HIGH C AND H CONTENTS OF CHONDRULES. Pascal Hanon, Marc Chaussidon
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Carbon and hydrogen concentrations (reported hereafter as [C] in ppm C and [H] in ppm
H$_2$O) of 33 chondrules of all petrological types and sizes, and belonging to some of the least
altered and metamorphosed chondrites were determined with the CRPG Nancy ion-microprobe.
Special care was taken in order to efficiently get rid of the terrestrial contamination. Before
analysis, each sampling area ($\phi=25\mu$m and $=50\mu$m for the smaller chondrules) was sputtered by
the O$_2^-$ primary beam (20nA) for 5 minutes. Precise chemical concentrations for H and C were
obtained for a -60V offset applied to the sample, along with an energy filtering of $\pm$ 10V. Mass
resolution (M/\Delta M) of 1800 is sufficient to discriminate the $^{24}$Mg$^{++}$ signal from the $^{12}$C$^+$. Mid-
ocean ridge basalts were used for calibration of C and H. Major element concentrations in phases
were obtained by electron probe analysis. Then, in each chondrule, phase proportions were
visually estimated allowing the calculation of a bulk concentration for the major elements. [C] and
[H] were obtained by two methods: 1) using internal chondrule correlations between individual
ion-probe spots for carbon (or H) and major elements contents or 2) by averaging all ion-probe
[C] and [H] determinations.

Fig. 1 shows the results in a log-log scale: [H] of bulk chondrules are plotted against [C].
[C] of chondrules range from $\approx$100 to $\approx$5000 ppm. Note that [C] in chondrules is generally lower
than in their respective whole-rocks but always of the same order of magnitude (See [1] and [2]
for [C] in whole-rocks). Systematically, type I (reduced) chondrules contain more carbon (up to
4000-9000 ppm) than type II (oxidized) chondrules (up to $\approx$2000 ppm). There is no systematic
relationships between bulk [C] and bulk major element concentrations.

[H] range from $\approx$200 to $\approx$1000 ppm: except for Clovis (not shown here), the [H] of the
two chemical types of chondrules are indistinguishable. Almost all porphyritic olivine chondrules
contain glassy regions with high and constant [H] while olivines have [H] $<$ 200ppm (i.e. less
than the background). Pyroxenes are concurrently enriched in C and H (1000-2000 ppm C and H)
regardless of type and texture.

It seems unlikely that matrix contamination occurred during the local and mild
metamorphism of type 3 chondrites. For example, the smaller type I chondrules are systematically
enriched in Na but not in H and the H-Na internal correlations shown by two chondrules from
Hedjaz overlap those presented by chondrules from less metamorphosed chondrites like
Semarkona. Our data are consistent with the presence of reduced C (and H?) grains among
the nebular precursors of chondrules since: 1) [H] and [C] are well above their equilibrium
solubilities between silicate melts and protosolar gaseous species at any pressure (even at 1 atm).
2) Organic grains found in carbonaceous chondrites have C/H ratios near 1.5 [3], a limit that
distinguishes C/H ratios of type I chondrules from those of type II chondrules (See the solid line
in fig. 1). 3) High [H] and [C] of pyroxenes seems difficult to explain unless C-H grains were
trapped during their growth. 4) The extreme heterogeneity in [C] and in D/H inside mineralogical
phases of chondrules, which is thus not due to partitioning during crystallization. Note also that
typically extraterrestrial D/H ratios were found in chondrules from LL3 chondrites (see the
companion abstract by Deloule & Robert), implying in turn that H does not result from silicate
and glass alteration on Earth.
Broad calculations of volatilization (for CO₂ and H₂O during the melting of 1mm chondrules) show that, for a given range of sizes and provided type I chondrules had similar thermal histories, chondrule precursors had higher amounts of C-H reduced grains than type II's. Moreover, in dynamic crystallization experiments 4 wt. % graphite is needed to completely reduce the San-Carlos olivines [4]. In other words, reduced carbon is likely to be responsible for the reduced state of type I chondrules.

Large scale chemical variations in solar nebula grains, pre-dating the formation of chondrules, is actually a plausible model to account not only for these volatile element concentrations but also for the chemical compositions of olivines. Such high concentrations in chondrules could strongly modify the H and C budgets of the primitive Earth.

Figure 1: