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GEOCHEMISTRY AND PETROLOGY OF PRIMITIVE ACHONDRITE METEORITES LEW 88280, MAC 88177, ALHA 81187, EET 84302, AND LEW 88663

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ABSTRACT

Primitive achondrites are meteorites that have mineral and bulk chemical compositions similar to the most primitive meteorites (chondrites) but have textures similar to more evolved meteorites (achondrites). The unique geochemistry and texture of the primitive achondrites suggest these meteorites may be genetic intermediates between chondrites and achondrites and may preserve evidence of processes occurring in the early solar system. Five primitive achondrites LEW 88280, MAC 88177, ALHA 81187, EET 84302, and LEW 88663 were examined in this study in order to classify the meteorites and to determine processes that have affected them. Bulk chemical analyses of Na_2O, K_2O, CaO, FeO, Cr, Co, Ni, Sc, Ir, Au, As, Sb, Se, Br, Cs, Ba, La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu were determined for each meteorite by Instrumental Neutron Activation Analysis (INAA). Concentrations of Hf, U, and Th were determined for some meteorites. Polished thin sections of the five meteorites were examined in transmitted and reflected light microscopy to identify minerals and examine petrographic relationships. Minerals found in the meteorites include olivine, orthopyroxene, clinopyroxene, plagioclase, Cr-spinel, phosphates, troilite, kamecite, and taenite along with other minor phases. Mineral compositions were determined with an electron microprobe. The initial study suggests that the meteorites have been altered by metamorphic processes although igneous processes may also have played a role in the evolution of these rocks. Further studies of isotope and bulk chemistry are planned for these meteorites.

INTRODUCTION

Meteorites are fragments of planetary bodies that impact into Earth. Some meteorites are thought to be fragments of the Moon, blasted into space by impacts that created the large craters on the lunar surface (Lindstrom et al., 1991; Yanai, 1991; Delaney, 1989) and a few meteorites are thought to possibly be fragments of Mars (Bogard et al., 1984). Most meteorites however, are thought to originate in the asteroid belt (McSween, 1987).

The most common meteorites to impact the Earth are called chondrites. Chondritic meteorites are composed of mineral grains, fragments of mineral grains, and features called chondrules, set in a fine-grained matrix of minerals and glass. Chondrules come in a wide variety of shapes and sizes but a typical chondrule is a round or rounded feature composed of a variety of minerals and glass. Olivine and enstatite are minerals commonly found in chondrules. In addition to their unique textures, chondrites have a distinctive chemical composition. Chondrites may be samples of the most primitive and least altered material left over from early planetary formation

Not all meteorites have chondritic textures. Meteorites without chondritic textures are called achondrites. Although texturally distinct from chondrites, some achondrites have chemical signatures which are similar to chondritic chemistries. These primative achondrites may be chondrites whose textures were altered or obliterated by deformational processes such as metamorphism or igneous processes such as partial melting or crystallization.

Igneous and metamorphic processes have undoubtably altered the early nebular material which was incorporated into planetary bodies like Earth and Mars. Examining and understanding processes which have affected primitive achondrites may help in understanding the processes which have shaped Earth and other planets.

PROCEDURES

Five achondrites were examined in this study in order to classify the meteorites and to ascertain their origin and evolution. The five meteorites , collected in Antarctica, are labeled ALHA 81187, LEW 88280, LEW 88663, MAC 88177, and EET 84302. A small amount of each meteorite was crushed into a powder and irradiated in a nuclear research reactor at the University of Missouri. A small group of major elements and a large group of trace elements were then determined using the INAA facilities at the Johnson Space Center in Houston.

Five polished thin-sections of the meteorites were examined optically by reflected and transmitted light microscopy. Minerals and petrographic relationships were examined and targets were selected for chemical analysis. Mineral chemistries were determined on the Cameca Camebax electron microprobe at the Johnson Space Center. Backscatter photographs of minerals and textures were also obtained from the Cameca microprobe.

METEORITE LEW 88280.23

Petrography

Meteorite LEW 88280.23 is a medium-grained rock composed of approximately 80 volume % silicate minerals and 20 volume % opaque metals, sulfides and oxides. Silicate minerals include olivine, clinopyroxene, and orthopyroxene. Olivine is the dominant silicate and comprises approximately 90 volume % of the silicates. The opaque suite of minerals is dominated by the Fe-Ni metal kamecite but smaller amounts of the Fe-Ni metal taenite and the Fe-sulfide troilite are present.

The rock has an overall granular texture defined by subhedral, roughly equant olivines. These mineral grains are commonly fractured and may contain small rounded inclusions of metals, sulfides, and pyroxenes. Larger subhedral elongate clinopyroxenes and smaller amounts of orthopyroxene are locally found in the meteorite. Clinopyroxenes contain abundant exsolution lamellae of orthopyroxene and minor rounded inclusions of olivine and elongate ovoid inclusions of metals and sulfides. Discrete orthopyroxene may contain small amounts of clinopyroxene exsolution lamellae.

Metal and sulfide phases are located in anhedral interstitial intergrowths between silicate minerals. The most abundant metal is kamecite which is crystallographically intergrown with more Ni-rich taenite. Distinct patches of troilite are common around the exterior of the kamecite/taenite intergrowths.

Veins of metals, sulfides, and Fe-oxide/hydroxide minerals cut across and fill in between silicates. Sulfides and metal intergrowths are generally surrounded by a rim or partial rim of Fe-oxide/hydroxides. These minerals are probably secondary alteration products.

Mineral Chemistry

Representative mineral analyses for LEW 88280 are given in Table 1. Olivines are magnesium rich (Fo_{87}) and contain small amounts of Mn and Cr. Orthopyroxene is also Mg-rich and has an average composition of $En_{85}Wo_3Fs_{12}$. The mineral contains minor amounts of Cr, Al, and Ca. Clinopyroxene is a Ca-Mg silicate containing small amounts of Al and Cr. Its average composition is $En_{50}Wo_{45}Fs_5$.

Kamesite varies in composition but has a general bimodal compositional distribution. One group of metals has an average composition of 93 wt % Fe and 7 wt % Ni and the other metal group has an average composition of 86 wt % Fe and 14 wt % Ni. Taenite in this sample contains approximately 64 wt % Fe and 36 wt % Ni.

Bulk Chemistry

The bulk chemistries of the five meteorites will be described relative to the C1 chondrite abundances of Anders and Ebihara (1982). This is a standard reference for examining abundances of major and trace elements in meteorites and terrestrial igneous rocks.

Meteorite 88280 is approximately chondritic in CaO content and slightly chondrite depleted in FeO. Potassium and sodium contents are very depleted with respect to C1 chondritic abundances. The rock is enriched in the metals Au, Cr, Ni, and Co and Depleted in rare earth elements (REE) when compared to the chondritic standard.

METEORITE MAC 88177.37

Petrography

Meteorite MAC 88177.37 is a medium-grained (0.1-0.7mm) granular rock which resembles a depleted terrestrial harzburgite in texture. The rock is composed of approximately 90 volume % silicates and 10 volume % metals, sulfides, and oxides. The major silicate phases present are orthopyroxene and olivine but minor amounts of clinopyroxene

TABLE 1.- MINERAL COMPOSITIONS FROM METEORITE LEW 88280.23

Oxide	Olivine	Opx	Cpx .
SiO2	40.43	57.46	55.06
TiO2	0	.09	.31
Al2O3	.01	.19	.94
Cr2O3	0	.15	1.17
FeO	12.69	8.30	3.39
MgO	46.90	32.66	19.40
MnO	.48	.51	.35
CaO	.04	.68	18.96
NiO	.06	.08	0 .
Na2O	.01	.01	.58
K2O	.01	0	.02
Total	100.63	.100.13	100.18

Oxide weight %

Element	Kam	Tae	Troi	Ni-Troi
Al	.02	.03	0	.01
Cr	.01	0	.83	.04
Mg	0	0	0	.05
Fe	91.91	64.14	61.26	57.76
Ni	7.19	35.61	1.04	13.05
S	0	.01	37.73	29.47
Total	99.13	99.79	100.86	100.38

Elemental weight %

are also present. Orthopyroxenes are euhedral to subhedral and colorless in plane light. They show zoned extinction and contain small localized regions of concentrated clinopyroxene and metal lamellae. Large round olivine inclusions are present in some grains. Discrete olivines are euhedral to subhedral and are slightly elongate. Some grains appear to be interstitial to orthpyroxenes. Olivines can be fractured but otherwise appear optically homogeneous. Clinopyroxene is found as rounded subhedral to angular interstial grains or as lamellae in orthopyroxenes. Orthopyroxene exsolution lamellae permeate most clinopyroxenes and sulfide and metal inclusions are common.

Opaque phases are dominantly discrete anhedral kamecites and troilites or intergrowths of kamecite + troilite or kamecite + troilite + chrome-spinel. The intergrowths are generally composed of coarse homogeneous regions of kamecite, troilite, and lesser amounts of chrome-spinel and patches of fine-grained intergrown kamecite and troilite. Some discrete grains of taenite and chrome-spinel occur in the sample. A small phosphate mineral was found associated with a kamecite + troilite + chrome-spinel intergrowth.

Mineral Chemistry

Orthopyroxenes in MAC 88177 have average compositions of $En_{84}Wo_{4}Fs_{12}$ (Table 2). Aluminum oxide contents average approximately 0.65 wt % and Cr_2O_3 and MnO contents average about 0.50 wt %. There are analyses that indicate rims of orthopyroxenes are slightly enriched in Ca and Fe and slightly depleted in Cr and Mn with respect to core compositions. Olivines are Mg-rich with an average

composition of Fo_{86}. The minerals contain approximately 0.5 wt % MnO but few other trace elements. Clinopyroxenes have an average composition of $En_{53}Wo_{40}Fs_{7}$ and contain approximately 1.2 wt % Al_2O_3 and 1.4 wt % Cr_2O_3. Minor amounts of TiO_2 and Na_2O are also present. The one analyzed phosphate grain is composed mostly of calcium and phosphorus. It does, however, contain small amounts of Fe, Na, and Cr. This mineral is tentatively identified as apatite.

Spinel in the opaque intergrowths is FeO (24 wt%) and Cr_2O_3 (59 wt%) rich and magnesium and aluminum poor. The oxide contains slightly less than 1 wt% of MnO and TiO_2. Approximately 0.5 wt% vanadium oxide is present in the spinel. Kamecite contains an average of 6 wt% Ni and Ni contents of taenite average about 25-26 wt%. Troilites contain little except Fe and S.

TABLE 2.- MINERAL COMPOSITIONS FROM METEORITE MAC 88177.37

Oxide	Olivine	Opx	Cpx	Apa	Cr-Sp
SiO2	40.74	57.24	54.22	.02	.03
TiO2	.03	.14	.32	.01	.85
Al2O3	0	.62	1.19	.01	9.01
Cr2O3	0	.54	1.34	.26	58.76
FeO	13.04	8.51	3.50	.44	23.38
MgO	46.20	31.33	17.04	.03	5.56
MnO	.52	.51	.32	.04	.98
CaO	.01	1.87	21.27	57.01	0 .
NiO	0	0	0	0	0 .
Na2O	.02	.05	.60	.25	0 .
K2O	0	.01	.01	0	0 .
P2O5	.01	0	.03	41.61	0 .
V2O3	.02	.08	.07	.02	.66
Total	100.59	100.90	99.91	99.70	99.23

Oxide weight %

Element	Tae	Kam	Troi
Cr	0	.03	.08
Mg	.02	.01	.01
Fe	73.82	93.29	62.47
Ni	25.49	5.73	37.67
S	0	.02	0 .
P	.02	.03	0 .
V	.02	0	0 .
Total	99.37	99.11	100.23

Elemental weight %

Bulk Chemistry

Meteorite MAC 88177 contains approximately chondritic amounts of CaO but is extremely depleted in Na2O and K2O and moderately depleted in FeO relative to C1 chondritic abundances. Ir, Au, Ni, and Co concentrations are lower than chondritic values but Cr content is higher. The rock contains negligible amounts of As, Sb, and Se.

METEORITE ALHA 81187.17

Petrography

Meteorite 81187.17 is a medium-grained (0.2-0.7mm) granular rock composed of the minerals olivine, orthopyroxene, clinopyroxene, chrome-spinel, kamecite, and taenite. The silicate portion of the rock is dominated by subhedral grains of orthopyroxene which constitutes approximately 80 volume % of the meteorite. Olivine accounts for most of the rest of the silicate fraction. A few clinopyroxenes are scattered through the sample. Kamecite dominates the opaque fraction of the meteorite. Small amounts of taenite locally rim the kamecite and small chrome-spinels are found at the edges of some metals.

Mineral Chemistry

Representative mineral analyses for meteorite ALHA 81187.17 are given in Table 3. Olivines are low in Fe content and have an average composition of Fo_{95}. These minerals also have minor concentrations of Mn and traces of Ni. Orthopyroxenes are also Mg-rich and have approximate average compositions of $En_{87}Wo_3Fs_7$. The pyroxenes contain up to 1.0 wt% Cr_2O_3, 0.6 wt% MnO and 0.5 wt% Al_2O_3. Clinopyroxenes are Ca-rich with an average composition of roughly $En_{50}Wo_{49}Fs_1$. These minerals also have minor amounts of aluminum, chromium, and manganese. Kamecite is approximately 94 wt% Fe and 6 wt% Ni and taenite contains roughly equal amounts of Fe and Ni. Spinels are chromium and iron rich but contain on average 9 wt% MgO and 8 wt% Al_2O_3.

Bulk Chemistry

Meteorite ALHA 81187.17 is enriched in Ir, Au, and Cr with respect to C1 chondrites but is depleted in Ni, Co, and As. Sodium, potassium, and iron concentrations are similar

TABLE 3.- MINERAL COMPOSITIONS FROM METEORITE ALHA 81187.17

Oxide	Olivine	Opx	Cpx	Cr-Sp
SiO2	42.12	58.27	55.03	0 .
TiO2	0	.20	.55	.31
Al2O3	0	.43	1.03	7.56
Cr2O3	.04	.96	1.81	63.22
FeO	4.13	4.45	1.94	15.29
MgO	52.34	33.40	18.20	9.21
MnO	.50	.60	.35	3.32
CaO	.13	1.75	20.33	.04
NiO	.03	.04	0	.07
Na2O	0	.09	.71	0 .
K2O	0	0	.01	.02
Total	99.29	100.19	99.96	99.04

Oxide weight %

Element	Kam	Tae
Al	0	.01
Cr	0	.01
Mg	0	.01
Fe	92.48	42.88
Ni	6.24	43.65
S	0	.04
Total	98.73	86.59

Elemental weight %

to those of the C1 chondrite standard and CaO totals are slightly higher. This rock is depleted in light REEs and has approximately chondritic heavy REEs.

METEORITE EET 84302.20

Petrography

Meteorite EET 84302.20 is a medium-grained (0.05-4.0mm) granular rock composed of approximately 55 volume % silicates and 45 volume % opaques. Orthopyroxene, kamecite, and chrome-spinel dominate the rock with olivine, clinopyroxene, and plagioclase occurring in significantly smaller amounts. The silicates are large subhedral discrete grains and the metal and oxide phases appear to have formed or filled in around the silicates. Orthopyroxenes generally contain tens to hundreds of rounded to elongate inclusions of metals. These metal inclusions are localized in linear patches within the pyroxene, dominantly but not always in the centers of the host grains. The rims of the orthopyroxenes are generally free of inclusions. Some orthopyroxenes also contain round inclusions of olivine. Clinopyroxenes are modally less important than orthopyroxenes but are larger than the average orthopyroxene. Orthopyroxene exsolution lamellae are abundant in clinopyroxenes and some euhedral inclusions of Na-plagioclase exist in some clinopyroxenes. Na-plagioclase is also present as partial rims around or as subhedral rounded grains adjacent to clinopyroxene containing Na-plagioclase inclusions. Rounded metal and olivines are also included in some clinopyroxenes.

Chrome-spinels are concentrated in one region of the rock and comprise about 30 volume % of the opaques. The grains are optically homogeneous. Kamecite dominates the opaque mineralogy but is generally absent in the region of spinel concentration. Some kamecites have thin rims of troilite and/or thin rims of alteration around them. No apparent chondrules are present.

Mineral Chemistry

Orthopyroxenes (Table 4) in this rock have an average composition of $En_{90}Wo_2Fs_8$. They contain approximately 0.5 wt% Al_2O_3, Cr_2O_3, and MnO and smaller amounts of Na and Ti. There is some suggestion of a slight iron enrichment in the orthopyroxene cores. Clinopyroxene has an average composition of $En_{52}Wo_4Fs_{44}$. The pyroxene contains around

TABLE 4.- MINERAL COMPOSITIONS FROM METEORITE EET 84302.20

Oxide	Olivine	Opx	Cpx	Plag	Cr-Sp
SiO2	41.33	58.04	54.96	66.20	.02
TiO2	.01	.20	.55	.05	1.09
Al2O3	0	.51	1.23	25.05	8.10
Cr2O3	.04	.49	1.59	.02	62.28
FeO	8.24	5.57	2.16	.08	15.66
MgO	49.04	33.34	17.52	.01	10.50
MnO	.43	.53	.28	0	1.08
CaO	.05	1.28	21.36	4.32	0
NiO	0	0	0	0	.03
Na2O	0	.03	.70	4.28	.02
K2O	.01	.01	.01	.57	.03
Total	99.15	100.00	100.36	100.58	98.81

Oxide weight %

Element	Kam	Troi
Al	0	.01
Cr	.06	.57
Mg	.02	0
Mn	.02	.02
Fe	94.19	61.36
Ni	5.09	.14
S	0	38.01
Total	99.38	100.11

Elemental weight %

0.7 wt% Na_2O, 1.2 wt% Al_2O_3, and 1.6 wt% Cr_2O_3. MnO concentrations average about 0.5 wt%. Plagioclase compositions in EET 84302.20 are approximately $Ab_{75}An_{22}Or_3$. Olivine compositional averages are about Fo_{87}. The mineral composition includes about 0.5 wt% MnO but few other trace elements are present.

Spinels are Cr- and Fe-rich and Al- and Mg-poor. MnO constitutes a substantial 1.0 wt% total in most of the spinels. Kamecite consists of roughly 95 wt% Fe and 5 wt% Ni. Troilite is composed dominantly of Fe and S but some grains have small amounts (<0.5 wt%) of Cr_2O_3.

Bulk Chemistry

The most distinctive feature of the bulk chemistry of EET 84302 is its elevated content of Fe, Ir, Au, Cr, Ni, Co, and As with respect to C1 chondrites. Gold contents range up to 8X chondritic abundances and FeO may be up to 2.5X chondritic values. These high contents reflect the high concentration of metal in the rock. Na and Ca totals are approximately chondritic in abundance. EET 84302 appears to have chondritic light REE abundances but slightly enriched heavy REE abundances.

METEORITE LEW 88663.17

Petrography

Meteorite 88663.17 is a granular achondrite composed dominantly of silicates. Metals make up only about 5 modal % of the sample. The major silicate phase is olivine (50 volume %) which is found as equant subhedral to anhedral rounded crystals poikiolitically surrounded by networks of orthopyroxenes (35 volume %) and plagioclase (10 volume %). Plagioclase and orthopyroxenes within individual networks are intimately intergrown. Small patches of clinopyroxene are associated spatially with orthopyroxene. Small grains of a phosphate mineral are intergrown with some orthopyroxene-plagioclase networks.

Large anhedral troilite grains are scattered through the meteorite. Smaller rounded troilites and Ni-rich troilites are present and occur throughout the meteorite but are concentrated preferentially with the orthopyroxene and plagioclase in the poikiolitic networks. Troilites, especially large grains, are badly altered by secondary Fe-oxides or hydroxides. Thin veins of troilite or Fe-oxide/hydroxide surround many of the silicates.

Mineral Chemistry

Olivine in meteorite 88663 is iron rich with an average composition of Fo_{76}. The mineral contains less than 0.5 wt% of MnO and Cr_2O_3. Orthopyroxene is also Mg-rich and has an average composition of $En_{76}Wo_4Fs_{20}$. Orthopyroxene generally contains approximately 0.5 wt% Al_2O_3, 0.4 wt% Cr_2O_3, and 0.4 wt% TiO_2. Iron appears to be enriched at the edges of the grains and depleted in the cores of the orthopyroxenes. Clinopyroxene is Ca-rich and has an average composition of $En_{48}Wo_{42}Fs_{10}$. The mineral contains an average of 0.9 wt% Al_2O_3, 0.6 wt% Na_2O, and 0.5 wt% MnO. Plagioclase in 88663 is Na-rich and has an average composition of $Ab_{75}An_{22}Or_3$. A few crystals of a phosphate mineral, tentatively identified as merrillite, exist in the rock. This mineral is composed of roughly equal parts calcium and phosphorus with minor amounts of Na, Mg, and Fe.

Opaque phases in the meteorite are mostly troilites, which contain Fe and S but little else. Some Ni-rich troilite (Ni = 8.5 wt%) is locally associated with olivine. Chrome-spinels are found with some troilites. These spinels contain an average of 56.9 wt% Cr_2O_3 and 30.5 wt% FeO. MgO contents are approximately 2.0 wt% and Al_2O_3 contents average 5.8 wt%. Poor analyses of a Ni-Fe metal intergrowth were obtained. The metal contains at least 34 wt% Fe and 43 wt% Ni.

Bulk Chemistry

Meteorite LEW 88663.17 contains approximately C1 chondritic abundances of Ca, Fe, and Na but has roughly 2X chondritic values of potassium. The rock is also relatively enriched in Au and Cr but is slightly depleted in Ir, Ni, Co, and As. Antimony is almost absent but Sc contents are slightly enriched relative to C1 chondrite standard abundances.

CONCLUSIONS

This study is in its preliminary stages and much work still needs to be done to reach definite conclusions. The bulk major element composition needs to be analyzed from fused beads and radioactive and stable isotopes composition must be determined in order to suggest with some certainty

TABLE 5.- MINERAL COMPOSITIONS FROM METEORITE LEW 88663.17

Oxide	Olivine	Opx	Cpx	Plag	Merr	Cr-Sp
SiO2	38.87	55.53	54.59	63.89	.01	.01
TiO2	0	.38	.43	.14	0	2.99
Al2O3	0	.48	.88	22.93	.01	5.71
Cr2O3	.02	.41	1.21	0	.02	56.83
FeO	22.05	13.23	5.75	.46	2.23	30.48
MgO	38.74	27.66	16.13	.02	3.27	2.07
MnO	.40	.40	.42	0	.90	.68
CaO	.01	1.70	19.99	4.41	45.74	.03
Na2O	.04	.06	.63	8.45	2.36	.03
K2O	0	.01	.01	.58	.10	.01
P2O5	.19	0	.03	.09	43.80	.01
V2O3	0	0	.06	0	.01	.70
Total	100.32	99.86	100.13	100.97	98.54	99.60

Oxide weight %

Element	Ni-Troi	Troi
Mg	.01	0 .
Mn	.03	.01
Fe	54.88	62.81
Ni	8.34	.01
S	36.87	37.55
V	0	.02
Total	100.13	100.40

Elemental weight %

an origin and evolutionary history of the five achondrites. Some preliminary conclusions have, however, been reached.

1. There are no apparent chondrules in the five achondrites studied.

2. All of the achondrites have textures which seem to be metamorphic or igneous in origin.

3. Meteorites MAC 88177 and LEW 88280 have mineral compositions and textures similar to a group of meteorites known as lodranites. This confirms the findings of other workers (Keil, et al., 1992).

4. Meteorite ALHA 81187 has mineral compositions and textures which resemble the textures and compositions of a group of meteorites known as winoaites.

5. Meteorite EET 84302 has mineral compositions that are intermediate between mineral compositions in lodranites and mineral compositions in winoaites. Texturally the meteorite has features similar to features in metal rich meteorites, lodranites, and winoaites.

6. Meteorite LEW 88663 is unusual in its mineral chemistry and textures. The mineral chemistries resemble the chemistries of L or LL chondrites but no chondrules are apparent. The poikiolitic orthopyroxene-plagioclase texture is similar to textures in some mesosiderites.

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