MICROSTRUCTURES IN OLIVINE FROM ORDINARY CHONDRITES: EVIDENCE FOR POST-SHOCK THERMAL ANNEALING AND SYN-METAMORPHIC SHOCK.

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Introduction: We used transmission electron microscopy (TEM) and optical petrography (OLM) to study olivine in seven O chondrites of high metamorphic grade, to better understand the roles of collisions in the early solar system and the deformation and thermal histories of chondritic parent bodies. Our results provide strong evidence that some shock stage S1 H and LL chondrites (Portales Valley (H6/7), Kernouvé (H6), and MIL99301 (LL6)) experienced significant post-shock annealing, most likely by deep burial in a warm regolith, which significantly reduced strain in olivine to give a weakly shocked appearance. We also found evidence that deformation occurred under high temperature conditions in Morrow County and Kernouvé, with the latter meteorite probably being deformed while the parent body was being thermally metamorphosed.

Methods: Four reference L6 chondrites of differing shock stages (Park, Leedey, Bruderheim, Morrow County) were studied to provide the basis for understanding shock-induced deformation and annealing, and were compared to three anomalous S1 H and LL chondrites (Portales Valley, MIL 99301, Kernouvé), proposed to have been annealed by thermal metamorphism either during or after shock [e.g., 1-3]. With TEM we examined multiple olivine grains in each meteorite to characterize microstructures, including dislocation densities, Burgers vectors, dislocation character (screw, edge, or mixed), and the relative number of dislocations present and not present in subgrain boundaries ("bound" and "free" dislocations, respectively). OLM data were used to measure deformation in individual olivine grains using the approach and criteria of Jamsja and Ruzicka [4], in which a shock stage [5] is assigned to each grain. Following the convention of Stöffler et al. [5], the overall shock stage can be equated to the highest stage experienced by at least 25% of the grains, but in addition a weighted shock stage can be calculated (multiplying grain shock stages by the corresponding number of grains), giving a more quantified measure of the shock character of the entire sample.

Results: Our OLM data agree with literature data on the shock stages of the meteorites studied, except for Leedey, which is reclassified as S4 from S3. TEM data for the reference L6 chondrites show that there is an overall correlation between average geometric dislocation density and weighted shock stage for olivine (Fig. 1a), and that most dislocations in these meteorites are "free" (Fig. 1b). The latter indicates that even in strongly shocked S4 and S5 meteorites, waste heat and time were insufficient to cause much dislocation climb into subgrain boundaries. In the anomalous chondrites, dislocation densities are ≥1-2 orders of magnitude lower, and many more dislocations are present in subgrain boundaries (Fig. 1). This suggests that the anomalous chondrites, unlike the reference L6 chondrites, experienced significant dislocation climb and annihilation during post-shock thermal annealing. Annealing probably occurred at depth in thick regoliths of warm parent bodies, possibly beneath recently-formed impact craters. Obvious differences in olivine microstructure between "reference" L6 Bruderheim and "anomalous" H6 Kernouvé are evident in TEM micrographs (Fig. 2).

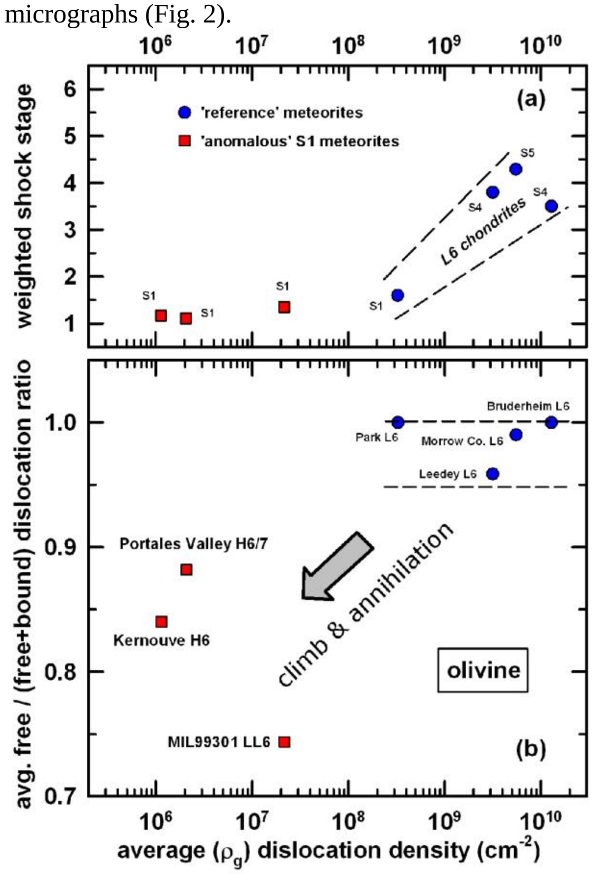

Fig. 1. Three anomalous S1 chondrites have unusually low average dislocation density (a) and an unusually high proportion of dislocations bound in subgrains (b), suggesting they experienced post-shock annealing.

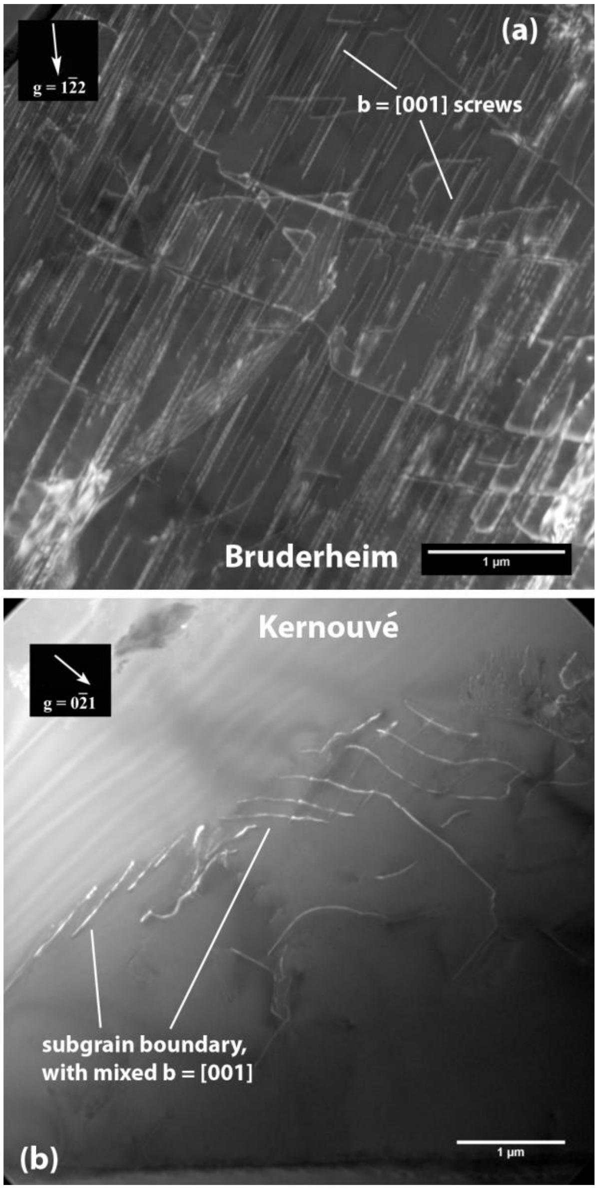

Fig. 2. TEM WBDF images showing contrasting miscrostructures in olivine from "reference" L6 S4 Bruderheim (a) and "anomalous" H6 S1 Kernouvé (b). This subgrain boundary in Kernouvé is less well-developed than those in Portales Valley and Miller Range 99301, suggestive of less annealing.

Two dislocation parameters in olivine that have been found to be sensitive to temperature during deformation in static deformation experiments are the number of dislocations with b=[100] and the number of b=[001] screw dislocations relative to edge or mixed character dislocations. The former is proportional and the latter inversely proportional to temperature, with b=[100] dislocations increasing and the number of b=[001] screw dislocations decreasing above 800-1000 °C [6-8]. Kernouvé and Morrow County contain a low proportion of b=[001] screw segments, and a high proportion of b=[100] dislocations (Fig. 3). This suggests that both meteorites were deformed under high temperatures.

In the case of strongly shocked Morrow County (S5), elevated temperatures could have been caused by high temperatures accompanying a strong pressure increase, but the data for Kernouvé (S1) are better explained by elevated ambient temperature during shock, caused by a warm parent body at the time of impact (i.e. syn-metamorphic shock). Thus, the Kernouvé H chondrite source area could have been warm prior to impact as a result of ongoing thermal metamorphism, and warm following impact as a result of deep burial in warm materials, which would explain all of the observed olivine microstructures, as well as complexly-structured metal veins [9], for this meteorite. Evidence for syn-metamorphic shock is less conclusive for other meteorites, but the data imply that MIL 99301 and Portales Valley were kept warm at depth following shock.

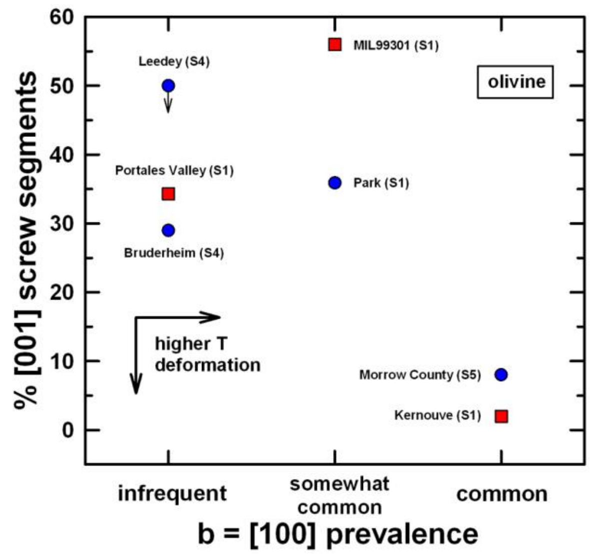

Fig. 3. Two parameters sensitive to deformation temperature in olivine suggest higher-temperature deformation for Morrow County and Kernouvé.

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