LL-CHONDRITE LAR 12325: A PRODUCT OF AN ASTEROID IMPACT CRATERING EVENT.
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Introduction: Collisional events, including impact cratering, are the dominant geological process affecting asteroids and other planetary surfaces. Impact melts and impact melt breccias, which formed as a result of crater-producing asteroid collisions, have radiometric and petrographic characteristics that can be used to unravel the collisional evolution of their parent bodies and the Solar System. To reconstruct this evolution, it is necessary to determine 1) the timing of the impact events, 2) the peak temperature generated by the impact event, along with the subsequent cooling rates, and 3) the size of the impact event on the parent asteroid.

This study explores the petrography, chemistry, and cooling rates of meteorite LAR 12325 in order to interpret its formation and evolution. This 263.9 g meteorite was recovered from Larkman Nunatak in Antarctica and was classified as an LL-chondrite [1], a group who's impact lithologies have not been as well studied as H and L chondrites.

Methods: *Point counts.* Point counting under reflected light of 2582 points was conducted at 500× magnification. Points were distributed along lines separated by 300 µm. The spacing of the points was 100 µm.

Electron microscopy. A Cameca SX-100 microprobe with five wavelength-dispersive spectrometers at the NASA Johnson Space Center in Houston was used. Fe,Ni-metals, sulfides and silicates were analyzed using an accelerating voltage of 15 keV, a beam current of 20 nA, and a beam diameter of 1 µm. In Fe,Ni-metals and sulfides, elements Mg, Si, P, S, Cl, Ca, Ti, Cr, Mn, Fe, Co, Ni, Cu and Zn, in silicates, elements Na, Mg, Al, Si, P, K, Ca, Ti, Cr, Mn, Fe and Ni were analyzed. All utilized standards are from the NASA Johnson Space Center standard collection.

Petrography: *General petrography.* Thin section LAR 12325,7 has an area of 167.4 mm^2 and is composed of 39.9% clast material and 60.1% melt. It contains two large clasts, 4×4.5 mm and 4×9 mm, and other clast fragments that are embedded in aphanitic matrix of olivine and pyroxene.

Clasts. These are composed of 85.0% silicates, 0.4% oxides, 0.4% metals, 5.2% sulfides and 2.5% undifferentiated metal and sulfide for <4 µm grains, which is consistent with LL-chondrites [2]. Fractures and holes make up 6.4% of the clasts. One of the clasts has a 1.3 mm barred olivine chondrule and a 1.5 mm granular pyroxene and olivine chondrule with a porphyritic olivine mantle. Large plagioclase grains (up to 400 µm) lie between olivine, low-Ca and high-Ca pyroxene crystals (Fig. 1a). Mono- and polymineralic metal, sulfide (troilite) and oxide particles up to 500 µm are present in clasts. The dominant metal and sulfide particle/aggregate size range is 4.0 to 15.8 µm. Olivine crystals in clast fragments display different stages of shock metamorphism, (*e.g.*, undulatory extinction, planar fractures, and mosaicism). These features, along with the presence of melt in the rock, indicate an S6 shock stage, *i.e.*, a shock pressure of ~45 to 90 GPa and a post-shock temperature increase of 600 to 1750 °C [3]. For the meteorite, the texture and chemistry of clasts (*e.g.*, only a few sharp chondrule edges, absent chondrule glass, >50 µm big plagioclase grains, relatively homogeneous olivine compositions, orthorhombic low-Ca pyroxene – see *Chemical composition* section) indicates thermal metamorphism to an LL5 state before the rock was shock-metamorphosed.

Melt. This is composed of 88.5% silicates, 0.6% oxides, 0.9% metals, 3.6% sulfides and 1.0% undifferentiated metal and sulfide for <4 µm grains, which is consistent with LL-chondrites [2]. Fractures and holes make up 5.5% of the melt. Predominantly subhedral relic olivine and pyroxene grains, typically 25 to 500 µm in diameter, are embedded in a partially crystalline melt matrix (Fig. 1b). The dominant metal and sulfide particle/aggregate size range is the same as in the clasts (4.0 to 15.8 µm).

Chemical composition. Olivine compositions ($Fa_{29.5-30.4}$, n=17) fall in the typical range of LL-chondrites [4]. Low-Ca pyroxene is orthorhombic and has compositions of $Wo_{1.3-2.7}En_{73.0-74.4}Fs_{23.6-25.0}$ (n=17). No statistically significant difference is apparent between olivine and low-Ca pyroxene in lithic clasts and those crystallized from the impact melt. High-Ca pyroxene in the clasts exhibits compositions of $Wo_{43.2-45.0}En_{45.5-46.1}Fs_{9.5-10.8}$ (n=9). Minor apatite occurs as anhedral grains in the meteorite. Metal particles are typically plessite with taenite rims (2 to 25 µm wide). Martensite particles with taenite rims and pure taenite (31.3 to 37.2 wt% Ni) are also present. The only kamacite in the thin section was found in association with taenite in a metal particle that has a plessite rim. This kamacite has high Co concentrations between 3.66 and 3.86 wt% (n=4) that are typical for LL-chondrites [5]. The average Co:Ni ratio of 1:20 in taenite corresponds to the cosmic abundance ratio and is similar to the 1:24 ratio indicated for LL-chondrites [6]. Most metal particles are associated with troilite that often forms rims around them.

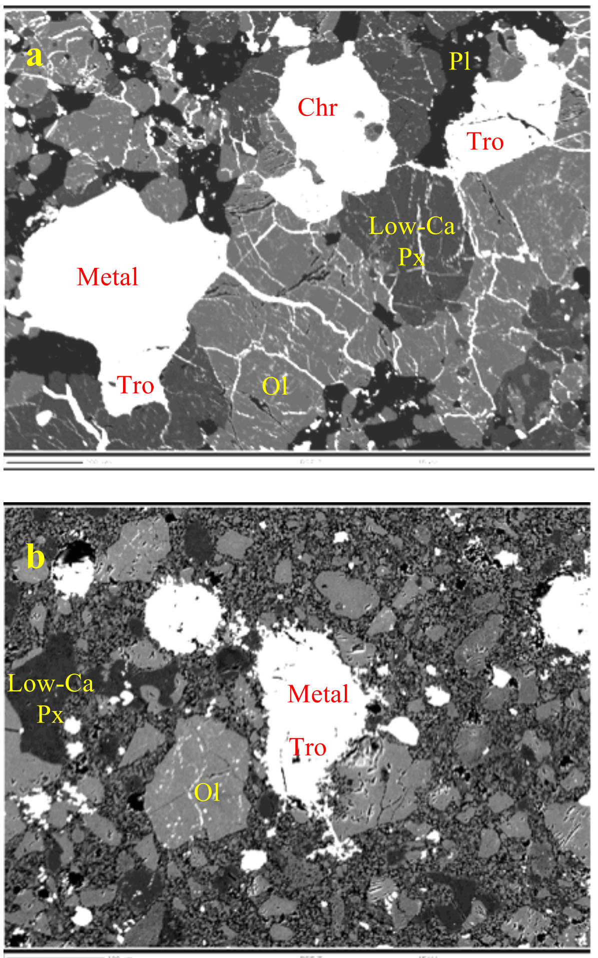

Figure 1. *BSE images of (a) clast material: metal, troilite, chromite, olivine, low-Ca pyroxene and plagioclase and (b) scattered relict target grains in a melt-derived matrix of <5 μm olivine and pyroxene. The scale bars in Figures 1a and 1b are 200 μm and 100 μm, respectively.*

Cooling rates: Cooling of material heated by an impact cratering event can be characterized by 2 cooling rates. Stage 1 cooling describes rapid cooling resulting in thermal equilibrium of the super-heated impact melt and the cool clastic debris. Stage 2 cooling reflects conductive cooling of the entire breccia to its surroundings.

Stage 1 cooling. To evaluate Stage 1 cooling rates, the spacing of metal cells in the largest, continuous metal troilite particles was measured [7]. Based on 10 spacings that ranged 14 to 30 μm, the cooling rate was between 27 and 247°C/s.

Stage 2 cooling. To evaluate Stage 2 cooling rates, Ni concentrations across individual metal particles were measured and compared with metallographic cooling rate curves calculated for chondritic meteorites [8, 9]. These cooling rates work best with bulk [Ni] less than 20% (like that in H or L chondrites), but are dubious for higher [Ni] typical of LL-chondrites. Nonetheless, if applied to our sample, one derives a very slow cooling rate of ~10^{-11} °C/s.

Discussion: The large proportion of relic clasts relative to melt, the relatively sharp contact between the clasts and melt, and the small grain size of the silicate melt matrix suggest relatively fast post-impact cooling. In addition, the metal-sulfide droplets in the melt have not assembled into large (*e.g.*, of order 1 mm) particles, also suggesting relatively fast cooling.

In contrast, the calculated stage 2 cooling rate of ~10^{-11} °C/s implies slow cooling at a burial depth of >1000 m [10], which is inconsistent with the petrographic properties. That demonstrates the method of [8, 9] to determine stage 2 cooling rates cannot be applied to metal in impact melts produced on LL-chondrite parent bodies.

Conclusions: The LAR 12325 parent body underwent thermal metamorphism to an LL5 stage, followed by impact-induced shock metamorphism. S6 shock stage indicates a shock pressure of ~45 to 90 GPa and a post-shock temperature increase of 600 to 1750 °C. The parent body reached a high-temperature thermal equilibrium at cooling rates between 27 and 247°C/s followed by conductive cooling to its surroundings at a slower, albeit still relatively fast cooling rate, that we cannot quantify, because the diffusion characteristics of Ni in metal systems with high (>20% Ni) concentrations are not sensitive to that cooling rate [8].

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