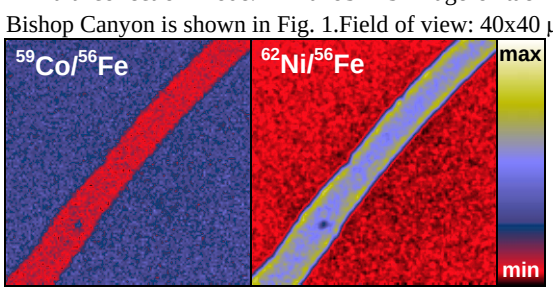
Use of Co/Ni Ratios at Kamacite/Taenite Interfaces to Determine Relative Cooling Rates of Iron Meteorites. John T. Wasson[1] and Peter Hoppe[2], [1]University of California. Los Angeles, CA 90095-1567; jtwasson@ucla.edu, [2]Max-Planck-Institut für Chemie, D-55128, Mainz, Germany; peter.hoppe@mpic.de.

Introduction: We report a pilot study of a new technique to use the distribution of Co between kamacite and taenite to infer relative cooling rates of iron meteorites; data of Widge and Goldstein [1] showed that the distribution is temperature dependent. A plot of the logarithm of the double ratio [$(Co/Ni)_{kamacite}/(Co/Ni)_{taenite}$] (abbreviated Rαγ) against inverse temperature yields a linear equation showing that the ratio ranges from ~2.5 at 1080 K to ~30 at 710 K. Thus, a measurement of Rαγ in the kamacite and taenite near the interface offers information about relative cooling rates; the lower the cooling rate, the higher Rαγ. Our study of two IVA irons with metallographic cooling rates differing by a factor of 25 [2] shows no significant difference in Rαγ and thus no difference in Co-based cooling rates. Two IIIAB irons reported to differ by a factor of 4.5 in cooling rate [3] have Co-based cooling rates that differ by a factor of 5 in the opposite direction; our data and those of [3] suggest that the Haig IIIAB iron has been altered by impact.

Experimental: We used the MPIC NanoSIMS to determine Co in kamacite and taenite; the NanoSIMS permits us to measure Co concentrations with spatial resolution of <1 μm, i.e. Co concentrations can be determined within ±1 μm of the interface with negligible levels of contamination by signals generated from the beam striking the other phase. NanoSIMS ion images consist of 256 x 256 pixels; analysis depths are estimated to be <100 nm. Fe, Co, and Ni abundances were determined in the IIIAB irons Haig and Cumpas and in the IVA irons Bishop Canyon and Duchesne by measuring positive secondary ions of ^{56}Fe, ^{59}Co, and ^{62}Ni, produced by bombardment of the samples with a ~400 (in 2 cases 800) nm-sized O^- primary ion beam (16 keV, ~1.5-15 pA) rastered over areas 20 x 20 μm^2 or 40 x 40 μm^2 in size, in multi-collection mode. A NanoSIMS image of taenite in Bishop Canyon is shown in Fig. 1.Field of view: 40x40 μm^2.



Distribution of Co between kamacite and taenite and its relationship to temperature: In Fig. 2 we plot log Rαγ against 1000/T using a regression line in which more weight is given to the high-temperature data (log Rαγ = -1.7206 +2283.9/T). Our NanoSIMS data are plotted on an extrapolation of this line. The two IVA irons and IIIAB Cumpas yield ratios that are the same within 1% and are plotted as a single point; however, Rαγ in our IIIAB Haig sample is about 30% higher than that in Cumpas, etc. According to the linear relationship, the former values correspond to a equilibration (blocking) temperature of ~746 K whereas the estimated Haig blocking temperature is ~718 K. Because of scatter in the data and the long extrapolation, we do not claim that the absolute temperatures are well defined. The important points are that the two IVA irons have the same blocking temperature whereas IIIAB Haig has an apparent blocking ~30 K lower than that of IIIAB Cumpas.

Large ranges in metallographic cooling rates: A problem of long standing are the wide, composition-dependent ranges in published metallographic cooling rates (MCRs). The metallic cores of differentiated asteroids are almost isothermal because the thermal conductivity is 30× higher in metal than in compact silicates and the difference is still larger if the silicates are porous. In the IVA irons MCRs range from 6600 K/Ma in LaGrange to 100 K/Ma in Duchesne. This high range forced Yang et al. [4] to conclude that the IVA body consisted of a bare core with a radius of 150 km and essentially no (<1 km) insulating mantle. There are many implausible aspects to such a scenario, and the alternative, that the MCR model is not adequately accounting for compositional or impact-alteration effects seems

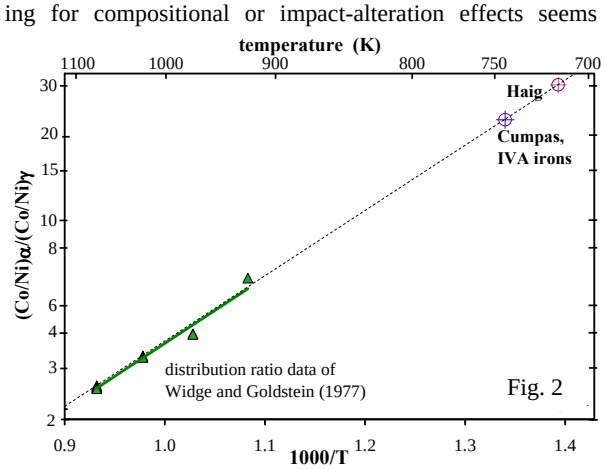


Fig. 2

more plausible [5]. The MCR range in IIIAB irons is only a factor of 6, but is claimed to be significant [2,3].

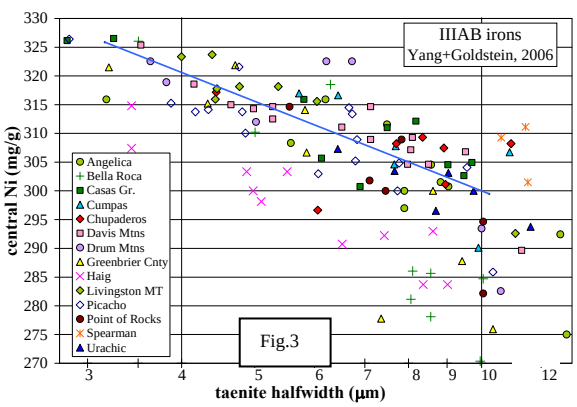
Discussion: Because we have only studied two IIIAB and two IVA irons our results must be considered preliminary. The IVA irons were chosen to cover a wide range of MCRs; that of Bishop Canyon is 2500 K/Ma, that of Duchesne 100 K/Ma [2]. Our Rαγ values for these two irons are both about 22 with 1σ errors of 7-8%. Our data are thus inconsistent with a large range of cooling rates in group IVA. We find a maximum range of 3 at 95% confidence.

Our IIIAB data are interesting because the Rαγ values are opposite of those expected based on the MCR values of 331 K/Ma for Haig and 73 K/Ma for Cumpas. The higher

MCR of Haig implies a higher equilibration temperature but, as shown in Fig. 2, it has a higher Rαγ implying equilibratiom to a lower temperature. Our data thus deny the negative correlation MCR-Au correlation , but create a new problem.

Reevaluation of the IIIAB metallographic cooling rate evidence : There are many factors that must be accounted for in models to invert observed compositions of taenite into cooling rates; these include the mean local Ni content of the metal, the contents of P and C, the distance between the α nuclei, the presence of inclusions, the abundance of structural defects, and the details of the thermal history (which may not be monotonic during the heavy bombardment period early in nebular history). In general, these effects become less important if one focuses on narrow taenite lamellae which equilibrate down to lower temperatures (than coarser) lamellae with the high-temperature conditions playing a diminished role in the final composition.

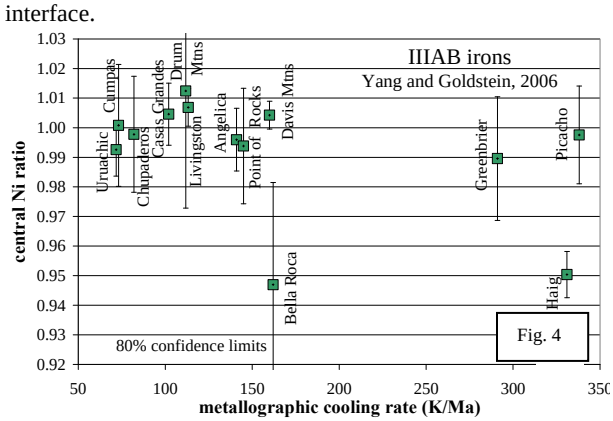
In an attempt to understand our peculiar results for the two IIIAB irons we transcribed and plotted the central taenite Ni contents of IIIAB irons against lamellar half-width [3]. Fig. 3 shows their data for lamellar halfwidths <13 μm. One of their 14 IIIABs did not have data in this range. We then limited our evaluation to lamellar halfwidths between 4 and 10 μm, the region between the two vertical lines. Eleven of the irons fell together on a single array implying similar cooling rates; the exceptions were Haig and Bella Roca.



To visualize the variation in cooling rates we fit a line to the 11 irons (Fig. 3) and used this to normalize the data. From the equation of the line we calculated the Ni content expected for that halfwidth, divided the observed Ni content by this value, and calculated a ratio (which was, of course, near unity in most cases). We then calculated the mean and Student's-t 80% confidence limits for each iron and plotted these against the MCR values of [3]. As shown in Fig. 4, mean ratios for the 11 well-behaved irons are in the range 0.99 to 1.01 and have overlapping error bars. There is no correlation with the reported cooling rates.

Bella Roca, for which the data fall into two very different clusters, has a low mean near 0.95 but a large uncertainty that extends to 0.98. In contrast, Haig has a value of 0.95 with small error bars and falls far below the 11-iron band.

We suggest that a relatively late impact may have created many defects in the Haig metallographic system, and that this can explain both the high metallographic cooling rate and the low Co-kamacite-taenite cooling rate. Fractures and defects in the high-Ni taenite near the interface could have led to enhanced diffusion due to both grain-boundary and body-diffusion effects. Cracks allowed Ni transport to the interiors of the taenite lamella and fractures resulted in smaller grain sizes and thus shorter body-diffusion distances. The result was a lower equilibration temperature near the interface.



At low temperatures the interiors of taenites ultimately transform into fine mixtures of α and γ at which point the mean Ni content ceases to evolve. Instead, the relative volumes of taenite and kamacite change while leaving the composition of grain assemblages unchanged. We suggest that an impact caused this transformation to occur at higher temperatures in Haig, thus resulting in the lower Ni content interpreted to indicate a higher cooling rate.

Conclusions: We report a promising pilot study making use of the Co distribution between kamacite and taenite to infer relative cooling rates for iron meteorites. Because we have only analyzed two IVA and two IIIAB irons our results are preliminary. Our data for the two IVA irons indicate no significant difference (less than a factor of 3 at 95% confidence) in cooling rate between the Bishop Canyon and Duchesne irons for which [2] reported differences of a factor of 25. Our results for the IIIAB irons are more complicated. Taken at face value our results imply that the cooling rate of Haig is 5× less than that of Cumpas whereas [3] reported that Haig cooled 4.5× faster than Cumpas. A reexamination of the data of [3] shows that Haig is exceptional. We suggest that shock effects account for the anomalous values by both the Co-kamacite/taenite method and the traditional taenite central-Ni content metallographic-cooling-rate method.

References: [1] Widge S. and Goldstein J. (1977) *Met. Tr.***8A**, 309.[2] Yang J., et al.. (2008) *GCA* **72**, 3043. [3] Yang J. and Goldstein J. (2006) *GCA* **70**, 3197. [4] Yang J., et al. (2007). *Nature* **446**, 888. [5] Wasson J., MatsunamiY., and RubinA. (2006) *GCA* **70**, 3149.