TRACE ELEMENTS IN ALUMINUM-RICH CHONDRULES FROM THE MOKOIA CV CHONDRITE.

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Introduction: Aluminum-rich chondrules have intermediate compositions between ferromagnesian chondrules and refractory inclusions. Bulk chemical compositions, trace element abundances, oxygen isotope ratios and the presence of relict refractory inclusions suggest that many Al-rich chondrules formed by mixing of precursor materials that included ferromagnesian chondrules and refractory inclusions [1]. Al-rich chondrules contain limited evidence for the presence of volatility-controlled trace element fractionations, such as group II REE abundance patterns [2-4] and ultrarefractory patterns [2, 5]. Al-rich chondrules described by [1] do not show such fractionations.

Most of the evidence for fractionated trace element patterns in Al-rich chondrules is in the form of bulk chondrule measurements. It is thus unclear whether the fractionated pattern is being carried by relict grains from CAIs or whether the Al-rich chondrule was entirely melted, resulting in redistribution of the fractionated pattern among melt-derived phases. We have measured trace element abundances in individual phases in two Al-rich chondrules from the Mokoia CV chondrite in order to establish how trace elements behave during chondrule formation. We also address the extent to which trace element fractionations, including those observed in REE, Th and U, are likely to be present in the general chondrule population.

Analytical method: Bulk chemical analyses of individual chondrules were determined by INAA [6]. The two Al-rich chondrules, 11C and 14C, were selected based on the presence of fractionated REE in the bulk chondrules [7]. Major element analyses on individual phases were obtained by EPMA. Some trace element analyses on individual phases in 11C were determined by SIMS and have been reported earlier [7]. New trace element analyses were determined by LA-ICP-MS with 40-54 μm diameter analysis spots.

Results: *Petrology.* Chondrule 14C consists mostly of mesostasis which is dominated by crystalline plagioclase ($An_{91}Ab_9$) and diopside. It has a low abundance of olivine phenocrysts ($Fo_{99.5}$, CaO = 0.33wt%) and minor $MgAl_2O_4$ spinel. Some olivine grains contain pockets of glass that are isolated from the surrounding mesostasis (Fig. 1a).

Chondrule 11C consists of intergrown pyroxene ($En_{98}Wo_{1.3}$) and plagioclase ($An_{92}Ab_8$) with minor olivine ($Fo_{99.4}$, CaO = 0.12wt%) and $MgAl_2O_4$ spinel (Fig. 1b; see also [7]).

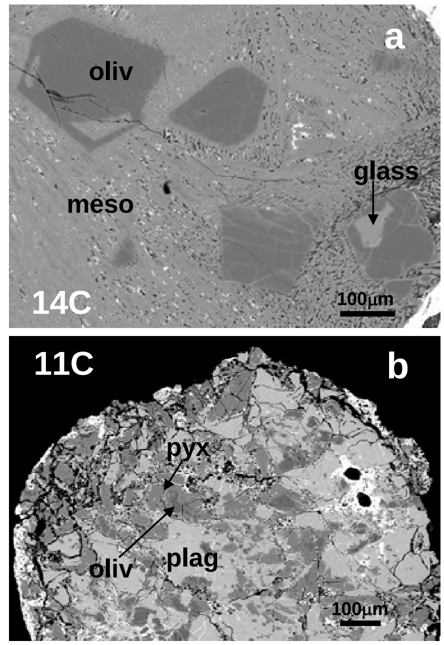

Fig. 1. BSE images of Al-rich chondrules.

Trace elements. Fig. 2 shows refractory trace element abundances relative to CI chondrite. A group II REE signature [8] is present in most phases. In 14C, a glass inclusion in olivine has comparable REE abundances to the bulk chondrule composition measured by INAA. REE abundances in the crystalline mesostasis are higher. Glass and mesostasis of 14C also contain high abundances of Ba, Sr, Ca, and Ti relative to CI. REE abundances in olivine are low, as would be expected for igneous crystallization. Partition coefficients for REEs between olivine and the glass inclusion are ~0.05. Sc is enriched in olivine, with a partition coefficient of ~0.5. In all phases, Y is significantly depleted relative to geochemically similar Dy and Ho, consistent with its abundance being controlled by volatility, as observed in group II CAIs [e.g. 9].

In 11C, LA-ICP-MS analyses are comparable to previous SIMS analyses [7]. Pyroxene and plagioclase have complementary trace element patterns, with negative and positive Eu anomalies respectively. Sr and Ca are strongly partitioned into plagioclase. The REE pattern for pyroxene is comparable to a group II pattern. REE abundances in pyroxene are comparable to the bulk composition determined by INAA.

Glass and mesostasis in 14C, as well as pyroxene in 11C, have elevated abundances of Th and U relative to CI. In 14C, Th/U ratios are ~4X the ratio in CI: this corresponds to Th/U weight ratios in glass and mesostasis of 16.9 and 14.7 respectively. The Th/U weight ratio in pyroxene in 11C is lower, 4.4.

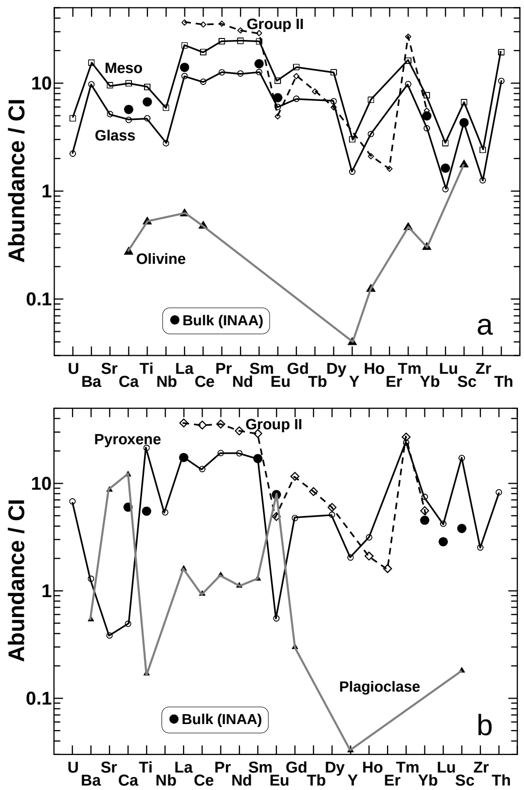

Fig. 2. LA-ICP-MS analyses of individual phases in Al-rich chondrules, arranged in the order used by [1]. Bulk compositions obtained by INAA [6]. Group II REE abundances from [8]. Glass and olivine compositions in (a) and plagioclase compositions in (b) are means of 5, 5 and 2 analyses.

Discussion: Both Al-rich chondrules, 11C and 14C, clearly carry group II REE signatures. A straightforward explanation is that their precursor material contained CAIs with group II patterns. Assuming an abundance for La of ~30xCI (Fig. 2), and assuming that ferromagnesian material contains 1X chondritic abundances, the precursor materials of 14C would have contained up to 30% CAI material. This material was completely melted during chondrule formation. Crystallization of olivine concentrated the REEs in the mesostasis; thus a second generation of chondrules containing a fragment of mesostasis from 14C could easily retain the group II signature. Elevated Ca, Sr and Ba abundances in 14C (and possibly 11C) indicate that the precursor material contained plagioclase [1].

We can investigate the extent of incorporation of fractionated refractory material into the general ferromagnesian chondrule population by examining the compositions of a large suite of 90 Mokoia chondrules [6]. Chondrules 11C and 14C have high La/Lu ratios and high Al contents (Fig. 3). In the general chondrule population, there is not a strong correlation between La/Lu ratio and Al content, although there are several chondrules that have La/Lu ratios around 2 and bulk Al contents from ~2 to 8 wt% (Fig. 3). The population of Al-rich chondrules potentially bearing a group II signature thus appears to be limited, rather than being a general characteristic of ferromagnesian chondrules.

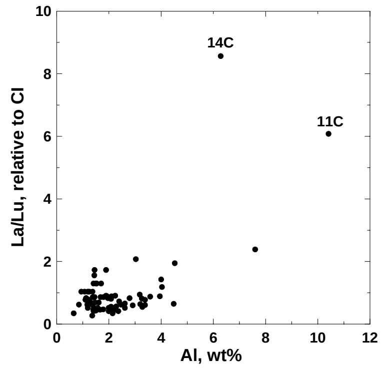

Fig. 3. Bulk compositions of Mokoia chondrules [6].

Th/U weight ratios vary from ~2 to 6 in different chondrite groups, with a value of 3.5 proposed for the average solar system [10, 11]. As a result, the value of Th/U used for the bulk Earth is the subject of some discussion [12, 13]. High Th/U ratios are known to be associated with refractory inclusions [9, 14, 15]. While the Th/U ratio in 11C is comparable to bulk chondrite data, the ratio in 14C is at the high end of the CAI range. We have shown that an elevated Th/U ratio is not necessarily limited to CAI carriers; it can be incorporated into Al-rich chondrules, and potentially also into the general chondrule population.

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Acknowledgments: This work was supported by NASA grant NNG06GF73G (RJ).