19940020876

N94-25358

A GEOCHEMICAL STUDY OF ACAPULCOITE AND LODRANITE METEORITES

Final Report
NASA/ASEE Summer Faculty Fellowship Program-1993
Johnson Space Center

Prepared by: Stephen W. Field, Ph.D.

Academic Rank: Assistant Professor

University & Department: Stockton State College
Dept. of Geology and
Environmental Studies
Pomona, New Jersey 08240

NASA/JSC

Directorate: Space and Life Sciences

Division: Solar System Exploration

Branch: Office of the Curator

JSC Colleague: Marilyn M. Lindstrom, Ph.D.

Date Submitted: August 20, 1993

Contract Number: NGT-44-001-800

ABSTRACT

Lodranites and acapulcoites (primitive achondrites) are two classes of meteorites with geochemical signatures similar to chondrite meteorites. Lodranites and acapulcoites, however, have few or none of the chondrules characteristic of the chondrites. Texturally the primitive achondrites appear to have been recystallized though planetary igneous or metamorphic processes. A study of five primitive achondrites; two lodranites, two acapulcoites, and one supposedly intermediate acapulcoite/lodranite were analyzed petrographically and geochemically to determine the igneous and metamorphic processes which have affected them. Acapulcoites show little evidence of melt extraction. The geochemistry of lodranite samples indicates silicate and metal/sulfide melts were removed from the rocks. The mineralogy and geochemistry of the intermediate meteorite suggest the rock is a metal rich acapulcoite and not a lodranite.

INTRODUCTION

Among the objects which have impacted Earth over the past 4.6 billion years are the achondrite meteorites and the chondrite meteorites. Chondrites are generally believed to be fragments of small planetary bodies, possibly asteroids. These meteorites are composed of matter which formed early in the history of the Solar System. These meteorites are characterized by the presence of small round or rounded mineral aggregates called chondrules. Chondrite meteorites show little evidence for high pressure planetary processes such as volcanism or metamorphism. Achondrite meteorites are generally believed to be rocks which have been modified by planetary processes, such as melting, volcanism, or metamorphism. Because the planetary source of achondrites and chondrites is still uncertain and unexplored, the origin and alteration processes that affected these rocks are still ambiguous.

Five achondrite meteorites were analyzed geochemically to determine the igneous or metamorphic processes which may have affected them. The study included reflected light microscope examination, transmitted light microscope examination, electron microprobe analyses of minerals, and instrumental neutron activation analyses (INAA) of major and trace element bulk chemistry.

PRIMITIVE ACHONDRITES

A number of different types of achondrites have been described. The classification of these meteorites is based on characteristics such as oxygen isotopic composition, mineral chemistry, and bulk chemistry. Primitive achondrites are rare rocks which resemble chondrite meteorites in some mineral and bulk chemical characteristics. Some primitive achondrites also contain mineral structures which resemble altered chondrules commonly found in chondrite meteorites. It is generally believed that primitive achondrites are chondrites which have been altered by high temperature and pressure planetary processes, such as igneous melting and metamorphism.

Several subcategories of primative achondrites have been described including winoaites (Prinz et al, 1981), acapulcoites (Palme et al, 1981), and lodranites (Bild and Wasson, 1976). Several unique primitive achondrites have been described but have not been placed into named categories. Acapulcoites and lodranites are two classes of primative achondrites which may be genetically related

(Zipfel and Palme, 1993; McCoy et al, 1992). Acapulcoites are granular rocks composed dominantly of Mg-Fe pyroxene, olivine, plagioclase, Fe-Ni metal, and troilite. Minor amounts of Ca-pyroxene, spinel, and phosphates may be present. Lodranites contain minerals with similar compositions.but contain little or no plagioclase and less troilite than acapulcoites (McCoy et al, 1993). It has also been observed that lodranites are coarser grained than acapulcoites, however, this may be a result of the small sampling population.

PRIMITIVE ACHONDRITE SAMPLES

Five primative achondrites, ALHA 81187, ALHA 81261, MAC 88177, LEW 88280, and EET 84302, were examined in this study. Two samples, ALHA 81187 and ALHA 81261, are classified as acapulcoites and meteorites MAC 88177 and LEW 88280 are classified as lodranites. Meteorite EET 84302 has been suggested as a rock intermediate in mineral and chemical characteristics between acapulcoites and lodranites (McCoy et al, 1993).

PETROGRAPHIC DESCRIPTION

Acapulcoites

ALHA 81187 is an equigranular, fine-grained rock composed of approximately 50 volume % orthopyroxene (opx), 25% olivine (ol), 20% Fe-Ni metal, 5% clinopyroxene (cpx), and less than 1% Cr-spinel. No plagioclase (plag) was found in this sample. The silicate grains are anhedral to subhedral. Patches of metal are common in the sample and fine-grained veins of metal and/or metal oxides and hydroxides rim or partially rim silicates. There are several apparently brecciated sections of the sample and fractures cut through some silicate grains. Metals, oxides, and/or hydroxides fill the fractures and brecciated sections of the sample.

ALHA 81261 is an unbrecciated, granular, fine-grained rock. The silicate minerals appear fresh and unchanged by low temperature alteration. The approximate mineral volume percents are opx 59, plag 15, Fe-Ni metal 10, Troilite 10, cpx 7, apatite 1.5, and merrilite 1.5. Olivine was present only as small round inclusions in enstatite and comprised less than 1 volume percent of the rock. Large subhedral to euhedral opx grains dominate the fabric of the sample.

These grains have straight or smooth slightly curving boundaries. Round inclusions of ol, troilite , and metal are present in some opx grains. Slightly smaller cpx grains are associated with the opx. Plagioclase grains are anhedral and appear to fill void spaces between larger opx grains. Metals and troilite also have anhedral shapes and fill gaps between silicate grains. Phosphates are associated with metal and troilite.

Lodranites

Meteorite MAC 88177 is a coarse-grained granular rock dominated by opx and olivine. The approximate modal percentages are opx 67, ol 21, Fe-Ni metal and troilite 10, cpx 2, Cr-spinel less than 1, and apatite less than 1. Opx and ol are subhedral to euhedral and anhedral metals and troilite fill spaces between these silicates. Small euhedral Cr-spinels and phosphates are associated with the metals and troilite. Some opx grains contain round metal and troilite inclusions. The sample is highly fractured but the fractures are not filled. A few large cpx grains are present. These minerals have concave , scalloped edges when in contact with opx. All of the cpx grains contain abundant exsolution lamellae of opx.

Meteorite LEW 88280 is a coarse-grained granular rock dominated by opx and olivine. Abundant metal and troilite are present interstitial to the silicates. A few large cpx grains are present and these always contain abundant opx exsolution lamellae. Larger rounded opx, ol, metal, and troilite inclusions are also common in the cpx. The inclusions and lamellae are concentrated but not exclusively found in the centers of the pyroxenes. The approximate modal percentages are opx 55, ol 30, metal and troilite 20, and cpx 5.

EET 84302

EET 84302 is a medium- to coarse-grained, metal-rich, granular rock composed dominantly of opx, Fe-Ni metal and Cr-spinel. The rock has some unusual and distinct textures. The Cr-spinel and metal are segregated into distinct domains within the sample. Approximately 1/3 of the sample is composed of silicates + Cr-spinels and the other 2/3 is composed of metal + silicates. Orthopyroxenes have subhedral rounded shapes and contain distinct, generally rectangular patches of rounded to euhedral metal and sulfide inclusions. These patches generally but not always are found in the interiors of the opx grains. The inclusion patches generally occupy only a small fraction (10-20 %) of the pyroxene, and the edges of pyroxenes are usually inclusion free. Large discrete, anhedral blebs of metals and Cr-spinel are also present. These minerals have concave rounded edges when in contact with silicates. Large cpx grains contain abundant lamellae of opx, large euhedral inclusions of opx, rounded inclusions of metal, and euhedral granular inclusions of plagioclase. Plagioclase is also found as anhedral partial rims or subhedral crystals at the edges of cpx grains. Approximate modal percentages are opx 50, Fe-Ni metal 30, Cr-spinel 10, cpx 5, plag 3, ol 2, and merrilite less than 1.

MINERAL CHEMISTRY

Acalpulcoites

Olivines in the Acapulcoites are Mg-rich. The forsterite composition of olivines in ALHA 81187 are Fo_{95} and the forsterite compositions in ALHA 81261 are Fo_{90}. Orthopyroxenes are Mg-rich in both Acapulcoites. Average compositions in ALHA 81187 are $En_{90}Fs_{6}Wo_{4}$ and $En_{89}Fs_{10}Wo_{1}$ in ALHA 81261. Corresponding cpx compositions are $En_{51}Fs_{2}Wo_{47}$ and $En_{52}Fs_{5}Wo_{44}$. These Ca-rich pyroxenes are diopsides. Average plagioclase compositions in ALHA 81261 are $Ab_{80}An_{17}Or_{3}$. Plagioclase was not detected in ALHA 81187.

Both kamecite ($Fe_{92}Ni_{6}$) and taenite ($Fe_{51}Ni_{49}$) are present in ALHA 81187 but only kamecite ($Fe_{92}Ni_{7}$) was detected in ALHA 81261. Troilite (Fe%=63) was present in ALHA 81261 but not ALHA 81187. Cr-spinel in ALHA 81187 has a Cr/(Cr+Al) ratio of .85. Merrilite in ALHA 81261 contains 2.2 wt% Na_2O and apatite in the same sample contains 0.29 wt% Na_2O. No phosphate was detected in ALHA 81187.

Lodranites

MAC 88177 contains Mg-rich olivine (Fo_{86}) and opx ($En_{84}Fs_{13}Wo_{2}$). Ca-rich cpx has a composition of $En_{50}Fs_{6}Wo_{44}$. Kamecite is variable in composition and ranged from $Fe_{89}Ni_{11}$ to $Fe_{86}Ni_{14}$. Taenite, spatially associated with the kamecite, is generally uniform in composition ($Fe_{63}Ni_{37}$). Spinel in the meteorite is chromium-rich with a Cr/(Cr+Al) ratio of .84. Apatite contains 0.26 wt% Na_2O and troilite contains 63 wt% Fe.

LEW 88280 also contains forsteritic olivine (Fo_{87}) which is similar to olivine in MAC 88177. Opx ($En_{86}Fs_{12}Wo_{2}$) and cpx ($En_{50}Fs_{5}Wo_{45}$) are also similar to corresponding minerals in MAC 88177. Troilite in LEW 88280 contains 61 wt % Fe. Kamecite is compositionally uniform with an average composition of $Fe_{92}Ni_8$. Taenite, which is spatially associated with kamecite, has highly variable compositions which range from $Fe_{86}Ni_{14}$ to $Fe_{79}Ni_{21}$. The highest Ni contents are present in taenite directly adjacent to kamecite.

EET 84302

EET 84302 contains forsteritic olivine (Fo_{91}), Mg-rich opx ($En_{90}Fs_8Wo_2$), and Ca-rich diopsidic cpx ($En_{51}Fs_4Wo_{45}$). Opx lamellae in the cpx has the same composition as discrete opx. Plagioclase compositions in this meteorite are highly variable and range from $Ab_{68}An_{29}Or_3$ to $Ab_{53}An_{44}Or_3$. This variability is suspect and may be caused by Na migration during the analysis. Average iron contents in this meteorite are 61 wt%. Kamecite has an average composition of $Fe_{92}Ni_8$. The Cr/(Cr+Al) ratio of spinels in this meteorite is .84.

BULK CHEMISTRY

The bulk chemistry of the five primitive achondrites was analyzed with INAA techniques. Among the elements analyzed were the major elements Na, Ca, Fe, and the minor or trace elements Ni, Cr, Eu, Sc, Se, La, Lu, Sm, Yb, Sb, Co, Ir, Au, and As. Other elements were analyzed, however, complete sets of data for the listed elements were obtained for all the primitive achondrites and these data are used for comparisons among the analyzed meteorite compositions. Because the primitive achondrites are thought to have originally had chondritic compositions and because of the need for a common standard, the chemical composition of primitive achondrites are compared to H-chondrite compositions.

The following system is used in this paper to compare primitive achondrite compositions to H-chondrite compositions. Elements in achondrites which have abundances of 0 to 0.30 times chondritic abundances are highly depleted, abundances of 0.31 to 0.70 are moderately depleted with respect to chondritic abundances, abundances of 0.71 to 0.90 are slightly depleted, abundances of 0.91 to 1.10 times chondritic abundance are chondritic, abundances of 1.11 to 1.30 times chondritic abundances are slightly enriched, abundances of 1.31 to 1.70 times chondritic are moderately enriched, and abundances greater than 1.71 times chondritic are highly enriched.

Acapulcoites

The two acapulcoites analyzed contain abundances which deviate only slightly from H-chondrite abundances. ALHA 81261 contains chondritic abundances of Na, Ni, Co, Au, Sc, Sb, and Se. Slightly enriched elements include Eu, La, Sm, and Ir; and moderately enriched elements include Ca, Cr, Lu, Yb, and As. The meteorite contains no elements which are highly enriched relative to H-chondrites. Iron is slightly depleted relative to H-chondrites but no other depleted element is present among the 17 elements used in the comparison.

ALHA 81187 has a similar pattern but some differences do exist. The elements Ir and Sm are chondritic; Ca, Cr, Eu, Sc, Lu, Yb, and Sb are slightly enriched; and Na, Co, Au, As, and La are slightly depleted. The elements Fe, Ni, and Se are moderately depleted relative to H-chondrite abundances.

Lodranites

The two Lodranites analyzed are characterized by a group of highly depleted elements, which clearly distinguishes them from the Acapulcoites. MAC 88177 contains highly depleted concentrations of Na, Eu, Ir, Sm, La, Ni, Co, Au, and As. Moderately depleted elements include Fe, Se, and Sb; and Ca, Lu, and Yb are slightly depleted with respect to H-chondrites. Only Cr and Sc are slightly enriched and no moderately or highly enriched elemental concentrations are present.

LEW 88280 , like MAC 88177, is also highly depleted in elements Na, Eu, Ir Sm, and La. However, unlike MAC 88177 Ni, Co, Au, and As are not highly depleted. The elements Ca, Lu, and Yb are moderately depleted; and Fe, Co, and Au are only slightly depleted with respect to H-chondrites. Chondritic abundances of Ni and Sc are present as are slightly enriched concentrations of As and Se, and moderately enriched concentrations of Cr and Sb. No highly enriched elements are present.

EET 84302

EET 84302 is characterized by a group of slightly depleted, chondritic, and slightly enriched elements and a group of moderately to highly enriched elements. Slightly depleted elements include Na, Sc, Sm, La, and Yb. Calcium abundances are chondritic and Lu abundances are slightly enriched relative to H-chondrite abundances. Moderately enriched elements are Fe, Ni, Eu, and Sb; and highly enriched elements are Cr, Ir, Au, Co, and As. Cr abundances are approximately 4 times H-chondrite abundances and Ir is approximately 3 times. Au, Co, and As have roughly twice the abundance of H-chondrites.

DISCUSSION

Lodranites and Acapulcoites differ in modal mineralogy, average grain size, and bulk and trace element geochemistry, however, evidence suggests these two types of meteorites are fragments of the same parent body and are genetically linked to one another. Similar isotopic compositions suggest a common parent body (Clayton et al, 1992), and mineral compositions (McCoy et al, 1993), geochemistry of trace and bulk elements (Zipfel and Palme, 1993), and radiometric ages (Bogard et al, 1993) suggest a common and genetically linked ancestry.

The similarity of the chemistry of acapulcoites and H-chondrites lead Palme et al (1981) and Schultz et al (1982) to the conclusion that acapulcoites were originally chondrites that had subsequently been altered to acapulcoites by melting or partial melting. Recent studies by Zipfel and Palme (1993) and McCoy et al (1993, 1992) support an origin by modification of a chondritic parent body through a range of partial to complete melting or solid state recrystallization. McCoy et al (1993) also suggest that lodranites have undergone higher degrees of partial melting than acapulcoites, and that the higher degree of partial melting included physical loss of silicate, metal, and/or sulfide melts from the original rock. Loss of a silicate melt would be reflected by a decrease in the abundance of or loss of plagioclase from the original rock. The acapulcoites may have experienced lower degrees of partial melting and the metal/sulfide melts may not have physically migrated out of the original rock (McCoy et al,1993)

Geochemical data from acapulcoites ALHA 81187 and ALHA 81261 support a chondritic origin for these meteorites. The abundances of most of the major and trace elements examined are roughly chondritic in abundance. Lithophile element (Na, Ca, Eu, etc) abundances suggest little or no silicate melt extraction. Plots of H-chondrite normalized Sm/Sc versus Na/Sc and Sm/Sc versus La/Lu which should indicate silicate loss show no evidence of silicate melt extraction. Conclusions from the geochemical data are supported by the modal mineralogy. Plagioclase is abundant in ALHA 81261, and although no plagioclase was found in our sample of ALHA

81187, it has ben reported in other studies (McCoy et al, 1993). Plots of H-chondrite normalized Au/Co versus Ir/Ni and Se/Co versus Ir/Ni which are indicative of siderophile and chalcophile element behavior show an increase in Ir/Ni ratios and decreases in Se/Co ratios for acapulcoites. This data indicates a metal and/or sulfide melt may have been extracted from ALHA 81187 and ALHA 81261.

Geochemical and mineralogical data from LEW 88280 and MAC 88177 suggest that these lodranites experienced loss of partial melts. Plagioclase is absent in both of these meteorites indicating extraction of a silicate partial melt from the rocks. The low abundance of Na and Eu with respect to H-chondrite abundances also is indicative of plagioclase removal. MAC 88177 is also highly to moderately depleted in Fe, Ni, Co, Au, Ir, As, and Sb with respect to H-chondrites suggesting a metal and/or sulfide melt extraction. Fe, Co, Ni, Au, and As abundances are roughly chondritic in LEW 88280 which suggests silicate melt extraction but not metal/sulfide melt extraction. This does not seem likely as metals and sulfides should melt at lower temperatures than silicates. An alternative explanation is suggested by plots of H-chondrite normalized Se/Co versus Ir/Ni and Au/Co versus Ir/Ni plots. These plots show increased Se/Co ratios and Ir/Ni ratios with respect to H-chondrites. These ratios will increase if a metal/sulfide melt is added to a rock with an initial chondrite composition. Lodranites LEW 88280 and MAC 88177 may have undergone initial metal/sulfide melt extraction along with silicate melt extraction, subsequently, however, another metal/sulfide melt may have invaded the initially depleted rock.

Primitive achondrite EET 84302 is a texturally unique rock which has been called both a lodranite (McCoy et al, 1993) and an acapulcoite (Takeda et al, 1993). Our data indicate EET 84302 is a metal-rich acapulcoite which has experienced little or no silicate melt extraction. Relative to H-chondrites Na, Ca, Sc, Sm, La, Yb, and Lu are roughly chondritic and are close to the abundances of these elements in acapulcoites ALHA 81261 and ALHA 81187. Lodranites LEW 88280 and MAC 88177 are highly depleted in Na, La, and Sm with respect to H-chondrites. Europium is moderately enriched in EET 84302 but is highly depleted in the two studied lodranites. EET 84302 contains moderately to highly enriched abundances of Fe, Ni, Co, Au, Ir, Cr, As, and Sb with respect to H-chondrites and LEW 88280 and MAC 88177 contain depleted and highly depleted concentrations of most of these elements. EET 84302 plots with acapulcoites in lithophile, siderophile, and chalcophile elemental plots, and is clearly separated from lodranite data. The bulk and trace element data of EET 84302 are more compatible with a alcapulcoite classification than a lodranite classification.

Mineralogy and textures also support an acapulcoite classification for EET 84302, rather than classification as an lodranite. Some textures are seemingly characteristic of lodranites. EET 84302 is coarser-grained than acapulcoites as are most lodranites, and cpx grains in EET 84302 contain opx exsolution lamellae like cpx grains in LEW 88280 and MAC 88177. However, more differences than similarities are present between EET 84302 and lodranites. EET 84302 contains abundant plagioclase, metal is extremely abundant, euhedral plagioclase inclusions are present in cpx, and opx grains are commonly full of metal and sulfide inclusions. Mineral compositions of olivine, opx, and cpx in EET 84302 are Mg-rich and are almost identical to acapulcoite mineral chemistries, whereas lodranites tend to have slightly more iron-rich olivine, opx, and cpx.

There are differences between EET 84302 and acapulcoites. EET 84302 is coarser grained, contains more metal, and contains more Cr-spinel than most acapulcoites. A possible explanation of these characteristics is that EET 84302 may be from a slightly deeper part of the acapulcoite parent body than average acapulcoites. The larger grain size may be a result of higher temperatures or slower cooling associated with a deeper stratigraphic position. Opx grains in EET 84302 contain higher concentrations of Al and Cr than opx grains in ALHA 81261 and ALHA 81187. Increased Al and Cr opx contents are generally suggested to indicate higher pressure and temperature conditions in terrestrial mantle peridotites and the same may be true for non-terrestrial rocks. The higher modal concentration of metal and Cr-spinel may also be a result of a deeper stratigraphic position. If the acapulcoite parent body is large enough to have developed a metal-rich core silicate rocks might have an increasing metal content with increasing depth.

CONCLUSIONS

EET 84302 is an acapulcoite, it contains approximately chondritic abundances of lithophile elements but enriched concentrations of siderophile and chalcophile elements. It contains larger grains, more metal, and more Cr-spinel than average acapulcoites, but these differences may be a result of a deeper stratigraphic position in the acapulcoite parent body. There is no geochemical or mineralogical evidence supporting silicate melt extraction from EET 84302.

Acapulcoites ALHA 81261 and ALHA 81187 are approximately H-chondritic in composition. Lithophile elements show no evidence that a silicate melt was removed from the acapulcoites. Siderophile and chalcophile elements show evidence that a metal/sulfide melt may have been removed from ALHA 81261 and ALHA 81187.

Lodranite lithophile elements suggest a silicate melt was removed from LEW 88280 and MAC 88177, which means lodranites are restites like mantle hazburgites on Earth. Low abundances of Fe, Ni, Co, Au, Ir, and As relative to H-chondrite abundances suggest a metal/sulfide melt may have been extracted from MAC 88177. There is no clear geochemical evidence to suggest metal/sulfide melt extraction from LEW 88280, however, the rock contains very little modal metal or sulfide. H-chondrite normalized Se/Co versus Ir/Ni plots indicate a metal/sulfide melt may have been added to lodranites LEW 88280 and MAC 88177 after initial silicate and metal/sulfide melt extraction.

REFERENCES

Bild, R.W., Wasson, J.T., 1976, The lodran meteorite and its relationship to the urelites. Mineralogical Magizine, v. 40, p. 721-735.

Bogard, D.D., Garrison, D.H., McCoy, T.J., Keil, K., 1993, ^{39}Ar-^{40}Ar ages of acapulcoites and lodranites: Evidence for early parent body heating. Abstracts of the 24th Lunar and Planetary Science Conference, p. 141-142.

McCoy, T.J., Keil, K., Clayton, R.N., Mayeda, T.K., 1993, Classificational parameters for acapulcoites and lodranites: The cases of FRO 90011, EET 84302 and ALH A81187/84190. Abstracts of the 24th Lunar and Planetary Science Conference, p. 945-946.

McCoy, T.J., Keil, K., Mayeda, T.K., Clayton, R.N., 1992, Monument draw and the formation of the acapulcoites. Abstracts of the 23rd Lunar and Planetary Science Conference, p. 871-872.

Schultz, L., Palme, H., Spettel, B., Weber, H.W., Wanke, H., Michel-Levy, M.C., Lorin, J.C., 1982, Allan Hills 77081-an unusual stony meteorite. Earth and Planetary Science Letters, v. 61, p. 23-31.

Takeda, H., Saiki, K., Otsuki, M., 1993, A new Antarctic meteorite with chromite, orthopyroxene and metal with reference to a formation model of S asteroids. Abstracts of the 24th Lunar and Planetary Science Conference, p. 1395-1396.

Wasson, J.T., Kallemeyn, G.T., 1988, Compositions of chondrites. Phil. Trans. R. Soc. Lond. A 325, p. 535-544.

Zipfel, J., Palme, H., 1993, Are acapulcoites and lodranites genetically related? Meteoritics, v28 #3, p.469.