THE THERMAL EVOLUTION OF IVA IRON METEORITES: EVIDENCE FROM METALLOGRAPHIC COOLING RATES;

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Abstract Unlike the other groups of iron meteorites for which a core origin is inferred, group IVA iron meteorites exhibit highly diverse metallographic cooling rates (20-3000°C/My). Furthermore, studies of the silicates in the IVA stony-iron Steinbach suggest that this meteorite cooled very fast (~100°C/hour) at high temperatures. We have determined metallographic cooling rates, and their variation with temperature, for 16 IVA iron meteorites in order to illuminate their thermal evolution [1]. Our results imply a complex thermal evolution of the IVA parent body, possibly a result of a catastrophic fragmentation and reassembly of the parent body after crystallization but prior to Widmanstätten pattern formation.

Introduction Group IVA iron meteorites is the third largest group of iron meteorites for which the chemical trends suggest a core origin. Unlike the other magmatic groups the metallographic cooling rates of IVA iron meteorites span more than two orders of magnitude. It has been suggested that the wide range in cooling rates could be due to cooling in metal pools scattered throughout the mantle [2,3], in two parent bodies [4], or in a rubble pile formed after a catastrophic fragmentation event [5,6].

Another indication of the unusual thermal evolution of IVA irons comes from studies of silicates in the IVA stony-iron Steinbach. Disordered clinobronzite in Steinbach indicates cooling rates of ~ 100°C/hour in the temperature range 1200-700°C [5,7,8].

We have determined the metallographic cooling rates of 16 IVA irons [1] using the most recent phase diagrams and diffusion coefficients [9]. We have also applied the technique of [10] to study the possibly non-linear thermal histories of these meteorites in order to reveal their unusual thermal history.

Results

Low-Ni IVA irons (10 meteorites, 7.6-8.5 wt% Ni)

The ten low-Ni IVA irons studied have high and diverse cooling rates (200-3000°C/My). Plots of Mid Profile Ni Concentration (MPC) *versus* Taenite Width (TW) for each of the low-Ni IVA irons are largely consistent with a constant cooling rate during Widmanstätten pattern formation and no substantial undercooling. The wide range in cooling rates is inconsistent with cooling in a common thermal environment.

High-Ni IVA irons (6 meteorites, 8.5-10.5 wt% Ni)

The six high-Ni IVA irons studied have much lower cooling rates ≈ 20°C/My. On MPC-TW plots the high-Ni IVA irons display similar trends consistent with cooling in the same environment. Wide taenite lamellae in high-Ni IVA irons have apparent cooling rates which are higher than those of narrow lamellae. This could either be due to a higher cooling rate at high temperatures or to undercooling. Using the technique of [10] we find that the observed trends could indicate a two-step cooling history during Widmanstätten pattern formation. At temperatures above ≈ 450°C the cooling rate was ca. 150°C/My and it then decreased to ca. 20°C/My below ≈ 450°C. Alternatively, the apparently higher cooling rates of wide lamellae could be due to late kamacite nucleations, but it cannot be due to uniform undercooling of the entire meteorite. Uniform undercooling of all lamellae in a meteorite results in a characteristic variation of MPC *versus* TW significantly different from those observed.

Discussion

Thermal evolution of the parent body

The range of cooling rates that we have found among the 16 IVA irons studied is too large to be consistent with cooling in a common core. This conclusion was also reached in several previous studies [2,3,4]. Willis and Wasson [11,12] found a much smaller range of cooling rates and argued for a common core origin. Their study was, however, confined to meteorites with a more narrow range of Ni-values and based on a phase diagram and diffusion coefficients which have later been refined [9].

It seems unlikely that the range in cooling rate is an artifact caused by the presence of P and/or C since these elements are found in both lower and higher proportions in other groups of iron meteorites (e.g. IVB and IIIAB) for which no significant range of metallographic cooling rates are found [13,14]. It also seems unlikely that the variation is due to shock since IIIAB's are generally more heavily shocked than IVA irons but have metallographic cooling rates consistent with cooling in a common core. The two-core model of [4] seems unlikely in view of the coherent fractional crystallization trends and similar cosmic ray exposure ages [15].

The evidence for crystallization in a common core and cooling in several different units could be explained in terms of the break-up and reassembly model of [5,6]. This model can also account for the evidence of rapid cooling of the Steinbach silicates. If this is indeed the correct model, our data suggest that the low-Ni IVA irons cooled in a number of fragments buried at diverse depths. The high-Ni IVA irons could have cooled in a single fragment buried deeper in the re-accreted rubble pile. The apparent two-step cooling history of the high-Ni IVA irons could have been caused by thermal equilibration between hot and cold fragments followed by slow cooling. An enigmatic feature of the break-up and reassembly model is the apparent exclusive sampling of high-Ni material by the slowly cooled fragment and the absence of high-Ni meteorites with fast cooling rates. It is also difficult to explain why the abundance of high-Ni material is close to that expected from a randomly sampled core [16]. This is not to be expected if all of the high-Ni material comes from a single deeply seated fragment.

Kamacite nucleation

On the basis of laboratory experiments it has been suggested that kamacite nucleations cannot take place prior to schreibersite precipition [17]. This would lead to substantial undercooling (≈ 200°C) in the P-poor low-Ni IVA irons. We find no evidence of undercooling for low-Ni IVA irons which suggests that kamacite nucleations did indeed take place prior to schreibersite precipition. This could be due to the difference in timescale between laboratory experiments and asteroidal cooling and/or kamacite nucleations could be triggered by large impacts on the parent body [14].

Conclusions The metallographic cooling rates found in this study imply a unique thermal evolution of the IVA iron meteorites. The cooling rates can be explained in terms of a break-up and reassembly model. There are, however, some unresolved problems with the break-up and reassembly model which suggest that we have not yet fully understood the thermal evolution of this unique group of iron meteorites.

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