

METAL-SULFIDE SEGREGATES FROM A CARBONACEOUS CHONDRITE IMPACT MELT: THE UNGROUPED IRONS LEWIS CLIFF 86211 AND 86498. N. G. LUNNING^{1,2}, T. J. MCCOY², D. L. SCHRADER³, K. NAGASHIMA⁴, C. M. CORRIGAN², and J. GROSS¹, A. KRACHER¹Rutgers, State University of New Jersey (nicole.lunning@rutgers.edu). ²Smithsonian Institution, ³Arizona State University, ⁴University of Hawai'i at Mānoa.

Introduction: The dearth of sulfide-rich iron meteorites has long puzzled planetary scientists [e.g., 1]. Sulfides are found in comparable abundances (by volume) to FeNi metal in many ordinary chondrites [2]. In the cores of differentiating planetesimals, sulfur behaved incompatibly relative to early crystallizing FeNi minerals and would accumulate in the late-stage core liquids [e.g., 3]. Thus, we expect sulfide-rich iron meteorites to have formed from chondritic melts and from the latter stages of planetesimal core crystallization.

Lewis Cliff (LEW) 86211 has been described as one of the rare sulfide-rich iron meteorites and is considered to be one of the most enigmatic ungrouped iron meteorites found in Antarctica [1,4]. LEW 86211 is enriched in refractory siderophile elements compared to most iron meteorites [4]. LEW 86211 and its pair LEW 86498 have fine-grained textures for iron meteorites [5-6]. A preliminary petrological study described silicate inclusions with reduction features, including reverse zoning in olivine [7]. [8] determined that the oxygen-three isotope signature of a silicate inclusion from LEW 86211 was most similar to the CR chondrite Renazzo. In this work, we investigate the petrogenesis of these unique paired meteorites by analyzing elemental chemistry and oxygen-three isotope signatures at higher spatial resolutions than were available in the 1990s [5-8] when the previous studies of LEW 86211 were undertaken.

Materials & Methods: We collected reflected light petrographic maps of five samples of LEW 86211 (,1 ,5 ,6 ,11 and ,12) and LEW 86498,8. These reflected light maps were analyzed with ENVI 5.3 software to assess the proportion of sulfide to metal within the pairing group.

We determined mineral compositions using the JEOL 8530F+ field emission electron microprobe at the Smithsonian Institution on the polished thick sections. Oxygen-three isotopic composition of olivine in LEW 86211,1 were determined *in situ* with the ims-1280 ion microprobe at the University of Hawai'i.

Results & Discussion: In both LEW 86211 and 86498, FeNi-metal is fine-grained with a martensitic texture, which occurs as cells and dendrites in a groundmass of fractured troilite (Fig. 1), consistent with the previous petrographic descriptions [3-4]. Our assessment of six samples confirms that this pairing group has equal proportions of sulfide and metal by volume. This confirms that members of this pairing group are among the most sulfide-rich meteorites known.

Impact Melt Formation. The fine-grained cellular to dendritic metal-sulfide texture and martensitic metal texture

of LEW 86211 and 86498 demonstrate that these meteorites underwent rapid cooling, as observed in other meteoritic materials that experienced impact melting [e.g., 9-10]. Impact melting of chondrites commonly forms two immiscible liquids, a silicate liquid and a separate FeNiS liquid [e.g., 11-12]. A handful of meteorites originally classified as ungrouped irons were determined to be FeNiS segregates from ordinary chondrite impact melts after detailed petrological investigations [13]; these meteorites exhibit similar metal-sulfide textures to those of LEW 86211 and 498.

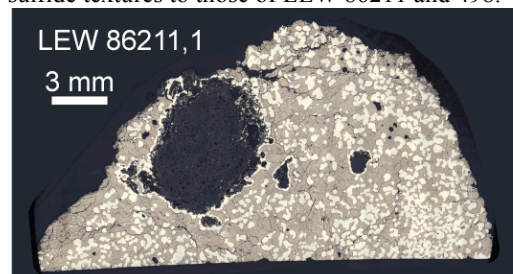


Fig. 1 Reflected light. Metal (white) and troilite (brown-ish).

Chondritic Provenance. The most compelling evidence that links LEW 86211 and 86498 to a chondritic (rather than an iron meteorite) impact melt are the siderophile elemental abundances determined by [4] compared to subsequent similar analyses of the metallic fraction of chondrites [14-16]; LEW 86211 is unfractionated relative to the metal in chondrites, including for elements highly compatible (e.g., Ir) in FeNi minerals. In contrast, the most sulfide-rich members of iron meteorite groups (IAB, IIAB, and IIIAB) and Soroti (only other iron meteorite with equal parts metal and sulfide) are substantially depleted relative to chondrites in Ir [3,17-20].

Carbonaceous Chondritic Provenance. Our *in situ* oxygen-three isotopic measurement of olivine (Fig. 2) fall at the intersection between the carbonaceous chondrite anhydrous mineral (CCAM) line and the CR chondrite mixing line, as defined by [21,22]. The *in situ* olivine measurements provide evidence that this chondritic impact melt is specifically a carbonaceous chondrite impact melt. The combination of the bulk measurement of [8] and our *in situ* analyses indicates that the precursor to this impact melt may have been CR chondrite-like.

Minimum Size of this Impact Melt Unit. This pairing group is predominately composed of the metal-sulfide from CR-like carbonaceous chondrite impact melt. Metal and sulfide are accessory components of unmelted chondrites and chondritic impact melts; by basic mass balance, LEW 86211 and 86498 are parts of a substantially larger impact melt unit. The CR chondrites with comparable sulfide-

metal proportions have ~1.2-2.8 vol.% total FeNiS components [22]. Using those as analogs for the unmelted precursor, the pairing group (297 g) was about 1/100th to 1/33rd of the volume of the impact melt unit they originated from. With a simple mass to volume calculation (using densities of FeNi metal and troilite), the LEW 86211 and 86498 impact melt unit would have a minimum size of ~200,000 cm³ (0.2 m³). This pairing group provides evidence for larger scale impact melting on carbonaceous chondrite-like asteroids than previously known from meteorite studies (mm-scale [12]). The minimum size for this impact melt unit could reasonably be observed by Hayabusa2 or OSIRIS-Rex, if similar unit/s are present on Ryugu or Benu.

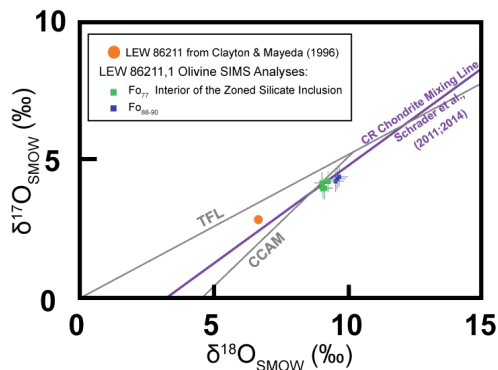


Fig. 2. Oxygen-three isotopic compositions.

Silicate Inclusions and Precursor History. The silicate inclusions in LEW 86211 and 86498 are consistently dominated by olivine with minor amounts of pyroxene. One silicate inclusion in LEW 86498 also has minor quantities of feldspathic glass. The olivine grains in most locations meet each other at 120° triple junction, a texture that indicates high temperature metamorphic re-equilibration rather than crystallization from a melt. Olivine also exhibits reverse zoning (Fe-rich cores and more Mg-rich rims) within grains in most silicate inclusions. In one silicate inclusion in LEW 86211 (Fig. 3) the reverse zoning trend extends across the entire inclusion: olivine grains in the core region meet at triple junctions and have homogenous major element compositions (Fo₇₇) and toward the edge of the inclusion transition to more Mg-rich olivine that co-exists with pyroxene and Fe metal. The preservation of equilibrated olivine with triple junctions indicates this inclusion was not melted by the impact event. These silicate inclusions appear to be “country rock” engulfed by a FeNiS liquid descending from an overlying impact melt unit which rapidly cooled in contact with the unmelted underlying rocks. The reverse zoning in olivine, especially accompanied by pyroxene and Fe metal, record reduction that occurred when these silicates came in contact with the molten FeNiS liquid.

Evidence of thermal metamorphism in the unmelted precursor is difficult to reconcile with a *sensu stricto* CR

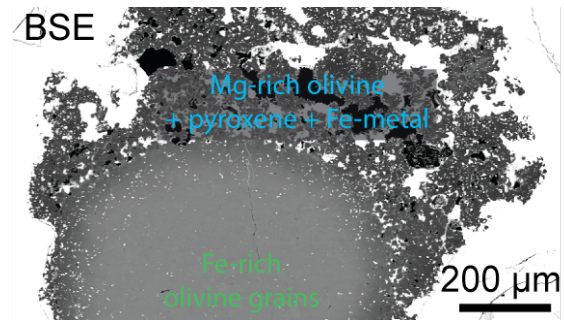


Figure 3: Zoned silicate inclusion.

chondrite precursor. The widely accepted CR chondrite group includes pristine (type 3.0) unaltered nebular sedimentary materials and an associated sequence of aqueously altered CR chondrites [e.g., 22]. For the CR chondrites, there is not a recognized progressive thermal metamorphic sequence, akin to those recognized for the ordinary, enstatite, and CK chondrites [23]. In recent years, highly metamorphosed meteorites with CR chondrite-like parent body isotopic systematics have been identified [e.g., 24]. However, no intermediate thermally metamorphosed CR chondrites or CR chondrite-like meteorites have been described. The pairing group (LEW 86211 and 86498) and other thermally metamorphosed CR-like carbonaceous chondrites may originate from either of the following: (1) a petrogenetic CR chondrite suite largely unsampled in our meteorite collections; or (2) from a separate parent body that shares a genetic nebular inheritance with the CR chondrites but experienced a distinctly different thermal history.

Conclusions: LEW 86211 and 86498 are a pairing group that represent the metal-sulfide segregate of CR-like carbonaceous chondrite impact melt. This pairing group originates from the largest carbonaceous chondrite impact melt unit recognized to date.

References: [1] McCoy et al. (2015) 35 Seasons of Antarctic Meteorites pp. 145-152 [2] Keil (1962) *JGR* 67, 4055 [3] Wasson (1999) *GCA* 63, 2875 [4] Wasson (1990) *Science* 249, 900 [5] Clarke (1992) *Smithsonian Contr. Earth. Sci.* 30, 37 [6] Kracher et al. (1998) *MAPS* 33, A88 [7] Prinz et al. (1991) *LPS XXII* pp. 1101 [8] Clayton & Mayeda (1996) *GCA* 60, 1999 [9] Scott (1982) *GCA* 46, 813 [10] Benedix et al. (2000) *MAPS* 35, 1127 [11] Mittlefehldt & Lindstrom (2001) *MAPS* 36, 439 [12] Lunning et al. (2016) *GCA* 189, 338 [13] Schrader et al. (2010) *MAPS* 45, 743 [14] Kong & Ebihara (1997) *GCA* 61, 2317 [15] Kong et al. [1997] *GCA* 61, 4895 [16] Kong et al. (1999) *GCA* 63, 2637 [17] Wasson & Kallemeyn (2002) *GCA* 66, 2445 [18] Wasson et al. (2007) *GCA* 71, 760 [19] Buchwald (1975) *Handbook of Iron Meteorites* [20] Kracher & Wasson (1982) *GCA* 46, 2419 [21] Schrader et al. (2011) *GCA* 75, 308 [22] Schrader et al. (2014) *EPSL* 407, 48 [23] Brearley and Jones (1998) *RIMS* 36, 3-1 [24] Sanborn et al. (2019) *GCA* 245, 577.