Olivine Microstructures in the Miller Range 99301 (LL6) Ordinary Chondrite
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Introduction: Miller Range 99301 (MIL 99301) is classified as an LL6 ordinary chondrite and has seemingly contradictory shock indicators [1]. Olivine and plagioclase grains show sharp optical extinction indicative of shock stage S1 [2], whereas other indicators such as the presence of polycrystalline troilite [3] and large grains of low-Ca clinopyroxene (e.g., 2, 4) suggest a shock stage of S4 or higher [1]. To account for these observations, Rubin [1] proposed that MIL 99301 experienced a complex thermal history with metamorphism to petrographic type 6, a later shock event equivalent to shock stage S4 or higher, and annealing to metamorphic levels equivalent to petrographic type 4 to remove defects in olivine and plagioclase. In support of Rubin’s model [1], MIL 99301 records 39Ar/40Ar evidence for two impact events, one at ~4.2 and another at ~4.23 Ga ago [5]. In the current study, we used transmission electron microscopy (TEM) imaging to examine microstructures in MIL 99301 olivine grains in order to understand more fully this meteorite’s deformation and thermal history.

SAMPLE AND TEM LOCATIONS:
Figs. 1 a-e
A small bulk sample of MIL 99301 was used to prepare a TEM section. The entire section is shown in Fig. 1a. The white circle surrounding the sample is the 3 mm copper support grid. In this BSE image, holes are black, fieldspar is dark gray, olivine, pyroxene, and phosphate are medium gray, and opaques are white. Electron transparent regions are found around the perforations in the center of the section. Fig. 1b and c show a BSE image and corresponding phase map (derived by X-ray principal component analysis; purple = holes) of the region around the perforations, which are labeled in Figs. 1 d and e. In Fig. 1d, fieldspar is now black, olivine is a medium gray, pyroxene is slightly darker gray than olivine and a large phosphate grain in the upper right of the image is a light gray. With the exception of region F, the perforations were surrounded almost entirely by olivine. The electron transparent area is immediately adjacent to the perforations and is thinner than the width (not length) of the scale bar in Fig. 1b. Fig. 1d and e are bright-field TEM images.

LOW OVERALL DISLOCATION DENSITY:
Figs. 2 a-c (all 3 images are bright-field TEM images)
All of the olivine grains examined have either no dislocations or very low dislocation densities. Figs. 2a and 2b show two olivine grains from region Gb. Bend contours and a grain boundary are visible. The latter is indicated by short red lines and “gb.” Only a few dislocations with b = [001] are visible near the top of this region (Fig. 2b). Fig. 2c, from region F, is typical of two areas which contain grains that lack any evidence of dislocations. Bend contours and a grain boundary are visible.

EVIDENCE FOR A SHOCK EVENT AT RELATIVELY HIGH TEMPERATURES:
Grain G5a (Figs. 3a and 3b) shows a kink band which cuts across and displaces long screw dislocations with b = [001]. The terminal dislocation of the kink band is the faint sharp line indicated by the arrow in Fig. 3b. Kink bands are formed during deformation, and can be distinguished from subgrain boundaries, which form by post-shock annealing, by their irregular spacing [6]. Kink bands per se do not require high temperatures, but in this case, the edge of the band is marked by a dislocation with b = [100], providing clear evidence for high temperature deformation. Additionally, this kink band cuts across and displaces other dislocations, including long edge dislocations with b = [001], suggesting that they too formed at elevated temperature.

EVIDENCE FOR LIMITED RECOVERY/ANNEALING FOLLOWING SHOCK:
An example of intersecting subgrain boundaries in Portales Valley. The meteorite contains several subgrain boundaries composed of dislocation arrays, implying a significant amount of annealing has occurred.

Fig. 7 a-b (both TEM images of Portales Valley) [12]
Fig. 7 is a weak-beam dark-field TEM image showing the variation in dislocation densities in a single olivine grain in Portales Valley. The center of Fig. 7a shows one of several regions of dense tangles. Fig. 7b is a bright-field image of one of these regions. No such features were observed in MIL 99301.

Fig. 8 (conical dark-field TEM image)
MIL 99301 contains 120 triple junctions, as shown in Fig. 8 of grains in region B. Visible in this image are grain boundaries (indicated by “gb”), and bend contours. No dislocations or subgrain boundaries are visible. The low-Ca pyroxene grains in this area are not twinned. The observed triple junctions most probably formed when the meteorite was heated to petrographic type 6, as there is no evidence that MIL 99301 experienced recrystallization resulting from intense shock.

Summary:
The microstructures in MIL 99301 olivine provide evidence that this meteorite experienced a shock event which the parent body was still undergoing thermal metamorphism. This evidence includes multiple slip systems, kink bands, dislocations with b = [100], and jogged and bowed dislocations which are indicative of climb. For MIL 99301, our data suggest that deformation occurred near peak metamorphic temperatures (~1000°C). As the dislocation density is so low, it was not possible to determine whether the meteorite cooled quickly or slowly following deformation. Kink bands, and “curved and jogged” dislocations attributed to climb, were observed in a TEM study of olivine in the Saint-Sevin (LL6) chondrite [12]. The authors of that study concluded that Saint-Sevin had experienced “mild shock” during “gradual cooling” while undergoing thermal metamorphism to petrographic type 6 [9]. A similar model of shock occurring during metamorphism and subsequent slow cooling was proposed for Portales Valley [11]. However, it is clear that Portales Valley experienced more recovery than either MIL 99301 or Saint-Sevin. The deformation in MIL 99301 conceivably corresponds to the ~4.52 Ga thermal event recorded by 39Ar/40Ar [5]. However, we see no evidence for the later significant thermal event suggested by Ar data [5]. Nor have we resolved the obvious discrepancy between optical shock indicators in this meteorite [1].

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