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CHROMITE-RICH MAFIC SILICATE CHONDRULES IN ORDINARY CHONDRITES: FORMATION BY IMPACT MELTING. Alexander N. Krot and Alan E. Rubin, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024, USA.

Chromium-rich chondrules constitute <0.1% of all ordinary chondrite (OC) chondrules and comprise three groups: chromian-spinel chondrules, chromian-spinel inclusions and chromite-rich mafic silicate (CRMS) chondrules. Chromian-spinel chondrules (typically 100-300 µm in apparent diameter) exhibit granular, porphyritic and unusual textures and occur mainly in H chondrites. Their morphologies are distinct from the irregularly shaped chromian-spinel inclusions of similar mineralogy. Chromian-spinel chondrules and inclusions consist of grains of chromian-spinel embedded in plagioclase (Pl) or mesostasis of Pl composition. Many also contain accessory ilmenite (Ilm), high-Ca pyroxene (Px), merrillite (Mer) and rare olivine (Ol); some exhibit concentric mineral and chemical zoning. CRMS chondrules (300-1100 µm in apparent diameter) are generally larger than chromian-spinel chondrules and occur in all metamorphosed OC groups. Most CRMS chondrules are nearly spherical although a few are ellipsoidal with a/b aspect ratios ranging up to 1.7. Textures include cryptocrystalline, granular, radial, barred and porphyritic varieties; some contain apparently relict grains. The chondrules consist of chromite (Chr), Ol and Pl, along with accessory Mer, troilite (Tr), metallic Fe-Ni (Met), Px and Ilm. The mesostasis in CRMS chondrules is nearly opaque in transmitted light; thus, they can be easily recognized in the optical microscope. Based on the similarity of mineralogy and chemistry between CRMS chondrules of different textures (opaque chromite-rich mesostasis, skeletal morphology of Ol grains, similar bulk compositions) we suggest that these chondrules form a genetically related population.

Chromite occurs as tiny (<1-5 µm) euhedral grains or larger (~200 µm) porphyritic and subhedral grains embedded in Pl-normative mesostasis. Chondrules Mg1 from H6 Magombedze and R1 from LL5 Richmond contain anhedral Chr grains intergrown with Tr, Met and Ilm embedded in albitic Pl; these intergrowths are probably relict. These relict Chr and Ilm grains have compositions similar to that of matrix Chr (Cr/(Cr+Al)=0.80-0.81; [1]) and Ilm [2]. Plagioclase surrounding Chr-Tr-Met±Ilm intergrowths in these two chondrules has a uniform sodic composition similar to that of matrix Pl in equilibrated OC (Ab 79-85). The other Chr grains in the CRMS chondrules consist of compositionally uniform or slightly zoned grains, although there is significant grain-to-grain compositional variation (Cr/(Cr+Al)=0.41-0.86). Olivine in the CRMS chondrules occurs as anhedral or skeletal grains. Its composition is similar to that of the host chondrites. High-Ca Px with $\leq$10.2 wt.% Al_2O_3 and $\leq$3.3 wt.% TiO_2 forms anhedral grains in interstitial areas between Chr grains. Three of the CRMS chondrules also contain large grains of Mer surrounded by Chr. Because the mesostasis of CRMS chondrules is highly enriched in tiny Chr and Ilm grains it is nearly opaque in transmitted light. The mesostases are Pl-normative; some are uniform and others are variable in composition (Ab 20-85 Or 0-6). In some cases mesostasis exhibits flow structure, i.e., differently oriented domains of aligned crystallites of Ol and Chr. Bulk compositions of CRMS chondrules are similar to the Na-Al-Cr-rich chondrules described by Bischoff and Keil [3].

There are two classes of models for the formation of CRMS chondrules. In *nebular models*, the high Cr/Mg ratios of CRMS chondrules (20-500xCI) indicate that their precursor materials contained chromian-spinel or chromite. However, nebular Cr condenses mainly as a metal alloyed with metallic Fe-Ni at $pH_2 \geq 10^{-3}$ atm [4,5] or as magnesiochromite dissolved in spinel or forsterite at $pH_2 \leq 10^{-4}$ atm [6]; it does not condense as chromite. Because 3 (of 20) CRMS chondrules contain large Mer grains that crystallized from the chondrule melt, it is apparent that P-rich precursor material was also present in the region where some of these chondrules formed. However, P does not form its own mineral phases in the most primitive OC (LL3.0 Semarkona; [7]); instead it occurs in solid solution in metallic Fe-Ni and sulfide grains. This is consistent with the siderophile and chalcophile behavior of P during condensation in the solar nebula [5]. Tiny phosphate grains (<1 µm) occur in association with metallic Fe-Ni and sulfide in the slightly metamorphosed OC, LL3.1 Bishunpur and Krymka [8,9]; it thus seems likely that phosphate grains were formed by oxidation of P-bearing metal during parent-body metamorphism. It seems impossible to produce Cr- and P-rich precursor material by condensation or by a mechanical process such as size sorting, selective adherence or stochastic sampling of fragments from previous chondrule generations. Although Krot et al. [10] suggested a solid-vapor fractionation at high nebular temperatures as a possible mechanism for enriching chondrules in Cr, ion probe bulk analyses of chromian-spinel chondrules and inclusions in OC by A.M. Davis (unpublished data) show no signs of high-temperature nebular fractionation effects in their rare earth patterns.

Another nebular model [11] maintains that Al-rich chondrules (a group that would include CRMS chondrules) formed from mesostases lost from normal mafic silicate chondrules during collisions. This model implies that mesostases in type-3 OC chondrules are Na- and Cr-rich; however, this is not the case [12-14]. Thus, both nebular models appear implausible.

In *impact-melting models* CRMS chondrules formed by impact melting pre-existing target rocks exposed at the surface of the host parent body. Chondrules that formed by such a process may exhibit various characteristics including relict chunks of target material, flow structures in the mesostasis, unequilibrated minerals and low modal abundances. We suggest that the CRMS chondrules were formed by preferential impact melting of Chr- and Pl-rich precursor material on the surface of metamorphosed parent bodies because: (1) they are present only in metamorphosed OC, (2) they have Chr and Pl of variable composition, (3) some of them contain coarse relict grains of minerals formed only during parent body metamorphism (e.g., Chr, Mer and Ilm), (4) they exhibit characteristic features of fast cooling (i.e., skeletal Ol grains and mesostasis with flow structure), (5) they constitute only ~0.08% of all OC chondrules, and (6) some melt pockets in shocked OC are similar to CRMS chondrules in mineralogy and texture. Although the impact-melting model is most probable for the CRMS chondrules containing relict grains of metamorphosed chondritic material, it is also applicable to the other CRMS chondrules because these chondrules differ only in being more completely melted. Because CRMS chondrules are rare in OC and some of them are rich in mafic silicates, we suggest that some mafic silicate chondrules (perhaps 3-5% of all OC chondrules) could also have been formed by impact melting. Potential criteria for recognizing them include (a) the presence of unmelted relicts of metamorphosed chondritic material such as Chr, Ilm and Pl, (b) the occurrence of coarse spherules of phosphate, (c) enrichment in a Pl component, and (d) mesostases containing flow structures. Ordinary chondrite regolith breccias are the most likely rocks to contain such chondrules.

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