

POSSIBLE FORMATION OF IVA IRONS BY IMPACT MELTING AND REDUCTION OF L-LL

CHONDRITE MATERIALS. John T. Wasson¹, Yoshiyuki Matsunami^{1,2} and Alan E. Rubin¹, ¹Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA. ²Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan.

Possible relationships between IVA irons and L-LL

chondrites.—Magmatic iron groups formed by fractional crystallization of molten cores inside differentiated asteroids. Oxygen isotopic similarities between some groups of irons and chondritic meteorites [1] point to likely precursor materials for the irons. Group IVA is a large magmatic group of iron meteorites. The mean $\Delta^{17}\text{O}$ ($=\delta^{17}\text{O} - 0.52 \cdot \delta^{18}\text{O}$) of the silicates is $\sim +1.2\text{‰}$, similar to the highest values in L chondrites and the lowest values in LL chondrites [2,3]. This implies that IVA irons formed by melting L-LL parental materials. However, the mean Ni content of IVA irons (83 mg/g) is much lower than that of a presumed L-LL parent (~ 170 mg/g), and the low-Ca pyroxene present in two IVA meteorites is Fs13, much lower than the Fs19-26 values in equilibrated L and LL chondrites. To achieve the low Ni content of IVA irons from L-LL precursors, large amounts of metallic Fe must have been added. This requires extensive reduction of FeS and FeO.

About half the required reduction could have been produced by concomitant oxidation of carbonaceous materials in the chondritic precursor. We suggest that the remaining reduction resulted from the thermal dissociation of FeS and FeO with loss of O and S.

Because the mean $^{26}\text{Al}/^{27}\text{Al}$ ratio in chondrules from LL Semarkona ($7.5 \cdot 10^{-6}$) [4] is too low to have caused melting and differentiation, our group has suggested that the IVA magma was formed by impact heating of a highly porous chondritic asteroid [5]. Impacts are well suited to produce dissociation of FeS and FeO because they produce wide variations in the residual temperatures of target materials and because there are many conduits to the surface through which gas can escape.

Silica-bearing IVA irons. Two members of the IVA group, São João Nepumuceno (hereafter, SJN) and Steinbach, contain moderate amounts of orthopyroxene and silica, and minor amounts of low-Ca clinopyroxene [6]. The absence of olivine in these silicate assemblages may indicate an even higher degree of reduction of materials at the core-mantle interface of the IVA asteroid, perhaps reflecting the initial presence of reducing agents in the core.

As shown on plots of log Ir vs. log Au or log Ir vs. log As (Fig. 1), SJN formed after $\sim 26\%$ crystallization and Steinbach formed after $\sim 77\%$ crystallization of the IVA core. Although fractional crystallization is best understood if the parental magma mainly crystallized from the inside out, it seems clear that some crystallization would also have occurred from the outside inwards. If 1% of the crystallization occurred at the outer edge of a core with a radius of 20 km, the entire range of IVA crystallization could have been preserved in the outermost 60 m of the core. We propose that the original radius of the magma body was much smaller, perhaps of the order of 1 km. Two other members of the group (Gibeon and Bishop Canyon) contain vein-forming

tridymite; both irons crystallized after $\sim 30\%$ crystallization of the magma. The silica veins probably formed by deposition from a cooling SiO-rich vapor, produced by reduction of pyroxene or SiO_2 .

It is clear that the silicates were incorporated into IVA irons after the initial metallic magma had crystallized. Because the γ -iron crystals in SJN are typically about 5 cm across (an order of magnitude smaller than in IVA irons that do not contain massive silicates), we infer that the metal was in the γ -iron field when the silicates were injected. The SJN and Steinbach silicate compositions are near the low-Ca-pyroxene/silica eutectic composition. We suggest that impact heating produced a eutectic-like liquid and injected it together with unmelted pyroxene grains into fissures in the solid metal core.

IVA cooling rates and parent-body models. Published estimates of IVA metallographic cooling rates range from 20 to 3000 K/Ma [7], leading to a hypothesized breakup of the core during a major impact followed by scrambling of the core and mantle debris [8,9]. This scrambling model is physically implausible and cannot explain the strong correlation of estimated cooling rates with metal composition [10]. Previous workers concluded that, because TEM studies of low-Ca clinopyroxene in Steinbach showed lamellae with both odd and even multiples of the unit-cell repeat distance, the low-Ca clinopyroxene in SJN and Steinbach formed from protopyroxene by quenching at a cooling rate of 10^{12} K/Ma [9]. This conclusion was cited as additional support for the impact-scrambling model. However, because the inferred cooling rates at both higher and lower temperatures are low (ca. 10^2 K/Ma), this scenario requires an implausible spike in cooling rate by a factor of 10^{10} .

This cooling-rate excursion can be avoided if the low-Ca clinopyroxene was formed by a late-stage shock event that converted orthopyroxene into clinopyroxene followed by minimal growth in the clinopyroxene field. This would have produced the odd multiples of the unit-cell widths that are not expected in shock transformation of orthopyroxene, probably because melt was also produced in the shock event.

We infer that metallographic cooling-rate estimates (e.g., based on the island-taenite method [11]) that yield similar values throughout the metal compositional range are more plausible. The IVA parent asteroid can thus be modeled by an energetic impact that melted porous L-LL chondritic material and caused differentiation and the formation of a metallic core. This event was followed by monotonic cooling of the metal core. A subsequent high-temperature impact event introduced silicates into the metal; a later, lower-temperature impact event occurred after the Widmanstätten pattern had formed. This event caused the partial conversion of orthopyroxene into low-Ca clinopyroxene and formed the SJN and Steinbach silicate assemblages.

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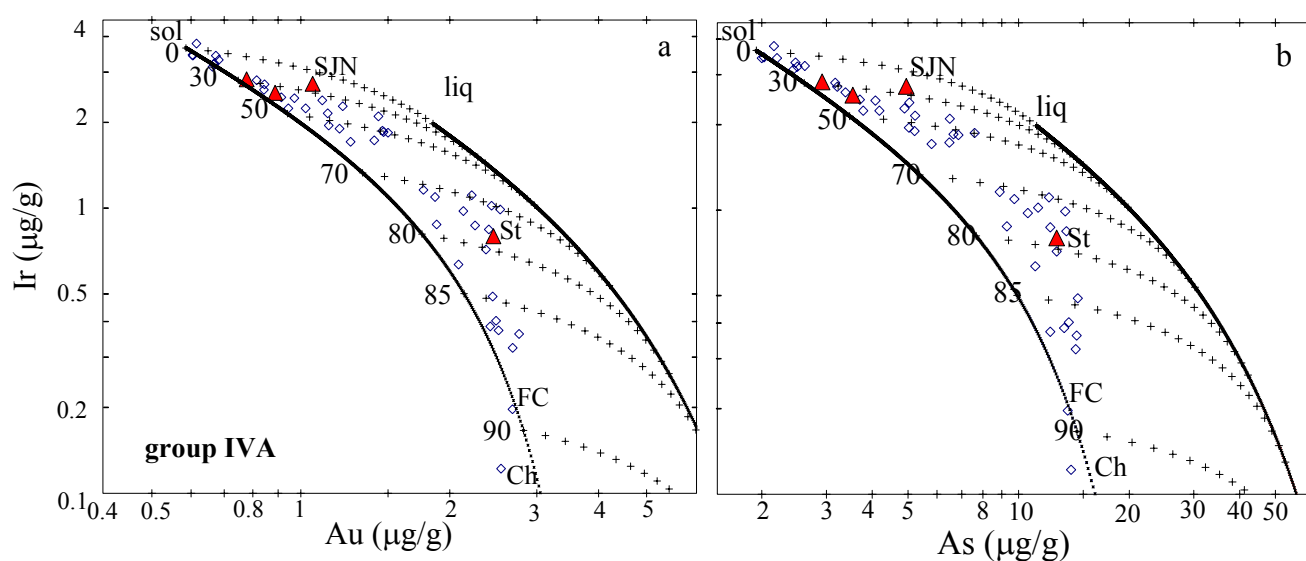


Fig. 1. Plots of Ir vs. Au and Ir vs. As for IVA irons show evidence of fractional crystallization (e.g., irons that plot near the solid track on the left) and melt-trapping (irons that plot at loci between the solid and liquid tracks). Numbers at the left of the solid track show the degree of crystallization in percent. Three of the silica-bearing IVA irons (red triangles; SJN is labeled) formed after ~30% crystallization whereas Steinbach (St) formed after 77% crystallization. Also labeled are Fuzzy Creek (FC) and Chinautla (Ch), the two most fractionated IVA irons.