

New Major and Trace Element Data from Acapulcoite-Lodranite Clan Meteorites: Evidence for Melt-Rock Reaction Events and Early Collisional Fragmentation of the Parent Body

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Introduction: New major and trace element data illuminate the magmatic and thermal evolution of the acapulcoite-lodranite parent body (ALPB). We observe major and trace element disequilibrium in the acapulcoite and transitional groups that provide evidence for melt infiltration and melt-rock reaction processes. In lodranites, which represent sources of the infiltrating melts, we observe rapid cooling from high temperatures (hereafter temps), consistent with collisional fragmentation of the parent body during differentiation.

Background: Primitive achondrites of the acapulcoite-lodranite clan (ALC) display a continuum of thermal metamorphism and partial melting with increasing temps. The ALC include: a newly recognized chondritic member of the clan (i.e., GRV 020043 [1]), “primitive” acapulcoites [2] that contain relic chondrules (e.g., GRA 98028), “typical” acapulcoites that have experienced incipient partial melting (<1 to ~5%) of metal-sulfide (e.g., Dhofar 125 [2,3]), lodranites that exhibit higher-degrees of partial melting (~5 to 20%) and have lost silicate partial melts (e.g., MAC 88177 [2,3,4,5]), “transitional” meteorites that have textural and chemical properties intermediate between acapulcoites and lodranites (e.g., EET 84302 [2,6]), and “enriched” ALC meteorites that host gabbroic partial melts (e.g., LEW 86220 [2,3,7]; FRO 93001 [8]). Based on cosmochemical, oxygen isotope, and cosmic ray exposure age data, this gradual sequence of thermally processed material is thought to originate on a common parent body [6,7,9,10]. Here, we apply major and trace element mineral chemistry (Fig. 1) plus several thermometric methods, including a REE-in-two-pyroxene thermometer [11], to 8 ALC meteorites in order to shed light on the geologic history of the partially differentiated ALPB.

Samples and Methods: Our sample suite includes three acapulcoites (Dhofar 125, MET 01212, NWA 2871), two transitional samples (LAR 06605, LEW 86220), and three lodranites (MAC 88177, NWA 5488, NWA 7674). Orthopyroxene (opx), clinopyroxene (cpx), and olivine (ol) were analyzed via EPMA with a focused 30 nA, 15 kV beam. For trace elements, we targeted large, proximal, and inclusion-free opx-cpx grain pairs, then measured REEs, Y, Ti, Sc, and Zr with LA-ICP-MS using a laser fluence of ~6.2 J/cm² at 10 Hz. Limits of detection (LoD) for REEs are ~20-50 ppb.

Trace Element Mineral Chemistry: Chondrite normalized REE+Y abundances are shown in Fig. 1a. Errors are 1 σ SD of replicate analyses of multiple (~2–6) grains. Light-REEs in opx are typically BDL but Dy to Lu (+Y) have sufficient concentrations for accurate characterization. Light-heavy REE+Y in cpx are above LoD and

patterns exhibit negative Eu anomalies. REE patterns are generally consistent among the three groups, however comparison of calculated equilibrium melts for acapulcoite and transitional cpx and opx demonstrates disequilibrium partitioning in those samples, especially for light-REEs in cpx. In contrast, lodranites are in apparent trace element equilibrium (Fig 1b). They are depleted in REE+Y relative to acapulcoite-transitional samples in cpx (Fig. 1a), and display consistent REE abundances except NWA 5488, which is considerably depleted.

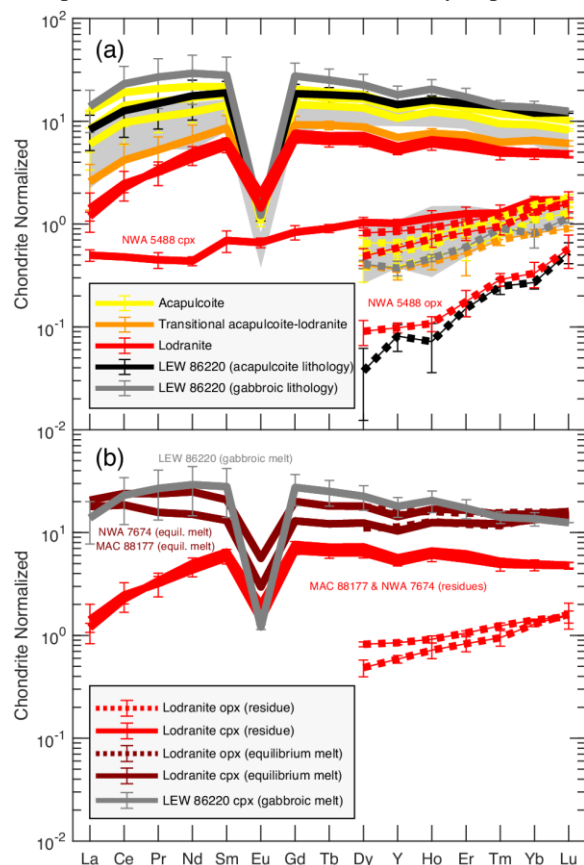


Figure 1. (a) REE+Y abundances in cpx and opx for acapulcoites, transitionals, lodranites, and the acapulcoite and gabbroic lithologies of enriched LEW 86220. Values for acapulcoite-transitional samples from [10] are shown as light gray fields. **(b)** REE+Y abundances for two residual lodranites (red) compared to their calculated equilibrium melt concentrations (dark red) and the LEW 86220 gabbroic melt cpx from Fig 1a.

Melt-Rock Reaction on the ALPB: LEW 86220 is an enriched ALC meteorite [2] as it consists of fine-grained acapulcoite-like “xenoliths” surrounded by a recrystallized, coarse-grained, plagioclase+cpx (+metal-sulfide) gabbroic-like melt (Fig 2; [3,7]). We measured REE+Y in pyroxene (px) for both the acapulcoite and gabbroic

lithologies of LEW 86220. In Fig. 1a acapulcoite xenoliths are strongly depleted in REEs+Y in opx (black); however, abundances in cpx are similar to other acapulcoites. REE+Y abundances in the gabbroic lithology (dark gray) are enriched $\sim 2\text{-}3\times$ relative to acapulcoite and transitional samples. REE+Y abundances in cpx for acapulcoite and transitional groups may be explained by cryptic melt infiltration of (REE+Y)-enriched partial melts complementary to residual lodranites. To corroborate this interpretation, we calculated [see 12] equilibrium melt compositions (dark red) of residual lodranites MAC 88177 and NWA 7674 (red) (Fig 1b). The equilibrium melt REE+Y patterns are consistent with the gabbroic pattern of LEW 86220 (Fig 1b), supporting the hypothesis that silicate partial melts originated in a lodranite source region and infiltrated an acapulcoite horizon. It appears that melt migration processes on the ALPB were caught in the act in LEW 86220 [2,3,7,13].

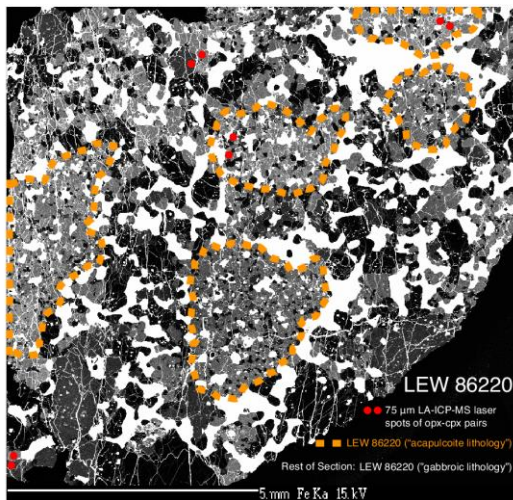


Figure 2. Fe K α elemental map of LEW 86220. Phases are plagioclase (black), cpx (dark gray), ol and opx (lt. gray), metal-sulfide (white). Acapulcoite-like "xenoliths" are surrounded by recrystallized gabbroic melts (section minus xenoliths). LA-ICP-MS laser spots (red; not to scale) indicated.

Origins of Mineral Zonation: We measured chemical zoning profiles of TiO₂, Al₂O₃, and Cr₂O₃ (and CaO in opx) in px of acapulcoite Dhofar 125 and lodranite MAC 88177. In Dhofar 125, TiO₂, Al₂O₃, and Cr₂O₃ exhibit gradual enrichments towards cpx rims. Conversely, in lodranite MAC 88177, Al₂O₃, Cr₂O₃, and CaO (in opx) decrease gradually towards rims, consistent with the results of [5]. This suggests acapulcoite concentration gradients are associated with melt infiltration, whereas lodranite concentration gradients are consistent with subsolidus redistribution during cooling.

Temperatures and Cooling Rates: REE diffusion is orders of magnitude slower than major element diffusion in px [14] such that the REE-in-two-px thermometer [11] can record temps 10's to 100's of degrees higher than two-px solvus thermometers (T_{BKN}) for samples that experienced slow cooling. T_{BKN} [15] can be compared to

T_{REE} as a proxy for cooling rate (Fig. 3). To first order, the larger the ΔT , the slower the cooling rate. In acapulcoite-transitional samples, T_{REE} record subsolidus temps $\sim 70\text{-}170^\circ\text{C}$ below T_{BKN} ($-\Delta T$ s), which likely reflects trace element disequilibrium in px (yellow field), consistent with grain-scale major element zoning. These samples record T_{BKN} ranging from $\sim 950\text{-}1110^\circ\text{C}$, near or $>988^\circ\text{C}$ (Fe-FeS eutectic), consistent with the low-degrees of partial melting inferred for these groups. Lodranites record T_{REE} $>$ T_{BKN} ($+\Delta T$ s) with T_{REE} ranging from $1125\text{-}1242^\circ\text{C}$, which we infer to reflect peak or near-peak magmatic temps, close to or $>1150^\circ\text{C}$ (silicate peritectic). Lodranites record rapid cooling rates of ~ 0.5 to $\sim 30^\circ\text{C/yr}$ from T_{REE} to T_{BKN} temperature intervals.

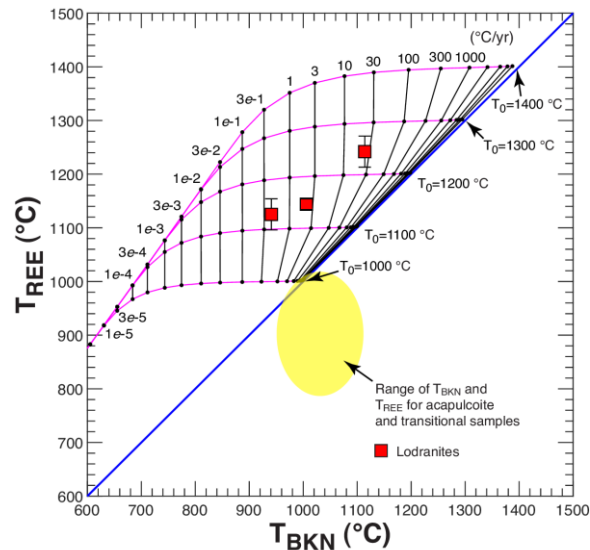


Figure 3. T_{REE} (y-axis) versus T_{BKN} (x-axis). Lodranites (red) record rapid cooling (~ 0.5 to $\sim 30^\circ\text{C/yr}$) from peak, magmatic temps. Temperature values for acapulcoite-transitional samples (yellow) most likely reflect trace element disequilibrium in pyroxenes. Initial temps (T₀) indicated next to blue 1:1 line.

Conclusions: The range of metamorphism and partial melting in ALC meteorites can be explained by segregation of partial melts from a deeper lodranite source that infiltrated a shallower acapulcoite horizon. Thermometric results record rapid cooling in lodranites from peak to near-peak temps, which suggests that ALC partial melting and metamorphism were interrupted by a collisional fragmentation event.

References: [1] McCoy et al. (2019) *Geochem.* 79, 125536. [2] Patzer et al. (2004) *MAPS* 39, 61-85. [3] Lucas et al. (2019) *MAPS* 54, 157-180. [4] McCoy et al. (1997) *GCA* 61, 623-637. [5] Miyamoto & Takeda (1994) *JGR* 99, 5669-5677. [6] Keil & McCoy (2018) *Chem. der Erde* 78, 152-203. [7] McCoy et al. (1997) *GCA* 61, 639-650. [8] Folco et al. (2006) *MAPS* 41, 1183-1198. [9] Mittlefehldt et al. (1996) *GCA* 60, 867-882. [10] Floss (2000) *MAPS* 35, 1073-1085. [11] Liang et al. (2013) *GCA* 102, 246-260. [12] Sun & Liang (2012) *CMP* 163, 807-823. [13] Floss (2000) *LPSC XXXI*, #1277. [14] Cherniak & Liang (2007) *GCA* 71, 1324-1340. [15] Brey & Köhler (1990) *J. Pet.* 31, 1353-1378.