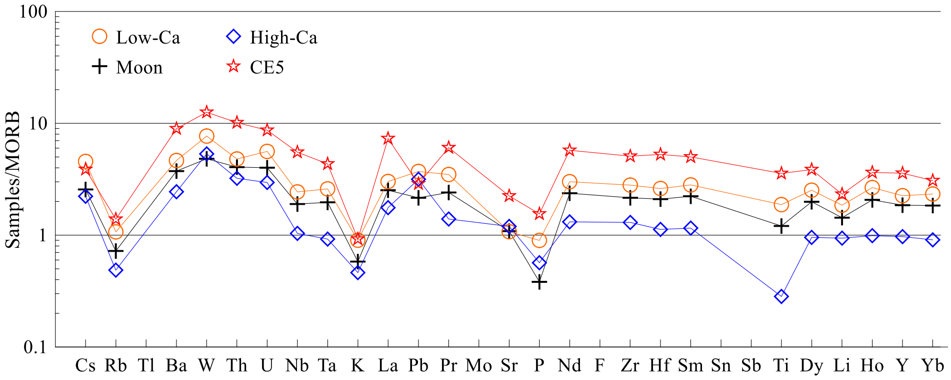

Figure 5. Spider diagrams of moon samples normalized to the MORB. Abundances of the MORB are from White and Klein [14].

With respect to the MORB in terms of their concentrations, the moon samples (including the Moon, low-Ca, and high-Ca) are all clearly rich in Cs, Ba, W, Th, U, and Pb (Figure 5).

With respect to the MORB, spider diagrams of moon samples (including the Moon, low-Ca, and high-Ca) are nearly flat (variations are limited to one order of magnitude), except for the clear depletion in Rb, K, and P (Figure 5). Furthermore, the diagram of high-Ca is also clearly depleted in Ti (Figure 5).

4.1.4. Other Trace Elements

Except for the aforementioned major oxides, REEs, and trace elements, there are only eight remaining elements of Sc, V, Co, Ni, Cu, Zn, Be, and B, which are reported abundances both of moon samples and the MORB. Here we supplement Ti, Cr, Mn, and Fe to the eight elements to form a series of the first transition elements plus Be and B. Therefore, 12 elements were used to form the spider diagrams of the moon samples which are illustrated in Figure 6.

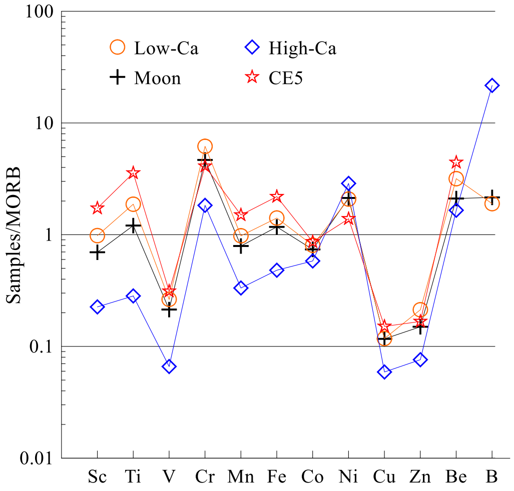

Figure 6. Spider diagrams of moon samples on first transition elements plus Be and B normalized to the MORB. Abundances of the MORB are from White and Klein [14].

With respect to the MORB in terms of their concentrations, the moon samples (including the Moon, low-Ca, and high-Ca) are all clearly rich in Cr, Ni, and Be and poor in V, Cu, and Zn (Figure 6).

With respect to the MORB, the spider diagrams of moon samples (including the Moon, low-Ca, and high-Ca) are nearly flat (variations are limited to one order of magnitude), except for the clear enrichment in Cr and depletion in V, Cu, and Zn (Figure 6). In addition, the diagram for the high-Ca moon sample is also clearly enriched in Ni and B (Figure 6).

In summary, the geochemical signatures of major oxides, REEs, and trace elements in moon samples (including the Moon, low-Ca, and high-Ca) are rich in Cr, REEs, Th, U, Pb, Zr, Hf, Cs, Ba, W, and Be and poor in Na, V, Cu, and Zn in terms of their concentrations, and are enriched in Cr and depleted in Na, K, Rb, P, V, Cu, and Zn in the spider diagrams, relative to the MORB. Among the total moon samples, low-Ca samples, and high-Ca samples, the low-Ca samples are closer to the total moon samples in concentration or patterns (or diagrams), which is not only illustrated in Figure 3 to Figure 6 but also consistent with the counts of analytical data with equal weighting used in this study. Except the 46 elements discussed in this paper, the other 26 elemental abundances in moon samples are not discussed here because of the data lack on the MORB.

4.2. Chang'E-5 Samples

4.2.1. Elemental Concentrations

Here we compile the analyzed elemental data of CE5 samples reported recently. The averages are used to represent the elemental concentrations of the CE5 samples which include 33 analyzed records, including two repetitions reported by different authors. If the elemental concentrations were only reported by Zong et al. [7], the suggested concentrations by Zong et al. [7] are used in this paper.

The calculated elemental concentrations of the CE5 samples are also listed in Table 3, including 11 major oxides, 15 REEs (including Y), and 28 trace elements (including Ti, P, Mn, and Cr).

4.2.2. Geochemical Signatures

The content of CaO of CE5 is 11.36%, which is lower than the boundary value of 13.5% for low-Ca and high-Ca moon samples. Therefore, the CE5 sample is the low-Ca type of moon sample. In terms of Ti content, moon samples can be divided into three types: high Ti ($TiO_2 \geq 6\%$), low Ti ($1\% \leq TiO_2 < 6\%$), and very low Ti ($TiO_2 < 1\%$) [11]. The content of TiO_2 of CE5 is 5.43%, which indicates that the CE5 sample is the low Ti type of moon sample.

According to the illustrations of moon samples, the geochemical signatures of the CE sample are also illustrated in Figure 3 to Figure 6.

With respect to the MORB, the CE5 sample is clearly rich in Cr_2O_3, TiO_2, and FeO and poor in Na_2O (Figure 3) in major oxides in terms of their concentrations, and is also enriched in Cr_2O_3, TiO_2, and FeO and depleted in Na_2O in the diagrams. The REE pattern of CE5 is tilted right slowly, except for the clear negative Eu anomaly, and its REE concentrations are clearly higher than those of the MORB (Figure 4). In the spider diagrams (Figures 5 and 6), the CE5 sample is clearly rich in Cs, Ba, W, Th, U, Nb, Ta, Pb, Zr, Hf, Ti, Li, Sr, Cr, and Be and poor in V, Cu, and Zn in terms of their concentrations, and is enriched in Cr and depleted in Rb, K, P, V, Cu, and Zn in the spider diagrams. Among the total moon sample, low-Ca sample, and high-Ca sample, the CE5 sample is closer to the low-Ca sample in concentrations or patterns (or diagrams), which are illustrated in Figure 3 to Figure 6. This is consistent with the low-Ca type of moon samples discriminated on CaO content, as mentioned previously.

With respect to the total moon sample, the CE5 sample is clearly rich in Ti, Fe, Mn, P, Sc, K, REEs, Th, U, Nb, Ta, Zr, Hf, Sr, Ba, W, and Be and poor in Mg, Al, Cr, and Ni in terms of their concentrations. From this view, the CE5 sample is the KREEP type of moon sample [49,50] because it is rich in K, REEs, and P relative to the moon sample. However, the contents of K_2O in the CE5 sample and the low-Ca sample are 0.175% and 0.171%, respectively, which are almost the same within the relative error. From this view, the CE5 sample is the non-KREEP type of moon sample [1] because of the non-enrichment of K relative to the low-Ca moon sample.

Except for the aforementioned studies on the CE5, more and more articles are being published [51–54] on hot and interesting topics, which are very helpful in promoting the research of the Moon. The elemental abundances of the CE5 sample in this paper will be improved on with more studies in the near future.

5. Conclusions

(1) The elemental abundances of moon samples, including the moon sample, the low-Ca moon sample, and the high-Ca moon sample, were derived from statistical distributions of analytical data reported in the literature. The classification criterion of low-Ca and high-Ca types of moon samples was 13.5% CaO content.
(2) With respect to the MORB of the Earth, the moon samples (including the Moon, low-Ca, and high-Ca samples) were rich in Cr, REEs, Th, U, Pb, Zr, Hf, Cs, Ba, W, and Be and poor in Na, V, Cu, and Zn in terms of their concentrations, and were enriched in Cr and depleted in Na, K, Rb, P, V, Cu, and Zn in the spider diagrams.
(3) The CE5 sample is the low-Ca type of moon sample and is clearly rich in Ti, Fe, Mn, P, Sc, REEs, Th, U, Nb, Ta, Zr, Hf, Sr, Ba, W, and Be and poor in Mg, Al, Cr, and Ni in terms of their concentrations relative to the moon and the low-Ca moon samples. If compared with only the moon sample, the CE5 sample is also clearly rich in K, REE, and P.

Author Contributions: Conceptualization, Z.H., Q.G., B.J., J.L. and Y.W.; Methodology, Q.G. and N.L.; Formal analysis, Z.H.; Data curation, Z.H., N.L., B.J., J.L., Y.W., J.H. and W.G.; Writing—original draft, Z.H.; Writing—review & editing, Q.G. and N.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We thank the authors who reported the geochemical data of moon samples used in this manuscript. We greatly appreciate the comments from the anonymous reviewers for their valuable suggestions to improve the quality of this manuscript.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Tian, H.C.; Wang, H.; Chen, Y.; Yang, W.; Zhou, Q.; Zhang, C.; Lin, H.L.; Huang, C.; Wu, T.S.; Jia, L.H.; et al. Non-KREEP origin for Chang'E-5 basalts in the Procellarum KREEP Terrane. *Nature* **2021**, *600*, 59–63. [CrossRef] [PubMed]
2. Li, Q.L.; Zhou, Q.; Liu, Y.; Xiao, Z.Y.; Lin, Y.T.; Li, J.H.; Ma, H.X.; Tang, G.Q.; Guo, S.; Tang, X.; et al. Two-billion-year-old volcanism on the Moon from Chang'e-5 basalts. *Nature* **2021**, *600*, 54–58. [CrossRef] [PubMed]
3. Che, X.C.; Nemchin, A.; Liu, D.Y.; Long, T.; Wang, C.; Norman, M.D.; Joy, K.H.; Tartese, R.; Head, J.; Jolliff, B.; et al. Age and composition of young basalts on the Moon, measured from samples returned by Chang'e-5. *Science* **2021**, *374*, 887–890. [CrossRef] [PubMed]
4. Hu, S.; He, H.C.; Ji, J.L.; Lin, Y.T.; Hui, H.J.; Anand, M.; Tartèse, R.; Yan, Y.H.; Hao, J.L.; Li, R.Y.; et al. A dry lunar mantle reservoir for young mare basalts of Chang'E-5. *Nature* **2021**, *600*, 49–53. [CrossRef] [PubMed]
5. Li, C.L.; Hu, H.; Yang, M.F.; Pei, Z.Y.; Zhou, Q.; Ren, X.; Liu, B.; Liu, D.W.; Zeng, X.G.; Zhang, G.L.; et al. Characteristics of the lunar samples returned by the Chang'E-5 mission. *Natl. Sci. Rev.* **2022**, *9*, nwab188. [CrossRef] [PubMed]
6. Yao, Y.G.; Xiao, C.J.; Wang, P.S.; Li, C.L.; Zhou, Q. Instrumental Neutron Activation Analysis of Chang'E-5 Lunar Regolith Samples. *J. Am. Chem. Soc.* **2022**, *144*, 5478–5484. [CrossRef]

7. Zong, K.Q.; Wang, Z.C.; Li, J.W.; He, Q.; Harry, B.; Hu, Z.C.; He, T.; Cao, K.N.; She, Z.B.; Wu, X.; et al. Bulk compositions of the Chang'E-5 lunar soil: Insights into chemical homogeneity, exotic addition, and origin of landing site basalts. *Geochim. Cosmochim. Acta* **2022**, *335*, 284–296; ISSN 0016-7037. [CrossRef]
8. Zhang, C.Q.; Li, J.H. Non-destructive Identification and Quantification of Ilmenite from a Single Particle of the Chang'E-5 Lunar Soil Sample. *At. Spectrosc.* **2022**, *43*, 284–291.
9. Su, B.; Yuan, J.; Chen, Y.; Yang, W.; Ross, N.M.; Hui, H.J.; Wang, H.; Tian, H.C.; Li, X.H.; Wu, F.Y. Fusible mantle cumulates trigger young mare volcanism on the Cooling Moon. *Sci. Adv.* **2022**, *8*, eabn2103. [CrossRef]
10. Yang, W.; Chen, Y.; Wang, H.; Tian, H.C.; Hui, H.J.; Xiao, Z.Y.; Wu, S.T.; Zhang, D.; Zhou, Q.; Ma, X.H.; et al. Geochemistry of impact glasses in the Chang'e-5 regolith: Constraints on impact melting and the petrogenesis of local basalt. *Geochim. Cosmochim. Acta* **2022**, *335*, 183–196. [CrossRef]
11. Tian, H.C.; Yang, W.; Zhang, D.; Zhang, H.J.; Jia, L.H.; Wu, S.T.; Lin, Y.T.; Li, X.H.; Wu, F.Y. Petrogenesis of Chang'E-5 mare basalts: Clues from the trace elements in plagioclase. *Am. Mineral.* **2022**, *600*, 59–63.
12. Palme, H.; Lodders, K.; Jones, A. Solar system abundances of the elements. In *Treatise on Geochemistry, Volume 1: Meteorites, Comets, and Planets*; Holland, H.D., Turekian, K.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 15–36.
13. Palme, H.; O'Neill, H.S.C. Cosmochemical Estimates of Mantle Composition. In *Treatise on Geochemistry, Volume 3: The Crust*; Holland, H.D., Turekian, K.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 1–39.
14. White, W.M.; Klein, E.M. Composition of the oceanic crust. In *Treatise on Geochemistry, Volume 3: The Crust*; Holland, H.D., Turekian, K.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 457–496.
15. Rudnick, R.L.; Gao, S. Composition of the Continental Crust. In *Treatise on Geochemistry, Volume 3: The Crust*; Holland, H.D., Turekian, K.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 1–64.
16. Chi, Q.H.; Yan, M.C. *Handbook of Elemental Abundance for Applied Geochemistry*; Geological Publishing House: Beijing, China, 2007; pp. 1–148.
17. Rose, H.J.; Cuttitta, F.; Dwornik, E.J.; Carron, M.K.; Christian, R.P.; Lindsay, J.R.; Ligon, D.T.; Larson, R.R. Semimicro chemical and X-ray fluorescence analysis of lunar samples. *Science* **1970**, *167*, 520–521. [CrossRef] [PubMed]
18. Rose, H.J.; Cuttitta, F.; Annell, C.S.; Carron, M.K.; Christian, R.P.; Dwornik, E.J.; Greenland, L.P.; Ligon, D.T. Compositional data for twenty-one Fra Mauro lunar materials. In Proceedings of the 2nd Lunar Science Conference, Houston, TX, USA, 10–13 January 1972; Volume 2, pp. 1215–1229.
19. Rose, H.J.; Cuttitta, F.; Berman, S.; Carron, M.K.; Christian, R.P.; Dwornik, E.J.; Greenland, L.P.; Ligon, D.T. Compositional data for twenty-two Apollo 16 samples. In Proceedings of the 2nd Lunar Science Conference, Houston, TX, USA, 5–8 March 1973; Volume 2, pp. 1149–1158.
20. Rose, H.J.; Cuttitta, F.; Berman, S.; Carron, M.K.; Christian, R.P.; Dwornik, E.J.; Greenland, L.P. Chemical composition of rocks and soils at Taurus-Littrow. In Proceedings of the 2nd Lunar Science Conference, Houston, TX, USA, 18–22 March 1974; Volume 2, pp. 1119–1133.
21. Rose, H.J.; Christian, R.P.; Dwomik, E.J.; Schnepfe, M.M. Major elemental analysis of some Apollo 15, 16, and 17 samples (abs). *Lunar Sci.* **1975**, *6*, 686–688.
22. Taylor, S.R.; Gorton, M.P.; Muir, P.; Nance, W.B.; Rudowski, R.; Ware, N. Composition of the Descartes region, lunar highlands. *Geochim. Cosmochim. Acta* **1973**, *37*, 2665–2683. [CrossRef]
23. Korotev, R.L. Some things we can infer about the Moon from the composition of the Apollo 16 regolith. *Meteorit. Planet. Sci.* **1997**, *32*, 447–478. [CrossRef]
24. Warren, P.H.; Taylor, G.J. The Moon. In *Treatise on Geochemistry, Volume 1: Meteorites, Comets, and Planets*; Holland, H.D., Turekian, K.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 559–599.
25. Crawford, I.A.; Joy, K.H.; Anand, M. Lunar Exploration. In *Encyclopedia of the Solar System, Part V: Earth and Moon as Planets*; Spohn, T., Breuer, D., Johnson, T.V., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 555–579.
26. LSPET. Preliminary examination of lunar samples from Apollo 11. *Science* **1965**, *165*, 1211–1227.
27. LSPET. Preliminary examination of lunar samples from Apollo 12. *Science* **1970**, *167*, 1325–1339. [CrossRef]
28. LSPET. Preliminary examination of lunar samples from Apollo 14. *Science* **1971**, *173*, 681–693. [CrossRef]
29. LSPET. The Apollo 15 lunar samples: A preliminary description. *Science* **1972**, *175*, 363–375. [CrossRef]
30. LSPET. The Apollo 16 lunar samples: Petrographic and chemical description. *Science* **1973**, *179*, 23–34. [CrossRef]
31. LSPET. Apollo 17 lunar samples: Chemical and petrographic description. *Science* **1973**, *182*, 659–690. [CrossRef] [PubMed]
32. Vinogradov, A.P. Preliminary data on lunar ground brought to Earth by Automatic Probe "Luna 16". In Proceedings of the 2nd Lunar Science Conference, Houston, TX, USA, 11–14 January 1971; Volume 2, pp. 1–16.
33. Vinogradov, A.P. Preliminary data on lunar soil collected by the Luna 20 unmanned spacecraft. *Geochim. Et Cosmochim. Acta* **1973**, *37*, 721–729. [CrossRef]
34. Barsukov, V.L. Preliminary data for the regolith core brought to earth by the automatic lunar station Luna 24. In Proceedings of the 8th Lunar Science Conference, Houston, TX, USA, 14–18 March 1977; Volume 2, pp. 3303–3318.
35. Qian, Y.; Xiao, L.; Wang, Q.; Head, J.W.; Yang, R.; Kang, Y.; van der Bogert, C.H.; Hiesinger, H.; Lai, X.; Wang, G.; et al. China's Chang'e-5 landing site: Geology, stratigraphy, and provenance of materials. *Earth Planet. Sci. Lett.* **2021**, *561*, 116855. [CrossRef]

36. Dickinson, T.; Taylor, G.J.; Keil, K.; Bild, R.W. Germanium abundances in lunar basalts-Evidence of mantle metasomatism? In Proceedings of the 19th Lunar and Planetary Science Conference Proceedings, Houston, TX, USA, 14–18 March 1989; Volume 19, pp. 189–198.
37. Neal, C.R. Interior of the Moon: The presence of garnet in the primitive deep lunar mantle. *J. Geophys. Res. Planets* **2001**, *106*, 27865–27885. [CrossRef]
38. Albee, A.L.; Chodos, A.A.; Gancarz, A.J.; Haines, E.L.; Papanastassiou, D.A.; Ray, L.; Tera, F.; Wasserburg, G.J.; Wen, T. Mineralogy, petrology, and chemistry of a Luna 16 basaltic fragment, sample B-1. *Earth Planet. Sci. Lett.* **1972**, *13*, 353–367, ISSN 0012-821X. [CrossRef]
39. Barsukov, V.L.; Tarasov, L.S.; Dmitriiev, L.V.; Kolesov, G.M.; Shevaleevsky, I.D.; Garanin, A.V. The geochemical and petrochemical features of regolith and rocks from Mare Crisium (preliminary data). In Proceedings of the 8th Lunar Science Conference, Houston, TX, USA, 14–18 March 1977; Volume 2, pp. 3319–3332.
40. Helmke, P.A.; Blanchard, D.P.; Jacobs, J.W.; Haskin, L.A. Rare earths, other trace elements and iron in Luna 20 samples. *Geochim. Cosmochim. Acta* **1973**, *37*, 869–874. [CrossRef]
41. Compston, W.; Berry, H.; Vernon, M.J.; Bruce, W. Rubidium-strontium chronology and chemistry of lunar material from the Ocean of Storms. In Proceedings of the 2nd Lunar and Planetary Science Conference Proceedings, Houston, TX, USA, 11–14 January 1971; Volume 2, p. 1471.
42. Taylor, S.R.; Kaye, M.; Muir, P.; Nance, W.; Rudowski, R.; Ware, N. Composition of the lunar uplands: Chemistry of Apollo 14 samples from Fra Mauro. In Proceedings of the 3rd Lunar and Planetary Science Conference Proceedings, Houston, TX, USA, 10–13 January 1972; Volume 3, p. 1231.
43. Wänke, H.; Palme, H.; Kruse, H.; Baddenhausen, H.; Cendales, M.; Dreibus, G.; Hofmeister, H.; Jagoutz, E.; Palme, C.; Spettel, B.; et al. Chemistry of lunar highland rocks-A refined evaluation of the composition of the primary matter. In Proceedings of the 7th Lunar and Planetary Science Conference Proceedings, Houston, TX, USA, 15–19 March 1976; Volume 7, pp. 3479–3499.
44. Gong, Q.J.; Deng, J.; Yang, L.Q.; Zhang, J.; Wang, Q.F.; Zhang, G.X. Behavior of major and trace elements during weathering of sericite–quartz schist. *J. Asian Earth Sci.* **2011**, *42*, 1–13; ISSN 1367-9120. [CrossRef]
45. Gong, Q.J.; Yan, T.T.; Wu, X.; Li, R.K.; Wang, X.Q.; Liu, N.Q.; Li, X.L.; Wu, Y.; Li, J. Geochemical gene: A promising concept in discrimination and traceability of geological materials. *Appl. Geochem.* **2022**, *136*, 105133. [CrossRef]
46. Aitchison, J. The Single Principle of Compositional Data Analysis, Continuing Fallacies, Confusions and Misunderstandings and Some Suggested Remedies. 2008. Available online: https://hdl.handle.net/10256/706 (accessed on 15 May 2020).
47. Egozcue, J.J.; Pawlowsky-Glahn, V.; Mateu-Figueras, G.; Barcelo-Vidal, C. Isometric logration transformations for compositional data analysis. *Math. Geol.* **2003**, *35*, 279–300. [CrossRef]
48. Sun, S.S.; McDonough, W.F. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. *Geol. Soc.* **1989**, *42*, 313–345. [CrossRef]
49. Meyer, C., Jr.; Hubbard, N.J. High potassium, high phosphorus glass as an important rock type in the Apollo 12 soil samples. *Meteoritics* **1970**, *5*, 210–211.
50. Meyer, C., Jr.; Brett, R.; Hubbard, N.J.; Morrison, D.A.; McKay, D.S.; Aitken, F.K.; Takeda, H.; Schonfeld, E. Mineralogy, chemistry, and origin of the KREEP component in soil samples from the Ocean of Storms. In Proceedings of the 2nd Lunar and Planetary Science Conference Proceedings, Houston, TX, USA, 11–14 January 1971; Volume 2, p. 393.
51. Qiao, L.; Chen, J.; Xu, L.Y.; Wan, S.; Cao, H.J.; Li, B.; Li, Z.C. Geology of the Chang'e-5 landing site: Constraints on the sources of samples returned from a young nearside mare. *Icarus* **2021**, *364*, 114480. [CrossRef]
52. He, Q.; Li, Y.H.; Baziotis, I.; Qian, Y.Q.; Xiao, L.; Wang, Z.C.; Zhang, W.; Luo, B.J.; Neal, C.R.; Day, J.M.D.; et al. Detailed petrogenesis of the unsampled Oceanus Procellarum: The case of the Chang'e-5 mare basalts. *Icarus* **2022**, *383*, 115082. [CrossRef]
53. Mitchell, R.N. Chang'E-5 reveals the Moon's secrets to a longer life. *Innovation* **2021**, *2*, 100177. [CrossRef] [PubMed]
54. Du, J.; Fa, W.Z.; Gong, S.X.; Liu, Y.; Qiao, L.; Tai, Y.S.; Zhang, F.; Zou, Y.L. Thicknesses of Mare basalts in the Chang'E-5 landing region: Implications for the late-stage volcanism on the Moon. *J. Geophys. Res. Planets* **2022**, *127*, e2022JE007314. [CrossRef]