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METEORITES FROM THE EARTH'S MOON

SPECIAL SESSION ABSTRACTS

FOURTEENTH LUNAR AND PLANETARY SCIENCE CONFERENCE

MARCH 17, 1983

Co-Chaired by

KLAUS KEIL AND JAMES J. PAPIKE

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LPI CONTRIBUTION 501

ANTARCTIC METEORITE ALHA 81005

This small, special meteorite has been the focus of much attention. It has attributes that suggest that it is indeed of lunar origin. Since its initial characterization in late 1982, it has been studied intensively in a variety of laboratories around the world. This special supplement to Lunar and Planetary Science XIV includes the very latest abstracts of data presented at the Fourteenth Lunar and Planetary Science Conference.

Sample No.: ALHA 81005 Location: Allan Hills
Field No.: 1422
Weight (gms): 31.4
Meteorite type: Anorthositic Breccia

Physical Description: Roberta Score
This is an unusual looking sample! Flow marks are apparent on the exterior which is covered with a pitted, glassy, greenish-tan colored crust. Immediately underneath this crust, the surface is a "dusty" gray color.

The interior consists of abundant angular clasts, which range in color from gray to white, set in a black matrix. The size of the clasts are as small as submillimeter and as large as 8 mm in diameter. The sample is very coherent. Some areas of oxidation were noted.

Dimensions: 3 x 2.5 x 3 cm.

Petrographic Description: Brian Mason
The specimen is a microbreccia of clasts (maximum dimension 4 mm) in a translucent to semi-opaque dark brown glassy matrix showing flow structure in places; clast:matrix ratio is approximately 40:60. The larger clasts are polymineralic, the smaller (less than 0.3 mm) may be individual mineral grains. The clasts consist largely of plagioclase, together with some pyroxene and occasional olivine; most of the mineral grains are plagioclase. The clasts show a variety of textures, including gabbroic, diabasic, and basaltic; many have been shocked and partly granulated. Some of the clasts resemble eucrites, but many appear to be more feldspathic than most eucrites. The section is notable for the complete absence of opaque minerals, except for a 1 mm metal grain. Microprobe analyses show that the plagioclase is very Ca-rich, averaging An 97 (range An 95-98); pyroxene is variable in composition, Wo 1-41, En 44-79, Fs 7-47 (richer in En than most eucrite pyroxenes); several grains of olivine, Fa 11-40, were analyzed. The meteorite is a breccia, but more feldspathic than most eucrites; some of the clasts resemble the anorthositic clasts described from lunar rocks.

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TRAPPED SOLAR GASES IN THE ALHA81005 LUNAR(?) METEORITE.

D. D. Bogard and P. Johnson, SN4/NASA Johnson Space Center, Houston, TX 77058

We have measured the isotopic abundances of the noble gas elements He, Ne, Ar, Kr, and Xe in a primarily matrix sample of Antarctic meteorite ALHA-81005, which may have had an origin from the Moon. This sample contained very large concentrations of what are obviously implanted solar wind gases (Fig. 1). Absolute concentrations and relative abundances of these trapped gases are quite similar to typical solar gas-rich soils and breccias returned from the Moon. Isotopic compositions of the trapped gas in ALHA81005 are also identical to solar gas trapped in lunar samples - e.g., trapped 4-He/-3-He = 2600, 20-Ne/22-Ne = 12.5, 40-Ar/36-Ar = 1.8. Isotopic ratios of Kr and Xe plot on the mass-fractionation trends for lunar soils (1), and there is no obvious evidence of excess radiogenic 129-Xe or fission-produced Xe.

Fayetteville and Pesyanoe (Fig. 1) are the two regolith-derived meteorites with the largest known concentrations of solar wind gases. Although the 4-He concentration in Pesyanoe is as high as ALHA81005, the other noble gas concentrations in Pesyanoe are much lower, and consequently Pesyanoe shows a much less fractionated noble gas abundance pattern compared to ALHA-81005 and to lunar fines and breccias. Meteorites rich in solar gases typically show considerably less mass fractionation of their gases (e.g., much larger 4-He/132-Xe) compared to lunar samples. This fact is probably due to the much higher levels of regolith gardening and ion re-implantation, with accompanying mass-fractionated gas loss, of lunar regolith compared to regoliths on meteorite parent bodies.

A preliminary value for the potassium concentration of the matrix of ALHA81005 (J.C. Laul, Pers. Comm.) indicates that $\sim 1.4 \times 10^{-5} cm^3/g$ of radiogenic 40-Ar should be produced in 4 Gy time. The measured 40-Ar concentration in ALHA81005 is $\sim$20 times this value, which strongly suggests the presence of an atmosphere-implanted 40-Ar component such as that which has occurred on the Moon throughout much of its history (2). Presumably for an asteroid parent body the much shorter gravitational escape time for 40-Ar, the much smaller cross-section of the parent body surface, and the likely weaker solar wind fields would greatly reduce the effectiveness of the atmospheric-implantation process. In fact, the 40-Ar/36-Ar ratios in Pesyanoe and Fayetteville are much larger than in ALHA81005 and lunar soils and much of the 40-Ar in the first two meteorites is due to in situ decay of K.

Even those noble gas isotopes with low relative abundances (e.g., 3-He and 38-Ar) are primarily of solar wind origin in ALHA81005. However, if we adopt a trapped 21-Ne/22-Ne ratio of 0.030, we estimate that about 17% of the measured 21-Ne, or $\sim 26 \times 10^{-8} cm^3/g$, is cosmic ray produced. For a lunar surface irradiation this value would represent at least 100 MY of cosmic ray exposure.

The presence of large concentrations of solar gases in ALHA81005 clearly indicate that the matrix was finely spread on a surface exposed to the solar wind for a period of time before breccia formation. The large concentrations of solar gases with a mass fractionation pattern like lunar regolith samples, the excess concentrations of radiogenic 40-Ar and the suggestion of an old cosmic ray exposure age are all consistent with an origin of ALHA81005 from the lunar regolith. Such characteristics are dissimilar to known meteorites and may be hard to reconcile with an origin from the regolith of an asteroid.

TRAPPED GASES IN ALHA81005?

Bogard, D. D. and Johnson, P.

References:
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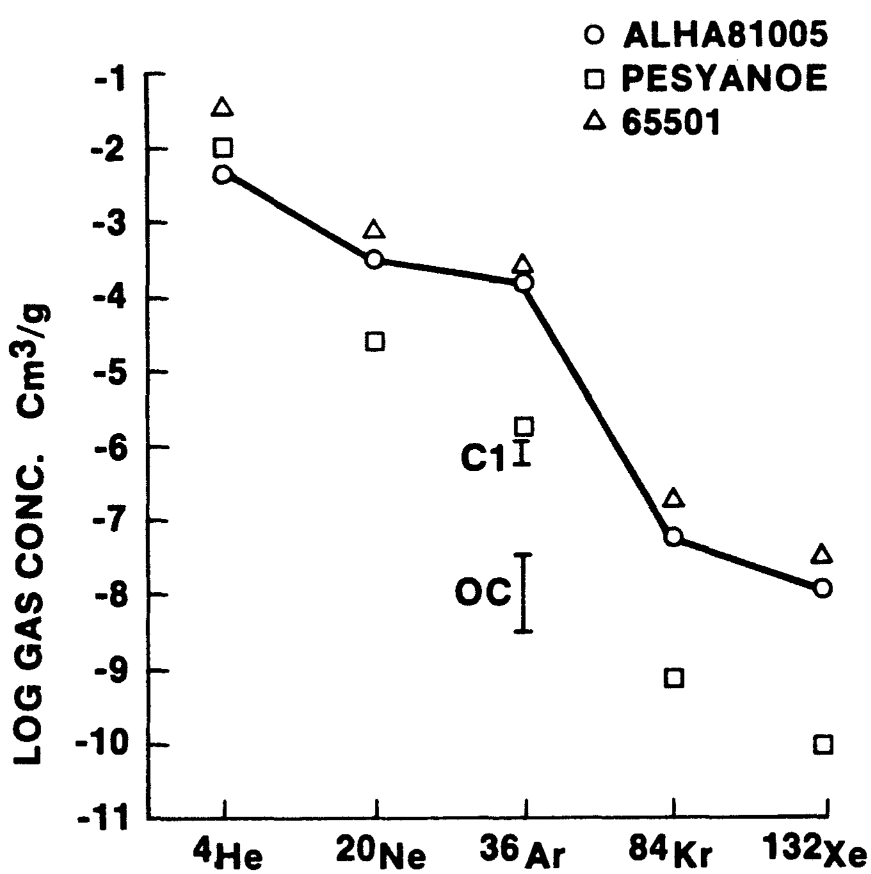
Figure 1: Measured noble gas concentrations in a matrix sample of ALHA81005, in the solar gas-rich meteorite Pesyanoe (3), and in lunar fines 65501 (4). Also shown are the typical range of 36-Ar concentrations in ordinary chondrites, OC, and in Type 1 carbonaceous chondrites, C1.



MINOR AND TRACE ELEMENTS IN CLAST AND WHOLE ROCK SAMPLES OF ALLAN HILLS A81005. William V. Boynton and Dolores H. Hill, Dept. of Planetary Sciences, Lunar and Planetary Laboratory, U. of Arizona, Tucson 85721.

The similarity between Allan Hills A81005 and lunar highlands rocks was noted by Mason (1), based on a preliminary examination of a thin section. Our data suggest a very strong relationship between ALHA 81005 and highlands rocks from Apollo 16. Based on two different sets of data, we conclude that it is most unlikely that this meteorite originated on a parent body other than the Moon.

<u>Samples.</u> - We received two pieces of ALHA 81005 (60 mg. and 20 mg.), which were analyzed separately to check for heterogeneity. Examination under the stereo microscope showed abundant light-colored clasts in a grey matrix. One of the clasts was removed from the larger whole rock sample and analyzed separately. This clast (1 mg.) was among the whitest of the clasts. It had a small pink grain (spinel?) visible on the surface, and a very few dark grains could be seen in the clast.

<u>Experimental.</u> - All data were obtained by INAA following a low-flux irradiation at the University of Arizona reactor. Most of the data to be discussed were taken after the samples had decayed to very low activities (The clast sample was counted at 0.25 cps, over 10^4 times weaker than our optimum count rate.). The samples were counted on our new Fast Anti-Compton Specrometer (FACS), which gives a dramatic improvement in signal-to-noise ratio. It is only because of the capabilities of this detector that we were able to get much of this data. We plan to re-irradiate at much higher flux to get our final data.

<u>Evidence for Lunar Origin.</u> - The first set of data which suggest a lunar origin is Fe and Mn concentrations in the whole rock and the clast. Laul and Schmitt (2) established that plots of MnO vs. FeO can distinguish lunar material from other known differentiated meteorites. Our data for the whole rock and clast plot in their field of lunar data (Fig. 1). The FeO/MnO ratio in the whole rock (65.8) and clast (55) are typical of lunar samples with low abundances of these elements. We feel, however, that these data are necessary but not sufficient to establish lunar origin. A similar FeO/MnO ratio could easily be established in an unsampled parent body. In fact, Laul and Schmitt indicate that FeO/MnO ratios are similar in lunar, meteoritic and terrestrial anorthosites.

More convincing data for a lunar origin of ALHA 81005 is provided by the abundances of incompatible trace elements. Our data for the whole rock and clast are shown in Fig. 2. Also plotted are data from Apollo 16 highlands samples 60626 and 60025 and KREEP (2). The trace element abundances in 60626 show the characteristic KREEP pattern with a linear decrease in abundances of REE from light to heavy and a increase in Hf, Ta, and Th. This shape pattern is found in a large number of highlands rocks with absolute abundances spanning a range of a factor of 50. These elements have different partition coefficients, which are a strong function of the minerals involved in the fractionation event(s), and hence their final abundance ratios will be dependent on the composition and size of the parent body and on the exact degree of fractionation (partial melting or fractional crystallization). There appears to be no agreement on how the lunar KREEP pattern was established, but it is clear that very extreme fractionations are required.

TRACE ELEMENTS IN ALHA 81005

Boynton W. V. and Hill D. H.

Because it is so difficult to generate this trace element pattern even on the Moon, there appears to be general agreement that this pattern was established only once, and the KREEP pattern was acquired by other rocks such as 60626 by mixing of this KREEP component (3). It is most unlikely that this pattern could be established on another parent body unless it had a similar bulk composition, size and thermal history as the Moon. Such a parent body clearly does not exist in the Solar System.

<u>Evidence for a Pristine Lunar Clast.</u> - The trace element data from the single clast which we analyzed from ALHA 81005 is also plotted in Fig. 2. The abundances are about a factor of 400 lower than that observed for pure KREEP. According to Warren and Wasson (4), all samples with incompatible elements less than 200 times lower than KREEP are pristine. The incompatible element attribute is second in importance only to low siderophile element in establishing the pristinity of samples. It appears then that ALHA 81005 may contain pristine samples of the early lunar crust. Clearly, more work on this interesting meteorite is in order. We are hopeful that investigations of other clasts will provide new insights into the origin of the lunar crust.

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2. Laul J.C. and Schmitt R. A. (1973) <u>Proc. 4th L.S.C</u>, p. 1349-1367.
3. Warren P.H. and Wasson J. T. (1979) <u>Rev. Geophys. Space Phys.</u>, <u>17</u>:73-88.
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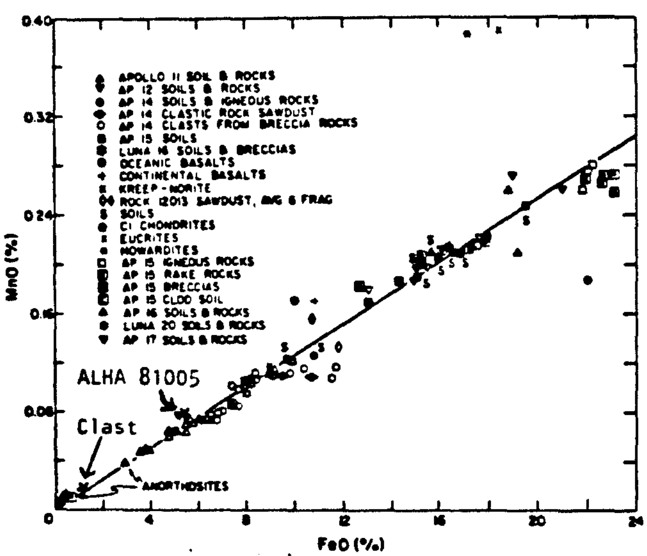


Fig. 1. MnO vs. FeO for lunar samples and samples of other differentiated meteorites (2). ALHA 81005 plots on the lunar line indicating that this meteorite may have come from the Moon, but these data do not demand a lunar origin for ALHA 81005.

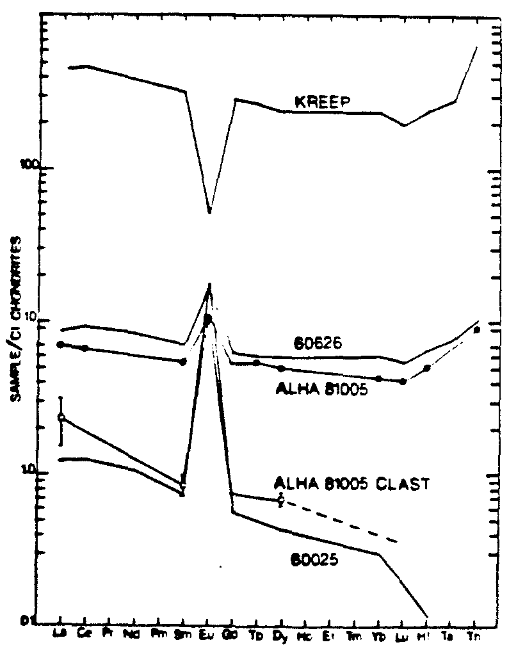


Fig. 2. Trace elements in Apollo 16 samples(2) and ALHA 81005. The presence of a KREEP type pattern in ALHA 81005 requires that this meteorite came from the Moon.

PROSPECTS FOR FUTURE METEORITE RECOVERIES ON THE ANTARCTIC ICE SHEET; W. A. Cassidy, Dept. of Geology and Planetary Science, Univ. of Pittsburgh, Pittsburgh, PA 15260.

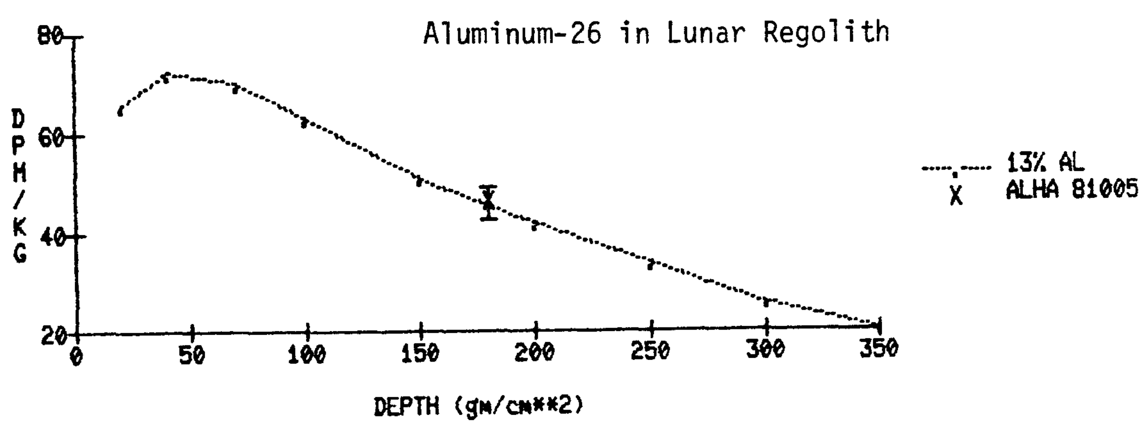
Until recently, there have been only two sites in Antarctica where meteorites have been found in great numbers -- the Allan Hills and Yamato sites. Other locations have contained one or a few specimens. Assessment of the Belgica Mountains site is incomplete; over 50 specimens have been recovered there by a Japanese party, and this could be a third major occurrence. During the field season just past a U.S. field party has discovered major new concentrations of meteorites at Pecora Escarpment and at structures associated with the Thiel Mountains. Both areas were visited on a reconnaissance basis only. Fifty specimens were returned, but at least twice that number were seen and left in situ for future collection. Because the reconnaissance surveys were incomplete very large areas of exposed ice remain to be traversed, particularly at Pecora Escarpment, and it seems a reasonable speculation that these areas also will be found to bear meteorites. A second U.S. field party, working west and north of the original Allan Hills site, established the occurrence of meteorites over very large areas of blue ice that might be considered to be extensions of the Allan Hills and Elephant Moraine sites. Specimen density in these areas seems lower, but the total added area of known occurrence is very large. The important conclusions for the meteoritical community is that a steady flow of new specimens now seems guaranteed; the rate of return may in fact increase; it should not decrease.

ALUMINUM-26 CONTENT OF ALHA 81005. J. C. Evans and J. H. Reeves, Geosciences Research and Engineering Department, Battelle, Pacific Northwest Laboratories, Richland, Washington 99352.

Since it was determined in preliminary examination that ALHA-81005 may be of lunar origin, there has been considerable interest in its recent cosmic ray exposure history. If the meteorite is of achondritic origin it is likely to be saturated in ^{26}Al at 100-130 dpm/kg.[1,2] Conversely, if the sample was excavated from the moon by a large impact, the exposure age should be very short before recapture in the earth-moon system. As part of the preliminary examination effort, the 23 gm main mass of the sample was hand-carried to Richland, Washington for one week of nondestructive gamma ray analysis at the Battelle Northwest multiparameter gamma ray spectrometry laboratory. One week of counting yielded an ^{26}Al content of 46 3 dpm/kg. This result is intermediate between the two possible cases discussed above and is thus subject to a variety of interpretations. The situation is further complicated by the possibility of long terrestrial age since it is an Antarctic specimen. In order to sort out the full bombardment and decay history of this unique sample, several other isotopic measurements such as ^{36}Cl, ^{10}Be, and ^{53}Mn will be required. The ^{26}Al measurement is consistent with the following interpretations.

1. Achondritic origin--
   In this case the sample either has a relatively short cosmic ray exposure age (500,000 y) or a very long terrestrial age (1.1 m.y). The latter is a bit unlikely since the longest terrestrial age seen to date is only 700,000 y.[3] Obviously some combination of the two is also possible.

2. Lunar origin--
   Several possibilities exist for a lunar origin. The sample could simply have been saturated at shallow depth on the moon and spent a short time in space and in the ice. That situation is illustrated in Figure 1.[4] The sample would be excavated in that case from a depth of only one meter which is rather shallow for an impact large enough to throw it into space. If excavated from a significantly greater depth then the situation becomes essentially the same as for the achondritic case, i.e., a time in space of at least 500,000 y which does appear a bit long for a spatial residence time of lunar ejecta.



ALUMINUM-26 CONTENT OF ALHA 81005

Evans, J. C. and Reeves, J. H.

The ^{26}Al content measured in this sample is thus a bit improbable for either a lunar or achondritic origin. Additional measurements of other isotopes should therefore prove extremely interesting.

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THE TERRESTRIAL ACCRETION OF LUNAR MATERIAL

D.E. Gault, Murphys Center of Planetology, Murphys, CA 95247

It is well established by both experiment and computer modeling that an impact of a meteoritic projectile on the lunar surface will eject lunar material free of the Moon's gravitation into cis-lunar and heliocentric space(1,2,3). In order to assess the amount of lunar material arriving on Earth and its probable origin on the Moon, two series of ejecta-trajectory calculations have been performed: 1)three-body calculations to determine the conditions for direct (i.e., first perigee) encounter with Earth, and 2)four-body calculations to determine the mass and equilibrium conditions (i.e., life times) of lunar material ejected into geocentric orbits. All calculations assume the Moon is in a circular orbit about Earth at its mean distance (384405 km) with an orbital period of 27.32 days (0.22997 radians/day). Co-planar orbits were used for the four-body series with starting conditions corresponding to a full-Moon phase. Capture radius of Earth was included a 100 km deep atmosphere and taken to be 6478 km. With these assumptions there remain five independent variables: latitude β and longitude δ of the point of impact, ejection angle with respect to surface θ and azimuth ejection angle λ, and the ejection velocity V_e. The latter was restricted to values less than 5 km/s as the physical limit for ejection of material in the vaporous state.

With $\theta = 45^o$, a good representative value for ejection angle, direct Moon-Earth trajectories can originate from almost 2/3 of the lunar surface, an area extending from 34^o W. along the equator in an easterly direction past the sub-terrestrial and anti-terrestrial points to 160^o W. and extending to the 80^o latitudes. Ejection velocities of V_e = 2.55- to 2.7 km/s make the the greatest contribution for direct trajectories; lower velocities produce mostly geocentric orbits and higher velocities lead to mostly heliocentric orbits. Steeper ejection angles move the area for direct trajectories eastward and in the limit for vertical ejection reduce the area to about 2-percent of the near-side surface. Conversely, more shallow ejection angles move the area westward and in the limit for tangential trajectories encompasses the entire lunar surface.

For the four-body calculations the northern hemisphere was divided into 12 equal areas (effectively 24 for the entire Moon with the mirror symetry of the co-planar orbits) with a centered point for ejection. Eight trajectories spaced 45^o apart in azimuth were calculated for each point for eight ejection velocities V_e = 2.4- to 3.2 km/s. The trajectories were traced until either impact occurred on the Earth or Moon, until the trajectories were modified into heliocentric orbits, or until the time exceeded 30 years. Of the original 768 starting trajectories, 523 made direct entry into heliocentric orbits, 9 made direct impact on Earth, and the remainder (236)entered geocentric orbits that were subsequently modified to produce 55 Earth impacts, 7 lunar impacts, and 172 injected into heliocentric space. Only two of the trajectories remained in geocentric orbits at the end of 30 years.

These four-body results, together with a model of the mass-velocity distribution of high-velocity ejecta derived from experimental results (1), indicate that with an isotropic flux of impactors approximately 0.5-percent of the mass escaping the Moon arrives at Earth on direct trajectories. The bulk of the ejected mass lost from the Moon, 85-percent, passes directly into heliocentric space, 13-percent enters geocentric orbits, and the remaining 1-percent is returned to the Moon. The subsequent modification of the geocentric orbits brings the final mass distribution to 94-percent into heliocentric space, 4-percent Earth accretion, and 2-percent swept back up by the Moon. It is intesting to note that the geocentric population of orbits appears to consist of two families of trajectories having 3- and 5-year half-lifes. Despite their relatively short life times in geocentric orbits, in the real environment of a steady, isotropic flux of impactors a small concentration or "cloud" of lunar material must be accumulated around Earth, and it is from this "cloud" that Earth accretes most of its lunar material.

With the present meteoritic influx rate on the Moon taken to be of the order of 10^8 - 10^9 grams/yr (4,5) for masses greater than a few milligrams, which are capable of producing fusion material larger than a few microns, it is estimated that the Moon is currently losing 10^9-10^{10} grams/yr. Of this total mass loss, it appears that no more than 10^7-10^8 grams/yr are accreted by Earth, the total derived from both direct trajectories and the "cloud" in geocentric orbits(estimated to be of the order of 10^{10}-10^{11}grams).

Although this estimated mass of lunar material arriving on Earth is small in comparison to other sources of extra-terrestrial matter (0.1 - 1.0-percent??), it is an inescapable conclusion that lunar material is ejected from the Moon and that some of that material ultimately arrives on Earth. Composition of the material favors a source from the large areas of highland units (anorthositic?) relative to the smaller areas of mare units (basic?). It is a tantalizing challenge for the geosciences for indentification of this lunar material.

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ALHA81005: A NEW SAMPLE FROM THE LUNAR HIGHLANDS? Gregory W. Kallemeyn. Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024.

Evidence is mounting that the Antarctic meteorite find, ALHA81005, represents the first lunar sample recovered without the expenditure of a significant portion of a nation's GNP. This would make it the first meteorite whose actual parent body can be deduced with hard evidence - although this hard evidence required the technological recovery of lunar samples.

Petrographically, ALHA81005 appears to be a regolith breccia, notably low in metal, with troctolitic clasts and a matrix containing swirly glass (Warren et al., this volume). Our 113 mg sample contains an estimated 40% clast material and is currently being studied by instrumental neutron activation analysis.

Several points can be made from our preliminary compositional data. The Fe (45 mg/g) and Mn (0.58 mg/g) contents of our sample are similar to those of Apollo-16 soils and rocks, and the bulk Fe/Mn ratio of 77 is near the mean lunar value of ~80. This Fe/Mn ratio is distinct from those of known chondritic and achondritic meteorites and from the Earth's mantle; it provides strong evidence for a lunar origin. The bulk Mg/(Mg+Fe) (0.71) vs. Ca/(Ca+Na+K) (0.96) of the sample plots just above the region defined by lunar ferroan anorthosites. Incompatible elements are low, 0.01-0.02× those in incompatible-rich lunar KREEP. The REE pattern (3-5× CI) is typical of anorthosites, with a small light/heavy enrichment and a strong positive Eu anomaly. Siderophile element concentrations are very low (which correlates with the low observed metal contents), and the meteoritic fraction is <1%. The Ir/Au ratio is near the CI value, somewhat higher than typical values in mature Apollo-16 soils; this suggests that the sample is from a younger, less-mature regolith.

The petrographic and compositional data for ALHA81005 suggest a lunar highlands origin, so a comparison to the bulk chemistry of the Apollo-16 and Luna-20 sites seems appropriate. In Figs. 1 and 2 we plot lithophile, siderophile and incompatible elements normalized to mean Apollo-16 and Luna-20 soils. The Na content of ALHA81005 (2.2 mg/g) is notably low relative to both locations, especially Apollo-16. Since the variation of Na among Apollo-16 sampling sites is quite small, the difference seems significant. The difference with Na at the Luna-20 location is much smaller and may not be significant as the lowest Luna-20 values are near ALHA81005. There seems to be a general trend of decreasing Na and increasing Mg in highlands samples from the center to east limb of the nearside (Warren et al., 1981); the high Sc/Sm and Ti/Sm ratios for ALHA81005 also suggest a closer relationship to Luna-20, and a provenance well-away from the center of the nearside. Unfortunately, nothing is known regarding the nearside far west or the entire farside, but it seems likely that they are similar to the Luna-20 site. Titanium is also quite low in ALHA81005 relative to both Apollo-16 and Luna-20, although this element shows a greater range of variation than Na among the different Apollo-16 sampling stations. It has been previously noted that the Apollo-16 location appears to have a high-Ti component, possibly from KREEP having a higher local Ti concentration (Korotev, 1981). Scandium is also depleted along with Ti in ALHA81005 relative to the Luna-20 site, perhaps reflecting a lower SCCRV component in the sample (Wasson et al., 1977).

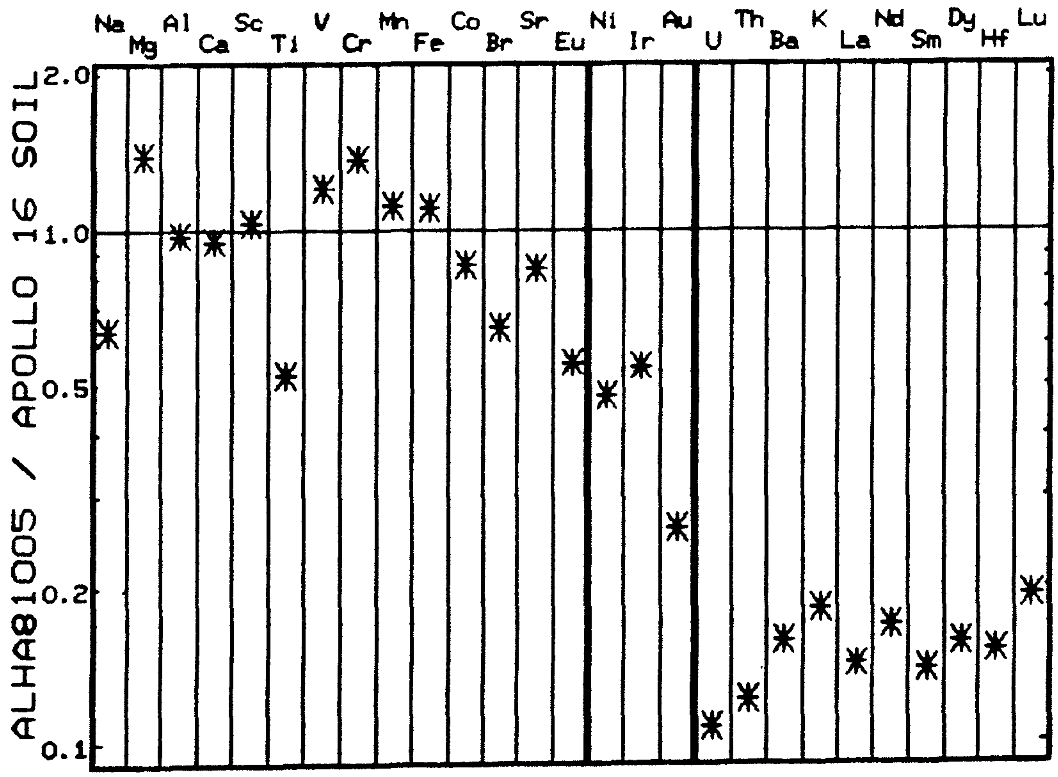
All compositional data are consistent with a lunar origin for ALHA81005. Its lunar location was probably well-away from the center of the nearside. Its composition is nearer that of the Luna-20 location than the Apollo-16 location, although there are sufficient differences to suggest a provenance

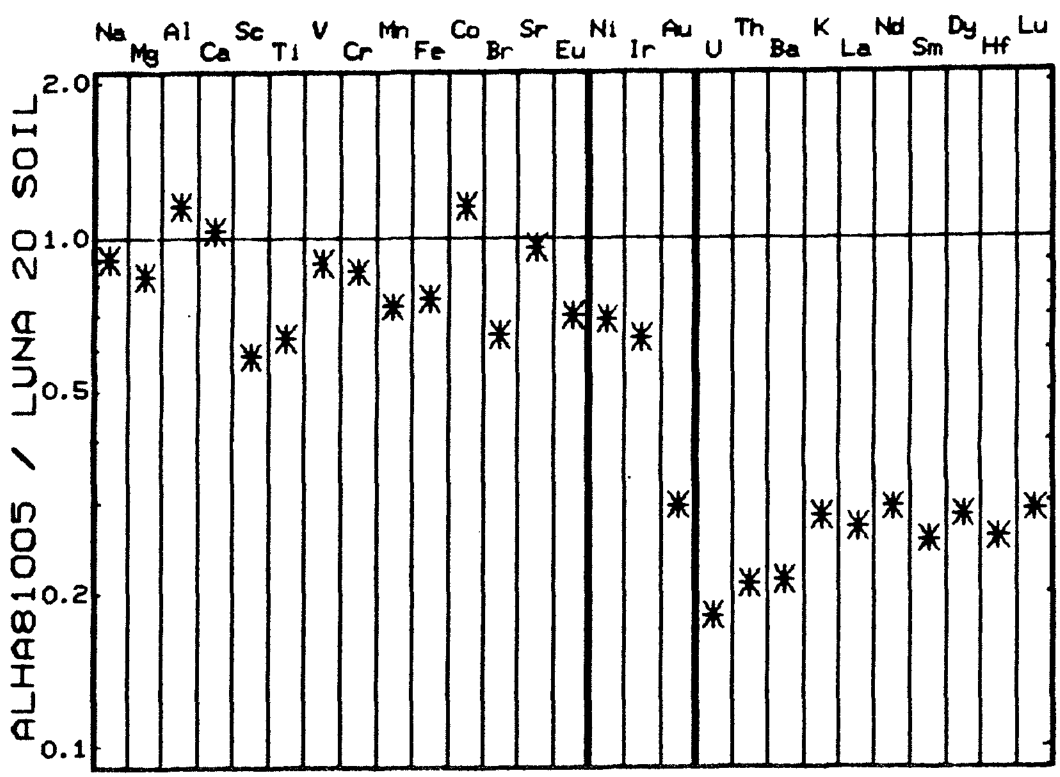
ALHA81005: A NEW SAMPLE

Kallemeyn, G.W.

remote from both both of these locations, including especially the far-eastern limb and the farside.

References: Korotev (1981) PLPSC 12th, 577. Warren <u>et</u> <u>al</u>. (1981) PLPSC 12th, 21. Wasson <u>et</u> <u>al</u>. (1977) PLSC 8th, 2237.





LUNAR HIGHLANDS BRECCIA 81005 (ALHA): SO APOLLO 18 FLEW, BUT WHERE DID IT SAMPLE?

Randy L. Korotev, Larry A. Haskin, and Marilyn M. Lindstrom, Dept. of Earth and Planetary Sciences and the McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130.

Seven subsamples of meteorite ALHA81005 totaling 78 mg were analyzed by INAA for 33 elements (Table 1). Two are primarily (>80%) white lithology (samples 1A,3A), four primarily (>90%) dark (samples 2M1,2M2,3M1,3M2), and one is residue (3R). Compositions of all seven are similar, with subtle differences between dark and light lithologies. ALHA81005 has a characteristic lunar highlands composition including high concentrations of Al and Ca and, relatively, Cr; low concentrations of Na and K; and interelement ratios and relative REE abundances unlike those of other meteorites and typical terrestrial rocks.

In bulk composition ALHA81005 resembles many lunar breccias and soils of anorthositic norite composition, but is slightly less rich in Na, much less in Ti, and very much less in K and the large ion lithophile elements (LILE) associated with KREEP. The closest matches for the major elements (ME) are certain Apollo 16 VHA impact melts (e.g., 60018, 60335, and 61016 [see 14]) and some "anorthositic gabbro" clasts from Apollo 17 breccias (e.g., 72235,36 [1], 77017,57 [9], and 76315,62 [13]). However, ALHA81005 has lower concentrations of Na (0.7±0.3x), Ti (~0.35x), and LILE (Sm, 0.07-0.6x). In ME composition, ALHA81005 also resembles soils from Apollo 16 station 5 and 6 [5], but has less Na, Ti, K, and LILE, slightly less Al, and 1.4x more Mg. Polymict highlands rocks with comparable LILE concentrations are more anorthositic (e.g., 64435 and 67455 [12,10]). The pristine samples closest in ME composition to ALHA81005 are anorthositic norites 67215 [11,16] and 15565,113 [19] and troctolites 73235,127 [18] and 76255,58 [17]. All but 76255 also have low LILE concentrations.

Relative LILE concentrations in ALHA81005 resemble those of many lunar highlands samples that have little or no KREEP (Fig. 1). The magnitude of the Eu anomaly is in the narrow range characteristic of highlands samples with similar REE concentrations, a strong geochemical argument for a lunar origin. Among meteorites, only the Moore Co. eucrite has similar overall REE concentrations and Eu anomaly, but the chondrite normalized concentrations increase slightly with atomic number unlike most lunar patterns [15]; Moore Co. ME are unlike those of ALHA81005.

Nearly all lunar samples with LILE concentrations as low as ALHA81005 are more anorthositic. Polymict lunar samples with similar ME concentrations are much richer in LILE. KREEP-poor, polymict, anorthositic norites (gabbros) are rare in the lunar collection, but they could be a predominant rock type in areas uncontaminated by KREEP.

ALHA81005 represents a new highlands sampling site. Detailed study will give insight into types and compositions of endogenous highlands rocks and the importance of materials like KREEP and anorthosite. ME concentrations of light and dark lithologies are similar but differences in LILE are substantial, with the light material slightly poorer in Fe, Sc, and Co and much poorer in Ti, K and LILE, but slightly richer in Mg, Na, and Cr and much richer in Br. Ni and Ir concentrations are consistent with a 1-2% chondritic meteorite component, typical of polymict highlands materials. There is no difference in Al concentration between the light and dark samples, yet Fe and Sc differ by 24% and the REE by 200%. Hence the light material is not dark material plus anorthosite. Nor is the dark material simply white material plus KREEP. Only 1% KREEP would be needed to account for the LILE, yet Mg and Cr, which have similar concentrations in KREEP and ALHA 81005, are 24% and 12% more enriched in the light samples compared to the dark. The two lithologies represent different but similar mixtures with overall anorthositic norite compositions.

The variety of clasts [2,20, U. Marvin, pers. comm.] suggests that ALHA81005 was once a soil. ALHA81005 is more similar than sampled soils to typical lunar highlands as estimated from data from the Apollos 15 and 16 orbiting gamma-ray experiments [4]. Its Th concentration is lower (0.5x) and its TiO_2 concentration much lower (0.15x), raising further question about the accuracy of the gamma-ray data for Ti [4,8]. The gamma-ray experiment indicated that KREEP is principally a lunar nearside phenomenon. KREEP-free ALHA81005 may be our most representative sample of typical lunar highlands surface material and may even have come from Moon's farside!

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Figure 1. Comparison of REE concentrations in ALHA81005 with those for some lunar samples [6,7,10,11].

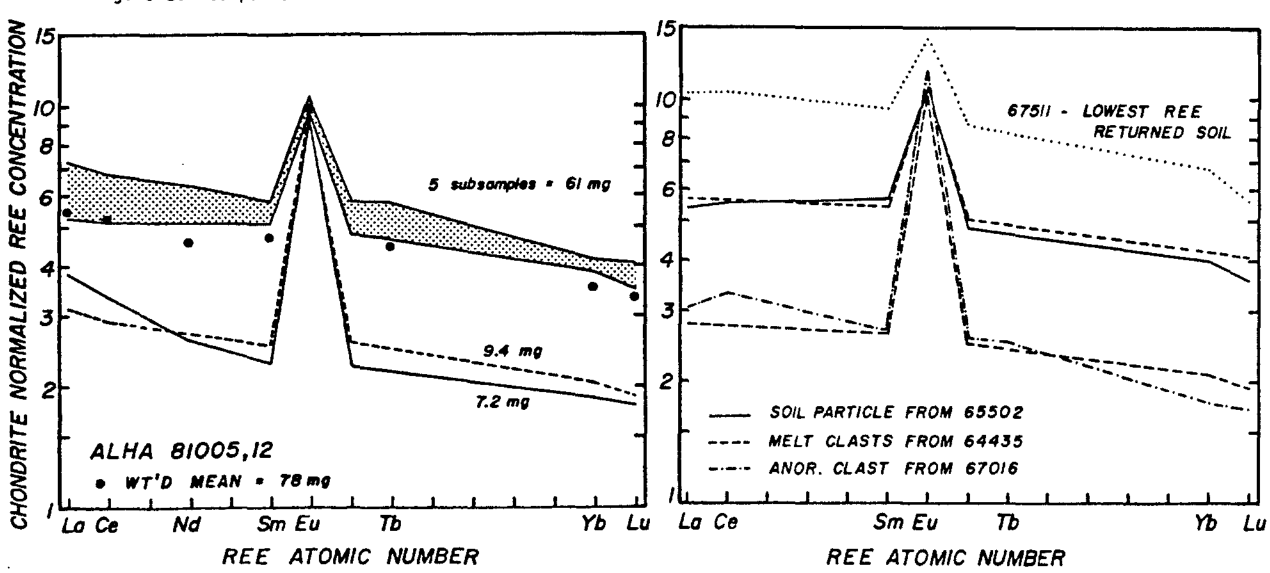

Table 1. Element concentrations in seven small samples of ALHA 81005,12 (along with the mass weighted means) and some standard rocks. Values in μg/g, except Ir in ng/g and oxides in % (total element as oxide).

Sample Designation	ALHA 81005 1A	3A	2M1	3M2	2M2	3M1	3R	±1	wt'd mean	Standard Materials BCR-1	DTS-1	AN-G	AN-G lit.	Flyash
TiO_2	<0.3	<0.3	0.27	0.24	0.37	0.30	0.23	0.10	0.23	2.5 .2	<0.3	0.26 .10	0.22	1.4 .2
Al_2O_3	25.1	24.7	24.8	25.7	26.6	24.6	24.8	0.3	25.1	13.6 .2	0.2 .1	---	29.8	27.0 .4
FeO_t	4.80	4.96	5.52	5.52	5.80	5.79	6.02	0.15	5.53	12.3 .3	8.06 .22	3.00 .08	3.02	12.23
MgO	9.7	11.0	7.3	8.6	8.5	8.9	9.2	1.5	8.8	4.7 1.2	56 3	3.0 1.2	1.8	<2.
CaO	14.6	14.5	15.4	14.9	15.3	15.0	14.6	0.3- 0.4	14.9	8.2 .3	---	15.9	15.9	2.25 .15
Na_2O	0.360	0.337	0.309	0.316	0.313	0.311	0.322	0.005	0.321	3.20 .06	0.015 .002	1.644	1.63	0.240 .010
K_2O	<0.03	<0.05	<0.12	<0.10	0.02	0.02	<0.08	0.01- 0.02	<0.04	1.5 .3	---	---	0.13	2.27
Sc	7.36	7.57	9.42	8.67	9.90	9.35	8.78	0.08	8.81	32.4 .3	3.44 .03	10.05 .10	10	38.6
V	25	22	21	22	24	25	21	6	23	380 50	10 2	---	70	260 30
Cr	945	995	870	865	870	870	915	10	900	10.8 .4	4250	46.3 .5	50	188 2
Mn	600	620	590	600	620	660	640	50	620	1400	820 30	380 40	300	230 30
Co	18.3	19.0	20.3	23.3	22.0	23.4	29.4	0.5	22.5	38.2 .8	143 3	25.1 .6	25	44.1
Ni	228	204	180	274	170	242	374	10- 15	243	<60	2410	40 11	35	132 30
Br	0.67	0.53	0.14	0.34	0.19	0.24	0.36	0.04- 0.08	0.33	---	---	3.59 .22	---	2.31
Rb	<4	<5	<5	<6	<6	<5	<8	(2)	<6	53 4	---	2.2 1.2	1	134
Sr	141	141	149	136	132	138	143	9-13	141	342 21	---	78 12	76	385
Zr	<35	<45	23	<50	38	22	23	8	19±12	122 18	---	---	15	240
Sb	0.020	0.041	0.026	0.027	0.063	0.012	0.031	0.008	0.030	0.60 .03	0.38 .02	0.091 .013	---	6.15
Cs	<0.08	<0.05	0.03	0.05	0.05	0.03	0.05	0.02	0.04± 0.02	1.00 .04	---	0.03 .02	---	10.42
Ba	11	13	26	34	30	25	24	4	24	665 20	---	31 5	34	1320
La	1.257	1.030	1.80	2.40	2.36	1.725	1.75	0.015- 0.02	1.80	24.0 .3	---	2.15 .03	2	76.7
Ce	2.95	2.55	4.5	5.95	5.5	4.55	5.0	0.3	4.55	52.2 .5	---	4.75 .09	4.7	168.8
Nd	1.56	1.56	2.7	3.8	3.4	2.85	2.9	0.2	2.75	29.4 .6	---	2.81 .17	2	81.4
Sm	0.414	0.456	0.952	1.047	0.978	0.920	0.945	0.006- 0.012	0.855	6.85 .08	---	0.747 .009	0.7	16.61
Eu	0.627	0.640	0.727	0.696	0.718	0.697	0.663	0.012	0.686	1.90 .03	---	0.361 .010	0.37	3.50
Tb	0.103	0.117	0.22	0.25	0.27	0.24	0.23	0.01- 0.02	0.21	1.12 .03	---	0.189 .009	0.2	2.69
Yb	0.375	0.41	0.785	0.77	0.83	0.78	0.805	0.015	0.705	3.41 .04	---	0.812 .018	0.85	7.68
Lu	0.0615	0.065	0.126	0.119	0.138	0.121	0.123	0.002- 0.003	0.113	0.527 .012	---	0.127 .003	0.12	1.146
Hf	0.27	0.31	0.70	0.64	0.90	0.70	0.73	0.02	0.63	5.08 .08	---	0.370 .023	0.38	7.29
Ta	0.030	0.023	0.094	0.084	0.089	0.114	0.084	0.010	0.079	0.78 .03	---	0.150 .013	0.2	1.93
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	5.66 .07	---	0.016 .011	---	24.0
U	<0.05	<0.07	0.05	0.04	0.05	0.04	0.05	0.02	0.04	1.5 .2	---	---	---	10.3
mass (mg)	7.246	9.391	16.224	13.852	7.360	11.564	12.074		77.71	12.66	31.15	14.73		20.99

The standard for each element and the concentration used are indicated by the underlined values; all other values except "AN-G lit." were determined in this experiment against the standard values listed. Dashes indicate that no upper limit estimate was made or that no recommended value is available. Except for Ti,Al,Mg,V, and Mn standard concentrations are values recently determined in this laboratory on multiple large samples against primary chemical standards (Korotev, in prep.). "Flyash" is NBS SRM 1633a (coal flyash). BCR-1 and DTS-1 are USGS standard rocks and AN-G is a GIT-IWG rock reference sample (Greenland anorthosite). Column "AN-G lit." contains "proposed" values (Govindaraju, 1980) for comparison. For Ti and Mg a synthetic reference standard was used. Ir concentrations were determined parametrically without benefit of a standard.

Uncertainties are one standard deviation estimates of precision the principal component of which is "counting statistics." They do not include uncertainty associated with the standard values or any systematic error associated with heterogeneity of the small standards.

METEORITE ALHA 81005 : A LUNAR HIGHLAND BRECCIA. Gero Kurat and Franz Brandstätter, Naturhistorisches Museum, Postfach 417, A-1014 Vienna, Austria.

Thin-section ALHA 81005,8 has been allocated to us for a restricted study period of four weeks starting February 10, 1983. This report necessarily has to be a preliminary one. Here we concentrate on our results on lithic and mineral components in ALHA 81005. Results on investigations of various glasses are included in the report by Fudali et al. (1).

Results : ALHA 81005 is a lunar regolith breccia. Figure 1 shows one of the possible chemical evidences for a lunar origin, the FeO/MnO ratio in olivines. ALHA 81005 is a compacted immature lunar highland soil consisting of a variety of lithic fragments, glass fragments, glass beads, chondrules, and mineral fragments suspended into a glass-rich fine-grained matrix which has been shock-melted in places, probably during compaction. The most common lithic fragments are granulitic metabreccias, followed by "basaltic" clasts, shocked anorthosites, chondrules, and complex microbreccias.

Igneous lithology : Most igneous rocks present (regardless wether they are real igneous rocks or melt rocks) are metamorphosed and partially equilibrated. Only one fragment (basalt A) of a felspathic basalt composition (low-K Fra Mauro basalt) is apparently not metamorphosed and displays a crystallization sequence of plag, plag+ol, and plag+px. The compositional variation of olivines and pyroxenes are shown in Fig.2 and typical analyses are given in Table 1. The meta-igneous rocks clearly can be devided into two groups : The Mg-suite (Fig.2) consists exclusively of fine-grained ophitic rocks which are all olivine bearing and which could be melt rocks. The Fe-suite is coarse to very coarse-grained and apparently of a deeper seated origin. "Metabasalt" H actually is only a large pyroxene fragment with some silica attached to it and we can only infer that it belongs to the basalt suite. The Fe-suite tends to be of noritic composition.

Anorthosites : Two large shocked anorthosite fragments have been encountered. Both belong to the ferroan rock suite (2-4), have different pyroxenes (Fig.3, Table 2) and are metamorphically partially equilibrated.

Metabreccias : All granulitic metabreccias are members of the Mg-suite (Fig.3, Table 2) and are of anorthositic noritic-troctolitic composition. Some are Mg-spinel bearing. Metabreccia B is a unique rock fragment consisting mainly of olivine, low-Ca pyroxene, some plagioclase and Cr-Ti spinel.Its real nature is not clear yet.

Chondrules : Three chondrules are present in ALHA 81005,8. All are of the typical ANT composition (5).

Mineral fragments : Most common is plagioclase followed by low-Ca pyroxenes and olivines. Rare are pink Mg-spinel, chromite, and metal. The mafic minerals belong to both Mg-Fe groups.

Summary : ALHA 81005 is a feldspathic lunar highland breccia. Its composition is dominated by highly magnesian, olivine bearing metabreccias and melt rocks derived thereof. The ferroan rock suite is relatively rare and consists of anorthosites, meta-igneous rocks, one metabreccia, and some mineral fragments. Most glasses compositionally overlap with the melt-rocks but not with the magnesian metabreccias. A search for KREEP revealed only one glass (1) and one basalt fragment of low-K composition.

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Table 1 : Electron microprobe analyses of mafic minerals in igneous lithic fragments, ALHA 81005.

	Basalt A				Metabasalt H		Metabas J	Metabas L
	Olivine	Pyroxene			Pyroxene		Px	Px
		Lo Ca	Hi Ca	Hi Fe	Lo Ca	Hi Ca		
No. of anal.	5	1	1	1	8	2	5	2
SiO_2	39.8	52.7	53.3	49.3	50.6	51.2	51.1	53.7
TiO_2	0.03	0.36	0.42	1.64	0.27	0.53	0.74	0.87
Al_2O_3	0.06	1.65	1.24	1.46	0.36	0.87	0.73	1.66
Cr_2O_3	0.18	0.45	0.36	0.15	0.15	0.24	0.20	0.60
FeO	17.8	16.2	14.5	27.1	31.2	17.3	24.3	12.3
MnO	0.28	0.29	0.28	0.48	0.61	0.35	0.49	0.30
MgO	41.5	21.0	16.7	8.4	11.8	9.6	15.4	23.9
CaO	0.26	5.8	13.7	11.2	4.2	18.7	5.9	5.3
Na_2O	-	-	0.09	0.07	0.06	0.06	0.06	0.07
Total	99.91	98.45	100.59	99.80	99.25	98.85	98.92	98.70

Table 2 : Electron microprobe analyses of mafic minerals in anorthosites and metabreccias from ALHA 81005.

	Fe-suite				Mg-suite					
	Anorthosites		Metabreccia		Metabreccias					
	G	M	B		N		Q	S	U	
	Px	Px	Ol	Px	Ol	Px	Px	Ol	Ol	Px
No. of anal.	2	6	4	4	5	2	5	6	1	8
SiO_2	51.7	52.5	36.3	52.9	40.5	56.0	54.5	40.5	40.0	56.8
TiO_2	1.11	0.34	0.07	0.55	0.12	0.50	0.85	0.12	0.17	0.64
Al_2O_3	1.60	0.53	0.09	0.81	0.06	1.07	1.81	0.08	0.08	1.22
Cr_2O_3	0.51	0.23	0.02	0.22	0.08	0.44	0.46	0.05	0.19	0.47
FeO	13.3	24.6	34.2	19.3	16.7	10.3	11.9	15.1	18.0	10.3
MnO	0.43	0.46	0.40	0.36	0.21	0.19	0.22	0.23	0.23	0.26
MgO	13.6	19.4	27.1	21.0	45.2	31.9	29.3	44.6	43.0	29.3
CaO	17.6	2.43	0.20	4.3	0.10	1.22	1.47	0.11	0.10	2.10
Na_2O	0.11	0.07	-	0.04	-	0.02	0.04	-	-	0.05
Total	99.96	100.56	98.38	99.48	102.97	101.64	100.55	100.79	101.77	101.14

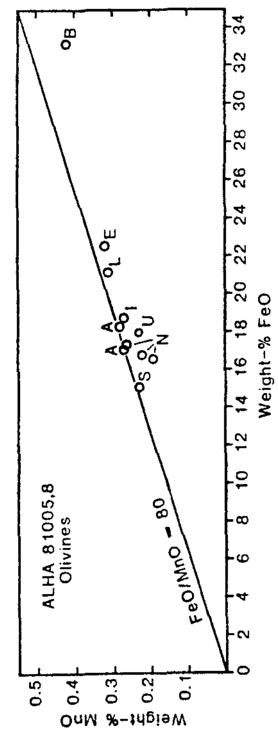

Figure 1

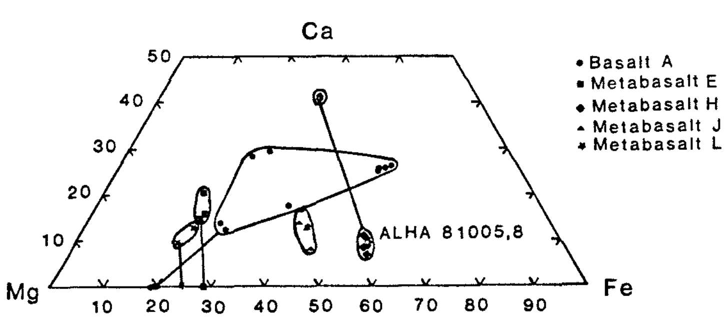

Figure 2 : Olivine (bottom) and pyroxene compositions in igneous lithic fragments.

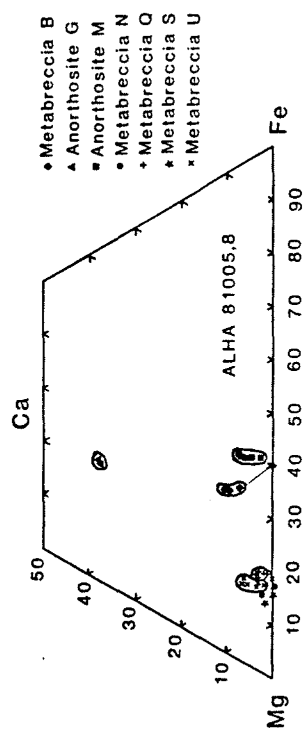

Figure 3 : Olivine (bottom) and pyroxene compositions in anorthosites and metabreccias.

ALHA 81005 METEORITE: CHEMICAL EVIDENCE FOR LUNAR HIGHLAND ORIGIN.

J. C. Laul, Radiological Sciences Department, Battelle Northwest, P. O. Box 999, Richland, WA 99352; M. R. Smith and R. A. Schmitt, Chemistry Department, Oregon State University, Corvallis, OR 97331.

Summary: Based on the well-established characteristic lunar and meteoritic ratios of FeO/MnO, Cr_2O_3/V and K/La, and REE patterns, ALHA 81005 meteorite is undoubtedly of lunar origin. Our conclusion is confirmed by oxygen isotopic (1), noble gas (2), and petrologic (3, 4) studies. The ALHA 81005 meteorite is an anorthositic gabbro (72 % Pl) and matches closely in chemical composition to Apollo 15 15418 (5) and Luna 16 21013 (6) highland rocks. The high content of siderophiles, Ni, Ir and Au (1-2% meteoritic component) in ALHA 81005 is similar to the siderophiles content in other lunar highland breccias, which strongly suggests that this rock was also subjected to a meteoritic impact on the moon. The terrestial ages of meteorites collected at the Antarctica including ALHA 81005 are relatively young 0.01 - 0.7 m.y (7, 8). Assuming a short space residence time, the young terrestrial ages indicate recent excavation of the rock by a cratering event on the moon. This implies that if a recent cratering event by a meteoritic impact can send lunar debris on the earth, then when major lunar basins were formed by planatesimal bodies during early (∿4 B.y) cataclysmic bombardment, the earth must have received enormous amounts of lunar material which is now mixed in the crust. The finding of a meteorite of lunar origin is the first documented case which further lends credibility to the suggestion (9, 10) that SNC achondrites may come from Mars.

Discussion on the bulk, matrix and clast: The bulk, matrix (dark) and clast (white) were analyzed for 30 elements by INAA. The petrology work on the same sample split was done by Papike's group (4). The chemical data are shown in Table 1. For comparison the data for 15418 and 21013 highland rocks are also included. The chondritic normalized REE patterns of these samples are shown in Fig. 1. The clast is low by ∿20% in REE and other trace elements relative to the matrix and bulk. The chemistry of the bulk is governed by the matrix. The strong element correlations of FeO/MnO and Cr_2O_3/V first noted by Laul et al (11) and K/La (12), and later found to be typical ratios for the moon is used to distinguish ALHA 81005 from other Ca-rich achondrite planetary bodies such as Eucrites, Howardites, Shergotittes, Nakhlites and Chassignites. These correlations are shown in Figs. 2-4. ALHA 81005 samples fall on the lunar line, whereas the other achondrites fall distinctly away from the lunar line. The FeO/MnO ratio of 80 provides the strongest evidence in favor of the lunar origin. The rock is reported as a regolith breccia (3, 4) indicating that the observed chemical signatures represent various lithic components similar to 15418 which is also a melt rock.

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ALHA 81005 METEORITE: CHEMICAL EVIDENCE

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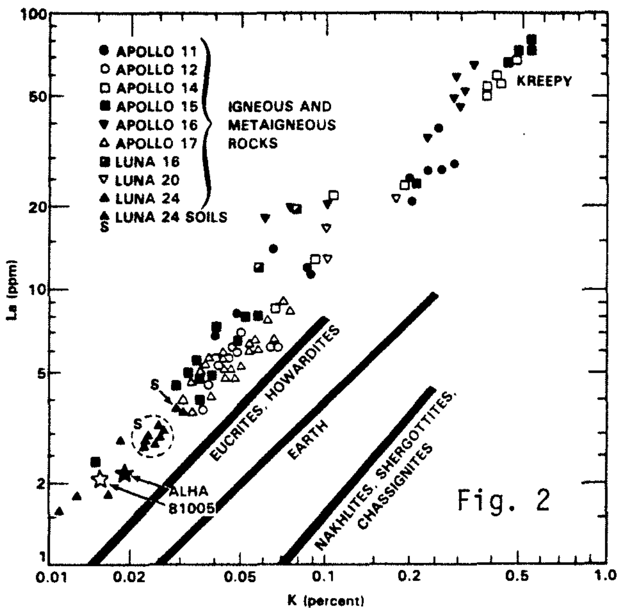

Fig. 2

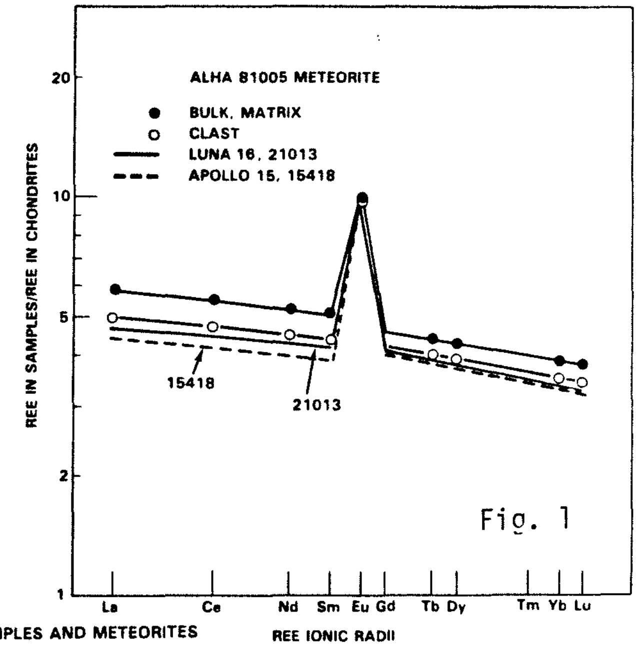

Fig. 1

MnO-FeO CORRELATION IN MOON SAMPLES AND METEORITES

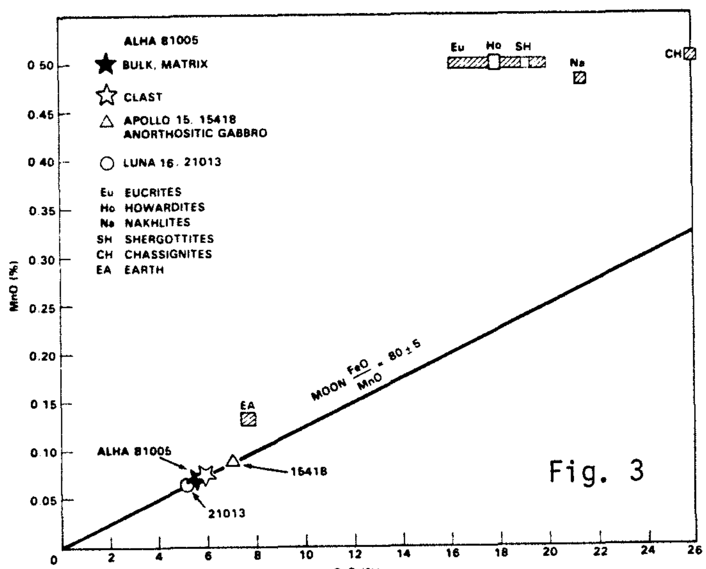

Fig. 3

CHEMICAL ABUNDANCES BY INAA

SAMPLE		ALHA 81005 METEORITE			APOLLO 15 15418	LUNA 16 21013
		CLAST	MATRIX	BULK	HIGHLAND ROCK	HIGHLAND ROCK Smith, et al (1983)
WT (mg)		9.3	23.0	20.5	22.0	
ELEMENT						
(%)	TiO_2	0.30	0.30	0.30	0.30	0.2
	Al_2O_3	25.9	25.6	26.3	26.4	27.0
	FeO	5.9	5.6	5.6	7.0	5.2
	MgO	9.0	8.0	8.0	6.0	7.8
	CaO	16.7	15.2	15.0	15.7	15.0
	Na_2O	0.31	0.31	0.31	0.29	0.31
	K_2O	0.020	0.025	0.025	0.011	0.021
	MnO	0.074	0.070	0.069	0.084	0.066
	Cr_2O_3	0.12	0.12	0.12	(0.28)	0.11
(ppm)	Sc	8.7	8.7	8.8	12.0	10.7
	V	25	25	25	25	28
	Co	17.0	19.0	19.0	(70)	10
	La	1.7	2.0	2.0	1.5	1.6
	Ce	4.0	4.8	5.0	4.0	4
	Nd	2.8	3.5	3.3	3.0	<6
	Sm	0.85	1.0	1.0	0.75	0.82
	Eu	0.70	0.73	0.75	0.73	0.79
	Tb	0.19	0.21	0.20	0.18	0.20
	Dy	1.2	1.3	1.3	1.2	1.3
	Yb	0.74	0.84	0.86	0.81	0.79
	Lu	0.11	0.13	0.13	0.12	0.11
	Hf	0.54	0.65	0.65	0.70	0.65
	Ta	0.050	0.10	0.080	0.09	0.042
	Th	0.25	0.30	0.32	0.25	0.19

*VALUES IN PARENTHESIS ARE SUSPECT OF CONTAMINATION.

V-Cr_2O_3 CORRELATION IN MOON SAMPLES AND METEORITES

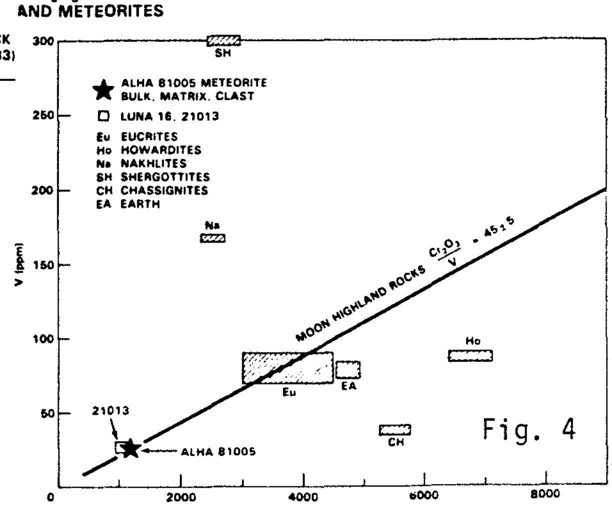

Fig. 4

SOME PETROLOGIC COMPARISONS BETWEEN ALHA81005 AND LUNAR HIGHLAND SOIL BRECCIAS. Ursula B. Marvin, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts, 02138.

Speciman ALHA81005 appeared unique when it was discovered on the middle western ice field of the Allan Hills region on the final snowmobile traverse of the 1981-82 season. The field photograph shows a small rounded breccia, about 3 cm across, with conspicuous white clasts under a thin fusion crust. Six other meteorites were found in the same ice field during helicopter reconaissance flights early in the 1979-79 season. None of the other specimens resemble 81005, which remains the only one of its kind found in Antarctica or elsewhere in the world.

Preliminary examinations of two thin sections (81005,3 and ,22) show that the rock is a heterogeneous mixture of mineral and rock fragments, colorless glass spherules, and masses of devitrified glass embedded in a dark, glassy matrix. Some portions of the matrix are flow banded and/or crowded with minute (2-4μm) vesicles. The clast and matrix compositions fall well within the range of lunar highlands materials but differ from those of familiar achondritic meteorites. The glass spherules are reminiscent of those found in lunar soils and regolith breccias.

Plagioclase is by far the most abundant component of the rock. It occurs as mineral fragments and in lithic clasts ranging from cataclastic and granulitic anorthosites to anorthositic gabbros and troctolites with granulitic, ophitic, and cumulate textures. Plagioclase is also an abundant constituent of the colorless glasses, the devitrified glasses, and the brown matrix glasses. Most of the plagioclase is Ca-rich (An 92-98; Av. An 97). Only two small plagioclase clasts among several dozen analyzed ran as low as An 75, Ab 24, Or 0.98. Most of the glasses, both colorless and brown, plot within the plagioclase field of the pseudoternary liquidus diagram of Walker, et al (1973) although a few mafic glasses fall within the olivine or spinel fields. The fusion crust is almost pure feldspar glass with a maximum of 2 Wt.% each of FeO and MgO.

Pyroxenes and olivines occur as monomineralic clasts up to 0.15mm across and as mafic components of polymineralic clasts. Lamellae of augite and pigeonite are measureable in numerous grains. The augites range from En 31-50, Fs 15-30, Wo 30-40; the pigeonites from En 43-81, Fs 52-17, Wo 1-10. Sparse ferroaugites are present with compositions averaging En 25, Fs 33, Wo 42. Most olivines range between Fo 60-86, but two grains were found averaging Fo 37. The Wt.% MnO/FeO values measured in the pyroxenes and olivines show an affinity diagnostic of a lunar origin (see Figure 1). The pyroxenes follow the line previously determined for the ratios in lunar pyroxenes; they plot below the fields determined for achondritic pyroxenes. Within 81005 the pyroxenes and olivines fall (as expected) above and below the trend established for lunar bulk rocks.

Two prominent lithic clasts in section 81005,22 can serve as examples of distinctly lunar materials. The largest clast in the section is a 3mm gabbroic anorthosite in which large plagioclase crystals have been crushed and partially randomized optically. The mode is 87% plagioclase (An 97, Or 0.1) and 13% pyroxenes (En 44, Fs 18, Wo 38 and En 64, Fa 34, Wo 2). Anorthosites of this general character are unknown in achondrites but are common among Apollo highlands samples. The second clast is a 2mm anorthositic gabbro with a relict cumulate texture in which chains of pyroxene and olivine grains lie among plagioclases, most of which have acquired a granulitic texture although the fabric includes two larger-than-average clasts of twinned feldspar. This clast resembles some of the cumulate eucrites, but similar textures and compositions (60% plagioclase, An 96-98; 35% pyroxene En 38-45, Fs 30-44, Wo 32-11; 15% olivine, Fo 38) occur among lunar rocks and the MnO/FeO values are characteristically lunar.

Antarctic meteorite ALHA81005 was propelled to the ice sheet from the surface of the moon.

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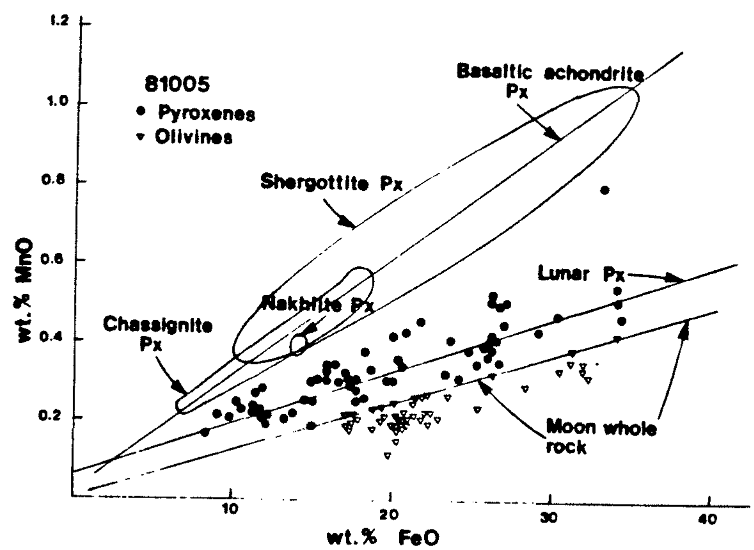
Figure 1. MnO-FeO values of pyroxenes and olivines in ALHA81005 as compared with those of lunar and achondritic pyroxenes and lunar whole rock analyses. (After Stolper et al, 1979).



OXYGEN ISOTOPIC COMPOSITION OF ALHA 81005; Toshiko K. Mayeda and Robert N. Clayton, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637.

The various planetary bodies and meteorite parent bodies have characteristic oxygen isotopic compositions established at the time of their accretion (1). The differences arise both from mass-dependent fractionation processes and from variable degrees of mixing of components of different nucleosynthetic origins. The major groups of achondritic meteorites form four different groups on the oxygen three-isotope graph: I eucrites, howardites, diogenites, mesosiderites, and pallasites; II shergottites, nakhlites, and chassignites; III aubrites; IV ureilites. All of these except the aubrites lie on mass-fractionation lines either richer or poorer in ^{16}O with respect to the terrestrial fractionation line. The rocks of the Moon are very homogeneous in oxygen isotopes and have a composition lying on the terrestrial fractionation line at a point within the range of terrestrial mantle rocks (2). Thus, the oxygen isotopic composition of the Moon is distinctly different from that of all meteorites except the aubrites.

Table 1 shows isotopic data for ALHA 81005 along with data for eucrites and a lunar highlands breccia, analyzed at the same time for comparison. ALHA 81005 is identical in isotopic composition with the Apollo 16 breccia, and is distinctly different from the eucrite samples. Of all the known sources of solar system rocks, only the Earth, the Moon, and the aubrite parent body have oxygen compositions compatible with that of ALHA 81005. Chemical data eliminate the Earth and aubrite parent as candidates, leaving the Moon as the likely origin.

TABLE 1

Oxygen Isotopic Compositions of ALHA 81005, Lunar Rocks, and Eucrites

Sample No.	Description	$\delta^{18}O$ (‰)	$\delta^{17}O$ (‰)	$\delta^{17} - 0.52\delta^{18}$
ALHA 81005,19	Anorthositic clast	5.48	2.92	+0.07
ALHA 81005,19	Whole rock	5.86	3.03	-0.02
60015,72	Lunar anorthosite	5.57	2.95	+0.05
60015,58	Lunar glass	5.59	2.94	+0.03
ALHA 79004,43	Eucrite clast C	3.37	1.53	-0.22
ALHA 79004,50	Eucrite clast F	3.53	1.59	-0.25
ALHA 79004,53	Eucrite matrix	3.40	1.60	-0.17
Serra de Magé	Whole rock	3.68	1.67	-0.24
Juvinas	Plagioclase	3.78	1.71	-0.26

References

(1) Clayton R. N. and Mayeda T. K. (1976) Earth Planet. Sci. Lett. 30, 10-18.
(2) Clayton R. N. and Mayeda T. K. (1975) Proc. Lunar Sci. Conf. 6th, 1761-1769.

IMPACT EJECTION, SPALLATION AND THE ORIGIN OF CERTAIN METEORITES.

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During the course of a major impact event, large quantities of target rock are ejected from the growing crater. Some of this ejecta reaches high velocity: both theory and experiments (1,2) suggest that significant amounts of ejecta may even exceed the escape velocity of the Moon, Mercury or Mars. Most such high-speed ejecta is strongly shocked and is either melted or crushed into small fragments (3,4). However, at least one calculation (5) indicates that some slightly shocked material is accelerated to high velocity.

The recent proposals that the SNC meteorites may have originated on Mars (6), that Eucrites may have come from Vesta (7), and the possible discovery of a lunar rock in Antartica (8) all require high-speed ejection of intact rock fragments from their parent bodies. The estimated fragment size varies--from a few tens of cm for the putative "lunar meteorite" up to 2 km for the SNC parent bodies (9). To date, however, there has been little discussion of how large rock fragments might be accelerated to high velocity by an impact.

Study of velocity gauge record data from underground nuclear tests has suggested a model for stress wave propagation subsequent to an impact that promises to yield information on ejecta fragment size, velocity and degree of shock damage. Comparison of the model to data from TNT explosion cratering tests [10] and secondary crater distributions near lunar and Martian craters [11] has yielded satisfactory agreement.

The shock front that propagates away from an impact site shortly after a meteorite strikes attains a nearly spherical form, centered on a point located a distance d below the surface. This "depth of penetration" d is comparable to the projectile diameter a. The rise time of the stress wave is of order $\tau \simeq a/U$, where U is the impact velocity. The stress wave is asymmetric, falling from its maximum value to near zero after a time $\tau d \simeq d/c_L$, where c_L is the target's P-wave velocity. The peak particle velocity v_P in the wave falls according to a power law [12]:

$$v_P \simeq \frac{U}{2}\left(\frac{a}{r}\right)^{1.87}$$

where r is the distance from the stress wave center at depth d.

This stress wave is reflected at the free surface. The superposition of the direct compressive wave and the reflected tensile wave results in a low stress environment for target material in the vicinity of the surface. Although this material is protected from experiencing high shock pressures by the reflected wave, it nevertheless acquires a large particle velocity (following the "velocity doubling" rule) which is of order

$$v_e \simeq 2\ v_P \frac{d}{r}$$

for large r, v_e thus falls as roughly $1/r^3$.

The vertical stress component becomes tensile after reflection. If the target material has a density ρ and dynamic tensile strength σ_t, spalls break off with velocity v_e and thickness

$$l_S \simeq \left(\frac{\sigma_t}{\rho c_L v_P}\right) r$$

beneath the spalls the sudden onset of large tensile stresses breaks the rocks into much smaller pieces [13]

IMPACT EJECTION

Melosh, H. J.

$$l_t \simeq \left(\frac{\sigma_t}{\rho c_L v_P}\right) c_L \tau$$

These sizes must be understood as upper limits--any flaws, joints or inhomogenieties of smaller scale than the l's above will produce smaller fragments.

These considerations lead to a relation between maximum fragment size and ejection velocity.

$$l_{max} \simeq \left(\frac{4\sigma_t}{\rho c_L 2}\right) \frac{c_L}{v_e} \; a$$

For example, if Copernicus was produced by a 5 km radius projectile and $c_L \simeq 5$ km/sec (basalt), $\sigma_t \simeq 100$ MPa [14], then debris ejected at 1 km/sec can be no longer than ca. 100 m in diameter. This result agrees reasonably well with the data on Copernican secondaries [11], although it does not predict the rapid dropoff in the number of secondaries beyond 1.5 km/sec. The drop-off is apparently due to crushing of even the spalls when stresses exceed the Hugoniot elastic limit.

A more complex version of this model shows that debris ejected nearly vertically close to the impact site, then at increasingly lower angles at greater distances until the ejection angle reaches an asymtotic limit governed by the poisson ratio ν of the target,

$$\Theta_\infty = 2 \cos^{-1}\left(\frac{1-2\nu}{2(1-\nu)}\right)^{1/2}$$

This model is in qualitative and even quantitative agreement with existing data. It indicates that, whereas small (10's of cm) fragments may be ejected to lunar or even Martian escape velocity by large impacts, ejection of 100 m size fragments from Mars, if it ever occurs, must proceed by a different mechanism than ballistic flight of spalled fragments.

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ALHA 81005: PETROGRAPHY, SHOCK, MOON, MARS, GIORDANO BRUNO, AND COMPOSITION:

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Summary: ALHA 81005,8 is a glassy, olivine-rich regolith breccia, beyond any reasonable doubt of lunar origin. It is dominated by feldspathic granulitic impactites, contains some cataclastic ferroan anothosites and minor mare basalt components, but lacks detectable KREEP. Its bulk composition (25.1 % Al_2O_3; 8.9 % MgO; 5.6 % FeO) has a higher Mg′ and is poorer in Na and Ti than other lunar soils, a reflection of its large plutonic troctolitic component (olivine fragments) and the poverty of KREEP. We contend that the sample is far more likely to be ejecta from Giordano Bruno than any other lunar crater, hence ALHA 81005 provides information about the Moon's NE limb. The sample was not detectably shocked during ejection from the Moon, although most of its components had already been shocked during regolith formation. Evidently escape of material from planets following impacts does occur without melting, and without the requirements for high indigenous volatiles. If Giordano Bruno is the source, then neither are oblique impacts necessary. The implications for meteorites of possible Martian origin are obvious.

Lunar Origin: The sample came from a planet which produced a feldspathic crust and is also otherwise indistinguishable from the Moon. It is low in volatiles (Na, K low; water absent), and has a low oxidation state (Fe-metal). MnO/FeO ratios in olivines ($\sim$100) and pyroxenes ($\sim$50) are similar to those in all other lunar rocks but not to those in basaltic achondites. Ni in olivines is low ($<$100 ppm) as in most lunar highlands rocks. ALHA 81005,8 contains lithic clasts similar to those of other lunar highlands breccias except that it lacks KREEP.

Shock: Shock effects in mineral clasts and glass beads in ALHA 81005,8 range from unshocked glass beads and weakly shocked plagioclase with fractures and undulous extinction ($\leqslant$15 GPa) to fractured olivine, planar elements in pyroxene (30–40 GPa) and diaplectic plagioclase glass (30–40 GPa) all of which is now recrystallized. Lithic clasts are fractured, one clasts shows planar elements in plagioclase. All shock features indicating high shock pressures were developed prior to the event which caused the ejection of the sample from the Moon's surface. The sample itself has not been shocked to more than 15 GPa, if at all, as no mosaicism or unrecrystallized diaplectic plagioclase glass is apparent and most of the glass beads are even unfractured. It is unlikely that the brown matrix glass formed during the ejection event as the sample still contains a high content of solar-wind rare gases (1). The shock pressure experienced by a sample ejected from a body of the size of the Earth's moon may thus be as low as 0–15 GPa. This is consistent with a possible Martian origin of meteorites which have been shocked to only 30–40 GPa, such as Shergotty. Dynamicists have stated that only a shock-melted sample could be accelerated beyond escape velocity upon impact. Not only is this disproved by ALHA 81005, but we now have 10 samples which came from large planetary bodies and not a sinle one of them has been totally shock-melted. The impact melt may have been finely dispersed, nevertheless we have to consider a mechanism which accelerates a low-shocked sample from a planetary body not containing large amounts of indigenous volatiles.

Giordano Bruno: The significance of ALHA 81005 for lunar petrology would be greatly enhanced if we knew from where on the Moon it came. Our petrographic/microprobe investigation requires that the sample has a highland source, far removed from a KREEP supply, but with mare basalts close enough to be components. Furthermore, unless ALHA 81005 has a terrestral age older than all other dated Allan Hills samples, it was ejected from the Moon less than 600,000 years ago, probably less than 200,000 years ago, i.e. very recently. Giordano Bruno is a 20 km crater, very young according to its large ray/crater diameter ratio (greater than the 2 million year old South Ray), and in its size and youth is unequalled as a potential source of ALHA 81005 (presumably, the larger the crater, the more likely to eject material from the planet). Giordano Bruno lies in highlands terrain, but with mare material only 150 km away, filling the areas in and around Maxwell and Lomonosov. The area was not overflown by Apollo, so no data on the possible proximity of KREEP is available; the orbital data taken 30° to the south lack KREEP. We conclude that Giordano Bruno is far more likely than any other lunar crater to be the source of ALHA 81005.

Petrography: ALHA 81005,8 has a brown, commonly vesicular glassy matrix, which encloses glass shards, blebs, and 3 beads, and shocked mineral and lithic clasts. In common with other regolith breccias, lithification destroyed the fragile nature of agglutinates. Much of the glassy matrix has the form of irregular, thin veinlets and blebs, and is evidently multigenerational. Our analytical study was intended to deduce the nature of the components of the rock and compare them with other known lunar materials. More details are given in the accompanying abstract. About 30 % of the lithic clast population (Fig. 1) is feldspathic granulitic impactite (only 2 pyroxene poikiloblastic clasts). These are olivine-rich, and generally have Mg′ $\sim$80, similar to lunar frontside granulites. Generally distinct from these in both their high plagioclase content and their Fe-rich mafic minerals are cataclastic anortho-

ALHA 81005 PETROGRAPHY

OSTERTAG R. and RYDER G.

sites, which are less abundant - there is a distinct hiatus between Mg-rich rocks and cataclastic anorthosites (Fig.2), but no lithic samples are similar to the lunar front-side Mg-suite rocks, many of which are related to KREEP. Feldspathic impact melts ranging from glass and fine-grained glassy breccias to subophitic/poikilitic are common. Some contain minor silica, but lack the abundant mesostasis glass, phosphates, and the opaque oxide materials which characterize KREEP. Two small "cumulate"-textured fragments fall with the anorthosites, one with more Mg-rich group. One 4 mm clast is a polymict breccia, distinct from the rest of the rock in that it lacks granulitic impactites, although it contains one of the poikiloblastic clasts.

Some glasses contain a mare component and some pyroxene fragments and one lithic fragment appear to be of mare basalt deriviation. All analyzed olivine mineral fragments appear to be of plutonic origin (low CaO) and have Ni less than 100 ppm, while pyroxenes include both plutonic and extrusive varieties. The "Mg-gap" apparent among lithic fragments (Fig. 2) is also apparent among single mineral grains. Of 48 mafic mineral fragments larger than 100 microns analyzed, 28 were olivines of plutonic origin, most more magnesian than Fo 77, and most are too large to have come from granulites.

We believe that the bulk composition of the rock is best represented by the clean, vesiculated glass of the fusion crust, away from interference by partly digested clasts. We analysed 6 such points and found them to be homogeneous - the average is presented in the Table and Figure 3.

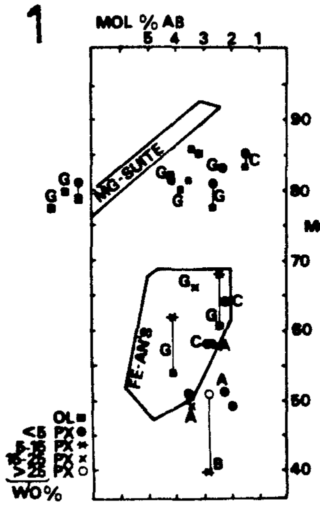
Possibly Na is low cf. bulk rock because of sodium volatilization during fusion but other glasses also have low Na. Analyses of other clear glasses cluster around this composition and support the contention that it represents bulk rock. It apparently agrees reasonably with the matrix analysis of Palme et al. (pers. comm.). The soil in the ALHA 81005 target area is more similar to L 20 soil than other soils but is more aluminous and has a higher Mg'. It is similar to granulites, but is more magnesian because of the olivine component. The anorthosite component is not as great as at Apollo 16. Generally, the composition is similar to the granulitic, anorthosite-poor highlands which can be deduced for the pre-Serenitatis surface at A 17. The low Ti in the sample supports the contention that most of the Ti in lunar frontside breccias is contributed by the KREEP component, which is also lacking in ALHA 81005. Quite likely KREEP is also the dominant source of Na in frontside breccias.

TABLE

ALHA 81005,8 Fusion crust	
SiO_2	45
TiO_2	0.27
Al_2O_3	25.1
FeO	5.6
MgO	8.9
CaO	14.6
Na_2O	0.24
K_2O	0.06

Reference: (1) Bogard, D. and Johnson, P. (1983) Lunar Planetary Science XIV

1



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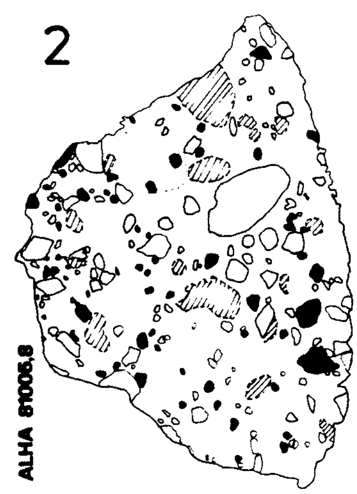

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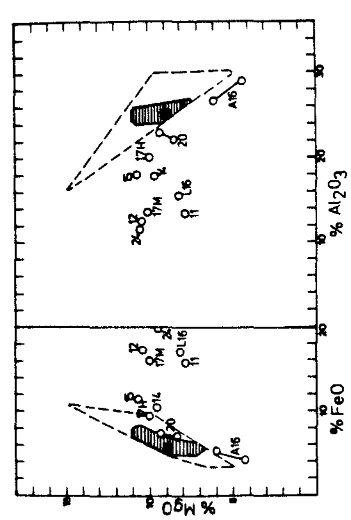

Fig. 1: Ab v. Mg'= (Mg/Mg+Fe) for lithic clasts in ALHA 81005. G = granulites, A = anorthosites, C = "cumulate"-textured clasts. The two granulites off the diagram had no plagioclase analyzed. Fields of front-side ferroan anorthosites and Mg-suite for comparison. Note gap of Mg'values 65 and 75. Fig. 2: Map of thin section ALHA 81005,8. Open = granulites, black = anorthosites and plagioclases, striped = varied impact melts. width 2 cm. Fig. 3: Fusion crust analysis for ALHA 81005 compared with other lunar soils. Black dot = fusion crust, striped = most other clear glasses in ALHA 81005, open = total range of glass in 81005. For its Al and Fe, ALHA 81005 glass is more magnesian than other samples, reflecting its high olivine /pyroxene ratio.

ANTARCTIC METEORITE ALHA 81005, A PIECE OF THE ANCIENT LUNAR HIGHLAND CRUST.

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"Der Mond ist ein unartiger Nachbar, weil er mit Steinen nach uns wirft." (The Moon is a naughty neighbor because he throws stones at us).
Georg Christoph Lichtenberg 1797

In 1660, an Italian physicist, P. M. Terzago maintained that meteorites are of lunar origin (1). Since then the idea has been repeatedly taken up by scientists, until lunar samples were found to be different from all known types of meteorites. However, it now appears that the old hypothesis was justified, at least with respect to the dynamical problem of transferring material from the Moon to the Earth. The results of our chemical analysis (instrumental neutron activation techniques, Table 1) of Antarctic meteorite ALHA 81005 undoubtedly show that it is a lunar highland breccia, confirming the original suspicion by Mason (2).

1.) Contents of Mn and Fe are in the range of lunar highland rocks (Fig. 1), Fe/Sc, Mg/Cr and Sc/V ratios are identical to the ratios in highland rocks. The latter three ratios are characteristic for highland rocks with a meteoritic component. "Pristine" rocks have different ratios.
2.) The chemical composition of ALHA 81005 fits into the multi-element lunar highland mixing diagram of Wänke et al. (3) (Fig. 2).
3.) The major element composition of ALHA 81005 is very similar to that of a group of lunar highland rocks, called feldspathic granulitic impactites (FGI) by Warner et al. (4). The composition of these FGI-rocks (e.g. 78155) and chemically related materials with about 25% Al_2O_3 (e. g. anorthositic gabbros (5)) comes very close to the proposed composition of the average lunar highlands (Table 2, (6)).
4.) Like FGI-rocks, ALHA 81005 has no KREEP-type pattern of incompatible elements. It has e. g. a flat heavy REE pattern (Fig. 3). Incompatible elements are in general less fractionated than those in KREEP (Table 4). The absolute content of incompatible elements is lower than in FGI-rocks.
5.) ALHA 81005 has, similar to FGI-rocks, a significant meteoritic component with an essentially chondritic pattern of siderophiles (1.5% C1-equivalent) (Fig. 4, Table 3).
6.) The abundances of "plagioclase trace elements" Sr, Eu, Na, Ga are similar to those of the most primitive cataclastic anorthosites, early crystallisation products of the lunar magma ocean. The composition of the mafic component of ALHA 81005 (assuming it is representative for a major crustal unit) may also be relatively primitive. Its mg-number (0.73) is similar to that for Ringwood's parental lunar crust magma (0.70), which represents the composition of the magma ocean, when plagioclase saturation is reached (6).

Conclusions: ALHA 81005 has the average lunar highland composition, far away from the KREEP--rich (high U) areas of the front sider around the great basins. The K and Th content of ALHA - 81005 is even below the estimates for the farside, deduced from the γ-ray experiments (7). This could indicate that a significant fraction of the farside may be lower in K and other incompatible elements than previously thought. Because of the absence of KREEP, ALHA 81005 was formed from a KREEP-free soil. Since the soils at the Apollo landing sites are inevitably contaminated with KREEP, ALHA 81005 may originate from the far side of the Moon, far away from the great basins, or it may have formed before the ejection of KREEP, 3.8 to 4 by ago, or more likely both, since soil breccias on the front side do not appear to have survived the great bombardment of the great basin forming bodies.

Highland rocks on the front side have in most cases ages between 3.85 - 4 by. Only some KREEP-free highland rocks have higher ages. The FGI-rock 78155 has a crystallization age of 4.22 ± 0.04 by (8). Other granulitic impactite clasts are also older than 4 by. This may indicate an age of more than 4 by for ALHA 81005.

Highland rocks formed around 3.9-4 by have almost without exception lower than chondritic Ir/Au ratios. Older rocks or clasts in rocks have higher Ir/Au ratios (9). Since ALHA 81005 has a chondritic Ir/Au ratio, it may be older than 4 by.This is an independent piece of evidence pointing to a high age for ALHA 81005.

Because of the brecciated nature of ALHA 81005 the age estimates are valid for its essential ingredients such as for example granulitic and anorthositic clasts. The compaction age could be much younger.

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Sources of data for Figs.: Figs. 1 and 2: all data this laboratory; Fig. 3: modified from Palme, H. et al. (1978) PLSC 9th. Fig. 4: data for 77017 from Laul, J.C. et al. (1974) PLSC 5th, 1047, other data this laboratory; Fig. 5: all data this laboratory. 67035 is a 9.12 g cataclastic anorthosite from North-Ray rake samples. Data unpublished.

Table 1: Major, minor, and trace elements in ALHA 81005 (128 mg).

	%	est.prec. in %		ppm	est.prec in %
Mg	4.78	5	Zr	30	15
Al	13.40	3	Sb	< 0.05	
Si	21.72	3	Cs	< 0.05	
Ca	10.80	3	Ba	34	15
Ti	0.14	10	La	2.44	3
Fe	4.20	3	Ce	6.9	5
			Nd	3.9	10
	ppm		Sm	1.18	3
			Eu	0.704	3
Na	2250	3	Gd	1.4	20
P	90	30	Tb	0.27	5
K	230	5	Dy	1.7	10
Sc	9.24	3	Ho	0.37	15
V	26	8	Tm	0.18	20
Cr	862	3	Yb	1.06	5
Mn	587	3	Lu	0.15	3
Co	20.2	3	Hf	0.92	3
Ni	186	5	Ta	0.12	8
Zn	18	20	W	< 0.13	
Ga	2.8	5	Ir	0.0073	10
Se	< 0.6		Au	0.0021	7
Rb	< 1.5		Th	0.35	8
Sr	128	10	U	0.103	15

Table 2:

	ALHA 81005	78155* (granulite)	highland** crustal compos.
SiO_2	46.46	45.33	45
TiO_2	0.23	0.28	0.56
Al_2O_3	25.32	25.34	24.6
FeO	5.40	5.63	6.6
MgO	7.92	6.42	6.8
CaO	15.11	15.18	15.8
Na_2O	0.31	0.39	0.45
K_2O	0.029	0.073	0.075
Cr_2O_3	0.12	0.14	0.10
total	100.9	98.8	100
mg'	0.73	0.68	0.66
ppm			
Ba	34	64	66
Sr	128	141	120
Yb	1.06	1.83	1.4
U	0.10	0.24	0.24
Sc	9.24	13.3	10
V	26	39	24
Ni	186	80	100
Co	20.2	14.3	15

* (10); ** (11)

Fig. 4

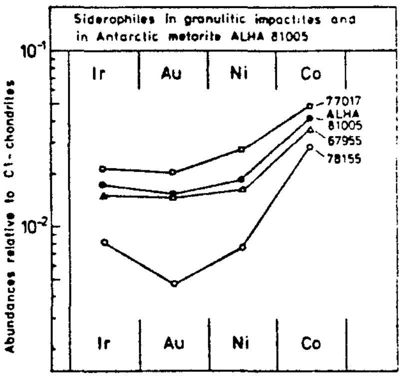


Fig. 5

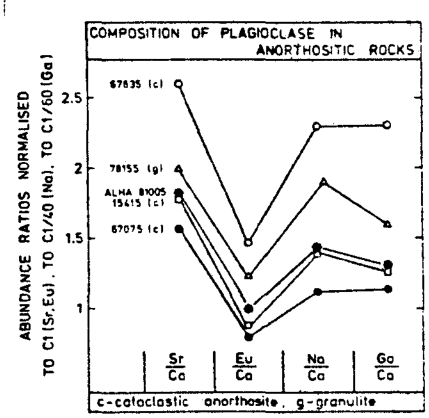


Table 3:
Ratios of meteoritic elements in ALHA 81005, assuming an indigeneous Co content of 10.5 ppm.

	C1	ALHA 81005
Ni/Co	21.5	19.2
Ni/Ir	22700	25500
Ir/Au	3.35	3.48

Table 4:
Ratios of incompatible refractory elements in ALHA 81005 and in KREEP.

	cosmic ratios (C1-chondrites)	ALHA 81005	KREEP
La/Sm	1.7	2.07	2.2
Sm/Yb	0.93	1.11	1.3
U/Ta	0.58	0.86	1.2
Zr/Hf	31.8	32	44

Fig. 1

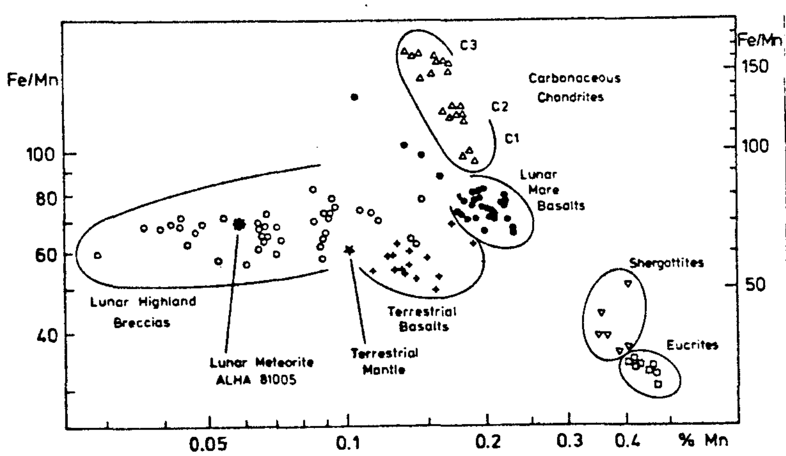
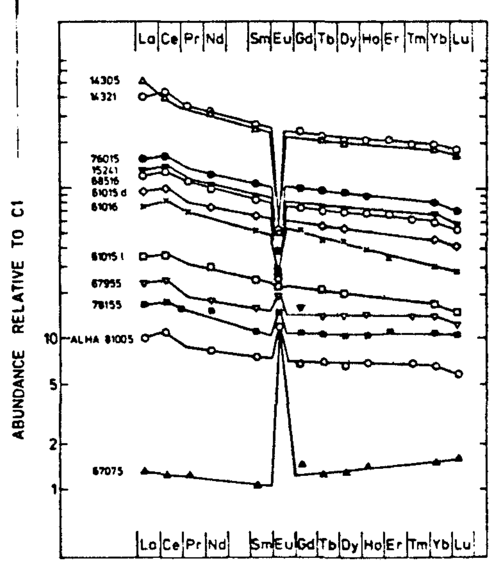


Fig. 3



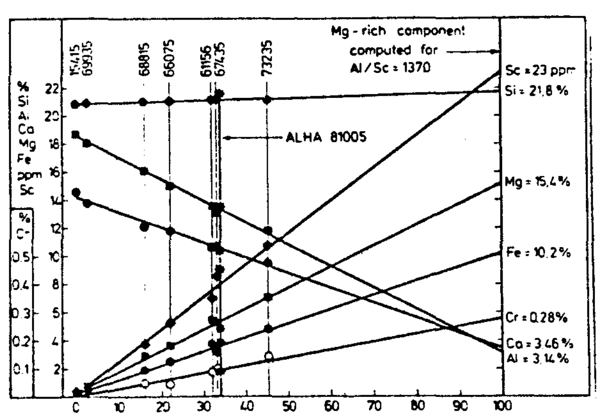


Fig. 2

IF ALHA81005 CAME FROM THE MOON, CAN WE TELL FROM WHERE? C.M. Pieters, Dept. of Geological Sci., Brown University, Providence, RI 02912

Careful documentation of lunar sample locations has been essential for understanding the geologic context of such valuable materials. Samples have been returned from nine locations on the lunar nearside, and each mission has brought new unsuspected surprises. Lunar scientists now seem to have acquired a sample from a 10th location, but without the desired supporting documentation.

Identification of possible source regions on the moon for meteorite ALHA-81005 is difficult, but not impossible if enough clues can be obtained. Presented here are preliminary results of laboratory and telescopic spectral reflectance measurements that are used to identify compositional information to link the mineral assemblages observed in the meteorite with those for unsampled areas on the nearside lunar surface. When combined with other data and the photogeologic evidence, this information could narrow the number of possible source regions considerably. If ALHA81005 is representative of a regional rock type, these first results suggest the source region for the meteorite is not a common surface unit for the lunar nearside and as such has not previously been extensively sampled by U.S. and Soviet missions. However, the general spectral character of ALHA81005 indicates a bulk mineralogy comparable to some specific lunar samples.

Results for Telescopic Reflectance measurements of the lunar nearside. Near-infrared (.7-2.5μm) spectral reflectance measurements have been obtained for about 150 small lunar areas (3-20 km in diameter) using earthbased telescopes. Compositional implications of data for highland craters are presented in Pieters (1) and are only summarized here. Most highland spectra indicate regional rock types with a mineral assemblage of feldspathic material containing orthopyroxene as the dominent mafic component. A few small fresh craters reveal rock types with a greater abundance of more calcium-rich pyroxenes as well. The large, usually older, craters with central peaks have apparently exposed a somewhat different suite of rock types with both more mafic components (olivine and calcium-rich clinopyroxenes) and more complete anorthositic rock types being observed.

Laboratory reflectance measurements of ALHA81005. A potted butt sample ALHA81005,2 was made available for laboratory spectral reflectance measurements prior to preparation of additional thin sections from the sample. Seventeen measurements were obtained using the Reflectance Experiment Laboratory (RELAB) over a period of two days: two visible spectra (.4 to .9μm) 13 near-infrared (.7-.1.8μm), and 2 continued near-infrared (1.7-2.7μm). Data for 12/21/82 were obtained for a smooth flat surface with i=0°, e=30°. The sample was roughened slightly with a coarse grit for the measurements made on 12/22/82. A monochromatic incident beam covered a sample area of about 10mm in length; the detector viewed a sample area of about 2mm in diameter within this beam, the precise location of which was undetermined. The near-infrared data were averaged to obtain a spectrum of the bulk properties of the sample. As is commonly observed for rock or slab spectra the near-infrared continuum was generally flat or negatively sloped. In order to allow direct comparison of absorption features with lunar telescopic data the spectra were divided by an estimated continuum and the residual absorptions examined.

An average for the 13 near-infrared measurements obtained on both days is shown in Figure 1. This spectrum would be comparable to a whole rock spectrum and is the current best estimate of the overall spectral character for this sample of ALHA81005. Since the sample was moved slightly between individual measurements, the location of each measurement and the resulting spectra varied. The top two spectra in Figure 2 are averages for the near-infrared data for all the first (a) and second (b) day's measurements respectively. The bottom two spectra (2c,d) are distinctive single measurements.

Data Interpretation for ALHA81005. Specific mineral components can be identified in the spectra of this meteorite. The band minimum between .9 and 1.0µm in all the average spectra (Figures 1,2a and b) as well as a second absorption observed near 2µm implies a pyroxene component. The broad multiple band with a center near 1.05µm in individual spectrum 2d is characteristic of olivine. The spectrum average for the second day (2b) contains these olivine measurements; its spectral character (broad band widening towards longer wavelenghts) is typical of olivine and pyroxene mixtures (2). The superimposed feature near 1.3µm seen in spectrum 2a is commonly interpreted as Fe-bearing feldspar (3), although a feature this strong usually requires a fairly Fe-rich (>.1%) plagioclase. Further laboratory measurements are required to determine relative contributions to the 1.3µm feature from Fe-bearing feldspar and from olivine in the whole rock spectrum average of Figure 1.

Discussion. Comparisons of the spectral characteristics of ALHA81005 were made with laboratory measurements of lunar highland samples of Adams (4, 5) and telescope measurements of highland areas of Pieters (1). Some returned lunar anorthositic troctolites and gabbros exhibit the same characteristics as ALHA81005: a broad absorption band centered between .95 and 1.0µm with a strong 1.3µm feature or inflection. The average of ALHA81005 data however, is unlike any specific lunar area measured telescopically although it does resemble a minor group of nearside craters that exhibit more majic mineral assemblages than most of the highlands. (The band center for most observed highland areas is at a much shorter wavelength, implying low-Ca orthopyroxenes as the major mafic component.) Of all the nearside lunar large craters with central peaks measured telescopically, only Tycho and Aristarchus would merit further study as possible source regions; both exhibit an absorption between .96 and 1.0µm and a strong 1.3µm feature or inflection.

Acknowledgement. NASA support (NAGW-28) for this research is gratefully acknowledged.

References. 1) Pieters C.M. (1983) LPS XIV 2) Singer R.(1982) JGR 86, 7967, 3) Adams, J.B. and Goulland (1978) PLPSC 9th, 2901, 4) Adams and Charette (1975) Moon 14, 483, 5) Charette and Adams (1978) LPS IX, 172.

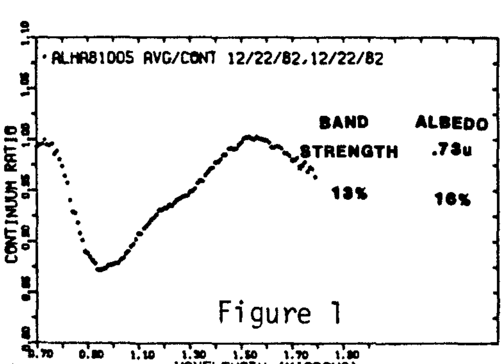


Figure 1

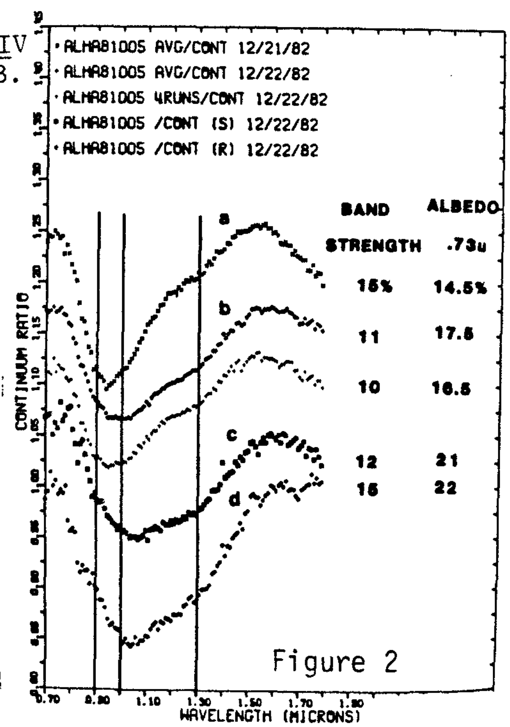


Figure 2

ALHA 81005: PETROGRAPHIC COMPONENTS OF THE TARGET.

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Introduction: Our petrographic and microprobe study of ALHA 81005 had the intention of determining the provenance of the component material e.g. plutonic or extrusive, and to compare them with other, known lunar rock types. Unfortunately we had less than one month to carry out the work, thus it is incomplete and some intersting observations and analysis could not be followed up and checked. We concentrated on single mineral analysis for mafic mineral fragments (major and minor elements), and in lithic clasts (granulites, anorthosites, and others, but not including crystalline impact melts), and on analysis of glasses - beads,blebs, and shards, nearly all clear and colorless, but also some brown matrix glass. Routine, 10-element analysis were the rule, but for Ca and Ni in olivines, and N, K, P, and Ti in some glasses, more precise analysis were made using manually-determined peaks and backgrounds and 100-second counts. Some of the latter analysis were performed at the Naturhistorisches Museum in Vienna.

Mafic mineral grains were studied optically and with the microprobe. Of those analyzed (about 50 larger than 100 µ. about 60 % were olivines.

Pyroxene fragments: Under the microscope pyroxenes are a diverse group, ranging from colorless to brown; from clear to inclusion-rich; and from unexsolved to finely-exsolved (less than 1 u. to 5 µ.) to less common, coarsely-exsolved varieties. Major element analyses (Fig. 1) show a corrésponding diversity. Attemps were made to resolve lamellae, but inadequate time produced inadequate results. Almost invariably the browner pyroxenes, and nearly all those which contain inclusions (Ti-oxide, sulfides) are Fe-rich. Some are more Fe-rich than known lunar ferroan anorthosites, and some are too Ti, Cr, and/or Al-rich to be from such samples. Several have compositions similar to pyroxenes from very-low Ti and low Ti mare basalts - these are Ca-rich and either unexsolved or finely-exsolved. The pigeonite at $En_{68}Wo_8$ is unexsolved, and has minor elements consistent with a low-Ti mare basalt source. Other pyroxenes are similar to those in ferroan anorthosites, with low Ti, Cr and Al abundances and either no or coarse (>10 µ) exsolution. Mg-rich pyroxenes (Mg' ~80) are colorless, and either unexsolved or coarsely exsolved, and similar to lunar front-side plutonic norites. They are much coarser than pyroxenes in the granulites in the sample. Several grains, both Mg and Fe-rich, are dominantly high-Ca pyroxenes; all show some exsolution. Pyroxenes appear to come from three major sources: Mg-rich plutonic norites. ferroan anorthosites, and extrusive or shallow-intrusive Fe-rich rocks, probably mare basalts.

Olivine fragments: Olivines are generally inclusion-free, and colorless to pale green. They are dominantly Mg-rich (Mg'>77), and although they cluster strongly around the compositions of olivines in the granulites (Fig. 1), many of them are coarser (>200 u.) than olivines in the granulites (rarely 100 u.), suggesting a different source. A few are iron-rich. Routine analysis showed no olivines with CaO above our detectability limit of ~0.15%, and more precise analysis (detectability better than 0.01 %) for 9 grains confirms the very low CaO (Fig. 2) far below the 0.2 to 0.5 % for olivines in mare basalts and highland impact melts. Most are similar to known plutonic rock samples. Ni in the 9 olivines ranged from 100 (±30) ppm in the Fo_{94} grain to less than the usual detectability limit of ~50 ppm. These Ni abundances are typical of lunar pristine rocks, and are lower than phenocryst olivines in low-Ti mare basalts.

Lithic fragments. We analyzed mafic minerals and plagioclases in clasts which were dominantly plagioclase (cataclastic anorthosites), in feldspathic granulite impactites similar to front-side granulites, and in 3 small " cumulate"-looking samples, as well as some other minor types (Fig. 3 and Fig. 1 of accompanying abstract). The anorthosites are all ferroan, and have pyroxenes with low minor element contents; a few contain iron-rich olivine. In general the compositions are clearly distinct from the granulites, but some granulites are also ferroan. The granulites are all olivine-rich, and are almost exclusively granulite rather than poikiloblastic. One of the "cumulates" is magnesian (Mg'84), similar to granulites except that it is coarser-grained (px >200 µ., rather than a few tens of microns), and lacks olivine. The other two "cumulates" are ferroan; both have pyroxenes and plagioclase 500 µ. across, and one is poikilitic with exsolved pyroxene. All plagioclases are calcic (Ab<5).
One lithic fragment consists of angular, coarse, very calcic plagioclase fragments embedded in a mafic glass (M in Table) whose dominant component appears to be a mafic troctolite. Several small clasts contain the assemblage Fo_{80} - En_{80} - An_{97}, unknown among lunar frontside plutonic rocks. Although this assemblage is similar to granulites, their grain size is coarser, and they may represent a plutonic igneous rock suite. One fragment consisting mainly of pyroxene may be a mare basalt (dots in Fig. 3) The pyroxene, mainly one grain is about 500 µ. across, and is not, under the microscope, visibly exsolved. Within the clast are two blebs of silica (~ 50 µ.) and minor plagioclase and troilite. The pyroxene is iron-rich and is analyses form two clusters, one high-Ca and one low-Ca, but these are not separate grains. Instead they represent either zoning or a tendency toward exsolution. Ti, Cr, and Al are inconclusive as to provenance, but are compatible with a slowly-cooled, very low-Ti mare basalt.

Glasses: Ou glass analyses were concentrated on clear, near-colorless impact glass, the fusion crust, some brown matrix glass, and the glassy matrix of a plagioclase-rich breccia. A range of analyses is shown in the Table, and all glass averages are plotted on Fig. 4 and Fig. 5. We believe that the fusion crust provides the best estimate of the bulk rock composition, and analyzed 6 points in the vesicular, clear-glass portion at the edge, far removed from interferences from partly digested clasts. This analysis (F in Table 1) is close to being an average of all the other clear glasses, except for the extreme compositions (Fig. 4). One of the beads is nearly identical in composition to the fusion crust except for even lower Na (B3). Three analyses of brown matrix glass are more dispersed. Phosphorous is extremely low, consistent with a lack of KREEP. Some of the more extreme glasses show some evidence of a mare component in their elevated Ti/K and Ti/P ratios: among known lunar rock types mare basalts have Ti/K of 30-50, all others less than 6; mare basalts have Ti/P 60, all others less than 20, mainly less than 10. The high Ti-glass (22) may have Ti contributed dominantly by a mare component, and certainly not from a KREEP component, the other known major source of Ti in lunar samples.

RYDER G. and OSTERTAG R.

Components of ALHA 81005: The fusion crust and main cluster of glass compositions are less aluminous than A 16 soils and have a higher Mg/Fe ratio, and lower TiO_2 and Na_2O (both<·3 %) than any other lunar soils, consistent with the dominance of troctolitic and granulitic components and the absence of KREEP. The "troctolitic" component is not well defined, except that, according to glass norms and the mafic mineral fragments in the rock, it is plutonic, magnesian, low in Ni, has a high al/px ratio, and, if it contains plagioclase, the plagioclase is very calcic. It could be similar to lunar front-side, Mg-suite troctolitic and/or similar to the olivine-rich component in L 20 soils. Several lines of evidence suggest the presence of a small mare basalt component.

TABLE: Glass analyses for ALHA 81005

	F	B3	B1	B7	✦5	✦22	M
SiO_2	45	45	37	41	46	46	45
TiO_2	0.27	0.271	0.240	0.259	0.223	1.62	0.567
Al_2O_3	25.1	25.1	30.4	23.9	20.3	21.2	16.7
Cr_2O_3	-	0.17	0.10	0.22	0.28	0.21	0.20
FeO	5.6	5.6	4.9	9.5	9.2	7.8	10.7
MgO	8.9	8.5	9.2	10.6	14.0	9.9	15.1
CaO	14.6	14.5	17.4	13.6	11.4	12.7	10.3
Na_2O	0.24	0.116	0.069	0.06	0.237	0.151	0.248
K_2O	-	0.047	<0.02	0.05	0.045	0.104	0.07
P_2O_5	-	<0.019	<0.012	-	0.032	0.058	-
Ni	-	170 ppm	-	84 ppm	-	-	-
Mg'	73.9	72.9	76.9	66.5	73.1	69.3	71.6
Ti/K	-	4.1	>10	>15	3.6	11.2	~5.8
Ti/P	-	>20	>24	-	9.6	40	-

Key: F = Fusion crust, B = beads, ✦ = blebs, M = matrix of glass breccia.

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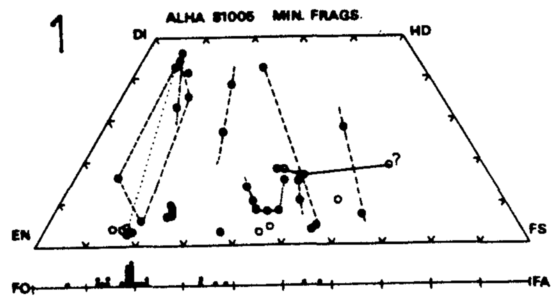

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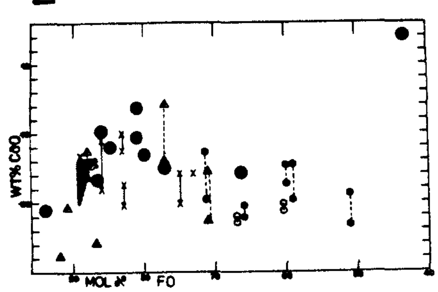

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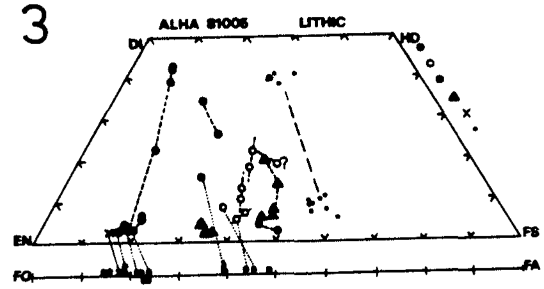

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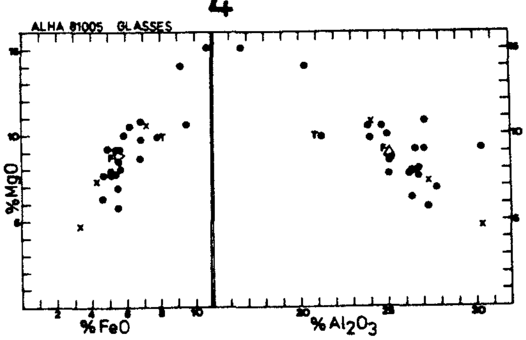

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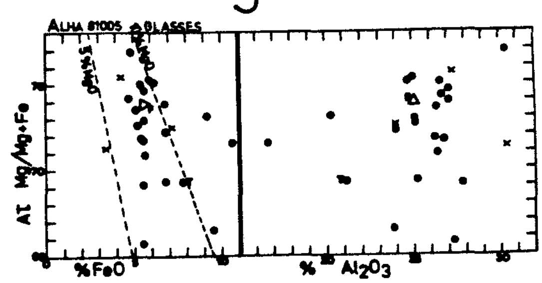

Fig. 1: Pyroxene and olivine compositions for single mineral fragments. Open circles, unexsolved, closed circles, exsolved. Dashed lines connect analyses on exsolved grains, solid lines connect analyses on unexsolved grains. Olivine analyses, each dot is the average for a single grain. Fig. 2: CaO in olivines, black dots = ALHA 81005, triangles = lunar Mg-suite, hexagons = anorthosites, x granulites. Dotted symbols = Chicago data, open symbols = our own unpublished work. Hatched area = our own numerous analyses of dunite 72415. For our own analyses, precision is better than ± 0.01 %. Fig. 3: Pyroxenes and olivines in lithic clasts. Figs. 4, 5: Glass compositions. Black dots = clear glass, x = brown glass, triangle = fusion crust, T = Ti-rich glass, open circle with dots = glass matrix of breccia.

PETROLOGY AND MINERAL CHEMISTRY OF ALHA 81005; S.B. Simon, J.J. Papike and C.K. Shearer, Institute for the Study of Mineral Deposits, South Dakota School of Mines and Technology, Rapid City, SD 57701

This unique meteorite, which was originally classified as an anorthositic breccia (1) is better described as a regolith breccia with abundant feldspathic lithic clasts. The breccia has been strongly shocked, which has resulted in the melting of the matrix, destroying most of the debris commonly found in a regolith breccia, and erasing the primary textures of most of the lithic clasts.

We have used our lunar classification system in the determination of the modal petrology (Table 1) of this sample. Norites, troctolites, and gabbros are the most abundant lithic types. Some are shocked and recrystallized whereas others are not. Lithic clasts present in lesser amounts are anorthositic fragments, feldspathic fragmental breccias, RNB/POIK's, and several small fragments that have possible basaltic textures. The largest clast that appears to have retained its original igneous texture is a 0.5 mm spinel troctolite fragment which contains calcic (An_{97}) plagioclase laths, olivine (Fo_{77-80}), and spinel (with 10 wt.% FeO and 5 wt.% Cr_2O_3). Plagioclase dominates the mineral fragment population in the matrix.

In Figure 1, the compositions of plagioclase grains found in the matrix are compared to those from lithic clasts. The ranges and relative abundances are nearly identical, indicating that the matrix grains were derived from lithologies very similar to those that are found in the breccia. This is not the case for polymict eucrites, for which it has been shown (2,3,4) that the matrix mineral population could not be completely derived from the lithic clasts. Pyroxenes (Fig. 2) and olivines (Fig. 3) exhibit wider compositional ranges than feldspar. Most of the pyroxenes are more Mg-rich than eucritic pyroxenes, in agreement with the preliminary analysis (1). Pyroxene compositions further support a lunar highland origin for this breccia. Figure 4 is a plot of Ti vs. Al in pyroxenes, and the distribution approximates that for highland pyroxene while exhibiting large differences from mare and meteoritic pyroxene (5). Figure 5 is a plot of wt.% MnO vs. wt.% FeO in pyroxenes from ALHA 81005 and from Pasamonte. The ALHA 81005 pyroxenes clearly define a trend which is non-eucritic and falls within the range for lunar rocks.

TABLE 1. MODAL PETROLOGY OF ALHA 81005

	SMALL CLASTS (20-200 μm)	LARGE CLASTS (200-2000 μm)
LITHIC FRAGMENTS		
Basalt	1.3	1.7
ANT	1.8	12.9
Brecciated ANT	2.2	6.9
Feldspathic Frag. Breccia	0.2	1.3
RNB/POIK	0.4	1.2
FUSED SOIL COMPONENT		
Dark Matrix Breccia	1.0	0.5
Agglutinate	3.2	2.0
MINERAL FRAGMENTS		
Mafic	2.2	0
Plagioclase	6.7	1.9
Maskelynite	0	0.9
Opaque	0.1	0
GLASS FRAGMENTS		
Orange/black	0	0
Yellow/green	0.2	0
Colorless	0.6	0
Brown	0.2	0
MISCELLANEOUS		
Devitrified glass	2.8	3.0
Others	0.1	0
TOTAL	23.0	32.3
MATRIX (<20 μm)	44.7	

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In conclusion, the petrographic, modal and mineral chemical data strongly indicate that this meteorite is a breccia from the lunar highlands.

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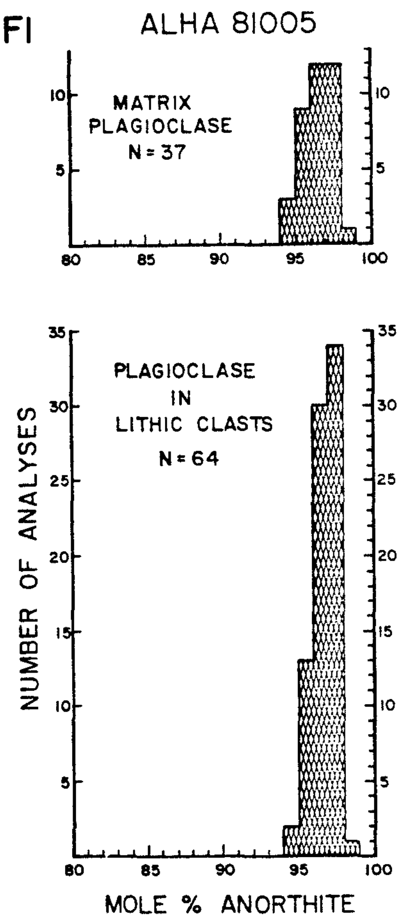
F1



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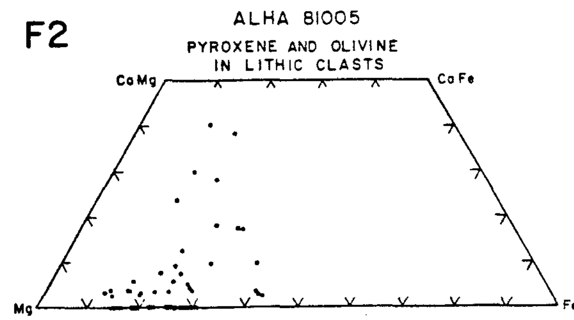

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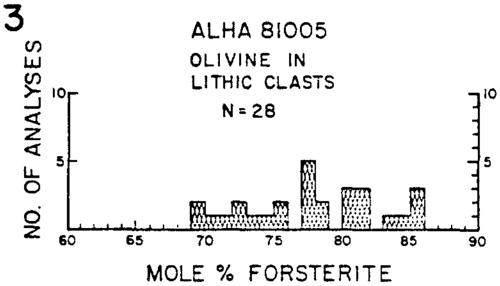

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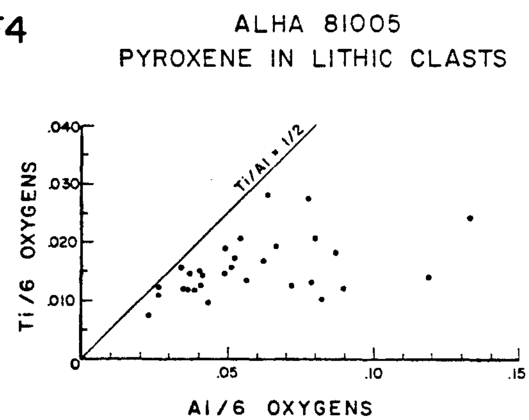

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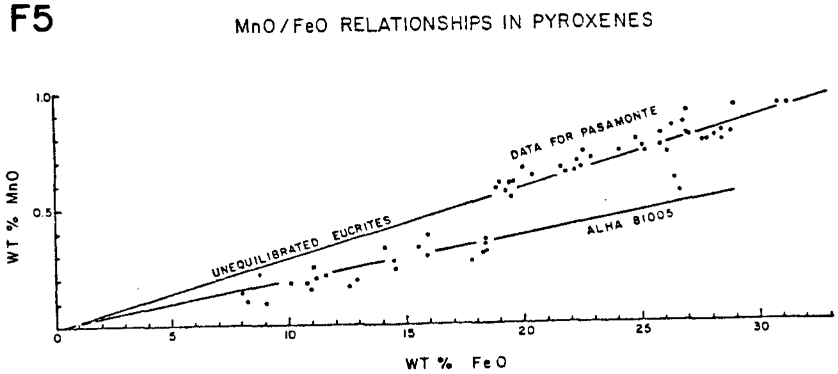

THERMOLUMINESCENCE AND TRACKS IN ALHA-81005: CONSTRAINTS ON THE HISTORY OF THIS UNUSUAL METEORITE S. R. Sutton and G. Crozaz, Earth and Planetary Sciences Department and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130.

Thermoluminescence measurements and a search for nuclear particle tracks were made in 3 fragments of ALHA-81005.

THERMOLUMINESCENCE: Equivalent dose (E.D.) curves determined for 1 mg aliquots of the three fragments are shown in figure 1a along with those of two Antarctic chondrites, ALHA-77003 and ALHA-77272. The ALHA-81005 chips plot well below the chondrites (factor of 10 lower at high glow curve temperatures and up to a factor of 100 lower at low glow curve temperatures). The small, high-temperature E.D. is best explained as the object's "pre-earth" equilibrium dose which is lower than that of chondrites because ALHA-81005 exhibits substantial anomalous fading. (In one week storage at room temperature, ALHA-81005 artificial TL decays by 25% compared to $\leq$ 5% for chondrites.) Comparing ALHA-77003 (short terrestrial age of 0.04 Ma) with ALHA-77272 (long terrestrial age of 0.54 Ma) (1) demonstrates that, at Antarctic storage temperatures, less than a factor of two thermal decay occurs for glow curve temperatures $\geq$275°C. ALHA-81005's TL is actually more thermally stable than these chondrites (Artificial TL decayed by a factor of 6 for chondrites stored for 40 minutes at 180°C while ALHA-81005 TL decayed by only a factor of 3.) Consequently, ALHA-81005's E.D. at 275°C would be expected to be about the same as its high-temperature E.D. of ~10^4 rads. The fact that its E.D. is a factor of about 5 lower indicates the object has been heated above the Antarctic storage temperature (about 0°C). This interpretation is supported to some extent by the observation that a 15 krad artificial glow curve measured after pre-heating to 290°C closely reproduces the natural glow curve in both shape and intensity (figure 2).

The object could have been heated during atmospheric entry, in a near-sun orbit or during a parent-body impact event. Atmospheric entry heating would seem to be ruled out because the high temperature required to explain the TL data (~300°C) occurs only within several mm of the fusion crust (2) and our three chips are random samples of a ~1.5 cm diameter fragment with fusion crust removed. A near-sun orbit is possible and a few meteorites show evidence of solar heating (figure 1b). However, such orbits are rare and probably occur for only a few percent of meteorites (2). Impact heating is the more likely interpretation. In this case, the low E.D. value at 275°C constrains the object's space exposure to be less than a few thousand years. Such a brief earth transit time lends support to the notion of a lunar origin for ALHA-81005.

TRACKS: Feldspar grains from all fragments were mounted, polished and etched in boiling 6.25N NaOH. In this solution, feldspar etching times vary from 30-60 minutes (revelation of solar flare tracks with densities in excess of 10^8 t·cm^{-2} in lunar samples) to 6 hours (full revelation of galactic cosmic ray tracks in the Estherville mesosiderite). Most feldspar grains from ALHA-81005 were so highly shocked that they fractured rapidly when etched. However, we succeeded in finding grains which resisted a 6 hr. etch. Despite the fact that these samples contain large amounts of solar gases (Bogard, private

THERMOLUMINESCENCE AND TRACKS IN ALHA-81005

Sutton, S. R., and Crozaz, G.

communication), no nuclear particle track was observed. Whether depth or temperature history is responsible for the lack of solar flare tracks is unclear. However, it should be noted that if the thermoluminescence was mainly acquired on the parent body (our preferred interpretation), the temperature reached by the material during the impact event (~300°C) would be insufficient to erase the tracks. The absence of galactic tracks is compatible with a short transit time between parent body and the earth but could also be explained, because of the rapid decrease of the cosmic ray track production rate with depth, by the shielding of ALHA-81005 in space, or on the parent body, by only ~10 cms of material.

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Fig.1a
E.D. Curves for Antarctic Meteorites

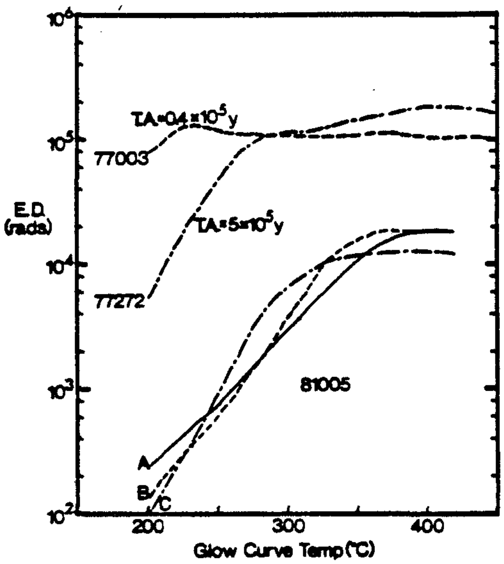


Fig.1b
E.D. Curve Comparison with Two Meteorites Showing Evidence of Solar Heating-77001 & Malakal

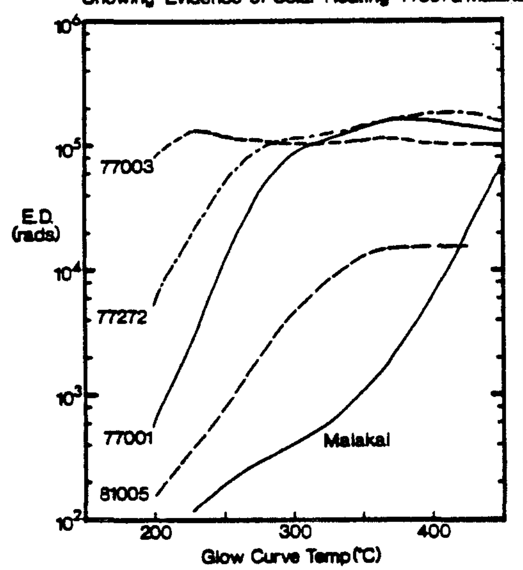
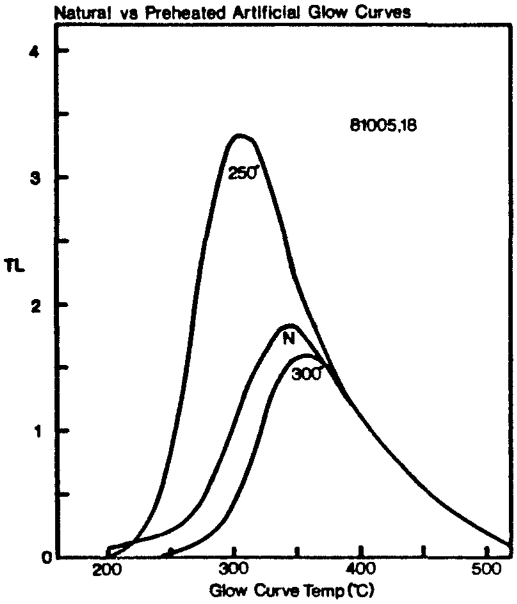


Fig.2
Natural vs Preheated Artificial Glow Curves



METEORITE FROM THE MOON: PETROLOGY OF TERRAE CLASTS AND ONE MARE CLAST IN ALHA 81005,9. Allan H. Treiman and Michael J. Drake. Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

INTRODUCTION

ALHA 81005 was first noted to be an unusual meteorite during preliminary examination by R. Score (1). Subsequently Mason examined a polished thin section. He noted that the microbreccia contains clasts which are more feldspathic than those in most eucrites and that they resemble anorthositic clasts from lunar terrae rocks (1). Petrographic and electron microprobe analyses confirm that ALHA 81005,9 originated in the lunar terrae and is the first recognized lunar sample transmitted to Earth by natural processes. A clast of VLT mare basalt in the breccia may restrict the possible source of the meteorite on the lunar surface.

GENERAL DESCRIPTION

ALHA 81005,9 is a microbreccia of lithic and vitric clasts set in a fine-grained matrix with pervasive glass. Lithic clasts include anorthosite, troctolite, spinel troctolite, and norite fragments. A majority of clasts retains igneous textures, but few clasts have not been modified thermally and/or mechanically. The remaining lithic fragments have textures varying from cataclastic to granulitic to variolitic with relict plagioclase. The presence of unmodified vitric clasts and matrix glass suggests that most thermal recrystallization preceded formation of the breccia. Deformational features which post date consolidation of the breccia are not observed.

CONFIRMATION OF LUNAR TERRAE ORIGIN

Pyroxene compositions, particularly molar Mn and Cr contents versus molar Fe/(Fe+Mg) ratios provide sensitive petrochemical criteria for distinguishing between rocks from different planetary bodies. The Mn content of pyroxenes from ALHA 81005,9 (except clast G) all fall within the lunar terrae field (Fig. 1) and indicate that the meteorite is not related to the basaltic achondrites (2). Similarly the Cr contents of the pyroxenes (except clast G) are inconsistent with a terrestrial or eucritic origin, but are consistent with a lunar terrae source (2). Thus, pyroxene chemistry confirms the petrographic observation that ALHA 81005,9 is from the lunar terrae.

TERRAE CLAST PETROLOGY

Compositions of plagioclase and mafic minerals from the anorthositic clasts plot in the field of pristine ferroan anorthosite (3). In other igneous clasts (except clasts I, U and G) plagioclase is An 96-98, and the molar Mg/(Mg+Fe) ratios of the mafic phases range from 0.52 to 0.84. These compositions extend from the pristine anorthosite field to the pristine Mg-suite field, and imply that the basaltic rocks are impact melts of a source containing anorthositic and Mg-suite protoliths. Anorthositic clasts could represent one protolith; a suitable Mg-suite protolith is not present in ALHA 81005,9, and its composition must be inferred. Plagioclase in the Mg-suite protolith must have been An 96-98 because igneous clasts all contain plagioclase of that composition. The presence of abundant magnesian pyroxene in the basalts implies that the Mg-suite protolith was noritic, with low-Ca pyroxenes of Mg/(Mg+Fe)> 0.84. Known pristine norites do not contain such magnesian pyroxene and calcic plagioclase (3), and the Mg-suite protolith may represent an undiscovered lunar rock type.

Two unusual basaltic clasts, I and U, contain plagioclase more sodic than An 96. Clast I is a spinel troctolite with 60% plagioclase laths (An 94), interstitial olivine (Fo 80), and a single crystal of brown spinel ($Mg_{0.64}Fe_{0.37}Al_{1.69}Cr_{0.28}Ti_{0.01}O_4$). Clast U is a norite with plagioclase laths (An 91-An 96) and interstitial low- and high-Ca pyroxene and olivine. Minor phases include troilite, Fe-metal, ilmenite, rutile, and Zr-armalcolite. By mineralogy, clast U is a Mg-norite (4), but I and U are probably both impact melts.

CLAST G: MARE VLT BASALT

Clast G is a unique, small fragment of Fe-rich basalt, consisting of 75% plagioclase laths with interstitial high- and low-Ca pyroxene and a silica polymorph (cristobalite?). Mesostasis areas contain pyroxene, ulvospinel, pyroxferroite, silica, troilite and glass (up to 1.9 wt.% K_2O). Plagioclase composition is relatively constant at An 95, but pyroxene compositions vary widely (Fig. 2). The extreme Fe-enrichment of the clast G pyroxenes is consistent with a lunar mare source and rules out a terrae origin (Fig. 1). This conclusion is reinforced by the Cr content and Ti/(Ti+Cr) ratios (Fig. 3) of the pyroxenes. Note that Ti/(Ti+Cr) ratios of the pyroxenes at a given Fe/(Fe+Mg) ratio are very low and are similar to very low titanium (VLT) basalts of Apollo 17 and Luna 24 (5).

ORIGIN OF ALHA 81005

There is little doubt that ALHA 81005 originated in the lunar terrae. However, the VLT basalt lithology (clast G) is consistent with a source for this meteorite in a terra region adjacent (within 100 km?) to areas of VLT mare basalt. Luna 24 returned VLT basalt from Mare Crisium, and spectral reflectance study (6) indicates that VLT basalts (some unsampled) also occur in Mare Somniorum, Mare Frigoris, Sinus Roris, northern Mare Imbrium, and western Oceanus Procellarum. The source of ALHA 81005 is probably a young crater in the terrae adjacent to one of these regions if the meteorite is from the Earth-facing hemisphere of the Moon.

PETROLOGY OF TERRA CLASTS AND ONE MARE CLAST...

Treiman A. H. and Drake M. J.

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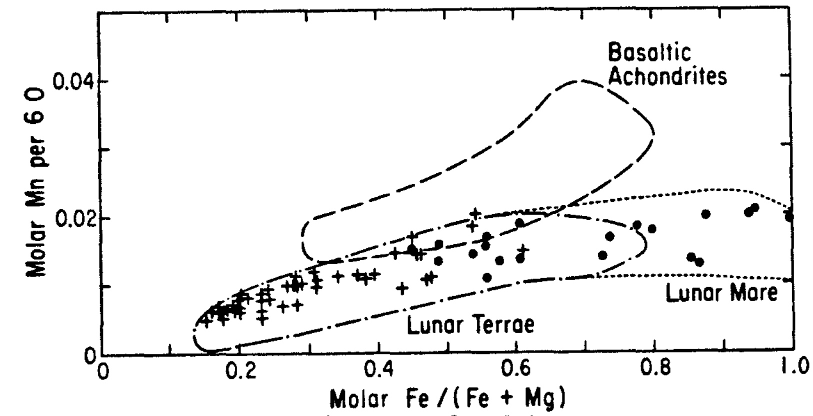

Fig. 1. Molar Mn content of pyroxenes from ALHA 81005,9. Clast G analyses shown as dots; all others as crosses. Fields of lunar terrae, lunar mare and basaltic achondrite compositions from (2).

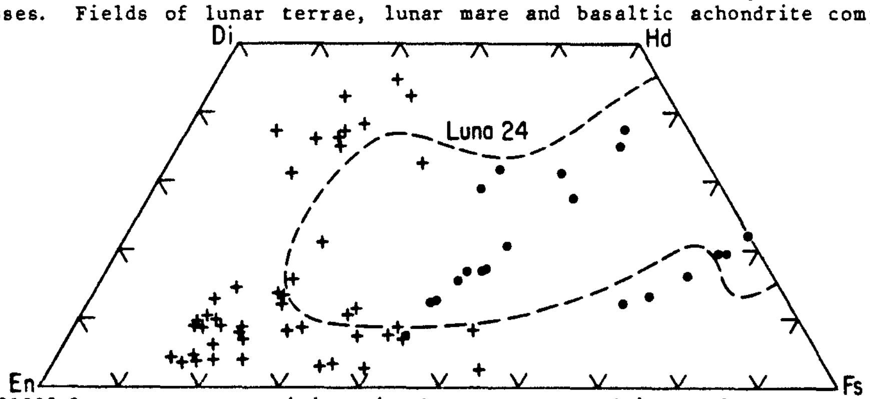

Fig. 2. ALHA 81005,9 pyroxene compositions in the pyroxene quadrilateral. Clast G analyses shown as dots. Field of Luna 24 very low titanium basalt pyroxenes from (5).

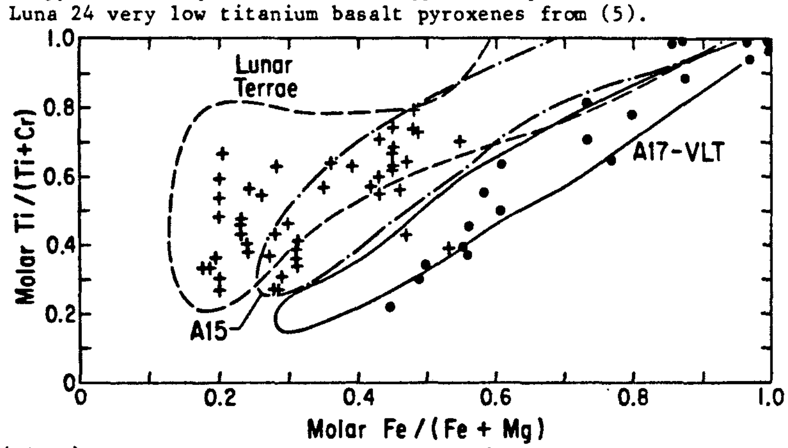

Fig. 3. Molar Ti/(Ti+Cr) content of pyroxenes from ALHA 81005,9. Clast G analyses shown as dots. Lunar terrae field from (2); Apollo 15 and Apollo 17 very low titanium basalt fields from (5).

RECENT COSMIC RAY EXPOSURE HISTORY OF ALHA 81005. C. Tuniz[1], D.K. Pal, R.K. Moniot[2], W. Savin[3], T. Kruse, G.F. Herzog, Depts. Physics and Chemistry, Rutgers Univ., New Brunswick, NJ 08903, and J.C. Evans, Geosciences Research and Engineering Dept., Battelle, Pacific Northwest Laboratories, Richland, WA 99352. ([1]Ist. Fisica, Univ. Studi, Trieste, Italy; [2]Dept. Phys., Fordham Univ., New York, NY 10023; [3]Dept. Phys., N.J. Inst. Tech., Newark, NJ 07100)

Score and Mason (1) note the similarities between certain lunar anorthositic breccias and the Antarctic achondrite, ALHA 81005. The recent history of this interesting object can be illuminated by a consideration of its cosmogenic radionuclide contents. We have measured the ^{10}Be content of a 25 mg sample to be 4.1±0.5 dpm/kg by using the tandem Van de Graaff of the Rutgers Nuclear Physics Laboratory as a high-energy mass spectrometer (2). Evans and Reeves (3) report an ^{26}Al content of 46±3 dpm/kg for the meteorite.

Table 1 shows the steady-state or saturation values of ^{26}Al and ^{10}Be estimated for four different sets of exposure conditions. It also gives the exposure and terrestrial ages calculated for various one-stage irradiation models, i.e., a single exposure under each of the four sets of conditions specified in Table 1 followed by terrestrial decay. The results are consistent with either a lunar or 'asteroidal' origin with certain restrictions.

1) ALHA 81005 evidently spent less than 1.1 Myr and probably less than 0.4 Myr in space as a small body. As a rule, the exposure ages of achondrites are considerably older (4); fewer than 5% of the chondrites have ages under 1 Myr (5) although the fraction is higher among carbonaceous stones (6).

2) ALHA 81005 could have accumulated its ^{26}Al and ^{10}Be entirely on the moon, somewhere within the topmost 100 cm. If so, its time in space was less than 0.1 Myr and its time in the Antarctic less than 0.6 Myr. Both these limits conform to expectations based on other studies. First, Monte Carlo calculations show that roughly 70% of the objects ejected from the moon and captured by the earth would have ages less than 2 Myr (7). Second, the average terrestrial age of Antarctic stones appars to be about 2-3x10^5 y (8), consistent with our result of t_{terr}<0.6 Myr.

3) More complex, n-stage irradiation histories beginning on the moon could also explain the ^{10}Be and ^{26}Al results subject to restriction (1) above. Measurements of ^{53}Mn and ^{36}Cl may be helpful in defining more closely the irradiation and decay history of ALHA 81005.

C. Tuniz

Table 1. One-stage exposure and terrestrial ages (Myr) for ALHA 81005.

Location	$^{26}Al_o$ dpm/kg	$^{10}Be_o$ dpm/kg	t_{exp}	t_{terr}
Lunar regolith (0 g/cm^2)	123[10]	13[13]	1.2	0.6
Lunar regolith (180 g/cm^2)	46[3]	6.5[14]	1.9	<0
Meteorite (avg.)	127[11]	24[15]	0.4	≲0
Meteorite (~50 cm)	57[11,12]	10[15,16]	1.1	<0

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SIDEROPHILE, LITHOPHILE AND VOLATILE TRACE ELEMENTS IN ALLAN HILLS A81005

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From the time of its discovery in Antarctica, Allan Hills A81005 seemed a likely candidate for the first recognized lunar sample naturally transported to Earth. To study its meteoritic admixture and its geochemical and thermal histories, we requested material from ALH A81005 and were allocated 139 mg of matrix containing 30-40% mm-sized admixed clasts, which were too numerous and small to separate. We divided the sample into two nearly equal-sized portions to assess heterogeneity and analyzed each for 16 trace elements - siderophile As, Au, Co, Ga, Sb; volatile/mobile Ag, Bi, Cd, In, Se, Te, Tl, Zn; lithophile Cs, Rb, U - by radiochemical neutron activation analysis. These elements are known to yield important genetic information on lunar and meteoritic materials, e.g. [1-4].

Our duplicate results are entirely satisfactory considering sample heterogeneity and small size and the ppb levels of nearly every element we measured. These data are entirely consistent with a lunar origin for ALH A81005, based on comparison with prior results for similar lunar samples. Siderophile markers of meteoritic admixture (Ag, As, Au and Sb) indicate 0.015 ± 0.005 Cl-equivalent, in accord with the 1-2% admixture found in Apollo samples, e.g. [2,3]. Three more volatile (but not siderophile) elements - Se, Cd and Zn - are also in this range, indicating no measurable extraneous volatile admixture (Fig. 1). The Cd content (Fig. 1) and Cd/Zn ratio, 4.0×10^{-3}, are similar to those in numerous lunar samples [3]. The Cs/U ratio, 0.046, is unusually low compared with prior data [2] but Rb/Cs, 30, seems quite normal [4]; preliminary Tl results will be presented. Cobalt is slightly high, at 0.044 Cl-equivalents, hinting at admixture by siderophile-rich projectile debris. Part of the Ga excess (Fig. 1) could be attributable to this but most, if not all of it probably reflects an indigenous component, i.e. anorthosite. Slightly lowered contents of Bi and Te (0.0065-0.0039 Cl-equivalents) are similar to those in lunar highlands samples [2] and may reflect marginal shock-induced mobilization.

In summary, little in the trace element make-up of ALH A81005 distinquishes it from samples returned by the Apollo missions - a remarkable fact considering its unusual history: it is neither unusually rich nor poor in siderophiles and volatiles/mobiles. Thus, the impact that provided ≥ 2.4 km/sec to launch ALH A81005 on its journey to the Antarctic ice sheet left marks no more severe than those found in samples that did not escape the lunar gravitational field. This conclusion is entirely consistent with the 20 GPa shock pressure estimated mineralogically by Warren _et al_. [5]. A Martian origin for SNC meteorites, requiring ≥ 5.0 km/sec, now seems more likely in view of the results for ALH A81005. Just as Apollo had his twin (Artemis/Diana), the Apollo program had its natural twin that launched other lunar samples to Earth, now waiting to be hunted down on the Antarctic ice sheet.

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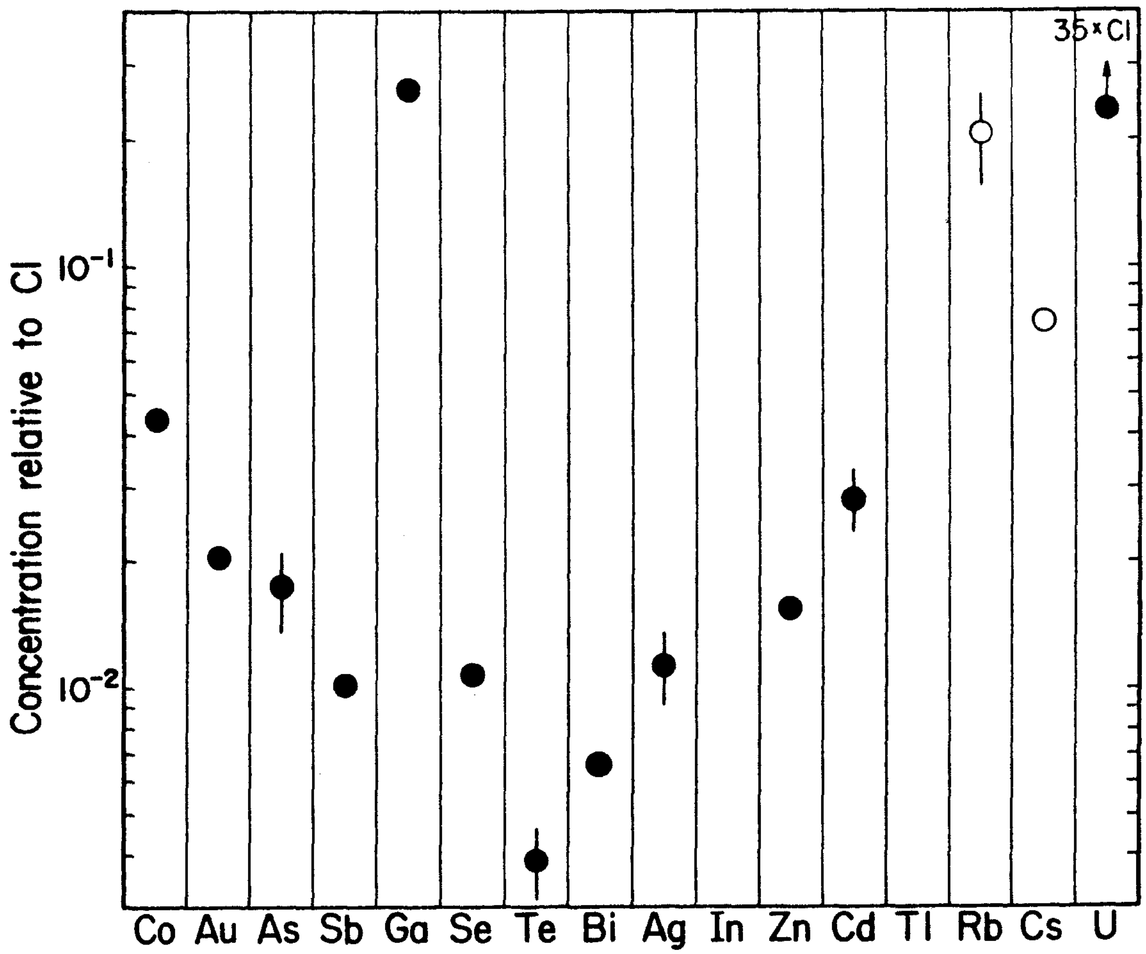

Fig. 1. Trace element contents of ALH A81005 normalized to those of Cl chondrites. Vertical lines indicate ± 1 sample standard deviation derived from the duplicate analyses. Open symbols indicate provisional values. Gallium, lithophilic Cs, Rb and U and, perhaps, Co probably reflect anorthosite; other elements indicate 1-2% (Cl) admixture by meteoritic matter, possibly coupled with slight thermal redistribution of mobile elements. These are features often seen in Apollo lunar samples, indicating that ALH A81005 was compositionally unaffected during its transit to Earth.

ALHA81005: A METEORITE FROM THE MOON -- BUT CAN WE RULE OUT MERCURY?

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There seems to be a clear consensus that ALHA81005 came from the Moon [1-6], but before assessing the implications, the remote possibility that it came from some other body should be addressed. Even if it is not lunar, the rock is profoundly important. The parent body would have to be remarkably similar to the Moon. It would have to have the same oxygen isotope ratios [1], the same FeO/MnO ratios [2-5], and the same anorthositc type of crust, as the Moon; and it must be atmosphereless, with a regolith containing approximately the same amounts of solar wind rare gases as that of the Moon [6]. It may well be that some planet or asteroid has several of these properties in common with the Moon, but it is extremely unlikely that any other body has all four. The only other plausible source would appear to be Mercury.

Earth, the Moon, and the enstatite chondrite/aubrite parent body, all have oxygen isotope ratios along a single mass fractionation line [7]. Because of their exceedingly low FeO/MgO ratios, it has been suggested that the enstatite chondrites formed in a high-temperature zone <<1 AU from the Sun [8]. Thus, it is conceivable that the entire inner solar system was homogenized with respect to oxygen isotopes. Presumably, the Moon became depleted in MnO relative to FeO (compared to similarly FeO-rich chondrites) due to the higher volatility of MnO. Among atmosphereless bodies, this too may be a function of distance from the Sun, for the eucrite parent body (presumably an asteroid) has a higher MnO/FeO than the Moon. But planet size (i.e., escape velocity) and other factors surely must also play a role. A MnO/FeO coincidence between Mercury and the Moon is unlikely, but not impossible.

Anorthositic crusts like that of the Moon probably only form on planets of roughly lunar size. If the planet is too large (i.e., has internal pressures that are too high), its aluminum does not form buoyant plagioclase during the early intense magmatism phase (the magma "ocean"), but instead forms dense mantle phase(s) such as garnet — this is what probably took place on Earth [9]. Moreover, its early crust is liable to be made over by ongoing geologic activity. If it is too small (i.e., asteroid-sized), it can never form sufficiently large intrusions to lead to global elutriation of plagioclase -- this is probably why anorthosites are only a very minor component from the eucrite parent body [10]. Mercury is 4.6 x more massive than the Moon, but its large core (60-70 wt.%) would have displaced all its aluminum towards the surface. The pressure at the base of Mercury's mantle is roughly 100 kb. For comparison, the lunar central pressure is ~47 kb, and the pressure at the base of Earth's mantle is ~1370 kb. Mercury is probably the right size to have produced an anorthositic crust, provided it was melted extensively like the Moon. Indeed, the visible reflectance spectrum of Mercury is sufficiently similar to spectra from lunar highlands soils to suggest [11] that Mercury's crust is similarly anorthositic, with roughly 5.5 wt% FeO, mainly as orthopyroxene.

Being only 39% as far from the Sun as the Moon, Mercury's surface is exposed to 6.7 x as much solar wind as the Moon's. A regolith breccia from Mercury will not necessarily have 7 x higher solar gas contents than one from the Moon, however. Another factor, the mean surface residence time (i.e., reciprocal cratering rate), differs between Mercury and the Moon. The cratering rate on Mercury is most likely ~2 x, but possibly 5 x, that on the Moon

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[12], so an avg. regolith breccia from Mercury probably, but not necessarily, has significantly higher solar gas contents than one from the Moon. ALHA81005 has noble gas concentrations that are low even for a lunar soil [6], and most regolith breccias have 2-4 x higher concentrations than soils [13]. If the noble gas data are an obstacle to accepting the lunar origin of ALHA81005, it is because they are too low, not too high. The explanation is probably that ALHA81005 is atypically poor in surficial "fines" material, for a regolith breccia. We have observed that it appears to contain considerably less of the swirly brown glass associated with such materials, too.

In summary, the possiblity should not be completely overlooked that ALHA81005 is from some body other than the Moon; Mercury is the most plausible alternative. But a powerful combination of circumstantial evidence is overwhelmingly in favor of its being from the Moon.

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