SHOCK METAMORPHISM IN ORDINARY CHONDRITES: EXAMPLES FROM CHELYABINSK (LL5) AND CHANTONNAY (L6) METEORITES. I. B. Baziotis[1], L. Ferrière[2], F. Brandstätter[2], D. Topa[2], and P. D. Asimow[3], [1]Dept. of Natural Resources Management and Agricultural Engineering, Agricultural Univ. of Athens, Iera Odos 75, 11855 Athens, Greece, ibaziotis@aua.gr, [2]Natural History Museum, Burgring 7, 1010 Vienna, Austria, [3]California Institute of Technology, Division of Geological and Planetary Sciences, Pasadena, California 91125, USA.

Introduction: Shock features in ordinary chondrites preserve a record from which one may attempt to quantify the parameters of (multiple) collisions between their parent asteroids (e.g., [1]). As such, meteorites showing evidence for shock and melting at various scales (from cm down to nm) provide an opportunity to explore collision events especially to constrain the P-T conditions of these collisions. The P-T-(*t*) conditions of shock metamorphism can be inferred from the occurrence of high-pressure (HP) mineral polymorphs (e.g., [2]). In addition, one can use transformation kinetics and melt vein (MV) cooling rates to estimate the duration of a shock pulse [3].

Here, we report results from two ordinary chondrites, Chelyabinsk and Chantonnay. Chelyabinsk is a highly shocked (shock stage S4) LL5 ordinary chondrite (e.g., [4]). Ozawa et al. [5] have verified the presence of jadeite in Chelyabinsk. Chantonnay is an equilibrated L6 ordinary chondrite known to be shocked (shock stage S4; see e.g., [6, 7]); the largest known sample is in the Natural History Museum Vienna (NHMV) collection. We provide here textural, compositional, and microRaman spectroscopy data to infer constraints on the pressure-temperature conditions of melt pockets (MP) and MV formation.

Methods: Three polished sections (N9832, N9834, and N9837) of Chelyabinsk and six sections (N9836, J1935, J1940, J2887, L3910, and M5621) of Chantonnay (all from the NHMV) were investigated. We carefully examined the light and dark lithologies from the Chelyabinsk meteorite, with intensive focus on the MPs and MVs. Similarly, we carefully searched the Chantonnay sections for shock effects in mineral grains and HP polymorphs. We used transmitted and reflected light microscopy and a JEOL JSM-6610 Scanning Electron Microscope (SEM) to characterize the texture and mineralogy. We also used a JEOL JXA-8530F Field Emission Gun Electron Microprobe (FEG-EMP) for precise determination of the chemical composition and variations at the scale of a single MV and to compare different MPs within a single sample. Finally, micro-Raman spectroscopy was used to verify HP/HT minerals and phases within MPs and MVs.

Results: The groundmass of Chelyabinsk is recrystallized, but chondrules are still clearly separated from the rest of the matrix, as reported previously [8,9]. Three lithologies are present: a light one, a shock darkened one, and a (vesicular) impact melt lithology. Although shock veins are present, neither maskelynite nor planar deformation features in minerals were found. The studied samples are rich in MVs of variable thickness (from ~30 μm to ~1 mm) made up of silicate clasts (mostly olivine), sulfides, and Fe-Ni metal grains (Fig. 1). The MVs show characteristic gradation from glass-rich rims, to segregated metal-rich layers ~20 μm from the MV boundary, to silicate clast-rich cores. All the minerals show preferred orientation parallel to the MV elongation.

In Chantonnay, three types of veins occur: dark-colored clast-rich silicate veins (cross-cut by a lighter-colored), clast-poor silicate veins, and metal-troilite veins that cross-cut both the silicate veins and the wall rock [6, 10].

More details on chemistry and textural relationships of matrix minerals can be found in [4, 11] for Chelyabinsk and [6] for Chantonnay.

Ozawa et al. (2014) identified the jadeite HP polymorph in Chelyabisnk but found no silica phases associated that might help to define the P-T conditions. In our sections, we have observed, for the first time, a pyroxene glass and a clinopyroxene hosting exsolved chromite needles (Fig. 1) in close contact within the same MV. Furthermore, we report here for the first time on the occurence of jadeite in Chantonnay, located at the center of a ~500 μm wide MV (Figs. 2,4). This HP polymorph occurs as wormy intergrowths within a plagioclase grain located in the melt.

Discussion: In the Chelyabinsk sections, pyroxene glass and chromite exsolutions in clinopyroxene are both found in the middle of ~40 μm wide MVs. The MVs formed from a melt that peaked at temperatures above the liquidus of the matrix material [5]. The maximum vein width of ~40 μm implies an extremely short time, on the order of ~0.1 ms, for a conductive cooling and the solidification of the vein. The absence of back-transformation of the pyroxene glass to low-pressure equivalents suggests a high-pressure duration of at least this long. Additional constraints arise from the presence of Cr-rich spinel exsolutions in clinopyroxene.

Exsolution of Cr- and Al-Tschermak components occurs by a discontinuous reaction of the general form Ca-Al-Cr-pyroxene (+olivine)→Al-Cr spinel + diopside, whose equilibrium constant is mainly temperature-sensitive [12]. Due to the small size of the exsolutions,

we were unable to separately measure exsolved chromite and host clinopyroxene compositions. However, using a broad-beam clinopyroxene analysis ($Wo_{44-45}En_{45-46}Fs_{10-11}$ and Di_{68-70} when recast into a 10-component stoichiometry) as a tentative proxy for initial composition, the thermometer of Gasparik [12], requires initial temperature of chromite exsolution from clinopyroxene >1400 ºC. Therefore, with the presence of nearby pyroxene glass, the minimum pressure is constrained at ~6-7 GPa. Further, a maximum P limit <10 GPa is implied by the absence of olivine polymorphs (such as ringwoodite or wadsleyite) in the HP assemblage.

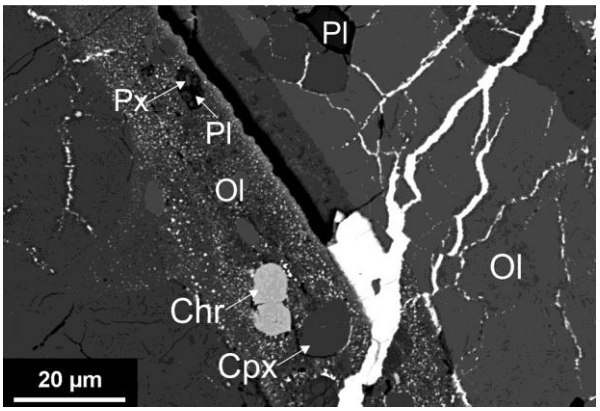

Figure 1: *BSE image of a MV in Chelyabinsk (N9834); at upper left pyroxene glass (Raman spectrum in Fig. 3) intergrowth with plagioclase, and at lower right a clinopyroxene with Cr-rich spinel exsolutions.*

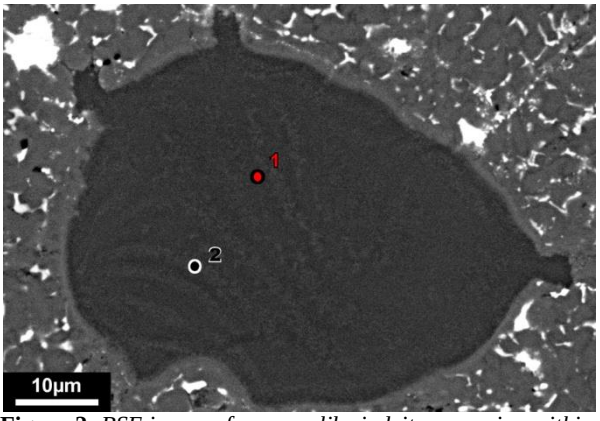

Figure 2: *BSE image of a worm-like jadeite occurring within plagioclase in contact with the melt (Chantonnay; M5621). Numbers are for locations of Raman spectra shown in Fig. 4.*

For the case of Chantonnay, the time for a complete solidification of the MV is ~18-20 msec, based on radial cooling of a 500 micron sphere from superliquidus temperatures (~2000 °C) while surrounded by cool matrix (~100 °C). The preservation of jadeite at the center of this MV suggests cooling below ~1150 °C while the rock was still at P > 7 GPa. Otherwise, complete back-transformation of jadeite to albite plus quartz would be expected.

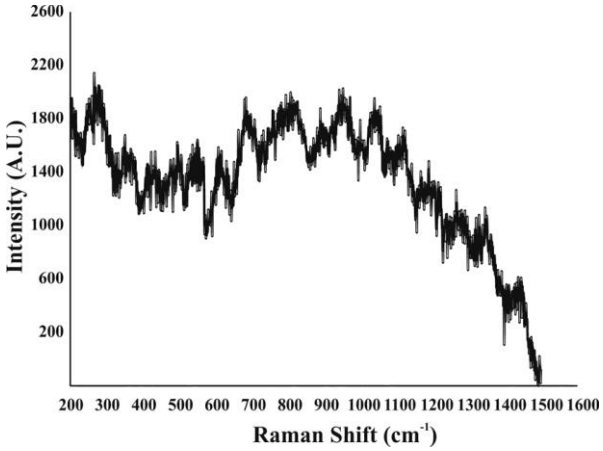

Figure 3: *MicroRaman spectrum obtained in Chelyabinsk. The spectrum corresponds to a pyroxene glass.*

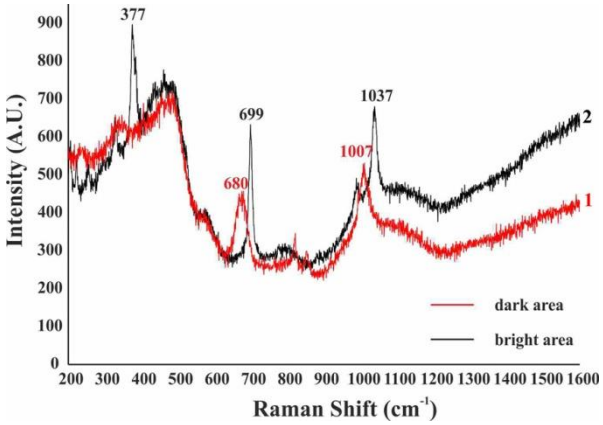

Figure 4: *MicroRaman spectra obtained in Chantonnay. The peaks at 699 and 1037 cm^{-1} are typical for jadeite.*

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