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# Lewis Cliff 87223, an anomalous enstatite chondrite and the diversity of enstatite chondrites

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**Abstract**–We studied a thin section of Lewis Cliff (LEW) 87223, an unusual EL3-related, enstatite chondrite (EC) that has primary and secondary features not observed in other ECs. We studied its metal-rich nodules, possible shock features, and chondrules, eight of which are Al-rich chondrules (ARCs). LEW 87223 has petrologic and compositional features similar to EL3s. Enstatite is the dominant mineral; chondrule boundaries are well defined; Si content of metal (0.5–0.6 wt%) is consistent with typical EL3; it has Cr-bearing troilite, oldhamite, and alabandite; and its O-isotopic composition is similar to other ECs. However, metal abundance in LEW 87223 (~13 vol%) is slightly higher than in other EL3s and its metal nodules are texturally and mineralogically different from other ECs. Both high and low Ni metals are present, and its alabandite has higher Fe (27.8 wt% Fe) than in other EL3s. Silicates appear darkened in plane polarized light, largely due to reduction of Fe from silicate. A remarkable feature of LEW 87223 is the high abundance of ARCs, which contain Ca-rich plagioclase and varying amounts of Na-rich plagioclase along chondrule edges and as veins. This suggests Na metasomatism and the possibility of hydrothermal fluids, potentially related to an impact event. LEW 87223 expands the range of known EC material. It shows that ECs are more diverse and record a wider range of parent body processes than previously known. LEW 87223 is an anomalous EL3, potentially the first member of a new EC group should similar samples be discovered.

## INTRODUCTION

Enstatite chondrites (ECs) are essential objects of study, as they are a potential match for the building blocks of the Earth. They have stable O, Cr, Ti, Ni, and Zn isotopic compositions, among others, similar to the Earth–Moon system (Clayton et al., 1984; Javoy, 1995; Paniello et al., 2012; Warren, 2011), as well as volatile H, N, and C isotope ratios similar to the Earth's (Gray et al., 2021a, 2021b; Piani et al., 2020). However, EC bulk chemistry (Al/Si, Mg/Si) and Si isotopes do not match the Earth (Dauphas et al., 2015; Kadlag et al., 2019), posing difficulties for modeling Earth from EC precursors. ECs are also among the most reduced solar system materials (Keil, 1968; Weisberg & Kimura, 2012) and could possibly be linked to the formation of Mercury as it is the most reduced planet (Ebel & Stewart, 2017). It is therefore important to further explore and document the range of petrologic, chemical, and isotopic properties of the EC reservoir.

It has recently become clear that there is considerably more diversity among the ECs than previously recognized. Lin and Kimura (2010) recognized Yamato 793225 (Y-793225) as a new kind of EC with properties intermediate between EH and EL potentially representing a new EC grouplet. Kimura et al. (2021) described a diopside-rich EL3

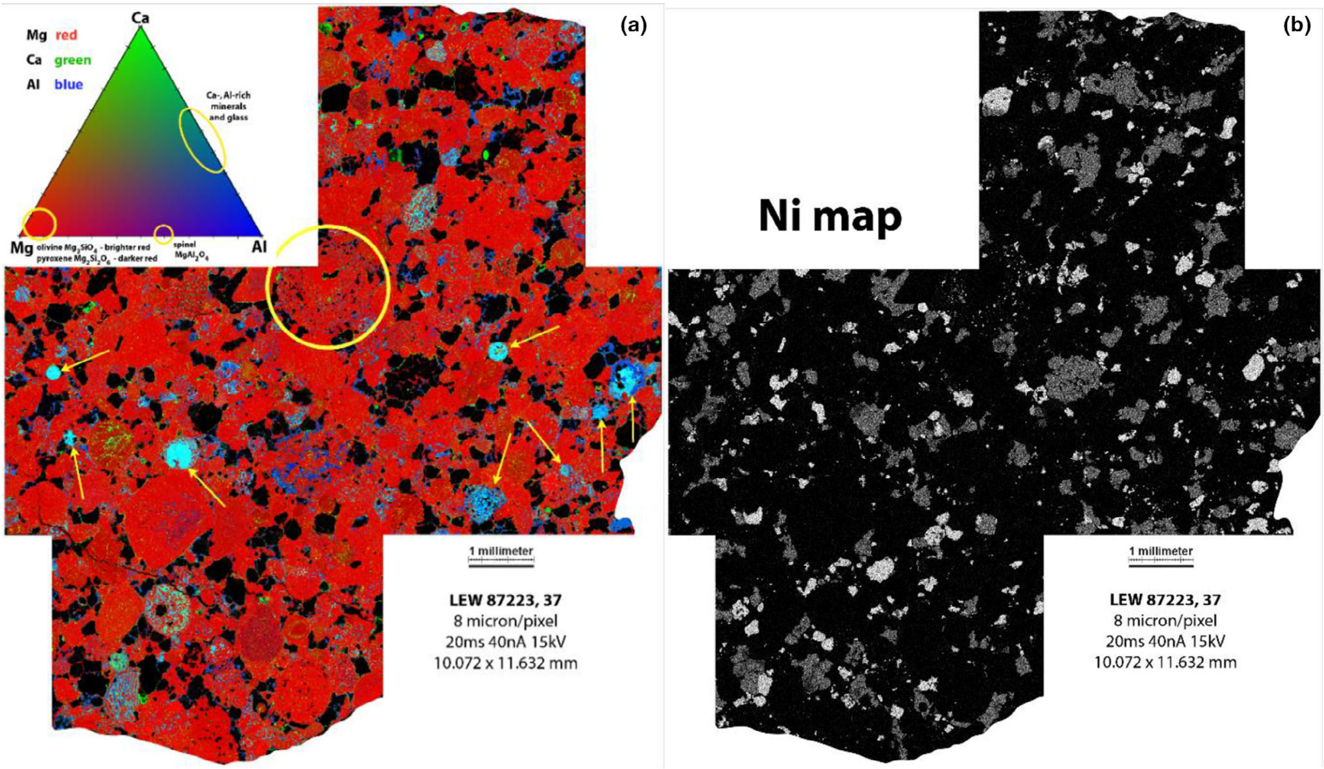


FIGURE 1. a) Mg-Ca-Al (red–green–blue) composite element map of LEW 87223, 37. Enstatite (En) is dark red and is the dominant silicate mineral. Olivine (Ol) is brighter red. Al-rich chondrules are highlighted with arrows. A layered chondrule with metal–sulfide-rich shells is circled. b) Ni element map of LEW 87223, 37, showing two FeNi alloy minerals. Medium gray is kamacite and lighter gray is mostly taenite, some is schreibersite ($FeNi_3P$). (Color figure can be viewed at wileyonlinelibrary.com.)

clast in the Almahata Sitta polymict breccia with a unique thermal history. Northwest Africa (NWA) 8785 is an anomalous EL3 with a high abundance of an oxidized matrix composed of magnetite and an amorphous silicate (Rindlisbacher et al., 2021; Weisberg, Kita, et al., 2021; Weisberg, Zolensky, et al., 2021). EC clasts in the Kaidun breccia contain hydrous minerals, unknown in any of the known EC groups (Higashi et al., 2019; Zolensky & Ivanov, 2003). Although the latter observation may be due to mobilization of water on the Kaidun carbonaceous chondrite parent body, in total these findings suggest that the EC, particularly the EL3, parent bodies were considerably more complex than previously understood.

Lewis Cliff (LEW) 87223 is an unequilibrated E3 chondrite that was recovered in Antarctica and assigned a weathering grade C (Mason, 1989). It has characteristics that have not yet been observed in any other E3 (Grossman et al., 1993; Weisberg & Kimura, 2012; Zhang et al., 1995a, 1995b). The Si content of its metal (~0.6%), the presence of alabandite (Mn,FeS) instead of niningerite (MgS), and its bulk W/Ni ratio are consistent with an EL classification, but the high amount of metal (23 wt%) and siderophile element abundances are closer to those of an EH (Grossman et al., 1993). It was originally classified as an E3 chondrite (Mason, 1989), then later interpreted as a possible link between the ordinary and E chondrites and thus classified as a "unique E3 chondrite" (Grossman et al., 1993). More recently, it was suggested that LEW 87223 may be a new type of EC (Weisberg et al., 1995; Weisberg & Kimura, 2012).

In order to better understand the formation of LEW 87223 and evaluate its classification and relationship to other ECs, we studied its metal-rich nodules, possible shock features, and chondrules, where we discovered a high abundance of Al-rich chondrules (ARCs) (Figure 1a), as also described by Grossman et al. (1995), many of which are also rich in Na. We also studied a more typical EL3 chondrite, Asuka-881314 (A-881314), for comparison. A-881314 is an unequilibrated EL3 also recovered from Antarctica (Kimura et al., 2021). Our goals are to document the diversity of ECs, understand the range of conditions that formed the ECs, and potentially use that information to gain insight into the formation of the inner planets such as Earth and Mercury.

## METHODS

We studied NASA (ANSMET) polished thin section LEW 87223, 37 and National Institute of Polar Research (NIPR) thin section A-881314, 51-1 using the petrographic microscope, scanning electron microscope (SEM), and electron probe microanalyzer (EPMA). The petrographic microscope (plane polarized and cross-polarized light) was used to identify features of shock, such as darkening of silicates within LEW 87223. We used the Hitachi S4700 Field Emission SEM with GW Centaurus backscattered electron detector and a Bruker Quantax 200 energy-dispersive spectrometer (EDS) to produce images of each sample, identify minerals, and gather qualitative data on the chemistry of the minerals. We also analyzed the metal in LEW 87234, a sample paired with LEW 87223.

The Cameca SX5 EPMA was used to generate element maps of each section, as well as gather quantitative chemical compositions of the silicates and metal. The element maps are wavelength-dispersive spectral (WDS) maps of Si, Al, Mg, Ca, Fe, Ti, S, P, Na, and Ni X-ray emission intensity. Operating conditions were 15 kV and 40 nA, with a dwell time of 12 ms on one micrometer spots spaced 6 μm apart (6 μm resolution) (Figure 1). Using these maps, we identified and numbered 66 chondrules, 8 ARC's, and 76 metal-rich nodules. Higher resolution maps at 1–2 μm pixel spacing were generated for several select chondrules and nodules. This allowed for detailed determination of the microdistributions of elements and phases in the chondrules.

Quantitative mineral compositions were determined on nominally 1–2 μm spots using the SX5. Natural and synthetic standards were chosen based on the compositions of the minerals being analyzed. An accelerating potential of 15 keV and a beam current of 20 nA were used for silicates and 20 keV and 25 nA for metal. Counting times were 20 s on peak, and 10 s on background (off-peak) spectrometer positions. Relative uncertainties (2 sigma), based on counting statistics, are calculated to be <2% for major elements Si, Fe, Mg; 5% for Al, Ca, K; and 10% for Ti, Cr, Mn, Na. Metal composition data were collected previously from LEW 87234, which is paired with LEW 87223. Data collected from silicates and metal are given in Tables S1 and S2, respectively.

## RESULTS

### General Petrography

LEW 87223 has characteristics that are typical of an E3, specifically EL3. The chondrules have sharp boundaries. Many are enstatite-rich with enstatite close to endmember ($MgSiO_3$) in composition (0.2–0.9 wt% FeO) and olivine is present but minor (Figure 1) and is generally near-endmember forsterite ($Mg_2SiO_4$) in composition. Pyroxene compositions in LEW 87223 were previously reported by Weisberg et al. (1994). Some chondrules and fragments have FeO-bearing pyroxene with up to 10.2 wt% FeO, as also shown by Weisberg et al. (1994). The most common chondrule texture is porphyritic pyroxene. LEW 87223 has chondrule sizes (most are ≥500 μm in apparent diameter) similar to those in EL3 chondrites (Schneider et al., 2002). One chondrule was identified as layered (Figure 1a), which is not typically found in ECs and is more commonly found in carbonaceous chondrites. It consists of an enstatite-rich core surrounded by an outer shell containing higher amounts of FeNi metal, Fe-, Ni-phosphide, daubréelite, and Fe-sulfide. In general, metal is abundant in LEW 87223 and two FeNi metal phases (kamacite and taenite) are present (Figure 1b).

In plane polarized light, in comparison to a more typical EL3 like A-881314, the chondrules in LEW 87223 appear darkened (Figure 2a,b). This darkening is similar to "shock darkening," a feature interpreted to be the product of impact heating, dispersing fine-grained metal and sulfides into silicates (Stöffler et al., 1991). Shock darkening in ECs was previously discussed by Rubin et al. (1997). Many shock veins have been observed within LEW 87223 as well (Zhang et al., 1995a). However, much of the darkening in LEW 87223 is the result of tiny (submicrometer) metal blebs within the mafic silicates, presumably due to reduction of Fe from the FeO-bearing silicates (see figure 1 in Weisberg et al., 1994). This is common to a lesser extent in other ECs and is not necessarily induced by shock. Most silicates in A-881314, in comparison, are clear in plane polarized light (Figure 2a).

### Al-Rich Chondrules

A remarkable feature of LEW 87223 is its high abundance of Al-rich chondrules (ARCs) that show varying degrees of Na-enrichment (Figure 1a). We identified eight of these objects in the one thin section we studied. They were identified by their dominantly blue (Al-rich) appearance in the Mg-Ca-Al (red-green-blue) element map (Figure 1a). One of these chondrules, C45, has an anorthite-rich interior with fine, in some cases skeletal, crystals of diopside (Figure 3a,b). Albitic plagioclase occurs on the chondrule edge and along fine Na-rich veins within the interior (Figure 3c). This chondrule is rimmed by a mixture of coarser anorthite, enstatite, and minor albitic plagioclase. Within some of the ARCs, we observe both coarse albitic and anorthitic

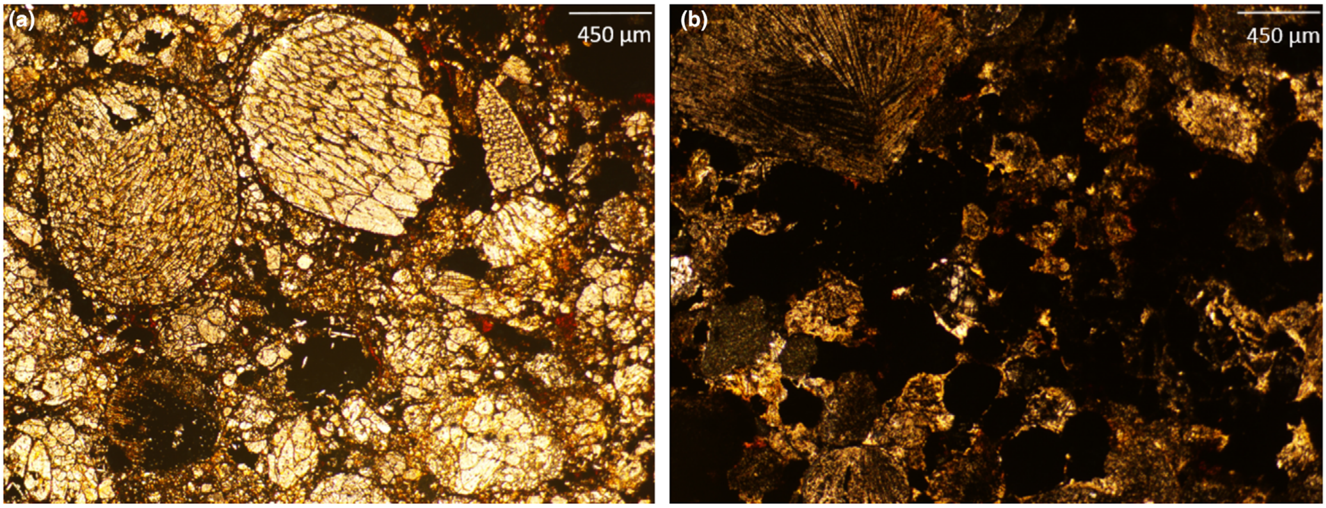


FIGURE 2. a) Photomicrograph of a typical EL3 chondrite, Asuka 881314, taken in plane polarized light. b) Photo of LEW 87223 taken in plane polarized light, where its chondrules look darkened compared to a typical EL3 chondrite. (Color figure can be viewed at wileyonlinelibrary.com.)

plagioclase occurring together. For example, C30 is composed of enstatite and forsterite with a barred-like structure, inter-fingered by a mesostasis containing fine crystals of anorthitic plagioclase ($An_{74}$, $Ab_{24}$) (Figure 3d,e). Parallel to the enstatite and forsterite laths is albitic plagioclase ($An_{21}$, $Ab_{74}$) (Figure 3d,e; Table 1). Another of these objects, C19, consists of an anorthitic plagioclase and diopside core surrounded by coarse albitic plagioclase ($An_{19}$, $Ab_{75}$) (Figure 3f,g). In another object, C24 (Figure 3h,i), two feldspars are present: anorthitic ($An_{90}$, $Ab_9$) and albitic ($An_{22}$, $Ab_{71}$) plagioclase (Table 1). The plagioclase grains are euhedral to anhedral and up to 60 µm in size. Chondrule C24 also shows vein-like intrusions of the albitic plagioclase into the anorthitic plagioclase (Figure 3i). These do not resemble the exsolution lamellae found in plagioclase in terrestrial granites. They are more similar to veins occurring in terrestrial rocks that have undergone a form of metasomatism referred to as albitization (e.g., Engvik et al., 2014). The albitic plagioclase in all the ARCs analyzed is generally similar in composition whereas the anorthitic plagioclase is more variable in composition. As discussed below, we interpret the anorthitic plagioclase to be a primary phase of the chondrule mesostasis and the albitic plagioclase as secondary.

**Metal and Sulfides**

Sulfides in LEW 87223 are present in the chondrules and associated with the metal-rich nodules. They include Ti- and Cr-bearing troilite (FeS), daubréelite ($FeCr_2S_4$), oldhamite (CaS), and ferroan alabandite (Mn,FeS). Troilite compositions have been reported as having 1.2 wt% Ti and 7.8 wt% Cr (Zhang et al., 1995a). The alabandite contains a higher FeS content than has been found in alabandite in any other EL chondrites, with 27. 8 wt% Fe (Zhang et al., 1995a). This suggests that the alabandite in LEW 87223 formed under higher temperatures than those inferred for most EL3 chondrites, according to the sulfide geothermometer of Skinner and Luce (1971, also displayed in figure 5c of Zhang et al., 1995a).

Metal abundance in LEW 87223 is higher than has been observed in most E3s (~13 vol%, Weisberg & Kimura, 2012; Zhang et al., 1995a). Most of the metal occurs in metal-rich nodules, as seen in other EL3s, but the nodules are texturally and mineralogically different from those in other EL3s. In most EL3s, the nodules appear near-spherical in shape and contain intergrowths of enstatite crystals in opaque phases (e.g., Van Niekerk & Keil, 2011; Weisberg et al., 2015), as also observed in A-881384 (Figure 4c). In LEW 87223, the nodules are irregular and look like aggregates of metal granules with silicate (enstatite and feldspar) interstitial to those granules (Figure 4a,b).

We analyzed metal in the nodules in LEW 87234, a paired sample of LEW 87223, and found both high and low Ni metal (Figures 4b and 5; Table 2). This is unusual, as in other E3 chondrites, there is generally only one metal composition (Weisberg & Kimura, 2012). The metal in LEW 87223 is taenite with ~11 wt% Ni and kamacite with ~4.8% Ni (Table 2), with both having ~0.5 wt% Si. From the Fe-Ni phase diagram, the metal compositions suggest an equilibration temperature of just under 700°C (Figure 5). Also present is the phosphide schreibersite (74.2% Fe, 8% Ni, 15.2% P).

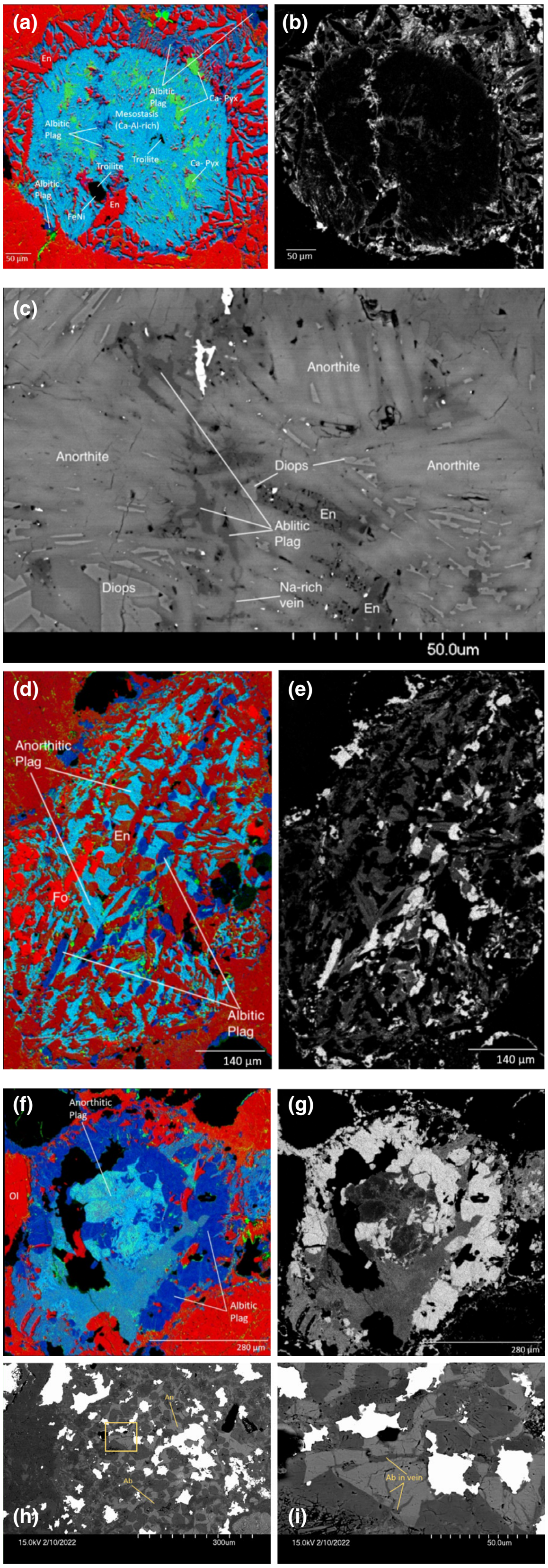


FIGURE 3. a) Mg-Ca-Al (red-green-blue) image of Al-rich chondrule C45. Red is enstatite (En), light blue is Ca-Al-rich mesostasis, darker blue is albitic plagioclase, green is Ca-pyroxene, black is FeNi metal or troilite. b) Na element map of C45 showing albitic plagioclase occurring along a fracture and on the chondrule edge. c) BSE image of C45 showing an Na-rich vein composed of albitic plagioclase. d) Mg-Ca-Al image of Al-rich chondrule C30. Dark red is enstatite (En), light red is forsterite (Fo), light blue is anorthitic plagioclase, dark blue is albitic plagioclase. e) Na element map of C30, with albitic plagioclase occurring on edges and along fractures. f) Mg-Ca-Al image of Al-rich chondrule C19. Light red is olivine (Ol), light blue is anorthitic plagioclase, dark blue is albitic plagioclase. g) Na element map of C19, with albitic plagioclase occurring prominently on the edge of the chondrule. h) BSE image of C24, an ARC. Darker gray areas are albitic plagioclase (Ab) and lighter gray areas are anorthitic plagioclase (An). Arrows point out the plagioclase. i) BSE image of C24 zoomed in (boxed in yellow). Albitic plagioclase appears to be intruding anorthitic plagioclase through vein-like structures. (Color figure can be viewed at wileyonlinelibrary.com.)

## DISCUSSION

### Classification and Thermal History of LEW 87223

LEW 87223 is an unusual E3 chondrite that exhibits both similarities and differences to other E3s, especially EL3s. Overall, enstatite is the dominant silicate mineral, similar to typical E3 chondrites, with minor olivine present. The sample also contains Cr-bearing troilite, oldhamite, and alabandite, all typically found in EL chondrites (Keil, 1968; Weisberg & Kimura, 2012). Within the oldhamite, rare earth element patterns that are typical of EL3 chondrites have been measured (Grossman et al., 1993). The Si content (0.5–0.6 wt%) of the metal in LEW 87223 is consistent with metal compositions in the range of EL3 chondrites. The whole rock oxygen isotopic composition of LEW 87223 is similar to other ECs, plotting on the terrestrial fractionation line in the oxygen three-isotope space (Weisberg & Kimura, 2012) and its chondrule silicates are also isotopically similar in composition to those in other E3 chondrites, plotting along the EC mixing line on the three-isotope oxygen diagram (Weisberg et al., 2011; Weisberg, Kita, et al., 2021).

Unusual petrologic features of LEW 87223 include its high abundance of ARCs. Calcium, aluminum-rich inclusions (CAIs) have been identified in ECs but are generally small and are generally similar in texture and mineral assemblages to the CAIs in carbonaceous and ordinary chondrites (Bischoff et al., 1985; Fagan et al., 2000, 2001; Guan et al., 2000; Lin et al., 2003). Although CAIs are generally less common in E chondrites than in other chondrite groups, Lin et al. (2003) reported

TABLE 1. Average feldspar compositions in LEW 87223 Al-rich chondrules.

| | LEW87-C19 | LEW87-C24-Ab | LEW87-C24-An | LEW87-C30-Ab | LEW87-C30-An | LEW87-C45-An |
|---|---|---|---|---|---|---|
| $SiO_2$ | 63.83 | 63.06 | 44.4 | 64.18 | 48.82 | 41.80 |
| $TiO_2$ | bd | bd | 0.05 | bd | 0.04 | 0.11 |
| $Al_2O_3$ | 22.3 | 22.16 | 34.89 | 22.97 | 32.03 | 36.63 |
| FeO | 0.31 | 0.21 | 0.32 | 0.09 | 0.32 | bd |
| MgO | bd | bd | 0.05 | bd | 0.66 | 0.28 |
| CaO | 4.09 | 4.77 | 18.63 | 4.39 | 15.36 | 20.24 |
| $Na_2O$ | 8.72 | 8.42 | 1.04 | 8.58 | 2.73 | 0.06 |
| $K_2O$ | 1.08 | 1.11 | 0.12 | 0.89 | 0.17 | bd |
| Total | 100.33 | 99.73 | 99.5 | 101.10 | 100.13 | 99.12 |
| Formula | | | | | | |
| Si | 11.293 | 11.245 | 8.265 | 11.244 | 8.96 | 7.845 |
| Ti | 0 | 0 | 0.007 | 0.001 | 0.006 | 0.016 |
| Al | 4.65 | 4.657 | 7.654 | 4.742 | 6.928 | 7.654 |
| Fe | 0.046 | 0.031 | 0.05 | 0.013 | 0.049 | 0 |
| Mg | 0 | 0 | 0.008 | 0.003 | 0.101 | 0.044 |
| Ca | 0.775 | 0.911 | 3.715 | 0.824 | 3.02 | 4.07 |
| Na | 2.991 | 2.911 | 0.375 | 2.914 | 0.971 | 0.022 |
| K | 0.244 | 0.252 | 0.028 | 0.199 | 0.04 | 0 |
| Total | 19.999 | 20.008 | 20.103 | 19.94 | 20.802 | 19.651 |
| No. oxygens | 32 | 32 | 32 | 32 | 32 | 32 |
| An | 19.3 | 22.4 | 90.2 | 20.9 | 74.9 | 99.5 |
| Ab | 74.6 | 71.4 | 9.1 | 74 | 24.1 | 0.5 |
| Or | 6.1 | 6.2 | 0.7 | 5.1 | 1 | 0 |
| Number of analyses | 13 | 17 | 12 | 5 | 2 | 3 |

Abbreviation: bd, below detection.

an unusually high abundance of CAIs in the Sahara 97096 EH3 chondrite. However, they are mostly type A and spinel-rich inclusions, unlike the ARCs we observed in LEW 87223. Although we cannot completely discount that the high abundance of ARCs in LEW 87223 may be due to sampling bias in our thin sections, it may be a primary feature of this unusual EL chondrite.

There is a higher amount of metal found in LEW 87223 compared to that in other EL3s. Weisberg and Kimura (2012) reported 13.2 vol% for LEW 872233, compared to 9.4–10.7 vol% in other EL3 chondrites, and at the higher end of the range for EH3 chondrites (4.3–13.4 vol%). Zhang et al. (1995a) reported 29 wt% kamacite, compared to the range of 6.4–25.9 wt% in other EL3 chondrites. Zhang et al. (1995a) suggested that ~15% of its metal was added to LEW 87223, possibly due to a shock heating event. They concluded that LEW 87223 formed from an EL3 starting material that was modified by impact and brecciation. However, the metal occurs as discrete nodules with sharp boundaries (e.g., Figures 1 and 4a,b), as is typical of both EH3 and EL3 chondrites, and the nodules are aggregates of metal grains with interstitial silicate. This suggests that the metal accumulated with the other components when the meteorite accreted and that the high metal abundance is a primary feature of LEW 87223. There is evidence of a heating event that modified LEW 87233. The metal-rich nodules found within the sample are texturally different from those in other EL3s, which characteristically have intergrowths of enstatite laths (Horstmann et al., 2014; Van Niekerk & Keil, 2011; Weisberg et al., 2013, 2015; Figure 4c). This may suggest a heating event and/or a different origin for the metal-rich nodules in LEW 87223. Additionally, it has two coexisting metal phases (low-Ni and high-Ni), which is not typical of EL3s. Separation of metal into coarse grains of kamacite and taenite is a characteristic of higher petrologic type chondrites, generally resulting from parent body metamorphism (Kimura et al., 2011). The metal compositions in LEW 87223 would be at equilibrium at temperatures of about 690°C (Figure 5).

Zhang and Sears (1996) showed that the alabandite in LEW 87223 has a higher FeS content than in other EL3s with 27.8 wt% Fe compared to other EL3s which generally have <10 wt% Fe, and higher than the FeS content in alabandite in many EL6 chondrites. When plotted on the FeS-MgS-MnS ternary, and applying isotherms from the experimental work of Skinner and Luce (1971) and reviewed by Sack and Ebel (2006, figure 7), the FeS contents of the alabandite record higher temperatures than the sulfides in many higher metamorphic grade ECs, suggesting a strong transient heating event for LEW 87223 (Zhang et al., 1995a).

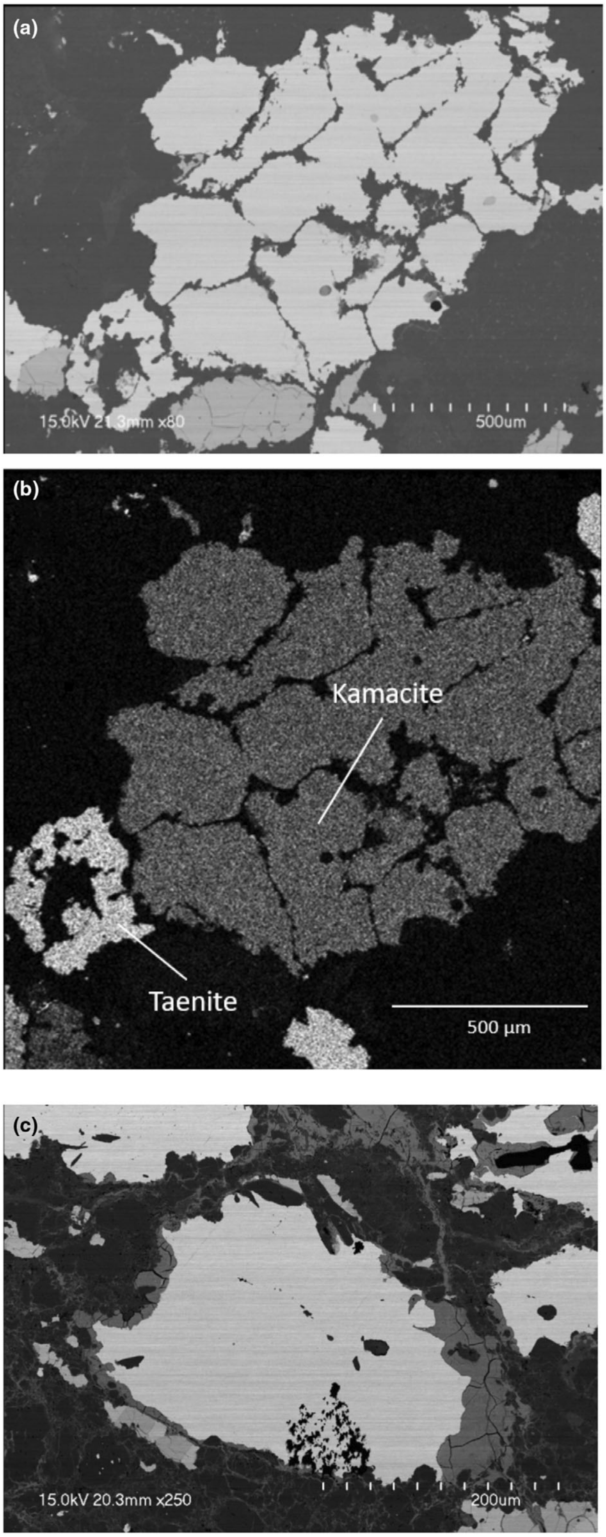


FIGURE 4. a) BSE image of M31 illustrating the appearance of metal-rich nodules resembling an aggregate of large metal grains with interstitial growth of silicates between these. b) Ni element map of M31. Kamacite and taenite are highlighted with arrows. c) BSE image of M2 in A-881314 illustrating a metal nodule in a typical EL3. Dark phases in white metal are enstatite.

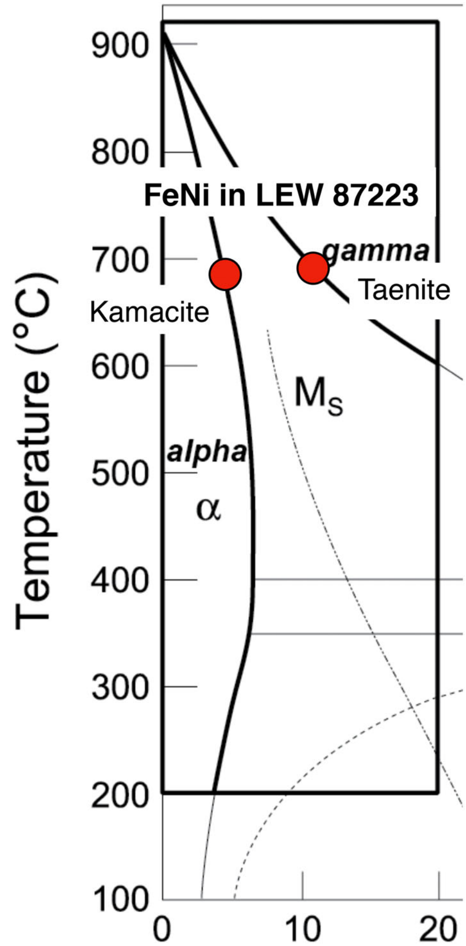


FIGURE 5. Metal compositions form LEW 87223 plotted on the Fe-Ni subsolidus phase diagram (modified from Yang et al., 1996). (Color figure can be viewed at wileyonlinelibrary.com.)

TABLE 2. Compositions of metal and phosphide in LEW 87223.

| Wt% | Average kamacite | Average taenite | Schreibersite |
|---|---|---|---|
| Fe | 93.05 | 89.46 | 74.16 |
| Ni | 4.78 | 11.03 | 9.77 |
| Co | 0.36 | 0.21 | 0.16 |
| Cr | bd | bd | 0.03 |
| P | 0.40 | 0.13 | 15.1 |
| Si | 0.55 | 0.51 | bd |
| Total | 99.14 | 101.34 | 99.22 |
| Number of analyses | 36 | 4 | 1 |

Abbreviation: bd, below detection.

The bulk composition of LEW 87223 is outside the range of typical EL3 chondrites (Zhang et al., 1995a). Ir, Ni, and Co were above the EH group average by 30%; chalcophile elements, with the exception of Cr, were below both EH and EL averages; Fe and Au were close to the EH average; and Al, Sc, Ca, V, and Mg were between EL and EH averages (Zhang et al., 1995a, 1995b). Thus, based on these data (Zhang et al., 1995a), LEW 87223 differs strongly from both EH and EL.

In summary, LEW 87223 has similarities to EL3 chondrites, such as the Si content of the metal, and the presence of alabandite but not niningerite. It also has primary characteristics that distinguish it from any other EL3s, including its high abundance of ARCs, high metal abundance, and anomalous bulk chemistry. Grossman et al. (1993) suggested that it represents a new type of chondrite intermediate between E and H chondrite groups. Y-793225 is a highly equilibrated E chondrite, shown to have intermediate petrologic features between EH and EL; therefore, Lin and Kimura (2010) temporarily classified it as the first member of a new "EI" group, the "I" for "intermediate". LEW 87223 may, with further evidence, be designated as the first member of a completely new group of EC. However, it is best considered an anomalous EL3 chondrite until additional examples of this type of E chondrite are found, as previously suggested (Weisberg & Kimura, 2012).

### Secondary Processes

Although LEW 87223 retains much of its primitive (primary) petrologic character, it appears to have been modified by at least one secondary thermal event, likely an impact on its parent body. The darkening of silicates observed in LEW 87223 may be due to reduction of Fe from silicate during a shock heating event. LEW 87223 was originally classified at shock stage S2 (Grossman et al., 1993). However, if the darkening of the chondrules is a result of shock, LEW 87223 would have experienced considerably higher pressures, possibly closer to a shock stage of S5. It has been suggested that LEW 87223 was altered by brecciation and heating, based on the presence of its darkened chondrules and the texture and shape of its metal and sulfides (Zhang et al., 1995a). The darkening in LEW 87223 is mainly due to the reduction of Fe from FeO-bearing silicates. This secondary reduction may be due to heat generated by a shock event or by a process unrelated to shock, possibly in the nebula, as suggested by Weisberg et al. (1994), or in the parent body. The darkening may be an indication that LEW 87223 initially had a higher abundance of Fe-rich silicate than other E3 chondrites.

We observed a high number of ARCs, something not observed in other ECs. They are texturally different from those found in ordinary chondrites (Elbert & Bischoff, 2016). The occurrences of Na-rich plagioclase as veins and along chondrule edges suggest that the albitic plagioclase is secondary, resulting from mobilization of Na due to heat, possibly derived from an impact event. The texture suggests a rapid, transient heating event. Elbert and Bischoff (2016) suggested a possible link between Na-rich and Ca-, ARCs, and CAIs in ordinary chondrites. They suggested that the Na within the Na-rich chondrules did not come from a metasomatic or metamorphic process on the parent body and did not result from a collision event, but rather was pre-accretionary, resulting from a mixture of refractory and volatile-rich chondrule precursors. However, studies of igneous CAIs have shown that after perhaps similar secondary metasomatic processes, melilite and anorthite became crosscut by veins of grossular, anorthite, clintonite, and spinel (Krot et al., 2022).

Our observation that albitic plagioclase is ubiquitous in the ARCs, coupled with its coexistence with anorthitic plagioclase, suggest that the albite is secondary. Additionally, the albitic plagioclase is fairly uniform in composition throughout LEW 87223 and its presence as vein-like intrusions within the ARCs as well as its occurrence on chondrule edges in LEW 87223 suggests it is a result of a secondary process, such as Na metasomatism, with similarities to albitization in terrestrial rocks. Thus, the heating event that modified LEW 87223 may have also resulted in mobilization of Na-rich (potentially hydrothermal) fluids on an EC parent body.

### Implications for Formation of Earth

Of all the chondrite groups, ECs have stable isotope compositions that are closest to the Earth–Moon system (Clayton et al., 1984; Gray et al., 2021a, 2021b; Javoy, 1995; Paniello et al., 2012; Piani et al., 2020; Warren, 2011). However, a problem in interpreting ECs as precursors to the Earth is their Si isotopes and relatively low Al/Si and Mg/Si values (Dauphas et al., 2015; Kadlag et al., 2019). Thus, it is important to search for new kinds of EC-like materials that may be compositionally closer to the Earth. LEW 87223 expands the range of known EC materials. The high abundance of Al-rich objects suggests that LEW 87223 may have a higher Al abundance than other ECs, with Al/Si possibly closer to the bulk silicate Earth composition. However, the bulk Al in LEW 87223 seems to be unremarkable compared to other ECs (from the bulk chemical data of Zhang et al., 1995a). Thus, either the Al in LEW 87223 is distributed differently than in other ECs or the samples analyzed for bulk chemistry were not entirely representative of bulk LEW 87223 and further work is required.

## CONCLUSIONS

LEW 87223 has petrologic and compositional features that are similar to other E3s, most specifically EL3s.

Enstatite is the dominant mineral; chondrule boundaries are well defined; the Si content in the metal is consistent with a typical EL3; it has Cr-bearing troilite, oldhamite, and alabandite; and its O-isotopic composition is similar to other E3s.

However, LEW 87223 also has unusual features that distinguish it from other ECs making it an anomalous EL3. Overall, it has a higher amount of metal, the textures of its metal nodules are different from other ECs, the alabandite has a higher FeS content, and it has a larger abundance of ARCs than has been previously observed in other ECs.

LEW 87223 expands the range of known ECs and reveals secondary processes that were active on the EC parent bodies. The darkening of silicates, due to reduction of Fe from silicate, suggests a shock heating event, with a shock stage close to S5. Alternatively, the reduction of Fe from silicates is not due to shock. In either case, chondrules in LEW 87223 may have initially had a higher abundance of Fe-rich silicate than other E3 chondrites. Na-rich (albitic) plagioclase found along chondrule edges and fractures suggest it is a secondary mineral and may be related to a shock heating event, where Na-rich plagioclase was formed due to the mobilization of Na-rich fluids, suggesting the presence of hydrothermal fluids on this EC parent body. LEW 87223 is an anomalous EL3 but may represent the first member of a new EC group, should similar samples be discovered. The ECs are more diverse and show a wider range of secondary processes than previously known.

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*Data Availability Statement*—The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

**Table S1.** Electron Probe analyses of feldspar grains used to compile Table 1. Also included are enstatite analyses.

**Table S2.** Electron probe analyses used to compile Table 2 and Figure 5.