THERMAL HISTORY AND ORIGIN OF THE IVB IRON METEORITES AND THEIR PARENT ASTEROID. J. I. Goldstein[1], J. Yang[1], J. R. Michael[2], P. G. Kotula[2], and E. R. D. Scott[3], [1]Dept of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA 01003, USA. E-mail: jig0@ecs.umass.edu. [2]Materials Characterization Department, Sandia National Laboratories, PO BOX 5800, MS 0886, Albuquerque, NM 87185, USA. [3]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA.

Introduction: The IVB iron meteorites are ataxites with microscopic Widmanstätten patterns consisting of kamacite platelets <20 μm in width which are derived from a fractionally crystallized core with <2 wt.% S [1,2,3]. Fast cooling rates of up to 10^4 K/Myr inferred from their kamacite bandwidths have been interpreted as evidence for core formation and cooling in a parent body with a radius of 2-4 km [4,5]. However, this radius is much smaller than the minimum radius of 10-20 km of a body melted and differentiated by ^{26}Al decay [6]. The purpose of this study was a) to obtain accurate cooling rates during kamacite formation for a diverse suite of IVB irons by measuring Ni gradients at the kamacite-taenite boundary, b) to reconcile their thermal histories with their simple fractional crystallization history, and c) to understand core formation and evolution of the IVB parent body.

Method: We examined 9 out of the 13 known IVB irons. In order to determine the nucleation mechanism and the nucleation temperature of the kamacite platelets, it is necessary to have accurate bulk Ni and P contents for each meteorite. We re-measured the bulk Ni and P content of each meteorite using X-ray area scans obtained with a Cameca SX-50 electron probe microanalyzer. The bulk Fe, Ni, Co and P compositions were measured by averaging 8 to 27 side by side 100×80 μm^2 area scans for each IVB iron.

Ni profiles in taenite and adjacent kamacite across kamacite-taenite interfaces were measured by using the analytical electron microscope (AEM). A dual beam FEI focused ion beam (FIB) instrument was used to obtain thin sections for AEM analysis. Selected kamacite/taenite interface regions in the thinnest areas of each FIB section were analyzed using a FEI Tecnai F30ST 300 keV field emission AEM. Quantitative Ni X-ray gradients 0.5-2 μm in length in taenite were measured with an X-ray spatial resolution of 2-4 nm. The size of the high-Ni particles in the cloudy zone next to the cloudy zone/tetrataenite boundary [7] was measured directly from the STEM image or the Ni X-ray scan obtained from the thin foil. The width of the outer taenite rim or tetrataenite region between the cloudy zone and the kamacite-taenite interface was also measured at several points along the kamacite/taenite interface in each FIB section.

In order to measure the cooling rates, information about the nucleation process of the Widmanstätten pattern, the nucleation temperature, the effect of impingement by adjacent kamacite plates, the Fe-Ni and Fe-Ni-P phase diagrams, and the interdiffusion coefficients which control the growth of the Widmanstätten pattern are needed [8]. Our measured bulk Ni and P content of each IVB iron meteorite along with the Fe-Ni-P phase diagram were used to determine the nucleation mechanism and the nucleation temperature for each meteorite. The Ni profile matching method [9, 10] was used to obtain a cooling rate for each individual measured taenite zoning profile, Fig 1.

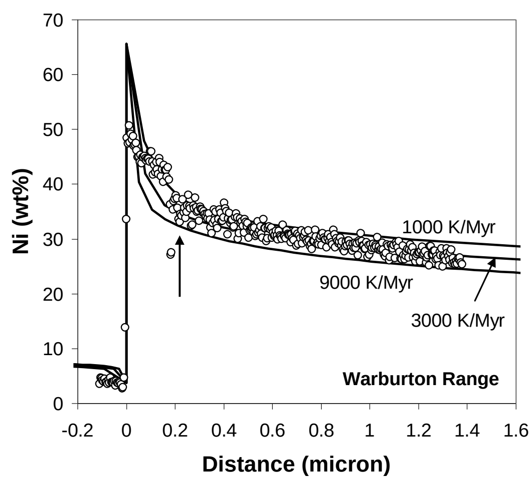

Fig. 1. Ni concentration profile across the kamacite-taenite interface obtained by AEM of a FIB section of the Warburton Range IVB iron. A cooling rate of 3,000 K/Myr was determined by comparing the observed Ni profiles with those calculated for a range of cooling rates.

Results: The cooling rates of the 9 IVB irons vary by a factor of 10 between 475 and 5,000 K/Myr and increase systematically with increasing Ni content. Apparently the IVB irons cooled faster than nearly all other iron and stony-iron meteorites. The cloudy zone regions and tetrataenite bands in all but two IVB irons are well developed and preserved with no evidence of re-heating. The high Ni particle size in the cloudy zone varies from 19 to 33 nm and decreases with increasing Ni content. The tetrataenite bandwidth varies from 150 to 265 nm and also decreases with increasing Ni content. The inverse correlations between cooling rate and both tetrataenite bandwidth and high-Ni particle size for IVB irons strongly support a significant positive correlation between cooling rate and bulk Ni, as shown by the metallographic cooling rates (Fig 2). Three independent techniques show that there is a significant range of cooling rates among IVB irons so they could not have cooled in an insulated core. In addition, all three techniques also show that the low-Ni IVB irons cooled slower than the high-Ni IVB irons giving important constraints on the formation and evolution of the IVB core.

Discussion: Fractionally crystallized iron meteorite groups are widely thought to be derived from melted cores of asteroids that cooled while they were surrounded by silicate mantles [11]. In such asteroidal bodies, iron meteorite samples from diverse positions throughout the core would have cooled at nearly identical rates because of the high thermal conductivity of metal compared with mantle and crust materials. However, there is evidence for diverse cooling rates in two fractionally crystallized groups, IVA and IIIAB [8, 10, 12]. Iron meteorite samples from these two groups could not have cooled after solidification in an insulated metallic core.

For fractionally crystallized groups with diverse cooling rates, the relative locations of the early formed low-Ni members and the late-formed high-Ni members depend on the crystallization history of the parent body. In group IVA, the low-Ni irons which crystallized first have faster cooling rates than the high-Ni members [8,12]. Thus the IVA metallic body must have crystallized inwards from the surface.

In the case of group IVB, the low-Ni irons cooled slower than the high-Ni irons, so the metallic body must have crystallized outwards from the center. Our data are the first evidence for outwards crystallization in iron meteorite parent bodies. For outwards crystallization to have taken place, the outside of the core could not have cooled quickly, as was argued for the IVA parent body. It therefore seems probable that the IVB body crystallized while it was still surrounded by an insulating mantle. However, the mantle must have been removed before the samples of the metal core cooled below 600^{0}C so that varying meteorite cooling rates could be established. Clean removal of mantle material by a glancing catastrophic impact after complete solidification seems less plausible as the core would probably have been damaged and partly scrambled. We propose instead that the collision occurred while the outer part of the core was still liquid and that the IVB irons are samples of the solid inner core of the IVB asteroid that cooled without any silicate mantle.

From a thermal model, we infer from the cooling rate of the lowest-Ni IVB iron that the minimum radius of the cooling body was 65 km. If a solid core of this size was removed after 80% crystallization, as the fractional crystallization model suggests, the radius of the original core would have been 70 km. Chemical trends within group IVB can be satisfied with fractional crystallization models for cores with 0-2 wt% S [2,3]

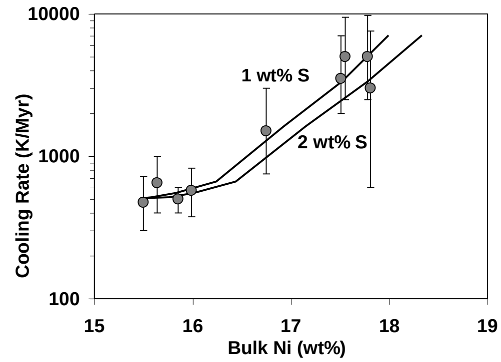

Fig. 2. Comparison between the metallographic cooling rates for nine IVB irons (o) plotted as a function of bulk Ni concentration and those calculated using the fractional crystallization and thermal models for a solid metallic core of radius 65 km that crystallized outwards in a molten core with a radius of 70 km and bulk S concentration of 1 and 2 wt%.

Figure 2 shows that these initial conditions provide an excellent match between the calculated cooling rate vs bulk Ni variation and the measured metallographic cooling rates of the IVB irons . Allowing for uncertainties in the cooling rates, we infer from further modeling that the IVB irons probably crystallized in a core that was 70±15 km in radius, in a body that was probably around 140±30 km in radius and that the 70 km core contained 1 wt.% S. The mantle was probably removed when the IVB body was torn apart in a glancing impact with a larger body, as these "hit-and-run" impacts were probably the dominant mechanism for extracting core material from differentiated asteroids [13].

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