LATE-STAGE FLUIDS ON THE LL CHONDRITE PARENT BODY: EVIDENCE FROM FELDSPAR IN THE LL4 CHONDRITES BO XIAN AND BJURBÖLE. R. H. Jones and A. J. Brearley, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, U.S.A. rjones@unm.edu.

Introduction: The ordinary chondrites show a metamorphic sequence, with degree of metamorphism increasing from petrologic types 3 to 6. Metamorphic conditions for each petrologic type are not well constrained, and the distinctions between types are not well defined [1]. We recently examined changes in feldspar compositions through the metamorphic sequence, for H and LL chondrites, in order to determine whether feldspar crystallization and equilibration can help to intepret metamorphic conditions [2]. For LL chondrites, feldspars showed significant differences between types 4, 5 and 6 and some features that suggested the possibility that fluids were present during metamorphism [2]. We have now examined feldspar in LL4 chondrites in more detail, and here we report the results of a TEM study of feldspar in two LL4 chondrites, Bo Xian and Bjurböle. We find indisputable evidence for the presence of late-stage fluids on the OC parent body. This finding is contrary to the common assumption that the ordinary chondrite parent bodies were dry during their metamorphic history.

Samples and techniques: Feldspar grains were located within readily identifiable chondrules in each chondrite. We examined textures using SEM and FEG-SEM, and obtained EPMA analyses. Bjurböle data have been reported previously [2]. TEM sections of individual feldspar grains were extracted from two Bjurböle chondrules and were prepared for TEM analysis using a FEI Quanta 3D DualBeam® FEGSEM/FIB. FIB-prepared samples were removed from the thin sections using the in situ lift out technique with an Omniprobe 200 micromanipulator. The microstructures in these grains were examined using a JEOL 2010F STEM. Characterization of the sample was carried out by conventional BF TEM, STEM, HRTEM, electron diffraction and EDS analysis.

SEM and EPMA results: In both chondrites, compositions of feldspar grains in individual chondrules range from An5 to An85, with a limited compositional range in each chondrule. Anorthitic plagioclase has very low Or contents (<1 mole%), while albitic plagioclase has low Or contents in Bo Xian but up to 10 mole% Or in Bjurböle.

In several Bjurböle chondrules we observed albite-rich rims, typically a few micrometers wide, on anorthite-rich cores, and in some cases separate patches of albitic feldspar ~10 μm across [2]. Additional FEG-SEM studies showed that anorthitic cores contain numerous pores and small (<1μm) inclusions that are clearly crystallographically controlled and occur in straight, parallel lines (Fig. 1).

Plagioclase in Bo Xian shows similar features, including narrow albitic rims on anorthitic plagioclase grains. Also, we observed the ubiquitous occurrence of fine nepheline lamellae in grains of anorthitic plagioclase (Fig. 2). Albitic feldspar compositions do not show this texture. In chondrule 1, the nepheline appears to be replaced by rows of pores (Fig. 2b).

TEM results: We extracted TEM sections from plagioclase grains in Bjurböle chondrules 2 and 6 using FIB techniques. Anorthitic plagioclase compositions are An83 and An56 in chondrules 2 and 6, respectively. In chondrule 6, the FIB section extended from pyroxene across the albitic rim and into the anorthitic core of the plagioclase grains. Both FIB sections were taken perpendicular to the rows of pores and inclusions (Fig. 1). In both samples, the pores and inclusions observed by FEG-SEM were found to extend throughout the depth of the section, showing that they occur along planes within the feldspar crystals (Fig. 3).

Inclusions in both plagioclase crystals consist of chromite with a variety of morphologies including platelets and elongate needles. The consistent alignment of these grains in common orientations within the feldspar indicates they are crystallographically aligned with host feldspar, suggesting that they formed by exsolution. The exact crystallographic relationships between chromite and host plagioclase remain to be investigated in detail. In both samples, two distinct types of voids or pores are present. In chondrule 6, the outer albitic rim contains irregularly distributed, faceted, elongate voids, ranging from <50 nm in size to ~200 nm. In contrast, the more anorthitic core contains myriad, faceted nanopores (< 20 nm), that are distributed homogeneously throughout the host feldspar grains. In chondrule 2, similar nanopores are also distributed throughout the feldspar. However, larger, faceted voids (~0.1 μm in length) occur only along the narrow, linear arrays that were observed by SEM. The coarsest-grained chromite inclusions are also associated with these arrays., Analytical TEM shows that the feldspar within these linear bands is more albitic than the anorthitic host grain, and that the central part of the band appears to be pure silica (Fig. 3).

Discussion: Plagioclase in chondrules in LL4 chondrites is secondary in origin and represents crystallization of chondrule mesostases during metamorphism. Differences in plagioclase compositions among chondrules within each chondrite probably reflect initial differences in mesostasis compositions [2].

Several features of plagioclase in Bjurböle and Bo Xian indicate that they were altered by fluids, and that this alteration occurred subsequent to initial plagioclase grain growth. In Bo Xian, we observed ubiquitous nephelinitization of anorthitic plagioclase. This reaction is also commonly observed in CO and CV chondrites [e.g. 3-5], and has been attributed to a variety of processes, including metasomatic events occurring on C chondrite parent bodies [5]. Rare observations of this reaction have also been noted in ordinary chondrites [e.g. 6]. In Bo Xian, as well as in C chondrites, nephelinitization occurs along crystallographically controlled planes within plagioclase, indicating that it postdates formation of plagioclase grains.

In contrast, in Bjurböle we observe chromite exsolution and associated faceted nanopores within the host plagioclase. These pores may be voids, fluid inclusions or a reaction product from chromite exsolution. Along crystallographically controlled planes, possibly cleavage planes, we observe a reaction that most likely represents plagioclase dissolution, with leaching of Ca and Al and the formation of albitic feldspar and SiO_2 as reaction products. This process is accompanied by precipitation of coarse chromite and formation of larger voids in the leached zones. Different degrees of reaction in different chondrules are probably controlled by different compositions of the host plagioclase.

We infer that anorthitic plagioclase grain growth occurred initially during prograde metamorphism, and that these grains were subsequently altered by interactions with late-stage fluids. Although water was clearly present during the early stages of OC metamorphism [7], more extensive metamorphism (petrologic types 4-6) is generally considered to be dry. However, halite in Zag and Monahans (b) indicates the action of late-stage fluids [8,9]. Fluids are also indicated by considerations of oxygen isotope diffusion in an L6 chondrite [10] and our studies of chlorapatite grains in St. Séverin (LL6) [11]. Since the presence of fluids during metamorphism will have a significant effect on reaction rates and diffusion timescales, we should consider the implications of fluids for the thermal history of at least the LL chondrite parent body.

References: [1] Huss G. R. et al. (2006) In *Meteorites and the Early Solar System II*, ed. Lauretta D. S. and McSween H. Y., Jr. Univ. of Arizona Press, pp. 597-586 [2] Kovach H. A. & Jones R. H. (2009) *Meteorit. Planet. Sci*., in press [3] MacPherson G. J. and Davis A. M. (1993) *Geochim. Cosmochim. Acta* 57, 231-243 [4] Kimura M. and Ikeda Y. (1997) *Antarct. Meteorit. Res.* 10, 191-202 [5] Tomeoka K. and Itoh D. (2004) *Meteorit. Planet. Sci.* 39, 1359-1373. [6] Bridges J. C. et al. (1997) *Meteorit. Planet. Sci.* 32, 555-565 [7] Alexander C. M. O'D et al. (1989) 53, 3045-3057 [8] Zolensky M. E. et al. (1999) *Science* 285 1377-1379 [9] Rubin A. E. et al. (2002) *Meteorit. Planet. Sci.* 37, 125-141 [10] Dyl K. A. et al. (2009) *Meteorit. Planet. Sci.* 44 (Supp), A65 [11] Jones R. H. and Dreeland L. (2010) *41st LPSC.*

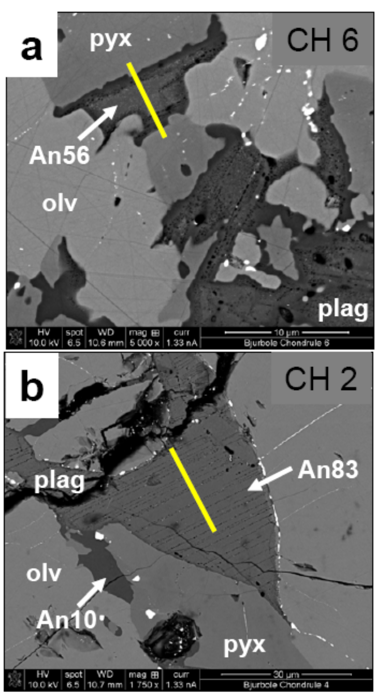

Fig. 1: BSE images of plagioclase in Bjurböle chondrules 2 and 6. Thick lines show positions of FIB sections (see Fig. 3).

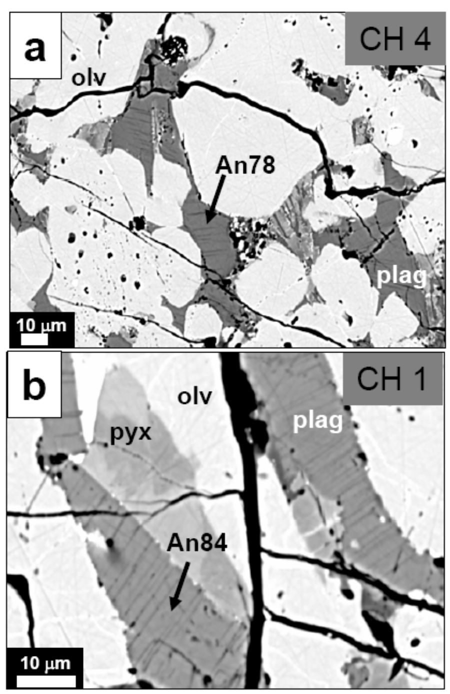

Fig. 2: BSE images of plagioclase in Bo Xian chondrules 1 and 4.

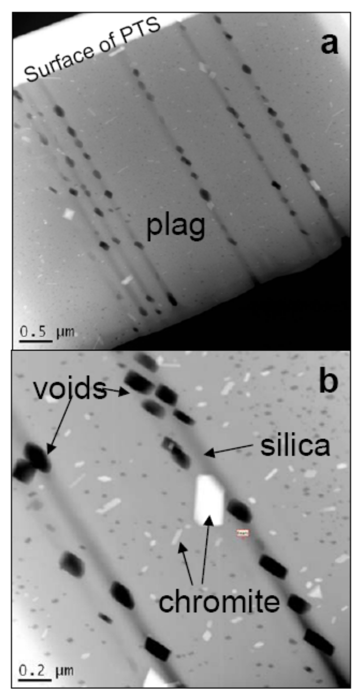

Fig. 3: Dark field STEM images of FIB section from Bjurböle chondrule 2 (see Fig. 1b).