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 element 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 FeO2, while group B1 chondrules were produced
under higher FeO2. 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 relic
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 chondrule 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.


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) Na_2O vs Al_2O_3 contents (wt%) of chondrules in Semarkona. Fig. 4. (bottom right) Al_2O_3 vs CaO contents (wt%) of chondrules in Semarkona.