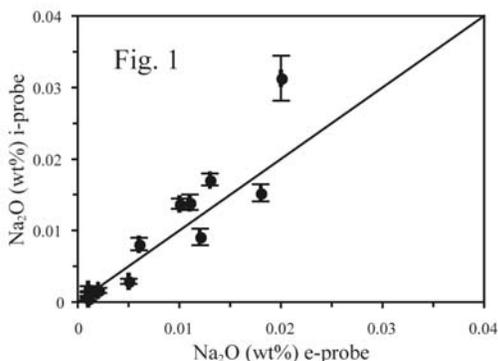


**DO WE NEED TO REASSESS THE FORMATION CONDITIONS OF CHONDRULES?** C. M. O'D. Alexander<sup>1</sup>, J. N. Grossman<sup>2</sup> and D. Ebel<sup>3</sup>. <sup>1</sup>DTM, Carnegie Institution of Washington, Washington D.C. 20015, USA (alexande@dtm.ciw.edu). <sup>2</sup>U.S. Geological Survey, Reston, VA 20192, USA (jgrossman@usgs.gov). <sup>3</sup>American Museum of Natural History, New York NY 10024 (debel@amnh.org).

**Introduction:** At the near liquidus temperatures of most porphyritic chondrules (1700-2100 K) experiments and calculations indicate that Na and K should be rapidly lost in a nebular environment [1, 2]. Alkali abundances in ordinary chondrite (OC) chondrules vary by almost three orders of magnitude. If this range was produced by variable degrees of evaporation under Rayleigh conditions, K should exhibit systematic isotopic fractionations, but to date these have not been found [e.g., 3]. [3] suggested that the alkalis were lost during heating of chondrules, but chondrules re-equilibrated with the gas at high temperature erasing any isotopic fractionations and on cooling recondensation occurred at close to isotopic equilibrium. Sodium CPX/glass ratios show that the Na contents of the residual chondrule melts reached their observed, relatively high abundances at ~1400-1200 K [3]. If Na abundances were low near the peak chondrule temperatures, then Na must have re-entered chondrules during cooling prior to CPX crystallization. In this case, Na abundances in chondrules would have varied considerably with temperature and time.

To test this hypothesis, we have measured the Na contents of olivine phenocrysts in type I and II porphyritic olivine chondrules. Olivine is generally the highest temperature liquidus phase and should therefore record any high-temperature changes in the Na content of the melt.

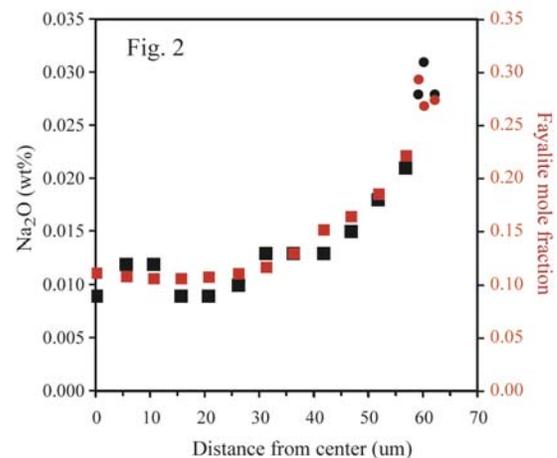


**Methods:** Na contents were measured by electron microprobe using a 15 kV 100 nA beam rastered over a 5x5  $\mu\text{m}$  area. Under these conditions and a total analysis times of ~1600 s, a 3 $\sigma$  detection limit of ~30 ppm was achieved. Repeat analyses showed that olivine is stable against Na loss at these conditions. Profiles across phenocrysts and the cores of olivine

microphenocrysts (~10  $\mu\text{m}$ ) were measured, along with the compositions of the mesostases and CPX.

To check to the accuracy of our analyses at such low concentrations, we also measured the Na contents of some olivine phenocrysts by ion microprobe. Figure 1 demonstrates the good correspondence between the two techniques.

**Results:** We have analyzed multiple olivine grains in 12 Semarkona type I (Fa <3 mol%) and type II chondrules. Figure 2 illustrates a fairly typical zoning pattern for a type II phenocryst (squares) and microphenocrysts in the mesostasis (circles). In general: (1) the microphenocrysts have similar or slightly higher Na<sub>2</sub>O contents than the rims of large phenocrysts, and (2), the total range of Na<sub>2</sub>O contents in type II olivine phenocrysts and microphenocrysts is a factor of 2-3 or less.

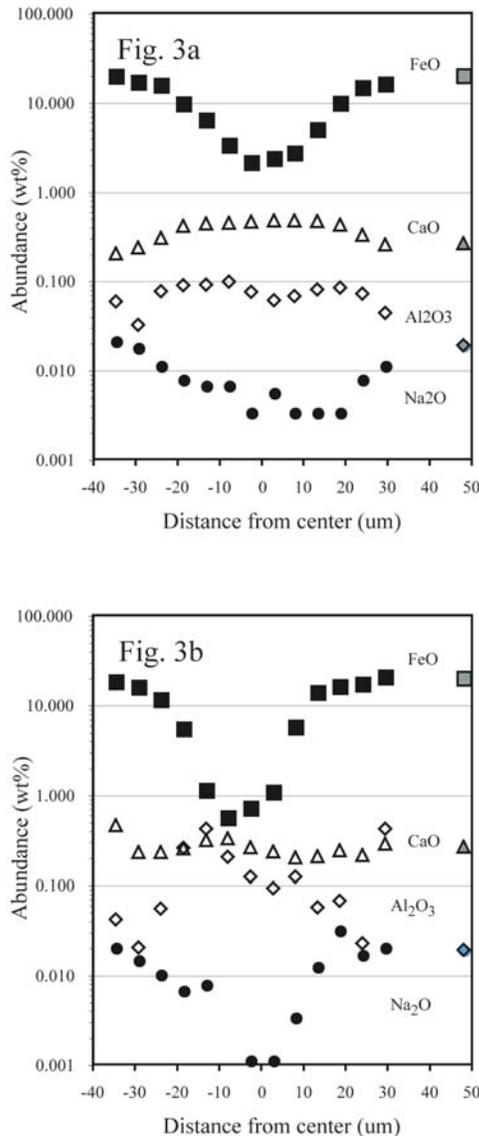


Na contents in type I chondrules tend to be low (<0.01 wt%) and relatively flat, although the higher errors associated with the low abundances mean that there is more scatter in the data than in type II chondrules.

From the Na compositions of the microphenocrysts and chondrule mesostasis, we estimate a Na olivine/melt K<sub>d</sub> of 0.0053±0.0023 for both type I and II chondrules.

We have also measured profiles across relict low-FeO grains in type II chondrules (Figs. 3). The cores of these grains have low Na contents that are typical of type I olivines. The fact that the regions of low Na (and high Al+Ca) are broader than the regions of low Fe suggests that Na diffuses more slowly than Fe. Charge balance requires that Na is incorporated via a coupled substitution with trivalent elements, such as

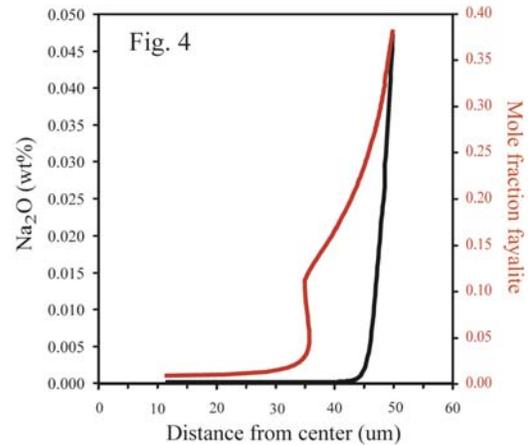
Al and Cr, and these elements may be controlling Na mobility.



**Discussion:** While the olivines from type I and II chondrules record different Na abundances in their melts during growth, compared to what is expected for canonical nebular conditions both types of chondrule exhibit remarkably little variation in Na abundance during olivine growth.

To model the process, we have conducted equilibrium calculations to predict chondrule compositions in a system of dust and gas heated to various temperatures. Only olivine, pyroxene, melt and metal are assumed to be present. At high temperatures the proto-chondrule is entirely molten and there is significant evaporation even of Mg and Si. At lower temperatures olivine begins to form and

Na (and other evaporated elements) gradually re-enters the proto-chondrule. To approximate the zoning profile one might expect in a ~50 μm radius phenocryst as it grows, we have calculated the radial position from the fraction of olivine condensed and the Na content from the Na content of the melt. Fig. 4 shows the results for  $P=10^{-3}$  bars and CI dust enriched by 1000xsolar, and Fig. 4 shows the fayalite content of the olivine.



It should be emphasized that these are not fractional crystallization calculations and should be treated as qualitative. Nevertheless, if a phenocryst preserves a record of growth from near the liquidus, the zoning profile will be quite different to what is seen in type II chondrules, although it more closely resembles that of the relict grain in Fig.3. Surprisingly, enriching the dust by another factor of 10 does not substantially change the Na profiles. Type I-like chondrule compositions produced using the same dust enrichments but with lower O contents in the dust have similarly steep Na profiles and Na contents at their edges.

**Conclusions:** Olivines in type I and II chondrules exhibit surprisingly modest Na zoning compared to expectations for canonical nebular formation conditions. The variations are roughly what might be expected for closed system crystallization. Slow Na diffusion in olivine suggests that this is not due to re-equilibration at lower T when Na contents in the melt were higher. If chondrules formed in the nebula under canonical conditions, the olivines grew at much lower T (<1500 K) than predicted. Otherwise, we must reassess the formation conditions of chondrules.

**References:** [1] Yu Y. *et al.* (2003) *GCA*, **67**, 773-786. [2] Ebel D.S. and Grossman L. (2000) *GCA*, **64**, 339-366. [3] Alexander C.M.O'D. and Grossman J.N. (2005) *M&PS*, **40**, 541-556.