

THE FOUR PRIMITIVE CHONDRULE GROUPS AND THE
 FORMATION OF CHONDRULES. Lu Jie¹, D. W. G. Sears¹, P. H. Benoit¹, M. Prinz²,
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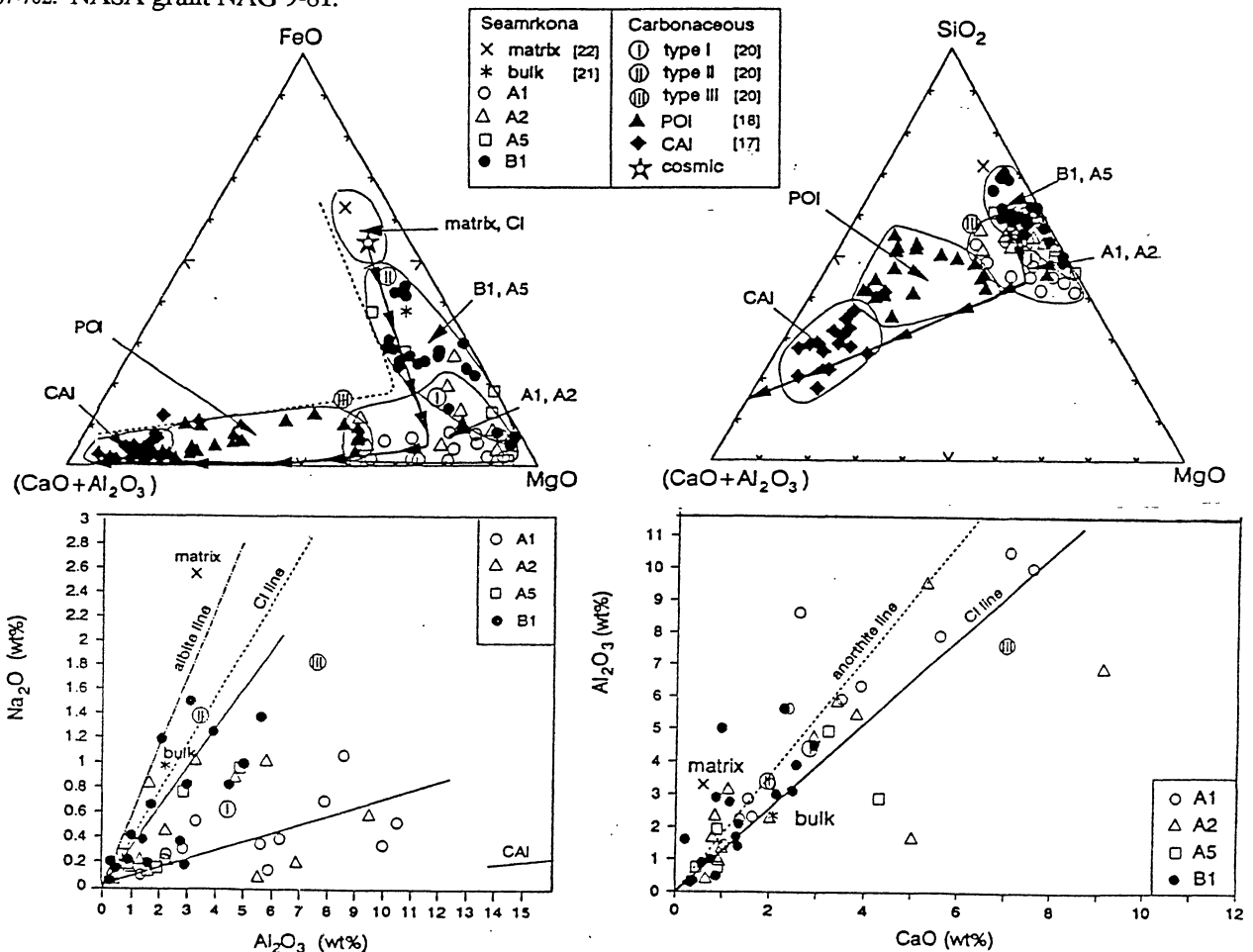
Introduction Recent studies show that chondrules in the least-metamorphosed ordinary chondrite Semarkona can be divided into four groups, each with distinctive CL properties and chemical composition [1-3]. Groups A1 and A2 are closely related refractory chondrules, containing CaO-rich mesostases and FeO-poor olivine/pyroxene, and are strongly depleted in lithophile volatiles. Group B1 are the most common chondrules, with SiO₂-rich mesostases and FeO-rich silicates, and elemental abundance patterns are similar to CI. The rare group A5 chondrules are similar to chondrules in equilibrated chondrites in their CL, silicate compositions and elemental abundance pattern, containing Na₂O-rich mesostases and FeO-rich silicates. Chondrules from carbonaceous and ordinary chondrites show many similarities, differing mainly in oxygen isotopic compositions, which vary with chondrule texture and size, and plot on a slope 1 line indicating mixing rather than mass-fractionation [4,5]. The compositional continuum between chondrules and CAI inclusions in carbonaceous chondrites has been ascribed to a condensation sequence [6] or to evaporation effects [7]. The various chondrule groups have been attributed to the diversity of chondrule precursors [8-10] or to differences in chondrule formation [1,2,11,12]. Grossman and Wasson suggested that chondrules from Semarkona were derived from a refractory, olivine-rich, FeO-free precursor and a non-refractory, SiO₂-, FeO-rich precursor [8]. Hewins recently argued that type II (a subset of group B1) chondrules in Semarkona are derived from a precursor of mainly forsterite+albite, while type IA (a subset of group A1) chondrules are produced from a mixture of mainly forsterite+CAI, and he argues that chondrules did not suffer volatile-loss (i.e. Na-loss) during chondrule formation [10]. Here, we review evidence that different chondrule groups were formed by the same processes acting with differing degrees of intensity on the same or very similar precursor material, and that volatiles were lost by evaporation during chondrule formation.

Data The compositions of the four primitive chondrule groups are summarized in Figs. 1-4. Chondrules from Semarkona produce a similar sequence to that of the least metamorphosed carbonaceous chondrites [6,13,14] when plotted on (CaO+Al₂O₃)-FeO-MgO or (CaO+Al₂O₃)-SiO₂-MgO ternary diagrams (Figs. 1 and 2), with groups B1 and A5 being lower in FeO and SiO₂ than Semarkona matrix but higher in FeO and SiO₂ than groups A1 and A2. Group B1 and group A1 chondrules form two poorly defined diagonal linear arrays on a Na₂O vs Al₂O₃ plot, with group A1 depleted in Na relative to group B1 and group A2 chondrules scattering between the other groups (Fig. 3). The chondrules in Semarkona also display a strong positive correlation between Al₂O₃ and CaO (Fig. 4). With few exceptions, which might reflect precursor heterogeneities or analytical error, chondrules of all groups show very similar Ca/Al. Similarly, a strong positive correlation between TiO₂ and CaO was also observed for the present chondrules.

Discussion The corners in Figs. 1 and 2 represent components of very different volatilities, with (CaO+Al₂O₃) < MgO-SiO₂ < FeO. The trajectories of evaporation calculated from the experiments of Hashimoto et al [7,15] are also indicated in Figs. 1 and 2. Therefore, when a system of cosmic composition undergoes evaporation at high T and low P, it will lose FeO and the data will move to the MgO corner. Redox conditions must also have played an important role during chondrule formation. Fe and Na evaporation can be greatly enhanced under more reduced conditions. Actually, considering the presence of low-FeO silicates and Ni-poor metals, group A1 chondrules were formed under much lower fO₂, while group B1 chondrules were produced under higher fO₂. With increasing evaporation, and after almost complete FeO loss, MgO volatilizes and the system migrates to the Ca- and Al-rich corner (Fig.1). Since Si has higher volatility than Mg, Si will be lost faster than Mg. However, when the SiO₂/MgO ratio decreases to that of forsterite, these elements will be lost in nearly constant proportion (Fig.2) [16]. The chondrules from the Semarkona chondrite follow the evaporation trajectories. The data for refractory inclusions from carbonaceous chondrites [17,18] are also plotted in Figs. 1 and 2. They apparently demonstrate the highest degrees of vaporization that are plausible in the presolar nebular environment. Hewins suggested that the different Na/Al ratios reflect different mixtures of forsterite, albite and the CAI minerals in the precursors [10]. Since type IA chondrules have much lower liquidus temperatures than CAI, one would expect to observe CAI or other refractory components as relict components in type IA chondrules, which is not the case. Na₂O in group A1 and A2 chondrules shows a negative correlation with the calculated liquidus temperatures, which might suggest evaporative loss of Na₂O during chondrule formation [12]. The Ca/Al ratios will be essentially unchanged during chondrule formation,

since Ca is highly refractory and mainly associated with Al present in chondrule mesostases (Fig.4). The four Semarkona chondrules analyzed by Clayton et al [5] are almost certainly group B1. Although laboratory experiments show that evaporation causes an enrichment in heavier isotopes [19], interaction with an isotopically unusual nebula gas may have overwritten such an effect. Wood pointed out that it was more likely that chondrules and matrix were produced from a common precursor of cosmic composition, and that such compositionally diverse material was brought together in just the right proportions to reproduce cosmic compositions [23]. The argument is even stronger in the present case, when chondrules themselves are of diverse composition and yet each of the chondrite classes is isochemical. The bulk chemical and mineralogical properties of the four chondrule groups are consistent with their formation by the same chondrule-forming processes acting with varying degree of intensity on the same or similar precursor material.

[1] Lu et al. (1991) Meteoritics 26, in press. [2] Sears et al. (1992) Nature in press. [3] DeHart et al. (1992) GCA, submitted. [4] Clayton et al. (1983) Chondrules and Their Origins, (ed. King), 37-43. [5] Clayton et al. (1991) GCA 55,2317-37. [6] McSween (1977) GCA 41, 1843-60. [7] Hashimoto (1983) Geochem. J. 17, 111-45. [8] Grossman and Wasson (1983) GCA 47, 759-71. [9] Grossman and Wasson (1982) GCA 46, 1081-99. [10] Hewins (1991) GCA 55, 935-42. [11] Lu et al. (1990) LPSCXIII, 720-21. [12] Sears et al. (1991) Meteoritics 26, in press. [13] McSween (1977) GCA 41, 477-91. [14] McSween (1977) GCA 41, 1777-90. [15] Hashimoto et al. (1979) EPSL. 43, 13-21. [16] Hashimoto et al. (1990) Nature 347, 53-55. [17] Mason and Taylor (1982) Smithsonian Contrib. Earth Sci. 25. [18] Sheng et al. (1991) GCA 55, 581-99. [19] Hashimoto et al. (1989) Meteoritics 24 275. [20] McSween et al. (1983) Chondrules and Their Origins, (ed. King), 195-210. [21] Dodd et al. (1967) GCA 31, 921-51. [22] Alexander et al. (1989) EPSL. 95, 187-207. [23] Wood (1985) Protostars & Planets II, 687-702. NASA grant NAG 9-81.



Figs. 1 (top left). and 2 (top right). Compositions of Semarkona chondrules, matrix and refractory inclusions from carbonaceous chondrites. The mean type I, II and III chondrule compositions are from McSween [20]; POI are plagioclase olivine inclusions [18]. The solid lines with arrows are the evaporation trajectories calculated from Hashimoto et al. [7,15]. Fig. 3. (bottom left) Na₂O vs Al₂O₃ contents (wt%) of chondrules in Semarkona. Fig. 4. (bottom right) Al₂O₃ vs CaO contents (wt%) of chondrules in Semarkona.