THE REDISTRIBUTION OF SODIUM IN SEMARKONA CHONDRULES BY SECONDARY PROCESSES. Jeffrey N. Grossman, 954 National Center, US Geological Survey, Reston, Virginia, 22092, USA.

Introduction: Sodium is the most easily measured volatile element in chondrules, accessible to nearly all commonly used micro- and bulk-analytical techniques. Experiments show that Na is easily lost from chondrule melts under certain conditions, making it one of the key elements for understanding chondrule thermal histories, precursor materials, and the environment in which chondrules formed. The apparent paradox that chondrules contain abundant Na, whereas theory and experiment seem to require that it should have been evaporated during the melting event have led to speculation that, (a) the experiments are not applicable, (b) chondrules formed in peculiar environments, or (c) the distribution of Na and other volatiles, particularly sulfur, in chondrules may be secondary. The latter suggestion has been particularly fueled by the recent discovery of a chondrule with zoned mesostasis in Semarkona, which is consistent with late entry of volatiles. I report three lines of evidence that support speculation (c). First, a significant fraction of Semarkona chondrules appear enriched in Na within mesostasis near the chondrule surface. Second, fine-grained chondrules almost always show evidence for significant secondary loss of Na from their surfaces. And third, all types of olivine-bearing chondrules contain glass inclusions in the olivine in which the inclusions are strongly depleted in volatiles compared to the intergranular mesostasis. I attribute these effects to subsolidus alteration of chondrules, probably by more than one process; candidates include very light metamorphism and aqueous alteration, changing the outer portions of chondrules, and an earlier, more pervasive metasomatism of chondrule glass. The setting for each process remains uncertain.

Experimental: Prior to the late-December 1995 US government furlough, the JEOL 8900 electron microprobe in Reston was programmed to do a long series of automated X-ray maps (Na, Al, S, Mg and Fe) of Semarkona thin section NMNH 1805-7. These covered an 8×10 mm area at 2 μm resolution, using 65 nA beam current, 20 kV accelerating potential, and 20 ms dwell time per pixel, taking 6 days to complete. An 8×8 mm area of Bishunpur was similarly mapped over the November 1995 government furlough, and a lower-resolution map of Allende was obtained during the December furlough period, all without operator intervention. Analyses of chondrule glass were done on the same probe under conditions to minimize Na loss, which can be extremely rapid from chondrule glasses. A minimally rastered beam (2 μm) was used because many glassy areas to be analyzed were tiny. Sodium was the first element analyzed, and was only counted for 10 s immediately after the beam was unblanked. Note that glasses analyzed under less favorable conditions in the literature would be too high in normative anorthite and quartz.

Results: Examination of the Semarkona X-ray maps reveals many chondrules with apparent enrichment of Na in mesostasis near the chondrule surface. The effect is usually subtle, and may only be present in narrow, glassy regions in contact with surrounding rim or matrix material. No relationship between type of chondrule, type of surrounding material and degree of Na enrichment was noted, although no quantitative data have yet been gathered. Similarly zoned chondrules in Allende have been noted in the literature; my X-ray map of Allende shows that sodic alteration severely affected the glass in most or all chondrules.

One striking feature of the Semarkona X-ray maps is the presence of Na- and Al-depleted regions at the surfaces of *all* fine-grained, nonporphyritic chondrules. (These are not rims or compound chondrules.) These zones penetrate 50 to 100 μm into the chondrules, are concentric with the rim (paralleling the path of any surficial "craters"), and have a sharp boundary with the interior, undepleted region. Depleted zones are interrupted by broken surfaces. I have observed white "bleached" margins on broken surfaces of separated cryptocrystalline chondrules, which appear to be the same feature. Broad-beam microprobe traverses reveal identical depletions in Na, K and Al of 50-70% in bleached zones in two cryptocrystalline chondrules, and ~10% depletion in Si. Mg, Fe and Ca are constant across the whole chondrule, including this zone. Chains of FeS crystals, common in nonporphyritic chondrules between the pyroxene fibers, are also undisturbed across the bleached zone. Surface features generally thought to be "chilled" rims have been noted previously in such chondrules, and are present outside the bleached zones observed here; depletions of Na, K and Al are much lower in these outermost areas. Bleached margins are also present around fine-grained chondrules in Bishunpur. These zones appear to be areas where at least half of the glass has been physically removed, most likely by a chemical process. Low analytical totals and tiny pits visible by SEM confirm this.

Olivine crystals in many chondrules contain small pockets that appear to have been trapped melt. These are typically ovoid in shape, and range from 10-20 µm to <1 µm in diameter. They contain isotropic glass and commonly a tiny opaque grain at one end. Melt inclusions are found in both porphyritic and barred chondrules, and in both group A and B chemical groups. Three of six group B chondrules, two of three group A1 chondrules, and the one group A5 chondrule studied contain at least one inclusion with a significantly lower Na/Al ratio than the intergranular mesostasis, with depletions of 2 to 10× in many of them (one was 100× depleted!) . Most of these also contain former melt pockets identical in composition to surrounding mesostasis. All four inclusions measured in the A5 chondrule were Na-poor. Potassium, Mn and P are depleted in many low-Na inclusions; a few are low in K but *not* in Na. Most melt inclusions (Na-poor and Na-rich) are similar in Al- and Si-contents to the mesostasis, and are almost all high in Cr. Some inclusion analyses show a significant olivine component, probably due to beam overlap. Na-poor inclusions are found in normally zoned olivine crystals, and are not associated with relict grains. Because inclusion compositions do not correlate with the host crystal compositions, the former cannot be explained by fractional crystallization. A subsolidus process affecting surrounding mesostasis is indicated.

Discussion: Clearly Na has been mobile since chondrules solidified, with at least two processes involved. The bleaching of fine-grained chondrules could be due to the dissolution of glass by aqueous fluids in an as yet unstudied process. If literature speculation is correct that FeS penetrating into fine-grained chondrules is secondary, then that process predated the bleaching process, in a complex alteration sequence. Perhaps the ubiquitous enrichment of matrix and chondrule rims in Na and Al noted in the literature results from release of Na and Al from alteration of chondrule glasses. The infiltration of Na into glass from chondrule surfaces might be linked to a more general sodic alteration experienced by chondrules with Na-poor glass inclusions. These processes might occur in either the nebula or parent body, although zoning of broken objects suggests that they preceded final lithification. These data are as yet difficult to reconcile with some previous bulk and microprobe Na and K data, including my own. Nevertheless, all previous conclusions about chondrule thermal history, formation conditions, and precursors based on alkalis should be reconsidered in light of these secondary processes.

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