CV-chondrites: High temperature gas-solid equilibrium vs. Parent body metamorphism.

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An important question in the study of carbonaceous chondrites is: to what extent do the observed mineral assemblages in the meteorite record nebular conditions prior to accretion of the parent body, and to what extent do they reflect metamorphism on the parent body? For example, do the FeO-rich matrix-olivines reflect metal/olivine equilibration at 400-600 K on a parent body, or did the small olivine grains acquire their iron by reaction with an oxidizing gas at around 1200 K? The first opinion is traditionally held. There is, however, evidence suggesting that they formed in the nebula and it will be shown below that many textural and mineralogical properties of Allende and other carbonaceous chondrites can be better understood by assuming gas-solid equilibration at high temperatures, as Kurat (1) has emphasized.

We propose the following model: Carbonaceous chondrites of type 3 contain three major primary components that were formed at high temperatures, presumably by condensation: Ca-Al rich oxides and silicates, iron poor olivine (forsterite), and some metal. Reaction of these components with the nebular gas at successively lower temperatures changed the mineralogy and chemistry of these phases. The extent of this "alteration" depended on the particular element, on the accessibility of a host phase and on the grain size. Small grains, partly accreted objects, and larger fragments were all simultaneously exposed to the same gas. In this view, the main difference between the reduced and the oxidized subgroup of the Vigaran type carbonaceous chondrites is simply the extent of the gas-solid reactions. Meteorites of the reduced subgroup (Vigaran, Leoville, Efronovka, Arch) (2) show the same mineralogical and chemical characteristics, resulting from gas-solid interaction, as members of the oxidized subgroup (Allende, Grossnaja, Bali) (2), only to a much smaller degree.

A good example illustrating the model is FeO. Several recent papers suggest that the large forsterite fragments and chondrules in Allende acquired their FeO-rich rims by condensation from a gas phase (3, 4). Recent data by Weinbruch et al. (5) support this view and it is unnecessary here to repeat all the arguments. Fayalitic rims could have condensed from a gas of solar composition at an oxygen fugacity more than two orders of magnitude higher than solar (6). Simultaneously with the formation of FeO-rims on large forsterites, small forsterite grains would have been completely transformed to FeO-rich olivine. The same gas phase would have reacted with spinels in large Ca-Al-rich inclusions, producing FeO contents in rim spinels of around 10%, and lower FeO-contents in spinels towards the interior of the inclusions. Fine-grained spinels within spinel-rich aggregates reacting with the same gas would have acquired a similar FeO-content (~10%).

The FeO contents in the same components in meteorites of the reduced subgroup are in every case much lower than those of the oxidized subgroup (see Table). This includes also matrix olivines, which are on average lower in FeO than in the reduced subgroup (2).

Formation of FeO-rich olivines by condensation at high temperatures contradicts the classical model of formation of iron-rich olivine. In that picture, forsterite and metal have separate origins, and alteration of olivine occurs at lower temperatures by solid state reaction of olivine and metal.

In our model MnO would condense into similar phases as FeO, only at somewhat lower temperatures (6). There are in fact correlations between FeO and MnO in the fayalitic rims of forsterite grains. In the traditional picture, MnO and FeO would be incorporated into olivine by very different processes: FeO by solid state reaction of forsterite with metal at temperatures of 400-600 K, whereas MnO would be incorporated into forsterite by condensation at much higher temperatures (1190 K at 10^-4 atm.) (7). Traditionally, therefore, one would expect MnO in the interior of large forsterite fragments, and FeO at the rims. However, recent data show a parallel behaviour of FeO and MnO in forsteritic olivines (4, 5, 8). Some forsterites contain inclusions of NiFe metal which has occasionally reacted with olivine to form fayalitic olivine. Weinbruch et al. (5) found that these olivines have higher Ni-contents. Fayalitic rim olivines, however, contain MnO but are low in Ni. Clearly, they were not formed by reaction with the NiFe metal in the matrix. At some temperature below the condensation of Mn, S would condense and partly transform Fe and Ni to sulfides. Since condensation of FeO on forsterites requires
relatively high oxygen fugacities, the residual metal must have been Ni-rich, which is of course observed in the Allende matrix. This Ni-rich metal was converted by the condensation of S to Ni-rich sulfides, which are omnipresent in all lithologies of Allende. The reduced subgroup has less Ni in the metal and consequently less Ni in the sulfide. This simple picture is inconsistent with the traditional formation history, which is as follows: The reaction of metal and olivine occurred at temperatures below the condensation of S, and thus there would have been no oxidized iron present before S condensed; consequently, metal should have had a uniform Ni-content before S condensation, resulting in uniform Ni-contents in later-formed sulfides. But we believe that the Ni-rich metal in Allende is a primary phase (perhaps a condensate formed under oxidizing conditions); it cannot have been produced by solid state oxidation since it is usually not closely associated with oxidized iron, and furthermore it occurs in all components of Allende.

Other more volatile elements show exactly the same behaviour as FeO. Gallium, for example, substitutes for Al in spinels from Allende, but to a much lesser extent in comparable inclusions from Efremovka (9). The alkali elements and Zn show a parallel behaviour, with high concentrations in rims and veins of coarse-grained objects, and throughout fine-grained components, of members of the oxidized group, but comparatively low contents in the same components of the members of the reduced subgroup. A somewhat similar behaviour can also be shown for Au. Although Au is roughly correlated with Na in coarse-grained Allende inclusions (10), the correlation breaks down with fine grained objects, simply because they do not contain the appropriate host phase for Au, namely metal. In summary, the similar behaviour of such geochemically different elements as Fe, Ga, Na and Zn excludes metamorphism on the parent body as a realistic possibility.