

VOLATILE ELEMENT ABUNDANCES IN CHONDRULES REVISITED: AN LA-ICP-MS STUDY OF QUE 97008 (LL3.05). J. N. Grossman¹, C. M. O'D. Alexander², R. D. Ash³, M. Luong³, and W. F. McDonough³. ¹U. S. Geological Survey, 954 National Center, Reston, VA 20192, USA, jgrossman@usgs.gov, ²DTM, Carnegie Inst. Washington, Washington D.C. 20015, USA, ³Dept. Geology, Univ. Maryland, College Park, MD 20742, USA.

Introduction: The abundances of volatile elements in chondrules may provide important constraints on many aspects of the formation of chondrules, including the nature of their precursor solids, the physical and chemical properties of their environment, and their thermal history. Several studies that have addressed this issue over the past 30 years, most using neutron activation analysis (NAA) methods on whole or partial chondrules extracted from primitive meteorites [e.g., 1-4]. With this method, it is difficult to be certain that extracted chondrules are free from contaminating matrix or rim material, which could compromise the analysis if the adhering material was volatile rich. Recently, [5] applied laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), a method that gives high sensitivity for a variety of elements and excellent spatial control, to the analysis of matrix material in several carbonaceous chondrites. However, they did not extend the method to chondrules in these meteorites.

Here we report LA-ICP-MS data on chondrules in the primitive ordinary chondrite Queen Alexandra Range (QUE) 97008, which has recently been shown to be nearly as primitive (LL3.05) as Semarkona (LL3.00) in its degree of metamorphism [6]. Our goals in this study are to: 1) measure the compositions of all types of chondrules and, later, matrix, to account for the entire elemental budget of the meteorite; 2) to determine the true volatile element content of chondrule interiors; 3) to assess sampling biases in NAA studies due to chondrule fragility that may have affected literature data.

Experimental: 41 chondrules spanning all petrographic types were selected randomly from a single polished thick section of QUE 97008. A grid of 100 points covering the surface of each chondrule was analyzed by electron microprobe and averaged to calculate the bulk composition; stoichiometric analyses were also used to compile mineral chemistry data. In several chondrules, the modal abundances of minerals were measured from detailed x-ray maps and combined with point analyses of each phase to calculate the bulk composition by a second method. To date, 14 of these chondrules have been analysed by LA-ICP-MS system at the University of Maryland using a single-collector ICP-MS (Element 2, Thermo Electron Corp) coupled to a laser ablation system with an output wavelength at 213 nm (UP213, New Wave Research).

The laser was operated with a uniform energy density of ~ 1.4 J/cm². The laser was rastered over the surface of the chondrule using an 80-100 μ m spot, a line spacing of 40-50 μ m, an 8 Hz flash rate, and moving at 10-30 μ m/s during ablation. In order to remove surface contamination, the same areas were either pre-ablated at low power or analyzed two or three times following the same tracks. Line scans 300 to 1000 μ m in length targeted areas within the chondrule, avoiding opaque assemblages on the chondrule surfaces and rims. Data were collected for the following masses: ²⁶Mg, ²⁷Al, ³⁰Si, ³¹P, ⁴³Ca, ⁴⁵Sc, ⁴⁹Ti, ⁵³Cr, ⁵⁵Mn, ⁵⁷Fe, ⁶²Ni, ⁶⁶Zn, ⁶⁷Zn, ⁶⁹Ga, ⁷¹Ga, ⁷³Ge, ⁷⁴Ge, ⁷⁵As, ⁷⁷Se, ⁸⁵Rb, ⁸⁸Sr, ⁸⁹Y, ¹⁰⁵Pd, ¹³³Cs, ¹³⁹La, ¹⁴⁰Ce, ¹⁴⁶Nd, ¹⁴⁷Sm, ¹⁵³Eu, ¹⁵⁷Gd, ¹⁶⁵Ho, ¹⁶⁹Tm, ¹⁷²Yb, ¹⁷⁵Lu, ¹⁹⁴Pt, ¹⁹⁵Pt, ¹⁹⁷Au, ²⁰⁸Pb, and ²⁰⁹Bi. Three standard reference materials (SRM 612, BCR-2g and BIR-1g) were analyzed before and after sample acquisition, providing calibration curves and constraining instrument drift. Data were processed with LAMTRACE [7], using the concentration of an internal standard in the unknowns (in this case, SiO₂ in chondrules determined by electron probe) for final calibration.

Results: Data were obtained for 5 type I (X_{Fa} or X_{Fs} < 3 mol%) chondrules ranging from type IA to IB (olivine-rich to pyroxene-rich), 6 type II chondrules ranging from IIA to IIB, and 3 radial pyroxene or cryptocrystalline (RP/C) chondrules. Si and CI normalized abundances are shown in Figs. 1 (lithophiles) and 2 (siderophile and other elements). Shown for comparison are averaged literature NAA data for Semarkona chondrules [1-4] (Si was estimated for each type of chondrule). All elements in the QUE 97008 chondrules were measured by LA-ICP-MS except Si, K, and Na, which were measured by electron microprobe.

Discussion: Our new data reproduce many of the known chemical properties of chondrules, but contain some surprises. Refractory lithophile abundances are highest in type I chondrules and lowest in RP/C chondrules; the abundance patterns of these elements, including all rare earths, are flat. Among type I chondrules, IA and IAB types are richer in refractories than pyroxene-rich IB chondrules. We reproduce literature Mn and Cr abundances in type II chondrules, but our data for these elements in type I chondrules are lower than in the literature. As is already known, volatile lithophile abundances are relatively low in type I chondrules, although we find that Cs and Rb are lower than

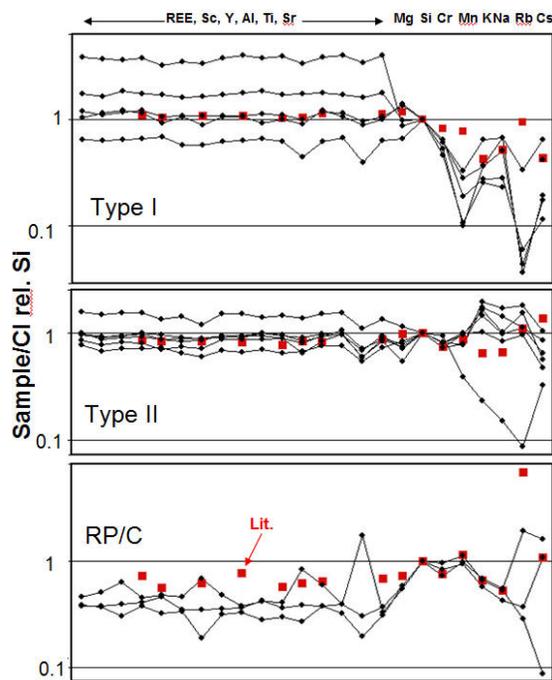


Figure 1

Na and K, contrary to [4]. We find that Rb behaves like Na and K in type II chondrites, with our Na and K data higher than values published for Semarkona; Cs, the most volatile alkali, is somewhat depleted relative to Na, K and Rb, again contrary to [4]. RP/C chondrites show a wide range of alkali abundances. Rb and Cs are enriched in one cryptocrystalline chondrite that shows evidence for bleaching, similar to data in [8]; aqueous alteration may mobilize these elements.

Most of the QUE 97008 chondrites show siderophile abundances that are lower than in literature data for Semarkona. This is probably due to our deliberate avoidance during analysis of surficial opaques and matrix or rims, although it is also possible that Antarctic weathering has removed some metal and sulfide (the weathering category is "A", but only minor rust was noted). The one refractory siderophile element we measured, Pt, displays large depletions in type II relative to Ni, whereas type I chondrite show a much smaller depletion. Similar behavior has been observed in NAA data for Ir. Phosphorus and Fe show large spikes in some of the abundance patterns of type II and RP/C chondrites, indicating that they were at least partly lithophile at the time of the metal-silicate fractionation that affected these chondrites. Gallium also shows a hint of lithophile behavior in type II and RP/C chondrites. The most volatile elements, Bi and Pb (of which there are few literature data for chondrites), plus Zn and Se are somewhat lower in abundance than siderophiles like Ni and Pd in type II chondrites, but these depletions are relatively modest. In type I chondrites, Bi, Pb, Zn and Se behave similarly, although

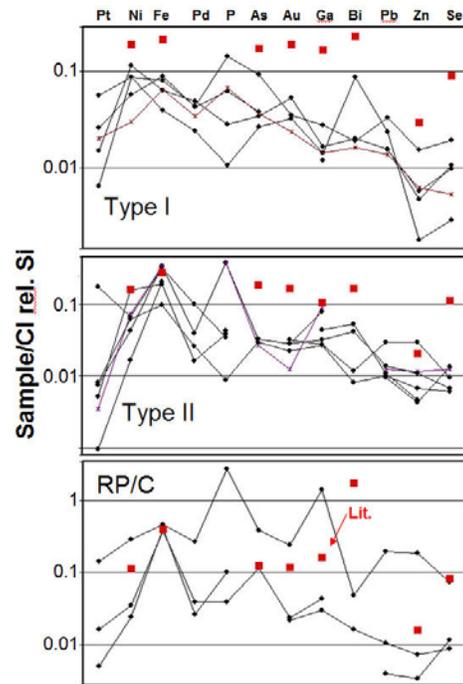


Figure 2

somewhat stronger depletions are seen in Zn and Se than in type II. Future analyses of our LA-ICP-MS scans should reveal the actual mineral affinities of all of these elements.

Despite the fact that our new analyses are representative only of chondrite cores, it is clear that they are not greatly depleted in volatile elements. Even type I chondrites, which are refractory-rich either because they formed at high temperatures or lost elements such as Fe and Si due to evaporation, are depleted by no more than a factor of ~10 in any element we measured compared to other elements of similar geochemical affinity. Chondrites clearly formed under conditions that were either not favorable for complete volatile loss via evaporation (perhaps because of high dust/gas ratios), or even their interiors managed to reequilibrate with surrounding gas during cooling.

Future work will extend this study to the remaining QUE 97008 chondrites, and then to chondrites in primitive CO and CR chondrites.

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