

AL-RICH CHONDRULES: PETROLOGIC BASIS FOR THEIR DIVERSITY, AND RELATION TO TYPE C CAIs. G. J. MacPherson¹ and G. R. Huss². ¹Department of Mineral Sciences, Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119 USA glenn@volcano.si.edu. ²Department of Geology and Center for Meteorite Studies, Arizona State University, Tempe, AZ 85287-1404 USA.

Introduction: Al-rich chondrules share mineralogical and chemical properties [1,2] with, and are intermediate in a volatility sense [3] between, CAIs and ferromagnesian chondrules. In some way they must be petrogenetic links between the two. A recent upsurge of interest in Al-rich chondrules is due to their constituent plagioclase feldspar and Al-rich glass being amenable to successful ion microprobe searches for radiogenic ²⁶Mg, the decay product of ²⁶Al ($t_{1/2} = 720,000$ y). This has allowed estimates to be made of the time duration between CAI formation and the onset of Al-rich (and possibly, by extension, ferromagnesian) chondrule formation, on the order of 1.5-2.5 million years [4,5].

Al-rich chondrules comprise a diverse group of objects. Many previous studies [e.g. 2, 6, 7, 8] focused either on a very limited number of objects or else those of a particular restricted type, and as a result the diversity of Al-rich chondrules and the causes of that diversity have been overlooked. The most comprehensive petrologic study of Al-rich chondrules was by [1] who recognized a wide and continuous spectrum of objects that they subdivided into Ca-Al-rich chondrules, Ca-Na-Al-rich chondrules, Na-Al-rich chondrules, and Na-Al-Cr-rich chondrules. Wark [9] recognized that some Al-rich chondrules merge in their properties with a variety of calcium-aluminum-rich inclusion (CAI) known as Type C, whose members are igneous in origin and consist mostly of calcic plagioclase, aluminous diopside and spinel. Sheng et al. [2, 10] were the first studies to look at Al-rich chondrules from an experimental phase equilibrium viewpoint. They studied in great detail a particular subset of Al-rich chondrules that they named Plagioclase-Olivine Inclusions (POIs, approximately equivalent to the Ca-Al-rich chondrules of [1]. What has been lacking in all this previous work is an overall petrogenetic understanding of how and why the varieties of Al-rich chondrules are related to one another, or how they relate to CAIs and ferromagnesian chondrules.

We previously [3, 5] introduced a new phase projection scheme that allows the diversity of Al-rich chondrules to be portrayed graphically along with CAIs and ferromagnesian chondrules in a single petrogenetically-relevant diagram. Figure 1 shows the data for Fe-poor Al-rich chondrules, silicate-rich CAIs, and Type IA ferromagnesian chondrules projected from spinel onto the plane Ca_2SiO_4 (henceforth, C_2S) –

Mg_2SiO_4 (Fo: forsterite) – Al_2O_3 (Cor: corundum). The diagram shows spinel-saturated liquidus phase equilibria, and is constructed using experimental data taken from the literature. The Al-rich chondrule data define a cohesive linear trend that crosses the forsterite anorthite (+ spinel) cotectic and straddles the tie line between forsterite and anorthite. Note that the intersection between the anorthite-forsterite tie line and the anorthite-forsterite cotectic defines the position of a thermal divide on that cotectic. Because the Al-rich chondrules straddle these two important topologic features, they fall naturally into four different groups that evolve into different mineral assemblages and textures during crystallization. This fact alone accounts for much of the great variety of mineralogical and chemical properties among Al-rich chondrules, and suggests a more rational system for nomenclature. The effect of primary phase volume is the more important, because the first crystallizing phase will largely control the final texture. Those Al-rich chondrules plotting within the forsterite phase volume will have forsterite + spinel as the first crystallizing (phenocryst) phases. We term these Olivine-Rich or Olivine-Phyric; they typically have large euhedral or barred olivine (\pm spinel) phenocrysts. Those Al-rich chondrules plotting in the anorthite phase volume will first crystallize anorthite + spinel. These Plagioclase-Rich or Plagioclase-Phyric Al-rich chondrules have textures dominated by long euhedral plagioclase crystals, and are equivalent to the POIs of [2]. The effect of the thermal divide is more subtle because in general it controls the later rather than earliest stages of melt evolution. As different melts of Al-rich chondrule composition evolve during initial crystallization, they will approach the forsterite-anorthite cotectic directly away from either anorthite or forsterite, depending on which primary phase field they plot in. Their subsequent evolution will depend on which side of the thermal divide they end up on. Those hitting the cotectic on C_2S -rich (left) side of the thermal divide will progress toward the calcium-rich pyroxene phase field whereas those hitting the cotectic on the C_2S -poor side of the thermal divide will progress in the opposite direction, toward the anorthite-forsterite-cordierite ternary eutectic. In the latter case, even a relatively small amount of FeO in the residual melt has the effect [10] of largely eliminating the fields of cordierite, sapphirine, and mullite. Such melts ultimately evolve off the diagram in Fig. 1

and toward silica saturation, where they encounter the fields of one or more low-calcium pyroxenes (ortho-/proto-enstatite, pigeonite).

Note on Fig. 1 that Type C CAIs occupy a slightly different region than do the plagioclase-rich Al-rich chondrules. They are separated by a tie line that connects the composition of the mineral anorthite with the distributary reaction point (labeled "R"). Melts of both Type C CAI and plagioclase rich Al-chondrule composition will crystallize plagioclase or spinel as their liquidus phase, but then evolve very differently because of what the dividing line represents. Type C CAI melts evolve toward the plagioclase-pyroxene cotectic and subsequently evolve toward the melilite field; they will never crystallize olivine. Plagioclase-rich Al-rich chondrules, in contrast, evolve to the olivine-plagioclase cotectic where they begin to crystallize olivine. Those to the left of the thermal divide then evolve toward the reaction point "R". At that point, plagioclase and olivine enter into reaction relationship with the melt to form pyroxene. Wark [9] correctly inferred the nature of the difference between the two groups of objects, but did not recognize the phase equilibrium basis for it: melts of Type C CAI composition will never crystallize forsterite, whereas melts of plagioclase-rich Al-chondrule composition always will, provided they are not quenched beforehand.

Figure 2 is an enlargement of part of Fig 1, showing the essential topology that distinguishes the different types of Al-rich chondrules and Type C CAIs and summarizing a proposed nomenclature based on composition-dependent mineralogical and textural differences. Those compositions plotting in the forsterite or anorthite primary phase volumes (+ spinel) are designated olivine-rich (or olivine-phyric) and plagioclase-rich (plagioclase-phyric) Al-rich chondrules, respectively. The tie line between anorthite and the distributary reaction point "R" separates plagioclase-rich Al-rich chondrules and Type C CAIs.

One variety of Al-rich chondrule has a much more complex origin. Those that are calcium-poor and sodium-rich plot on or near the right margin of the ternary (corundum-forsterite side) in Fig. 1 ([5] referred to these as Glass-rich Al-rich chondrules; they are Na-Al-rich in the system of [1]). These have distinctive trace element patterns with large depletions in Eu and Sr. Our studies of Plagioclase-rich Al-rich chondrules show that the feldspar is commonly replaced in part by nepheline, and the latter phase has large depletions in Eu and Sr unlike the plagioclase it replaces. Remelting of such altered plagioclase-rich chondrules will produce the glass-rich (Na-Al-rich) Al-rich chondrules.

References: [1] Bischoff A. and Keil K. (1984) *GCA* 48, 693-709. [2] Sheng Y. J., Hutcheon I. D. and

Wasserburg G. J. (1991) *GCA* 55, 581-599; [3] MacPherson G. J. and Huss G. R. (2000) *Lunar Planet. Sci.* XXXI, #1796; [4] Kita N. T., Nagahara H., Togashi S. and Morishita Y. (2000) *GCA* 64, 3913-3922; [5] Huss G. R., MacPherson G. J., Wasserburg G. J., Russell S. S., and Srinivasan G. (2001) *MAPS* 36, 975-997; [6] Nagahara H. and Kushiro I. (1982) *Meteoritics* 17, 55-63; [7] Bischoff A., Palme H. and Spettel B. (1989) *EPSL* 93, 170-180. [8] McCoy T. J., Pun A. and Keil K. (1991) *Meteoritics* 26, 301-309. [9] Wark D.A. (1987) *GCA* 51, 221-242. [10] Sheng Y. J. (1992) Ph. D. Thesis, Caltech; [11] Jones R. H. and Scott E. R. D. (1989) *Proc. 19th Lunar Planet. Sci. Conf.*, 523-536. [12] Bischoff A. and Keil K. (1983) *Univ. New Mexico Spec. Pub.* 22; [13] Beckett J.R. (1986), *Ph.D. dissert.*, Univ. Chicago.

Supported by NASA NAG5-10468 & NAG5-7396 (GJM) and NAG5-11543 & NAG5-8158 (GRH).

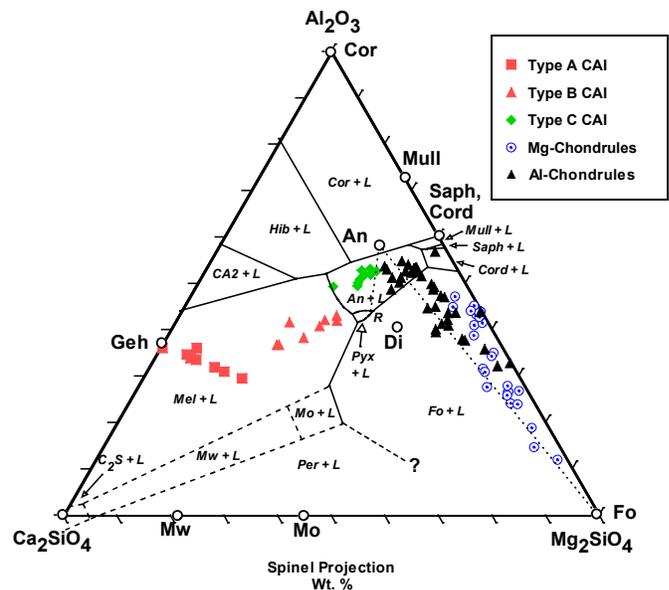


Fig. 1 [from 3, 5; data from 2, 11, 12, 13]

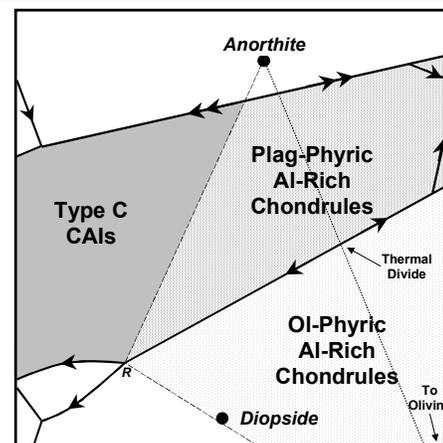


Fig. 2