

An Application of REE-in-Two-Pyroxene Thermometry to Primitive Achondrites: Illuminating the Thermal Histories of Partially Differentiated Asteroids

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Introduction: Primitive achondrites include several groups of stony meteorites that are residues of low-degrees of partial melting, hence they have experienced higher temperatures (temps) than chondritic meteorites. Cosmochemical, oxygen isotope, and cosmic ray exposure age data for several primitive achondrite groups (and associated silicate-bearing irons) overlap and point to formation on the same asteroid parent body. In particular, the acapulcoite and lodranite groups are thought to originate on a common acapulcoite-lodranite parent body (ALPB) [1]. Acapulcoites have experienced low-degrees of partial melting (<1 to ~5%) and have been heated to ~950-1050°C, warm enough to induce metal-sulfide melting [2]. Lodranites show higher-degrees of partial melting (~5 to 20%) and have experienced temps of ~1050-1200 °C, hot enough to segregate silicate partial melts [3]. Another primitive achondrite clan includes the rare winonaite group that have oxygen isotopic compositions similar to silicate-bearing IAB iron (and IIICD) meteorites, which suggests formation of these groups on a common parent body [4,5]. Rocks from the winonaite-IAB iron parent body (WIPB) experienced highly variable temps, consistent with the idea that the WIPB experienced collisional fragmentation and reassembly after reaching peak temps [6]. Here, we apply traditional two-pyroxene and Ca-in-olivine thermometry, complemented with a recently developed REE-in-two-pyroxene thermometer [7] that relies on the relatively slow diffusive exchange of REEs between coexisting pyroxenes, to a suite of primitive achondrites. These data furnish insights into the thermal history of the ALPB and WIPB. Accurate thermal histories in turn allow for a more critical evaluation of models regarding the geologic evolution of partially differentiated asteroids.

Samples and Methods: We selected 8 acapulcoite-lodranites and 6 winonaite-IAB irons for analysis (see Table). Meteorites were provided by the NASA Meteorite Working Group (MWG) as polished thin/thick sections or were acquired commercially and prepared in our lab. Orthopyroxene (opx), clinopyroxene (cpx), and olivine (ol) were identified with a petrographic microscope and analyzed via EPMA at the University of Tennessee with a focused 30 nA, 15 kV beam. For Ca-in-ol, we used a count time of 150 s to achieve a detection limit for CaO=0.011 wt%. REEs, Y, Ti, Sc, and Zr were measured in opx and cpx by LA-ICP-MS at the University of Texas with a laser fluence of ~6.2 J/cm² at 10 Hz and a spot size of 75 μm. We analyzed large, proximal, and inclusion-free grain pairs to maximize the potential for

chemical equilibrium. At these analytical conditions, detection limits for REEs are ~20-50 ppb.

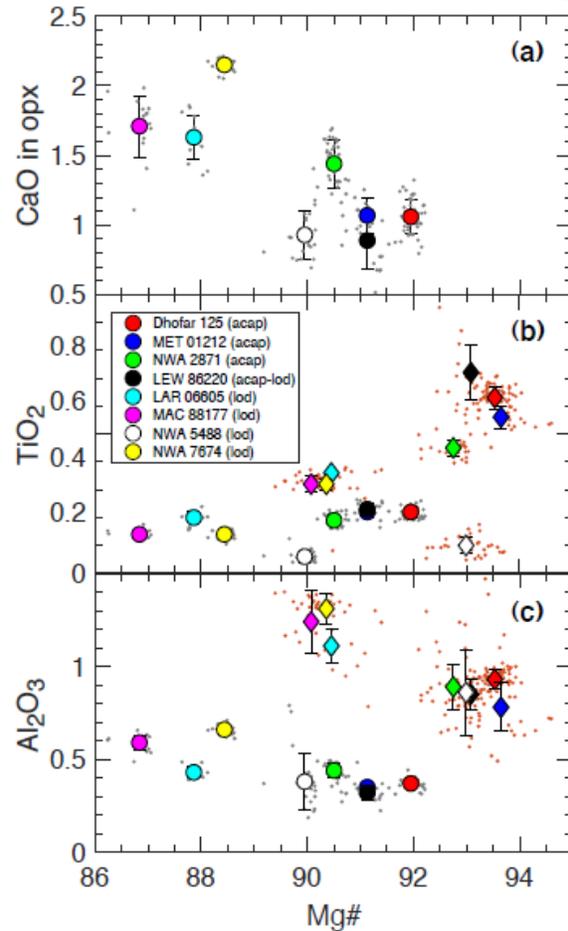


Figure 1. Major element variations in eight acapulcoite-lodranite clan meteorites. Small gray (opx) and orange (cpx) dots show the mineral compositions of all spots analyzed; large colored circles (opx) and diamonds (cpx) are the averaged compositions of each sample.

Major and Trace Elements: Major elements are plotted in Fig. 1. Clouds of gray (opx) and orange (cpx) dots show the range of compositions for all spots analyzed. Averaged compositions for each sample are plotted using large colored symbols; error bars indicate 1σ standard deviations. Acapulcoites have silicates that are more reduced (Mg-rich) than lodranites, which is opposite the expected partial melting trend. Samples show some compositional variation in opx within each group, but generally demonstrate compositional homogeneity in cpx. In terms of major elements, lodranite NWA 5488 appears to be chemically similar to the acapulcoite group (Figs. 1a;

1c), but is depleted in Ti and REEs relative to the other ALC samples (Figs. 1b; 2). Chondrite normalized REE+Y abundances are shown in Fig. 2. Replicate analyses of multiple (~4–6) grain pairs for each meteorite show consistent patterns and exhibit negative Eu anomalies (except NWA 5488). Light-REEs in opx are typically below detection limits but Gd, Dy, Y, Er and Yb have sufficient concentrations for accurate characterization. Light-heavy REEs in cpx are above detection limits and replicate analyses show good reproducibility.

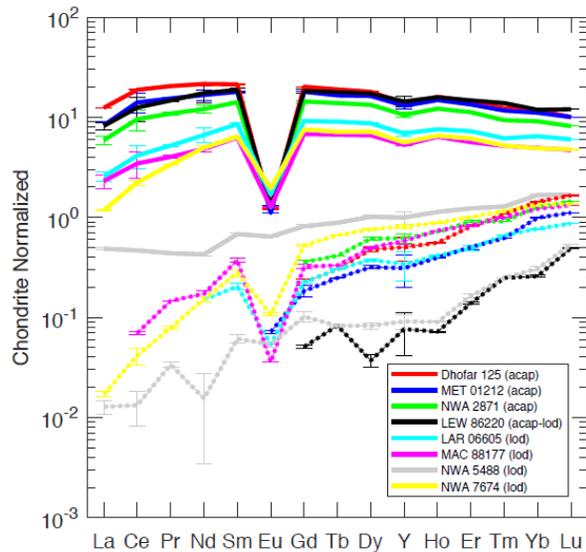


Figure 2. Chondrite normalized REE+Y abundances in cpx (solid lines) and opx (dotted lines) for ALC meteorites. Error bars are 1σ standard deviations of replicate analyses.

Temperatures: REE-in-two pyroxene (T_{REE}) temps [7], two-pyroxene Brey & Köhler (T_{BKN}) temps [9], and Ca-in-olivine ($T_{\text{Ca-OI}}$) temps [10] are listed in the Table (T_{REE} for 6 winonaite-IAB irons forthcoming). T_{REE} for the acapulcoite group are ~100 to several 100's of °C lower than T_{BKN} temps. Lodranite samples generally have T_{REE} that are higher than T_{BKN} and approximate (1103-1208 °C) the silicate peritectic (~1150 °C). Winonaite-IAB irons have T_{BKN} near or above the Fe-FeS eutectic (~988 °C), consistent with the low-degrees of partial melting observed for this clan. $T_{\text{Ca-OI}}$ (670-851 °C) are in good agreement within meteorite groups and reflect subsolidus closure temps. T_{REE} uncertainties are obtained from the multi-element temperature inversion and originate partly from analytical scatter; additional sources of uncertainty may include failure of the sample to attain chemical equilibrium or late chemical disturbance (e.g., due to melt infiltration or shock metamorphism).

Discussion: Trivalent REE diffusion is ~1-2 orders of magnitude slower than divalent major element diffusion in pyroxene [11] such that the REE-in-two pyroxene thermometer often records temps tens to hundreds of degrees higher than major element-based thermometers

(e.g., T_{BKN}) for samples that experienced slow cooling. T_{BKN} can be compared to T_{REE} as a proxy for cooling rate. To first order, the larger the ΔT , the slower the cooling rate for the sample can be inferred. In the case of the acapulcoite samples (see Table), T_{REE} record subsolidus temps much lower than two-pyroxene (T_{BKN}) temps (i.e., negative ΔT s), which may suggest late heating or trace element disequilibrium. Three of four lodranites in this study record higher T_{REE} than T_{BKN} , which we infer as reflecting peak or near-peak temps. These temps are high enough to segregate silicate partial melts. The lack of preservation of partial melts that are complementary to residual lodranites, or their crystallized products, in the meteorite record may suggest that they were removed from the asteroid parent body by pyroclastic volcanism early in Solar System history [2]. However, several acapulcoites have been described that are host to gabbroic-like partial melts (e.g., LEW 86220 [1,2,12]; FRO 93001 [13]), which provides compelling evidence that these complementary partial melts existed on the ALPB.

Sample	T_{REE}	2-Px ^a	T_{BKN}	ΔT	$T_{\text{Ca-OI}}$
Dhofar 125 (acap)	852±12	1120 ^a	1034	-182	851
MET 01212 (acap)	734±18	-	948	-214	728
NWA 2871 (acap)	905±16	-	1030	-125	693
LEW 86220 (trans)	519±1	-	965	-446	718
LAR 06605 (lod)	905±38	-	1047	-142	700
MAC 88177 (lod)	1112±32	1200 ^b	1006	+106	700
NWA 5488 (lod)	1103±12	-	941	+162	822
NWA 7674 (lod)	1208±41	-	1114	+94	686
GRA 12510 (win)	-	-	978	-	723
NWA 725 (win)	-	-	944	-	728
NWA 4024 (win)	-	-	891	-	686
QUE 94535 (win)	-	-	1030	-	750
GRO 06050 (IAB)	-	-	991	-	742
LAR 06876 (IAB)	-	-	942	-	670

Data from [14]^a and [15]^b; All temperatures given in °C

We hypothesize that the subsolidus T_{REE} recorded by the acapulcoite samples reflect interaction of partial melts, which were segregated from residual lodranites, with an acapulcoite layer on the ALPB. Future efforts will explore the possibilities of late heating by magmatic interaction, or trace element disequilibrium produced by crystallization of cpx from impregnating melts.

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