THERMAL, SHOCK, AND IMPACT HISTORY OF GROUP IVA AND OTHER IRON METEORITES AND THEIR PARENT ASTEROIDS. Edward R. D. Scott[1], Joseph I. Goldstein[2], and Jijn Yang[2, 3], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA. [2]Dept of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA 01003, USA. [3]Carl Zeiss NTS, LLC, Peabody, MA 01960, USA. E-mail: escott@hawaii.edu

Introduction: Observations of shocked meteorites combined with results of shock experiments, theoretical studies, and radiometric dating provide important constraints on the impact histories of meteorites and their parent bodies. Although most shocked and reheated iron meteorites are well characterized optically [1], it is not clear when the irons were reheated and whether impacts were always responsible. If reheating resulted from shock, it should be possible to identify progressive stages of shock metamorphism for irons like those for chondrites [2], but no similar scheme exists for iron meteorites. Here we discuss constraints from peak temperatures and subsequent cooling rates inferred from detailed studies of the chemical compositions of the micrometer and sub-micrometer sized phases in reheated irons [3].

Thermal Histories of Reheated Irons: The microstructures of six reheated iron meteorites including two IVA irons, Maria Elena (1935) and Fuzzy Creek were characterized using SEM, TEM, EPMA, and EBSD to determine their thermal histories [3]. Maria Elena and Hammond (ungrouped) were heated below ~700 to 750°C so that kamacite recrystallized and taenite exsolved in kamacite and recrystallized in plessite. Both meteorites retained a record of the original Widmanstätten pattern. Fuzzy Creek, Ternera (IVB) and the ungrouped irons, Babb's Mill (Blake's Iron), and Babb's Mill (Troost's Iron), which show no trace of their original microstructure, were heated above 600-700°C and recrystallized to form 10-20 μm wide homogeneous taenite grains. This would have required ~800 years at 600°C or ~1 hour at 1300°C. All six irons contain ~5-10 μm wide taenite grains with internal micro-precipitates of kamacite and nanometer-scale M-shaped Ni concentration profiles up to ~40% Ni indicating cooling over 10^{2-4} yr [4].

Connecting Shock and Thermal Histories: Although many reheated irons show evidence for shock, other heat sources may have been important: e.g., shear deformation, impact heat transferred by conduction, or solar heating near perihelion [1]. To test this we compiled constraints on the shock or reheating history of IVA irons from the following features: cloudy taenite [5], M-shaped Ni profiles in taenite [6], Neumann twin lamellae, martensite, shock-hatched kamacite resulting from formation above 13 GPa of the high-pressure hcp phase, recrystallization, micro-precipitates of taenite in kamacite, shock melting of troilite, and deformation of the Widmanstätten pattern [1].

After excluding terrestrially reheated irons [1], the IVA irons were divided into four groups according to their shock and reheating features (Table 1). Stage 1 irons have features characteristic of normal slowly cooled and unshocked irons: kamacite with Neumann twin lamellae, taenite with M-shaped Ni profiles and cloudy taenite borders, and mostly monocrystalline troilite nodules. Stage 2 irons mostly have shock-hatched kamacite, largely shock-melted troilite nodules, M-shaped Ni profiles in taenite when analyzed by EPMA, and modified or absent cloudy taenite. Stage 3 irons are characterized by recrystallized taenite lamellae, partly or wholly recrystallized kamacite plates with micro-precipitates of taenite on grain boundaries, and completely shock-melted troilite nodules. Extensive recrystallization near shock-melted troilite shows that reheating was induced by shock. Stage 4 irons show complete recrystallization of kamacite and taenite and the total absence of Widmanstätten pattern.

Nature of impacts on parent bodies: Since group IIIAB and IVA irons have many shocked meteorites (~50% of IVAs are stage 2-4) and are the only two groups with prominent clusters in the cosmic-ray exposure ages, Keil et al. [7] suggested that the asteroidal cores (or large fragments of them) were shocked during the impact that exposed the irons to cosmic rays. However, meter-sized hot irons should cool at ~0.1°C /sec, not at ≈0.5°C /yr, like Fuzzy Creek. To cool by conduction at ≈0.5°C/yr, the recrystallized irons must have been part of km-sized reheated metallic masses. IVA and IIIAB irons were probably shocked when the metallic bodies in which they cooled were destroyed. Most shock heating occurred when the largest bodies were catastrophically broken up as the specific energy for break up of bodies >1 km in size increases with increasing size ($Q^*_D \alpha\, d^{1.5}$ e.g., [8]). The lack of metallic asteroid families suggests break up occurred >3 Gyr ago.

History of Group IVA Irons: Thermal and crystallization modelling shows that three major impacts formed the IVA irons [6]. The first was a hit-and-run glancing impact between protoplanets that generated a molten metallic body ~300 km across without a silicate mantle soon after core formation. The second impact created a fragment >30 km across or more plausibly a rubble-pile asteroid with fragments from diverse depths ~20 Myr later. The third created a swarm of m-sized metallic fragments 400 Myr ago delivering meteorites to earth. The thermal histories of Maria Elena and Fuzzy Creek and other arguments discussed above clearly point to the second impact as the one that shocked and reheated the IVA irons.

This history is remarkably consistent with the Pb-Pb ages of troilite inclusions in two IVA irons determined by Blichert-Toft et al. [9]. They inferred from their 4565.3±0.1 Myr age for Muonionalusta that it cooled to ~300°C within 2-3 Myr of CAI formation. Given Hf-W isotopic constraints, the first impact that created the 300 km molten body occurred 1-2 Myr after CAIs. This suggests that Muonionalusta cooled at >500°C/Myr—the same rate that the cooling rate-bulk Ni relationship of Yang et al. would predict. Since bodies that were large enough to have been melted by ^{26}Al would have had radii of >15 km [10], their cores would have cooled at <150°C/Myr if they had silicate mantles [11]. Thus the Pb-Pb age requires that the IVA irons cooled without a silicate mantle.

Blichert-Toft et al. [9] determined a Pb-Pb age of 4544±7 Myr for a troilite inclusion in Gibeon and inferred that the troilite was shock melted ~20 Myr after CAIs formed. Since Gibeon was probably located ~10 km below the surface of the IVA body when it cooled [6], this impact could have demolished the body.

Destruction of the 150 km radius IVA body in a single impact would have required a projectile tens of kilometers in size. This may have happened in the main belt when the total mass was very much higher [6]. Alternatively, if iron meteorite parent bodies formed at 1.5-2 AU [12], they may have been destroyed there too after cooling. Since 50% of IVA irons were shocked above 13 GPa (stage 2-4; Table 1) and Fuzzy Creek was reheated above 650^0 C when it was probably located tens of km below the surface, the destruction of the IVA metallic core probably involved a conventional head-on collision rather than a glancing collision. Impact velocities at 1-2 AU would probably have been higher than those at 2-3 AU causing higher shock pressures and more extensive heating.

Studies of primary cooling and shock reheating studies in other irons suggest that other bodies may have shared many aspects of the IVA history including early core formation, mantle loss, cooling, and core destruction within 10-20 Myr of CAI formation.

References: [1] Buchwald V. F. (1975) *Handbook of Iron Meteorites*. Univ. Calif. Press [2] Stöffler D. et al. (1991) *Geochim. Cosmochim. Acta* 55, 3845-3867. [3] Yang J. et al. (2011) *Meteoritics & Planet. Sci., submitted*. [4] McCoy T. J. et al. (2010) *Geochim. Cosmochim. Acta* submitted. [5] Goldstein J. I. et al. (2009) *Meteoritics & Planet. Sci.* 44, 343-358. [6] Yang J. et al. (2008) *Geochim. Cosmochim. Acta* 72, 3043-3061. [7] Keil K. et al. (1994) *Planet. Space Sci*. 42, 1109-1122. [8] Bottke W. F. et al. (2005) *Icarus* 179, 63-94. [9] Blichert-Toft J. et al. (2010) *Earth Planet. Sci. Lett.* 296, 469-480. [10] Sanders I. S. and Taylor G. J. (2005) *ASP Conf. Series* 341, 915-932. [11] Haack H. et al. (1990) *J. Geophys. Res.* 95, 5111-5124. [12] Bottke W. F. et al. (2006) *Nature* 439, 821-824.

Table 1. Progressive stages of shock and reheating in IVA irons.

Stage	Taenite	Cloudy taenite	Kamacite	Troilite	Peak temp. °C	Freq %	Examples
1	Lamellae have M-shaped Ni profiles	Present	Monocrystalline with Neumann twin lamellae	Mostly monocrystalline, minor shock melting and recryst.	<300	53	Bishop Canyon Bushman Land Duchesne New Westville
2	Lamellae have M-shaped Ni profiles	Absent	Shock-hatched $\alpha \rightarrow \varepsilon \rightarrow \alpha$	Largely shock melted	<400-450	23	Gibeon Jamestown Obernkirchen Seneca Twp
3	Recrystallized lamellae Widmanstätten preserved	Absent	Largely crystallized with taenite micro-precipitates on grain boundaries	Totally shock melted	500-650	21	Cratheús (1931) Maria Elena Mart Serrania de V.
4	No trace of Widmanstätten pattern	Absent	Totally recrystallized	Totally shock melted and mobilized*	>650-700	3	Fuzzy Creek