THE TISHOMINGO IRON: RELATIONSHIP TO IVB IRONS, CR CLAN CHONDRITES AND ANGRITES AND IMPLICATIONS FOR THE ORIGIN OF VOLATILE-DEPLETED IRON METEORITES.

C.M. Corrigan[1], D. Rumble III[2], T.J. McCoy[1], R.D. Ash[3], W.F. McDonough[3], J. Honesto[3] and R.J. Walker[3] [1]Dept. of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119 USA (corrigca@si.edu), [2]Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC 20015 USA, [3]Dept. of Geology, University of Maryland, College Park, MD 20742 USA.

Introduction: Of the ~1,000 known iron meteorites, ~85% fall into clusters thought to represent individual parent bodies. These are the well-known groups of irons (e.g., IIIAB, IVB). The remaining ~15% fall outside these clusters and have been termed "ungrouped". The origin of these ungrouped irons is unclear, with possibilities including their formation as impact melts from chondritic bodies, products of extreme fractional crystallization or liquid immiscibility within the main groups, or that they are the only samples of their parent bodies. The last of these is particularly intriguing, since perhaps 40 distinct parent bodies are needed to account for the diversity of ungrouped irons [1] – more than all other meteorites combined. Thus, they may serve as a tremendous resource of untapped information in understanding the diversity of meteorite parent bodies. We have begun a study of ungrouped irons spurred not only by this fact, but by the availability of a population of Antarctic irons with an anomalously high percentage of ungrouped irons [1] and emergence of a suite of techniques for study of irons in the last decade. In this study, we report on our work on the Tishomingo iron and discuss its relationship to group IVB and CR clan chondrites.

Results: In 1997, the Smithsonian Institution cut several large slices from the 97 kg mass of Tishomingo held by Texas Christian University (courtesy of A. Ehlmann of TCU), acquiring one of the slices. These slices (measuring ~21 x 18 cm) provided the first substantial surface area available for examination. Like the small piece studied by [2,3], the larger slices display a martensitic structure indicative of a single crystal. Also present are scattered troilite nodules up to 6 mm with martensite-free rims. In one slice, we identified a semi-translucent mineral of a few mm in dimension that we tentatively identified as SiO_2.

The SiO_2 grain has been the major target of our study. X-ray diffraction analyses revealed that the grain is stishovite, confirming its extraterrestrial origin. Silica grains are relatively common in iron meteorites and are rarely subjected to structural analyses. The only previous report of stishovite in an iron meteorite came from the IVA iron Muonionalusta [4]. We subsequently undertook oxygen isotopic analyses using the laser fluorination system at the Carnegie Institution of Washington. Replicate analyses yielded $\delta^{17}O$ = 3.06, 3.05‰; $\delta^{18}O$ = 6.08, 6.04‰; $\Delta^{17}O$ = -0.15, -0.14‰ (Fig. 1). Although the deviation from the terrestrial mass fractionation line is small, it is outside the uncertainty for the determination of the TFL.

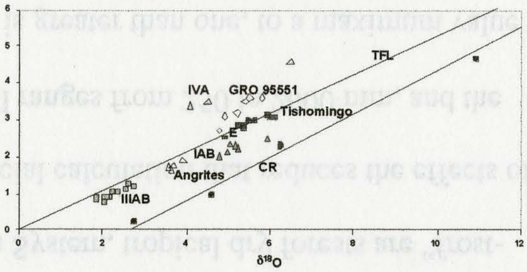

Figure 1. Oxygen isotopic composition of stishovite in Tishomingo, compared with several groups of irons, achondrites and metal-rich chondrites [5-7].

As part of our continuing study of siderophile element compositions in IVA and IVB irons, a 10x6 mm section of Tishomingo was cut, polished and analyzed for its trace element composition by laser ablation ICP-MS at the Univ. of Maryland. Individual analyses consisted of raster ablation lines ~1mm long x 100 microns wide across the polished section that revealed the presence of small inclusions of sulfides and most likely carbides. These inclusions revealed a heterogeneous distribution of W, Ag, Ga, Sb, Pb and V (variations of 45-65% between scans) and in some cases spikes of Nb and Ta. Previous authors [8,9] have noted the unusual composition of Tishomingo, including its high Ni concentration (32.5 wt.% Ni). Our data expands previous data sets that pointed to Tishomingo being enriched in refractory and highly depleted in volatile siderophile elements, a pattern shared by IVB irons (Fig. 2).

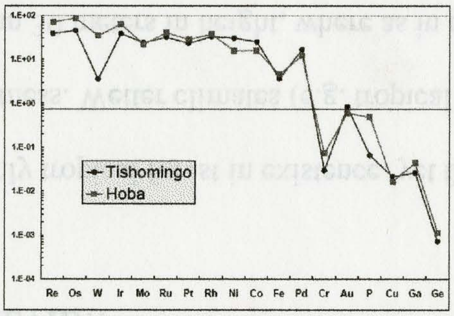

Figure 2. CI-normalized siderophile element concentrations for Tishomingo and the IVB iron Hoba.

Discussion: Our new data on Tishomingo allows us to discuss possible relationships between this ungrouped iron and other groups of irons, achondrites and, possibly, precursor chondritic materials.

Several meteorite groups share similarities with Tishomingo but genetic relationships seem unlikely. Enstatite meteorites (aubrites and E chondrites) are similar in oxygen isotopic composition, but more reduced than the SiO_2-bearing Tishomingo. IIIAB irons share a similar $\Delta^{17}O$, but do not show the pronounced depletions of the volatile siderophiles. Groups IAB and IVA (the only other groups known to contain stishovite) also lack this depletion and differ in $\Delta^{17}O$ from Tishomingo.

A possible link between IVB irons and the high-Ni irons Tishomingo and Willow Grove has been suggested by several authors [e.g., 9]. At face value, the similarity in siderophile element concentration patterns (Fig. 2) would seem to support such a link. However, a detailed examination suggests some problems with expansion of group IVB to include these high-Ni irons. A preliminary comparison of platinum group elements between Tishomingo and IVB irons [10] suggests that Tishomingo does not fall on a reasonable extrapolation of group IVB trends. Further, the structure of Tishomingo is consistent with slow cooling of a high-Ni, low-P iron meteorite [11]. However, IVB irons show increasing concentrations of the incompatible P with increasing Ni [12]. Thus, a high-Ni IVB should also be high in P, quite opposite to our measured low P abundance in Tishomingo. Thus, the data in hand, while suggesting an interesting similarity between Tishomingo and IVB irons, does not forge a link between these groups. Additional data are needed to evaluate expansion of group IVB, including completion of the PGE analyses and analyses of oxygen-bearing phases in IVB irons. We are unaware of any oxygen isotopic analyses for IVB irons, although [13] reported SiO_2 in Santa Clara and chromite in Warburton Range and we observed a large chromite in Hoba.

IVB irons and Tishomingo may share a common history, even if on two separate parent bodies. Campbell and Humayun [12] argue that IVB irons experienced both formation from a volatile-depleted precursor and substantial oxidation, producing the fractionated $(Fe/Pd)_{CI}$ ratio observed in group IVB. Tishomingo exhibits a more fractionated $(Fe/Pd)_{CI}$ ratio, a fractionated $(W/Ir)_{CI}$ ratio not present in IVB irons, and a much higher Ni concentration than observed in IVB irons. Thus, one might reasonably argue that Tishomingo also experienced a similar history of formation from a volatile-depleted precursor and oxidation. Whether such an early oxidation might reasonably explain the depletion of P in Tishomingo is an open question. If the entire parent body of IVB irons experienced this oxidation event, [12] argue that the complementary silicate should be an oxidized achondrite depleted in volatile elements, with angrites as the most likely candidate. Interestingly, Tishomingo shares the same $\Delta^{17}O$ as angrites, although they differ by ~2‰ in $\delta^{18}O$. Oxygen isotopic analyses of IVB irons might further test a possible genetic link between Tishomingo, IVB irons and angrites.

Finally, it is interesting to speculate on whether we might have samples of the precursor chondritic material which melted to form the cores from which IVB irons and high-Ni irons like Tishomingo formed. There are chondrites which also exhibit depletions of volatile siderophiles and are thought to include high-temperature nebular condensate metal [14] – the CR chondrite clan. This clan includes CR and CH chondrites, and the so-called CB chondrites (including bencubbinites). Several authors [15] have noted that the average Ni concentration in CR/CH/CB chondrite metal is less than in IVB irons and far less than in Tishomingo, although it is unclear whether the postulated oxidation event might reasonably explain this discrepancy. While Tishomingo might well have formed by melting of a volatile-depleted precursor chondrite, our oxygen isotopic data do not strengthen this link. Tishomingo plots in $\delta^{17}O$ between the CR chondrite Renazzo and the metal-rich ungrouped meteorite GRO 95551, but distinct from each. While it is likely that a range of metal-rich, CR-like meteorites existed in the early solar system, our data do not support a direct link between Tishomingo and any of the chondrites currently in our collection.

References: [1] Wasson J.T. (1990) *Science, 249*, 900-902 [2] Buchwald V.F. (1975) *Handbook of Iron Meteorites.* [3] Ives L.K. et al. (1978) *GCA, 42*, 1051-1066. [4] Holstam D. (2003) *MAPS, 38*, 1579-1583. [5] Clayton R.N. and Mayeda T.K. (1996) *GCA, 60*, 1999-2017. [6] Clayton R.N. and Mayeda T.K. (1999) *GCA, 63*, 2089-2104. [7] Weisberg M.K. et al. (2001) *MAPS, 36*, 401-418. [8] Kracher A. (1980) *GCA, 44*, 773-787. [9] Birch W.D. (2001) *MAPS, 36,* A247-A254. [10] J. Honesto et al. (2005) this volume. [11] Yang J. and Goldstein J.I. (2003) *MAPS, 38*, A33. [12] Campbell and Humayun (2005) *GCA* (in review). [13] Teshima J. and Larimer J.W. (1983) *Meteoritics, 18*, 406-407. [14] Krot A.N. et al. (2002) *MAPS, 37*, 1451-1490. [15] Haack H. and McCoy T.J. (2003) *Treatise on Geochemistry.*

Acknowledgements – We are grateful to A. Ehlmann (TCU) for the sample, J. Post and B. Isaacs (SI) for XRD analyses, and R.S. Clarke, Jr. and J.I. Goldstein for discussions.