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ANTARCTIC METEORITE ALHA81005 - NOT JUST ANOTHER LUNAR ANORTHOSITIC NORITE

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Abstract. Seven subsamples of meteorite ALHA81005, a regolith breccia from the lunar highlands, were analyzed by INAA for 32 elements. Four of them were also studied petrographically. In bulk composition the rock corresponds to anorthositic norite with a very small component of KREEP and is very similar to estimates of average lunar highlands surface. Compositions of the white clasts and the dark matrix are similar, but the clasts are more magnesian and 30-50% as rich in KREEP-related elements. The white clasts have fine-grained granulitic textures and are generally similar to Apollo 16 and 17 granulitic anorthositic norites, but are more magnesian and only 20% as rich in KREEP-related elements. Some granulitic clasts are dominated by a magnesian anorthositic norite component not represented among the "pristine" Apollo samples.

Introduction

The discovery in Antarctica of a meteorite composed of lunar surface material makes an old question refreshingly topical: Why does the bulk composition of the lunar surface correspond to that of anorthositic norite? ALHA81005 (hereafter 81005) is a polymict breccia composed of consolidated material of the lunar highlands regolith. In normative composition it is an anorthositic norite (AN). Concentrations of the rare earths (REE) and other large-ion, lithophile (LIL) elements are very low compared to Apollo samples of similar bulk composition. Hence, 81005 is nearly free of contamination by KREEP, the noritic material rich in K, REE, P and other LIL elements whose chemical signature dominates the LIL element abundances of most Apollo polymict materials [e.g., Warren and Wasson, 1979]. In terms of having low KREEP content and normative AN composition, 81005 is similar to estimates of average lunar highlands surface. Because of the ways it is both similar to and different from other lunar materials with AN compositions, 81005 is a very important lunar sample.

Analytical Procedures

Our sample, 81005,12, consisted of whitish clasts in a dark matrix. It was received as 3 pieces. Piece 1, which was primarily white, was analyzed as received and designated 1A. Pieces 2 and 3 were subdivided by cracking with an agate mortar and pestle. Piece 2 yielded two subsamples, 2M1 and 2M2, both of which consisted mostly of matrix with small (up to 0.5mm) clasts. Piece 3 yielded four subsamples: 3A (a composite of 20 white chips), 3M1 and 3M2 (matrix-rich, similar to 2M1 and 2M2), and 3R (residual fines).

The 7 subsamples were analyzed by INAA by procedures similar to those of Korotev [1982]. However, the initial irradiation was for 50 hours, the irradiation for short-lived isotopes was done 35 days later for 2 minutes, and NBS SRM 1633a was used as the standard for most elements. Additional details regarding standards are given in Korotev et al. (1983). After analysis subsamples 1A, 2M1, 3M1, and 3M2 were thin sectioned, yielding a total of 16 mm^2 for petrographic study.

Results

General Compositional Characteristics

The four subsamples consisting primarily of dark matrix (2M1, 2M2, 3M1, 3M2) and the residue sample (3R) are almost mutually indistinguishable in their concentrations of the major elements (Table 1). Some variation does occur for the trace elements. The mean Ni concentration in the 5 samples (250 μg/g) is equivalent to a that of 2.3% component of carbonaceous chondrite. Compared to the other 4 samples, 3R is enriched in Ni, Ir, Co, Fe, and Cr by amounts attributable to a 70% greater proportion of the chondrite component. Among LIL elements the greatest variation occurs for La, which ranges over 34% of the mean value compared to only 9% for Yb.

The two predominantly (>90%) white samples are also mutually similar, but not as compositionally distinct from the dark samples as might be expected. The white and dark samples have similar concentrations of Al, Ca, and Sr, but the dark samples are richer in Fe and Sc and poorer in Mg, Na, and Cr by 10-25%. Differences in concentrations of Fe and Mg lead to a significant difference in the value of mg' (molar Mg/(Mg+Fe)): 0.72 for the dark samples and 0.78 and 0.80 for samples 1A and 3A. The greatest differences are for the LIL elements and Br. The dark samples are 2 and 3 times richer in Sm and Th but the white samples are 2.5 times richer in Br. REE distributions for all 7 samples are similar to each other and to those of other lunar samples in the same REE concentration range.

Petrography

Sufficient petrographic study was done to provide a general characterization of the samples. Defocussed beam electron microprobe analyses were made of areas in 1A and of a number of clasts in 2M1. Quantitative spot analyses were made of plagioclase, olivine, and pyroxene grains in lithic clasts and the glassy matrix.

Sample 1A consists of two white granulitic clasts separated by a thin band of matrix. The more feldspathic clast is a noritic anorthosite

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TABLE 1. Element concentrations in seven small samples of ALHA 81005,12 and the mass weighted mean. Values in μg/g except Ir in ng/g and oxides in % (total element as oxide). One standard deviation uncertainties are measures of precision and do not reflect any systematic errors.

Sample	1A	3A	2M1	3M2	2M2	3M1	3R	±1s	mean
TiO_2	<0.3	<0.3	0.27	0.24	0.37	0.30	0.23	0.10	0.23
Al_2O_3	25.1	24.7	24.8	25.7	26.6	24.6	24.8	0.3	25.1
FeO_t	4.80	4.96	5.52	5.52	5.80	5.79	6.02	0.15	5.53
MgO	9.7	11.0	7.3	8.6	8.5	8.9	9.2	1.5	8.8
CaO	14.6	14.5	15.4	14.9	15.3	15.0	14.6	0.3-0.4	14.9
Na_2O	0.360	0.337	0.309	0.316	0.313	0.311	0.322	0.005	0.321
K_2O	<0.03	<0.05	<0.12	<0.10	0.02	0.02	<0.08	0.01-0.02	<0.04
Sc	7.36	7.57	9.42	8.67	9.90	9.35	8.78	0.08	8.81
V	25	22	21	22	24	25	21	6	23
Cr	945	995	870	865	870	870	915	10	900
Mn	600	620	590	600	620	660	640	50	620
Co	18.3	19.0	20.3	23.3	22.0	23.4	29.4	0.5	22.5
Ni	228	204	180	274	170	242	374	10-15	243
Br	0.67	0.53	0.14	0.34	0.19	0.24	0.36	0.04-0.08	0.33
Rb	<4	<5	<5	<6	<6	<5	<8	(2)	<6
Sr	141	141	149	136	132	138	143	9-13	141
Zr	<35	<45	23	<50	38	22	23	8	19±12
Cs	<0.08	<0.05	0.03	0.05	0.05	0.03	0.05	0.02	0.04±.02
Ba	11	13	26	34	30	25	24	4	24
La	1.257	1.030	1.80	2.40	2.36	1.725	1.75	0.015-0.02	1.80
Ce	2.95	2.55	4.5	5.95	5.5	4.55	5.0	0.3	4.55
Nd	1.56	1.56	2.7	3.8	3.4	2.85	2.9	0.2	2.75
Sm	0.414	0.456	0.952	1.047	0.978	0.920	0.945	0.006-0.012	0.855
Eu	0.627	0.640	0.727	0.696	0.718	0.697	0.663	0.012	0.686
Tb	0.103	0.117	0.22	0.25	0.27	0.24	0.23	0.01-0.02	0.21
Yb	0.375	0.41	0.785	0.77	0.83	0.78	0.805	0.015	0.705
Lu	0.0615	0.065	0.126	0.119	0.138	0.121	0.123	0.002-0.003	0.113
Hf	0.27	0.31	0.70	0.64	0.90	0.70	0.73	0.02	0.63
Ta	0.030	0.023	0.094	0.084	0.089	0.114	0.084	0.010	0.079
Ir	5.9	3.8	5.9	9.2	6.9	7.5	12.7	1-2	7.6
Th	0.055	0.085	0.228	0.246	0.243	0.235	0.210	0.015	0.198
U^*	0.07	0.05	0.10	0.07	0.12	0.07	0.15	0.03	0.09
mass (mg)	7.246	9.391	16.224	13.852	7.360	11.564	12.074		Σ=77.71

U values (Korotev et al., 1983) have been corrected for a systematic error, values here are about 2x greater. Sb is deleted, previous values are erroneously high due to a significant silica tube blank.

consisting of 85% plagioclase (An96) and 15% orthopyroxene (En79) with rare olivine (Fo75). The more mafic clast is an AN with 70% plagioclase (An97), 18% orthopyroxene (En86) and 12% olivine (Fo85). We assume that 3A is also composed of granulitic clasts because it has similar composition and color.

Sample 2M1 contains the widest variety of lithic and mineral clasts. Lithic clasts include a) white granulites, some with highly magnesian bulk composition and mafic phases [olivine (Fo80) and pyroxene (En83)] and others with less magnesian bulk compositions; b) dark impact melt rocks [one containing clasts of relict plagioclase and magnesian olivine (Fo84)]; c) a ferroan anorthosite with a single large olivine grain (Fo55); and d) a dark glassy area rich in iron. Most olivine and pyroxene clasts are magnesian (mg'=0.75-0.86) but occasional Fe-rich olivines (Fo50) and exsolved Fe-rich pyroxenes were found. The other matrix-rich samples appear generally similar to 2M1 in thin section. Sample 3M1 contains a 50x150 μm clast of orange glass, rich in FeO (14%) and TiO_2 (3%).

Discussion

Lunar Origin

No aspect of its bulk composition argues against 81005's being a sample of the lunar highlands crust. In all respects 81005 is more similar in composition to materials returned by the Apollo and Luna missions than to other meteorites, typical terrestrial materials, or all nonlunar materials of which we are aware. In particular, the high Al and Ca concentrations, the high Cr and low Na and K concentrations, and the relative concentrations of the REE, including Eu, are all distinctly lunar. In light of the similar conclusions based on other studies in this volume, any explanation for the origin of 81005 other than the lunar crust would have enormous geochemical and cosmochemical implications.

Chemical Components of the Clast-Laden Matrix

A likely cause for the lower mg' value of the dark samples compared to the granulitic clasts of which they are in part composed is the presence of mare basalt components in the matrix. Clasts similar to Apollo 17 and Luna 24 very-low-Ti (VLT) basalts are reported in 81005 by Treiman and Drake [1983] and Ryder and Ostertag [1983]. Our samples contain ferroan mafic components presumably of mare origin. If mare basalt is the principle cause of the lower mg' of the matrix, then its proportion in the dark samples can be estimated. Ten to 20% of nearly any mare basalt can account for mg', but the similarity in Cr, Sc, and Ti between the dark and light samples requires a basalt with low concentrations of those elements. A good fit to the average composition of the dark samples can be obtained by a mixture of 71% granulitic clast component (our subsample 3A), 16% anorthosite [e.g., Taylor, 1982], 0.8% KREEP [Warren and Wasson, 1979], and 11-12% Luna 24 VLT basalt [24109, Ma et al., 1978]. A mare basalt similar to 24109 but having greater LIL element concentrations could eliminate the need for KREEP in the mixing calculations, and using a ferroan AN instead of anorthosite would decrease the amount of mare basalt.

Comparison to Other Lunar Materials

In lunar highlands samples, because of the relatively simple mineralogy, concentrations of Fe+Mg anticorrelate with that of Al [e.g., Taylor, 1982, Fig. 5-13]. Most polymict samples with 19-26% Al_2O_3 are anorthositic norite in normative mineralogy based on the classification of Stöffler et al. [1980]. The rest are anorthositic gabbros or troctolites. The principal compositional differences among such samples involve siderophiles, the elements associated with KREEP, and the ratios of Fe to Mg. Some specific comparisons are made below.

Highlands Surface. Estimates of the composition of the highlands crust correspond normatively to AN. Taylor [1982] estimates 24.6% Al_2O_3 and mg'=0.64 for the average highlands crust; Korotev et al. [1980] estimate 26.5% Al_2O_3 and mg'=0.69 for "typical" highlands surface. Both estimates are based on the results of the orbiting gamma-ray and X ray experiments and returned samples. Concentrations of major elements in 81005 are similar to the estimates of highlands surface composition. The estimates have 25% lower Mg concentrations and lower *mg*', but these values are not well constrained by the orbital data [Haskin and Korotev, 1981].

Estimates of LIL element abundances for the highlands surface are based on the Th concentration derived from the orbiting gamma ray data and the ratios of Th to LIL elements observed in returned samples with this Th concentration. The 0.5 μg/g average Th concentration obtained by Metzger et al. [1977] for the farside highlands is the best estimate of the most "typical" concentration in the entire highlands [Haskin and Korotev, 1981]. The Th concentration in 81005 is 0.4 times that value, compared to 2, 4, 5, and 7 times that value in highland soils from Luna 20 and Apollos 16, 17, and 15. The comparisons for K (a LIL element on Moon) are similar, but less extreme. The low LIL element concentrations in 81005 are consistent with an origin distant from the KREEP-rich Imbrium-Procellarum region, possibly on the lunar farside.

ALHA81005 has only one-sixth the concentration of Ti estimated to be typical of farside highlands [Haskin and Korotev, 1981; data of Metzger and Parker, 1979]. 81005 is not anomalously depleted in Ti. The Ti/Sm ratio is typical of that of other lunar samples with similar Sm concentrations and Sc/Sm ratios. This supports the suspicion of Korotev et al. [1980] that Ti concentrations derived from the orbiting gamma-ray data for the farside and other low-Ti regions are systematically high.

Other Polymict Samples. Samples with 25% Al_2O_3 are common among materials returned from all highlands sites. Relatively few such samples are endogenous igneous rocks; most like 81005 are polymict breccias. Textures suggest that most of these are solidified impact melts (impact melt breccias) or metamorphic rocks formed by recrystallization of breccias (granulitic breccias or granulites) [see Stöffler et al., 1980]. Some Apollo 16 impact melt breccias, the 'VHA basalts', and the Apollo 16 soils, which contain fragments of VHA basalt as a significant component, are similar to 81005 in major element composition but are up to 15x richer in KREEP-related elements. Compositionally, many of these appear to be simple mixtures of granulitic AN and KREEP. The high KREEP contents may also explain their enrichment in Ti and Na over 81005 and other ANs with low KREEP contents.

Few Apollo and Luna ANs have K, REE, and Th concentrations as low as bulk 81005. None is as low as the granulitic samples 1A and 3A. REE concentrations in most Apollo granulites are 4-6+ times greater. Most of these are from Apollo 17 (25±2% Al_2O_3, *mg*'=0.71-0.76); some are from Apollo 16 (27±2% Al_2O_3, *mg*'=0.75-0.78). Similar fragments are a major component of the Luna 20 soil (mean Al_2O_3=24.6%, *mg*'=0.74 [Prinz et al., 1973] and account for the overall compositional similarity of that soil to 81005. None of these are as magnesian as the 81005 granulites. Curiously, those Apollo ANs with the very lowest LIL element concentrations are much more ferroan (*mg*'=0.58-0.64); e.g., granulitic breccias 15418 and 77017, brecciated cumulate 67215 and plutonic clasts from 67016 [Lindstrom and Salpas, 1983]. The large difference in *mg*' between these and the granulitic AN component of 81005 argues against a common origin for all KREEP-poor ANs.

Pristine Rocks. Ratios of Sc and Ti to Sm are useful for discriminating among the categories of samples recognized as endogenous igneous (pristine) rocks [Norman and Ryder, 1980; James and Flohr, 1983] and are also useful for relating polymict samples to the igneous rock types from which they derived [Korotev, 1983]. The low REE concentrations in 81005 lead to high Sc/Sm and Ti/Sm ratios for both the matrix-rich and white subsamples (assuming >0.1% TiO_2 for the latter). These ratios are similar to those of the pristine ferroan anorthosites (*mg*'=0.4-0.65), some KREEP-poor granulitic ANs (15418, 67215, 77017, *mg*'= 0.65), most low-Ti mare basalts (*mg*' <0.45), some pristine Mg-gabbronorites (particularly 73255, *mg*'=0.74 [James and Flohr, 1983]), and the pristine dunite 72417 [*mg*'=0.87, Laul and Schmitt, 1975]. Except for these last two, all are far more ferroan than our granulitic samples from 81005. Nearly all nearside samples with *mg*' > 0.75 (e.g., granulites, VHA basalts, pristine norites and troctolites) have lower Ti/Sm and Sc/Sm ratios. Assuming that the granulitic clasts in 81005 represent mixtures of pre-existing rock types [James and Hammerstrom, 1977], their high Mg/Fe, Ti/Sm, and Sc/Sm ratios require that at least one of the rock types have ratios at least as high as the clasts and that this component be the major carrier of Fe, Mg, Ti, and Sc. None of the Apollo granulites or samples recognized as pristine meets all of these requirements. Hence the 81005 granulitic clasts cannot be explained as a mixture of known pristine rocks and, although not themselves pristine, may represent an endogenous igneous rock type dissimilar to any currently recognized in the Apollo collection.

Conclusions

We have argued previously that at least one component which is ferroan (*mg*' <0.65), poor in LIL elements, at least as mafic as anorthositic norite, and not well represented in the suite of endogenous igneous rocks must be an important primary constituent of lunar nearside soils and breccias [Lindstrom and Salpas, 1983; Korotev, 1983]. We now argue that 81005 requires the existence of a component similarly poor in LIL elements and just as mafic, but magnesian (*mg*' ≥ 0.8) rather than ferroan. Although no such component has yet been observed in nearside samples, as an end-member in mixing models it would conveniently account for the composition of some polymict samples which heretofore have been difficult to explain as mixtures of endogenous rock types (e.g., VHA basalts, Apollo 17 granulitic ANs). Thus, our results suggest that the early lunar crust contained as primary igneous rocks a significant proportion of both ferroan and magnesian anorthositic norites. Such a conclusion is at variance with models that treat materials of anorthositic norite composition as mixtures of anorthosite plus norite, troctolite, and dunite. Once again, sampling of a new, if unknown, lunar site has brought evidence for new rock types, emphasizing both the variety of compositions of

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