

GEOCHEMICAL, MINERALOGICAL AND PETROLOGICAL RELATIONSHIPS IN ENSTATITE CHONDRITES. Alan E. Rubin, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA. (aerubin@ucla.edu).

Introduction

The EH and EL enstatite chondrites are the most reduced chondritic samples in our collections. The meteorites contain graphite and Si-rich metallic Fe and are characterized by very low concentrations of oxidized iron, high abundances of siderophile elements, high modal abundances of kamacite, and by sulfide phases that contain elements that are lithophile under more oxidizing conditions. Some EH chondrites and most EL6 chondrites are impact-melt breccias.

Relative to ordinary chondrites and most carbonaceous-chondrite groups, enstatite chondrites are enriched in volatile and moderately volatile elements.

Unlike all other chondrite groups, EL6 chondrites are depleted in rare-earth elements (REE) and in Ca relative to other refractory-lithophile elements (e.g., Al and Sc). The REE themselves are fractionated in EL6 chondrites, with light REE (LREE) such as La showing moderate depletions relative to heavy REE.

Compared to the mineral compositions in other EH chondrites, several phases in the Abee EH impact-melt breccia have extreme (or near-extreme) concentrations (high or low) of Mn.

These geochemical, mineralogical and petrological peculiarities reflect (1) nebular processes that produced the reduced precursor materials of enstatite chondrites and (2) collisional events on their parent asteroids that caused some rocks to undergo extensive melting, brecciation and annealing.

Volatile Enrichments in Enstatite Chondrites

Enstatite chondrites (particularly EH) are enriched in five geochemical classes of volatile and moderately volatile elements – siderophiles, chalcophiles, alkalis, halogens and nitrogen. These enrichments reflect the composition of the gas in the nebular region where enstatite chondrites formed. The local gas was reducing and may have had high C/O and/or high $p\text{H}_2/p\text{H}_2\text{O}$ ratios relative to gas in other nebular regions.

Siderophiles. Enstatite chondrites are enriched in all siderophiles, irrespective of volatility. A large fraction of the siderophiles in these rocks condensed as metals that combined with metallic Fe. The high Mg-normalized siderophile abundance ratios in enstatite chondrites compared to those in other chondrite groups may have resulted from the failure of Mg-rich particles in the enstatite-chondrite region to settle quantitatively to the nebular midplane during accretion.

Chalcophiles. The enrichment in chalcophiles can be accounted for if the local gas had a high $p\text{H}_2\text{S}/p\text{H}_2$ ratio that caused a larger fraction of the chalcophile elements in the enstatite-chondrite region to react with

metals than in the regions where the precursor phases of ordinary and carbonaceous chondrites condensed. In these latter zones, the chalcophile elements may have had a greater tendency to remain in the gas phase or to condense as fine particles that did not settle efficiently to the midplane prior to planetesimal formation.

Alkalis. Although alkali elements are lithophile under oxidizing conditions, they are partially chalcophile under reducing conditions, forming such phases as caswellsilverite (NaCrS_2) and djerfisherite ($\text{K}_6\text{Na}_9(\text{Fe,Cu})_{24}\text{S}_{26}\text{Cl}$). The alkalis reacted with metals in the enstatite-chondrite region of the nebula; elsewhere, alkalis were more likely to remain in the gas or to condense as fine particles that did not settle efficiently to the midplane.

Halogens. The Cl- and Mg-normalized halogen abundance ratios (F: 3.40; Cl: 0.89; Br: 0.61; I: 0.27) in EH chondrites [1] are strongly correlated with the electronegativities (Pauling scale) of the individual halogens: F (3.98), Cl (3.16), Br (2.96), I (2.66). The correlation is strong: $r = 0.981$, $n = 4$, $2\alpha = 0.02$. EL chondrites also show a strong correlation ($r = 0.953$, $n = 4$, $2\alpha = 0.05$). The halogens are very reactive; the correlation between abundance and electronegativity suggests that, under reducing conditions, the most reactive halogens were the most efficient at forming compounds that were incorporated into enstatite-chondrite precursor materials. These compounds may have included simple metal halides such as FeCl_2 , MgF_2 and FeBr_2 . Under the more-oxidizing conditions that existed in other nebular regions, a larger fraction of the halogens remained in the gas or condensed as fine particles that did settle efficiently to the midplane.

Nitrogen. Nitrogen may have been incorporated into enstatite chondrites as simple nitrides that did not condense under the more-oxidizing conditions that occurred in the regions where other chondrite groups formed. Enstatite chondrites have low bulk $\delta^{15}\text{N}$ ($\sim -20\%$) [2] relative to most ordinary (-5 to $+20\%$) [3] and carbonaceous chondrites ($+20$ to $+190\%$) [3-6]; this may reflect the contribution in enstatite chondrites of small amounts of nitride condensates with $\delta^{15}\text{N}$ values close to the proposed nebular mean ($\sim -360\%$) [7,8]. In contrast, N in carbonaceous chondrites is contained mainly within ^{15}N -rich organic matter [9].

The halogen- and nitrogen-bearing phases in EH chondrites include djerfisherite (with ~ 1.5 wt.% Cl) [10], chondrule mesostases (≤ 4.4 wt.% Cl) [11], fluorrichterite ($\text{Na}_2\text{Ca}(\text{Mg,Fe})_5\text{Si}_8\text{O}_{22}\text{F}_2$) (4.0-4.5 wt.% F) [12,13] and rare fluorphlogopite ($\text{KMg}_3(\text{Si}_3\text{Al})\text{O}_{10}\text{F}_2$) (~ 5 wt.% F) [14]. These minerals may be secondary.

Fluor-richichterite and fluorphlogopite occur only in EH-chondrite impact-melt rocks and breccias. The N-rich minerals in enstatite chondrites are osbornite (TiN) [15-17], sinoite ($\text{Si}_2\text{N}_2\text{O}$) [18-21] and nierite ($\alpha\text{-Si}_3\text{N}_4$) [22-24]. Osbornite and sinoite occur in rocks that have been impact melted; nierite may have formed by exsolution of Si and N from kamacite $\alpha\text{-(Fe,Ni)}$, perryite $(\text{Ni,Fe})_5(\text{Si,P})_2$ or schreibersite $(\text{Fe,Ni})_3\text{P}$ during thermal metamorphism.

REE Fractionations in EL Chondrites

Literature data show that refractory-lithophile elements in most chondrite groups are unfractionated relative to CI; the principal exception is the EL group whose falls (all of which are petrologic type 6) are depleted in Ca and LREE [25]. For example, the mean EL6 Ca/Al and Ca/Sc abundance ratios (0.90 and 0.86, respectively) are appreciably lower than those in mean EH chondrites (1.00 and 0.97). Recent UCLA INAA data on EH3 chondrites [26] show some scatter but are consistent with the EH group being nearly isochemical irrespective of petrologic type. Rare earth elements are fractionated in EL6, but not in EH3-5 chondrites. Mean EL6 La/Yb and Eu/Yb abundance ratios are 0.79 and 0.92, respectively; the corresponding values in mean EH chondrites are 1.05 and 1.01.

It is improbable that the REE fractionations in EL chondrites were caused by terrestrial weathering or sample preparation. Most analyzed EL6 chondrites are observed falls that exhibit little weathering; in contrast, some Antarctic EL3 chondrites (which are all more weathered than observed falls) have essentially unfractionated REE abundances and significantly higher Ca than EL6 chondrites. Although water could dissolve oldhamite (CaS) (the major REE carrier in enstatite chondrites [27,28]) during sample preparation, both fractionated and unfractionated samples have been cut using water as a lubricant.

Bulk data [26,29,30] show that some EL3 and EL4 samples are much less fractionated in LREE than EL6 chondrites; other EL3 samples exhibit fractionations similar to those of EL6 chondrites. Parent-body impact processes may be responsible for producing the EL fractionations in refractory-lithophile elements. Many EL6 (and some EL3 and EL4) chondrites have been shocked and partly melted [e.g., 21]. When large amounts of heat were deposited during impacts, oldhamite and plagioclase may have been melted and transported to regions not commonly included in analyzed samples; the "normal" EL6 chondrite matter is the residuum that is depleted in LREE and Ca.

Mineralogical Peculiarities in Abee (EH)

Keil [31] showed that, among EH chondrites, Abee exhibits unusual mineralogical traits. These include very low MnO in enstatite (<0.01 wt.%), higher Mn in troilite (0.24 wt.%) and oldhamite (0.36

wt.%) than in EH4 Indarch and EH3 Kota-Kota (which are not impact-melt rocks), low Mn in keilite (Fe,MgS) (3.6-4.3 wt.%), high modal abundances of keilite (11.2 wt.%) and silica (~ 7 wt.%, but ranging locally up to 16 wt.% [32]), and low modal abundances of total silicates (58.8 wt.%) and troilite (5.8 wt.%) [31].

These features result from Abee's complex history of shock melting and crystallization. Impact heating caused the loss of MnO from enstatite and sulfidation of Mn. Troilite and oldhamite that crystallized from the impact melt acquired relatively high Mn contents. Keilite [33] and silica also crystallized from the melt; these phases (as well as metallic Fe) were produced at the expense of enstatite, niningerite and troilite, e.g.: $\text{MgSiO}_3 + \text{MgFeS}_2 + 2\text{FeS} = 2\text{FeMgS}_2 + \text{SiO}_2 + \text{Fe} + \frac{1}{2}\text{O}_2$ (wherein the formula units for niningerite and keilite are doubled). Melting of niningerite and troilite produced a S-rich liquid with higher Fe/Mg and Fe/Mn ratios than in the original niningerite (Mg,FeS), allowing the crystallization of keilite.

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