MICROSTRUCTURES OF HIGH-PRESSURE MINERALS IN THE SIXIANGKOU L6 CHONDRITE: CONSTRAINTS ON THE DURATION OF SHOCK EVENTS IN CHONDRITES T. G. Sharp[1], M. Chen[2], A. El Goresey[3]. [1] Bayerisches Geoinstitut, Universität Bayreuth, D-95440 Bayreuth, Germany; Gaungzhou Institute of Geochemistry, Academia Sinica, 51064 Guangzhou China; [3]Max-Planck Institut für Kernphysik, D-69029 Heidelberg, Germany.

High-pressure minerals in the Sixiangkou (L6) chondrite contain micro-structures that can be used to constrain the time scale of shock metamorphism. Crystallization of majorite-pyrope garnet and magnesiowüstite from a silicate melt at high pressure and temperature required μm-scale diffusion at high pressure. Large polycrystalline ringwoodites and majorites, formed by solid-state transformations, show evidence of annealing and dislocation recovery. These diffusion-controlled processes are inconsistent with the micro-second time scales generally accepted for shock metamorphism of chondrites.

Introduction: High-pressure minerals in shocked chondrites provided an early glimpse into the mineralogy of the earth's mantle and the microstructures of high-pressure minerals [1,2]. Developments in high-pressure experimentation have allowed us to investigate the formation conditions of high-pressure minerals and the microstructures that develop from processes such as phase transformations and deformation. Based on our understanding of microstructures in synthetic samples from high-pressure experiments, it is possible to interpret the microstructures of high-pressure minerals in shocked chondrites for a better understanding of shock metamorphism. The Sixiangkou (L6) chondrite contains veins of high-pressure assemblages that show almost no transformation back to low-pressure minerals, making this an ideal sample for the interpretation of shock-induced microstructures. We have used analytical transmission electron microscopy (ATEM) to characterize the microstructures of these high-pressure minerals to better understand the mineralogical processes and duration of shock events in chondrites.

Microstructures of matrix minerals: The shock veins in the Sixiangkou chondrite consist of large polycrystalline grains of ringwoodite and majorite surrounded by a fine-grained matrix that is either metal-rich or metal-poor. The metal-poor matrix assemblage consists of predominantly majorite-pyrope garnet plus magnesiowüstite with additional kamacite, troilite, magnetite, and silicate glass. The garnets are euhedral or subhedral and range in size from 1 to 4 μm. They are surrounded by branching grains of magnesiowüstite that fill interstitial channels between the garnets and occur up to 5 μm long. Associated with the magnesiowüstite are small grains of kamacite and troilite as well as a silicate glass that wets grain boundaries and fills triple junctions. The garnets and magnesiowüstite represent the first minerals to crystallize from a chondritic melt at high pressure and temperature, with the kamacite, troilite, and glass representing residual metal-sulfide and silicate liquids. Based on crystallization studies of chondritic [3] and peridotitic [4] melts at high pressure, the majorite-pyrope plus magnesiowüstite assemblage represents crystallization at 2050 to 2300 °C and 20 to 24 GPa [5]. The majorite-pyrope garnets have cubic symmetry with no twins or other defects. The magnesiowüstite contains numerous inclusions of magnetite ranging in size from 2.5 to 200 nm in size. The larger inclusion occur at grain margins and represent the breakdown of wüstite to magnetite plus kamacite whereas the tiny grains exsolved from a nonstoicheometric magnesiowüstite [6]. These magnesiowüstite reactions are the only post-shock reactions visible in the high-pressure phases.

Microstructures in polycrystalline ringwoodite and majorite: The polycrystalline ringwoodite consists of 3 to 6 μm crystals. Although stacking faults are common, the density of stacking faults is less than previously seen in shocked meteorites [1,2] or in synthetic ringwoodite from static experiments of short duration [7]. There is no evidence for extremely high fault densities or highly disordered spinelloid phases that develop during short duration static experiments [8]. The relatively large grain size and low fault densities suggest significant time for growth and annealing of the ringwoodite at high pressure, suggesting a longer duration shock event. The polycrystalline majorites consist of crystals up to 10 μm in sized with numerous dislocations. The dislocations are well organized into subgrain boundaries separating μm-sized subgrains, similar to those seen in synthetic majorite samples [9] and in natural majorite-rich garnets found in diamond inclusions [10]. This dislocation microstructure represents recovery by dislocation clime as well as deformation by dislocation creep, the former being a diffusion-controlled process that is inconsistent with a micro-second time scale for annealing.

Discussion: Although the time scale of shock metamorphism cannot be quantitatively determined from microstructures, semi-quantitative constraints can be put upon the duration of the shock induced high-pressure regime by the kinetic processes inferred from microstructures in the high-pressure minerals. The garnet-magnesiowüstite matrix contains no sign of dendritic or spinifex textures that are typical of silicate melts quenched from high temperature in one to two seconds [3]. Grain sizes of the garnets and magnesiowüstites up 5 µm indicate diffusion of melt components over distances of several micrometers during crystallization at high pressure. Assuming a shock duration of micro-seconds, micrometer-scale diffusion would require unrealistically high diffusivities in the melt. Relatively large crystals in the large polycrystalline ringwoodites required time for nucleation and growth without the formation of disordered spinelloids. Finally, dislocation recovery rates in majorite garnets would require either time scales much longer than microseconds or unrealistically high dislocation densities to have formed by shock deformation. Based on the kinetics of dislocation recovery [11], recovery at 2000 °C on a microsecond time scale would require an initial dislocation density of 10^{20} m^{-2} whereas a more reasonable dislocation density of 10^{14} m^{-2} could be accounted for with a second-long recovery period.

These kinetic constraints indicate that high pressure and temperature conditions were maintained for much longer than the microsecond time scale accepted for shock events. The microstructures and grain sizes that we observe are inconsistent with origins from devitrification of diaplectic glass phases. Growth and crystallization of micrometer-sized crystals of high-pressure phases could only occur at high pressures. Dislocation recovery and annealing could not have occurred during post-shock high-temperature conditions because such high temperatures would have caused transformation back to low-pressure forms. The only back-transformation reaction observed is that of magnesiowüstite to magnetite plus kamacite, which occurs at relatively low temperatures of ≤ 600 °C [12]. The long-duration of high pressure conditions in the Sixiangkou L6 chondrite indicates that either this chondrite experienced an extraordinarily long shock event or the models of shock metamorphism are incorrect.

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