CRYPTIC METAMORPHIC EFFECTS IN CHONDRULES FROM HIGHLY UNEQUILIBRATED ORDINARY CHONDRITES: AN INSIDIOUS PARENT-BODY PROCESS.

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Introduction: Type 3 ordinary chondrites display a wide variety of metamorphic grades, ranging from little metamorphosed type-3.0 chondrites up to nearly equilibrated type 3.9's. Researchers commonly assume that pristine-looking chondrules found in the lowest petrological subtypes have been unaffected by metamorphic processes, and can be used to constrain pre-accretionary processes. Last year, we reviewed various effects that result from parent-body processing in chondrules from highly unequilibrated ordinary chondrites [1]. Some are easily observed with a microscope or backscattered-electron imagery, such as "bleaching" and formation of hydrated minerals in mesostasis, but some are cryptic, such as the chemical zoning of chondrule glass that can only be observed using techniques like x-ray mapping. We presented preliminary results on another cryptic effect that might be related to secondary processing of chondrules, the formation of "inhomogeneous" mesostasis. We found that mesostasis in certain chondrules is composed of a mixture of two alkali-bearing phases: glass with high K/Na, and crystalline albitic feldspar with very low K/Na.

Herein, we report the results of further studies of the distribution and composition of chondrule mesostasis in LL chondrites with petrologic type ≤3.4. We show that albite-bearing mesostasis forms during the early stages of metamorphism, altering the primary record of pre-accretionary processes in all ordinary chondrites, including type-3.0 Semarkona. The silica-rich glass found in type II chondrules is extraordinarily sensitive to metamorphic alteration, and, for related reasons, is far more difficult to analyze using electron-beam methods than many researchers have realized.

Experimental: We continued our study [1] of albite-bearing chondrules using the TEM at the University of New Mexico. Two chondrules each from Semarkona and Chainpur were examined. A survey of alkali abundances in chondrule mesostasis in the least equilibrated ordinary chondrites was also carried out to measure changes in the abundance and composition of minerals as a function of metamorphic grade. Mesostasis and silicates from 50-75 chondrules selected at random from each of six meteorites, Semarkona (LL3.0), Elephant Moraine (EET) 90161 (LL3.1), Bishunpur (LL3.1), Meteorite Hills (MET) 96503 (LL3.1), St Mary's County (LL3.3), and Chainpur (LL3.4), were analyzed by electron microprobe. Special care was used in the measurement of sodium to make sure the element was not lost during analysis.

Results: A*nalytical pitfalls*. During our survey of random chondrules in Semarkona, we discovered a systematic difference between the mesostasis composition of chondrules that we had earlier characterized by x-ray mapping methods and that in new chondrules that we had never before analyzed. Alkali-rich chondrules that had been x-ray mapped had mesostasis at least 20% lower in Na than those which had not been mapped. Thus, it appears that these chondrules, all of which are type II or group B, have mesostasis that is *extremely* susceptible to beam damage. Under our analytical conditions (15 kV accelerating voltage, 20 nA beam current, 5×5 µm rastered beam), the Na count rate in glass drops by a factor of two in ~20 s. We normally measure the Na peak in the first 10 s of each analysis, so that resultant Na values must be corrected by ~15%. Harsher microprobe conditions used in many previous studies resulted in erroneously low determinations of Na. Preceding microprobe analysis with x-ray mapping (and possibly cathodoluminescence studies) also degrades the results. We find that analyses of chondrule mesostasis giving >30% normative quartz or any significant normative corundum are likely to have been affected by analytical Na loss.

Type II chondrules. The mesostasis of FeO-rich (type II) chondrules (defined here as those with >5 mol% Fa or Fs in mafic minerals) changes dramatically with increasing metamorphic grade, from type 3.0 to 3.4 (Figure 1). In type 3.0 (Semarkona), the alkali content of the glass phase is the lowest and K/Na transitions from subchondritic to superchondritic ratios with increasing alkali concentrations. Type II chondrules in the three LL3.1 chondrites studied have significantly higher alkalis glass than do those in type 3.0, and K/Na is mostly superchondritic. K/Na is highest in glasses in Chainpur (LL3.4) and St Mary's County (LL3.3), although the latter has the higher K/Na despite a slightly lower metamorphic subtype.

The increase in K/Na of glass with metamorphic grade is accompanied by an increase in the abundance of crystalline albite in mesostasis. In Semarkona, albitic compositions are rarely observed in randomly selected points in type II chondrules, although detailed examination using x-ray mapping reveals albite in ~20% of chondrules with the "classic" type II porphyritic olivine texture [2]. Semarkona also contains a small number of chondrules that have mesostasis that is dominated by albite: these are the group A5 chondrules noted by the Sears group [e.g., 3]. Type II chondrules in the LL3.1 chondrites contain much more albite than do those in Semarkona. About 10-20% of randomly selected mesostasis points are albite, indicating the presence of this phase in a high percentage of chondrules. In Chainpur, crystalline albite accounts for about half the volume of type II mesostasis, and in St Mary's County, albite is the dominant mesostasis phase. Type II chondrules in St Mary's County also contain a significant amount of crystalline mesostasis with a more anorthitic composition, generally around chondrule margins (to be the subject of future studies).

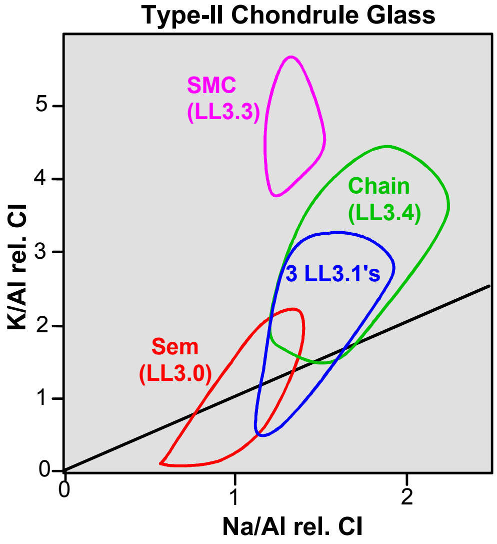

Figure 1. Composition of glass in mesostasis of type II chondrules in Semarkona (Sem), LL3.1 chondrites (Bishunpur, EET 90161, and MET 96503), Chainpur (Chain), and St Mary's County (SMC).

Type I chondrules. The composition of glass in low-FeO chondrules also changes as metamorphic grade increases from 3.0 to 3.4. More than half of Semarkona type I chondrules have glass with Na/Al < 0.25 × CI, with subchondritic K/Na. Type 3.1 EET 90161 is similar to Semarkona, but with a slightly greater proportion of alkali-rich type I chondrules. Bishunpur and MET 96503 have few type I chondrules with low-alkali glass. Chainpur and St Mary's County type I chondrules have glass that is nearly as alkali-rich as that in their type II chondrules, and some have begun to develop crystalline albite.

TEM studies. Albite in Semarkona chondrule mesostasis occurs as twinned, triclinic crystals, some containing inclusions of augite. Albite in Chainpur is untwinned, grains are more massive, and nm-sized inclusions of secondary minerals are abundant. Interfaces with glass are irregular and porous.

Discussion: Thermal metamorphism from type 3.0 to type 3.4 conditions was sufficient to change thoroughly the composition of glass in chondrules. Even by petrologic type 3.1, few type II chondrules preserve glass compositions like those found in Semarkona. The rapid movement of alkalis through these glasses during mild heating also makes them extremely difficult to analyze by microprobe, and much literature data on these must be incorrect. Type I chondrules were similarly affected by metamorphism, although not to as great an extent. Alkalis clearly entered all of these chondrules from the outside during metamorphism, with the source almost certainly being the fine-grained matrix of the meteorite. Our data also show that alkali increases were balanced by the loss of CaO from glass; the lost CaO probably entered the matrix.

Albite crystallized from chondrule glasses during metamorphism. This process resulted in the net removal of Na from chondrule glasses, increasing their K/Na (Figure 1). Observed whole-chondrule K/Na fractionation in alkali-rich chondrules from Semarkona and, especially, Chainpur [e.g., 4, 5] almost certainly indicates that alkalis readily crossed chondrule borders not just to enrich glass in alkalis, but also to provide Na during the formation of albite. *Chondrules that experienced these processes do not retain a nebular chemical record.*

Do any chondrules in the least equilibrated ordinary chondrite, Semarkona, represent the starting material from which higher petrologic types formed, or has chondrule mesostasis been affected by metamorphism even in petrologic type 3.0? Semarkona does contain chondrules with elevated alkali content, superchondritic K/Na, and crystalline albite, all of which we have shown to be products of thermal metamorphism. Semarkona also contains zoned type I chondrules [6], in which radial increases in alkalis mimic the compositional trends displayed by glasses in chondrites of higher petrologic type. It is possible that primary albite crystallized during igneous processes in alkali-rich chondrules, and formed nucleation sites for metamorphic albite. Our TEM data may support this scenario, as Semarkona albite is texturally different from that in Chainpur. However, it is difficult to explain K/Na fractionation by this process. We think it is much more likely that chondrules showing any of these properties, even in Semarkona, have been affected by incipient metamorphism.

References: [1] Grossman J. N. and Brearley A. J. (2002) *LPS XXXIII,* Abstract #1599. [2] Jones R. H. (1990) *GCA* 54, 1785-1802. [3] Dehart J. M. et al. (1992) *GCA* 56, 3791-3807. [4] Kurat G. et al. (1984), *EPSL* 68, 43-56. [5] Grossman J. N. (1996) in *Chondrules and the Protoplanetary Disk*, 243-253. [6] Grossman J. N. et al. (2002) *MAPS* 37, 49-73.