NORTHWEST AFRICA 12281: The story of an unequilibrated LL3 chondrite through the lens of sawtooth pyroxene. H. L. Bercovici[1], G.S. Franco[1], J. Dolinschi[1], J. Garani[1], G. Loescher[1], E.T. Dunham[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85282 (hbercovi@asu.edu)

Introduction: Chondrules are considered some of the earliest solar system solids [1] and are the main constituent of ordinary chondrites. Amongst this group of meteorites, Type-LL ordinary chondrites are the most oxidized; the oxidation state is inferred from the highest abundance of FeO compared to metallic Fe [1]. Ordinary chondrites have a diversity of chondrule mineralogical assemblies and textures, which exposes the different cooling histories of these objects [2, 3].

Northwest Africa (NWA) 12281 is classified as a Type LL3 ordinary chondrite [4]. It contains predominantly porphyritic olivine and pyroxene (POP) chondrules, followed by porphyritic olivine (PO), porphyritic pyroxene (PP), barred olivine (BO) and radial pyroxene (RP). Many chondrules are rimmed by Fe-Ni metal and troilite. Two specific chondrules exhibit a distinct texture where olivine phenocrysts within the chondrules are enveloped by a pyroxene rim which has a "sawtooth" morphology [5] (Fig. 1A). In this study, we investigate the geochemistry and petrography of the distinctive olivine phenocrysts surrounded by pyroxene within two chondrules in NWA 12281, to better understand the multiple heating and cooling events which produced them.

Methods: A thin section of NWA 12281 was analyzed under petrographic microscope where the abundance and distribution of the meteorite components were estimated visually. The mineral chemistry analyses were obtained with a JEOL JXA-8530F in the LeRoy Eyring Center for Solid State Science, at Arizona State University. For BSE imaging, EDS, and WDS the beam was calibrated to 20 kV accelerating voltage, 20 nA beam current, and 10.8 mm working distance. The EDS compositional maps were made with 20 kV accelerating voltage and 60 nA beam current. The "sawtooth" patterns were analyzed with EDS.

Geochemical and Petrographical Description of the Sawtooth Texture: The sawtooth pattern in two NWA 12281 chondrules, one of which is armored by a Fe-Ni-FeS rim, is composed of ~2-5 µm thick ragged pyroxene rims on the edge of ~20-100 µm diameter olivine phenocrysts. The olivine cores are either euhedral (Fig. 1A) or subhedral (Fig. 1B), and their compositions range between Fa_{62-97}. The fayalite (Fa) content of olivine crystals in the bulk chondrite overlap with the Fa content of olivine crystals in the sawtooth-textured chondrules, including barred olivine in other chondrules. The olivine phenocrysts are for the most part normally zoned, with increasing FeO wt.% towards the rims (Fig. 1A), although the ~20 µm olivine phenocrysts lack zoning.

The pyroxene in the sawtooth pattern regions can be divided into three groups: 1) Ca-rich pyroxene which forms dendritic phenocrysts in the matrix (Figs. 1A and B), 2) Ca-poor pyroxene which forms crystals around the olivine rims, giving shape to the sawtooth texture (Figs. 1A and B), and 3) Ca-rich anhedral pyroxene crystal in the core of an olivine crystal (Fig. 1A). For group one, the Ca-rich dendritic crystals measure 3-7 µm and are abundant in the matrix, they have a compositional range $Fs_{12.9-24.8}Wo_{33.5-37.1}$ (n=3). In group two, the sawtooth thickness varies from ~2 to 5 µm and the chemical compositions range from $Fs_{2.0-34.3}$ and $Wo_{0.0-59.7}$ (n=24, Fig. 2B). The last category comprises a single 3 µm anhedral pyroxene crystal in

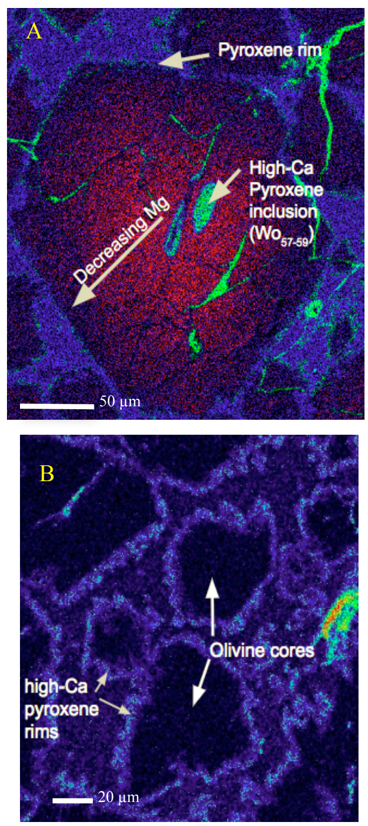

Figure 1: *EDS elemental maps.* A) of an euhedral olivine crystal with a thin pyroxene "sawtooth" rim. Mg = red, Ca = green, Al = blue. Also featured are dendritic pyroxene in the matrix and an anhedral Wo_{57-59} pyroxene inclusion in the olivine crystal. B) Ca EDS map of an anhedral olivine crystal with a pyroxene "sawtooth" *rim.* The pyroxene rims zone into more calcium rich towards the matrix.

the core of an olivine crystal (Fig. 1A) which has composition $Fs_{2.8}Wo_{59.7}$ (Fig. 2A). In chondrules that exhibit the sawtooth pattern, the pyroxene crystals decrease in Ca contents towards the olivine crystals (Fig. 1B).

Discussion: The sawtooth pattern we see in NWA12281 is most often described in ureilites. In these cases, olivine is correlated with the presence of graphite, which suggests that the environment in which the meteorite formed in is highly reduced [3]. However, in this ordinary chondrite, no graphite lamellae were found with the silicate minerals, and iron is mainly present in the chondrite as FeO (19-20 wt.% FeO vs. 4% Fe-Ni metal and FeS). The presence of iron predominately in its oxidized form supports the formation of this meteorite in an oxidized environment, which is consistent with other Type LL chondrites [1].

The presence of both sawtooth and dendritic pyroxene crystals in the same chondrule indicates that the textures are in close association, but may reflect distinct heating events. We suggest that at least three distinct heating events were necessary to produce the features present in these chondrules. During the first event, zoned olivine crystals formed as the chondrules were heated to a high temperature but then cooled slowly. So, the olivine crystals that show normal zoning cooled slowly enough to form rims of increasingly fayalite-rich olivine [6].

The second heating event followed, producing the pyroxene sawtooth rim and equilibrated the small olivine grains so no zoning is observed. Experimental studies have shown that sawtooth patterns form around a nucleus crystal when cooled quickly [2]. A similar texture of pyroxene sawtooth rims were suggested to form by cooling at 5˚C/hr from 1550˚C [5], and olivine sawtooth textures are documented to form from pure olivine cooling at 100˚C/hr from 1500˚C [7]. The maximum temperature during this event was likely not quite as hot as the first because only the small olivine phenocrysts re-equilibrated.

The final heating event produced the pyroxene dendritic needles in the matrix; fast quenching is associated with the formation of dendritic crystals, without the presence of nuclei [8]. So, this event exhibited a lower peak temperature and very quick cooling. Our hypothesis that chondrules containing olivine phenocrysts surrounded by irregular pyroxene rims formed during three distinct heating events is consistent with a chondrule formation scenario of either bow shocks or gravitational instability-driven shocks. Both models are able to accommodate the various cooling rates and might produce three heating events with distinct heating and cooling parameters [9].

Conclusions: The Northwest Africa 12281 ordinary LL-3 chondrite contains porphyritic olivine chondrules in which the individual olivine phenocrysts are enveloped by pyroxene. The pyroxene displays a sawtooth morphology within two chondrules. These chondrules were likely produced after experiencing three heating events: the first generated zoned olivine phenocrysts, the second created the pyroxene rims and equilibrated small olivine grains, and the third formed the abundant quenched matrix pyroxene needles. The olivine-rich chondrules contain barred and porphyritic olivine, which indicates that they most likely formed in the mid-plane of the solar nebula in a dust-rich region [2]. These chondrules, likely formed through either bow shocks or gravitational instability-driven shocks [7], undergoing three distinct heating events.

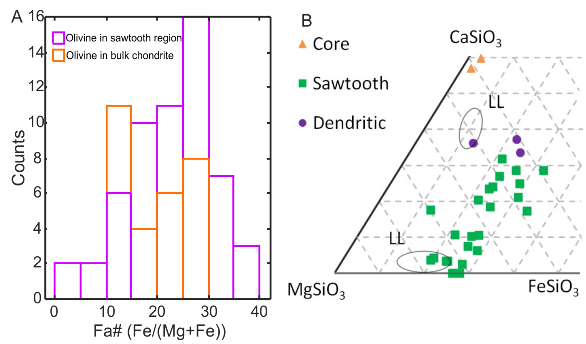

Figure 2: *Olivine and pyroxene compositional data.* A) Histogram of Fa content from the bulk chondrite in orange (n=29) and from the sawtooth regions in purple (n=57). Sawtooth olivine grains show Gaussian distribution with peak around Fa# 25. B) Ternary diagram with pyroxene analyses from the chondrule with sawtooth texture and pyroxene compositional domain of LL chondrites.

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