THERMOCHEMICAL EVOLUTION OF THE WINONAITE AND IAB IRON METEORITE PARENT BODY.

B. A. Anzures[1,2,3], N. Dygert[1], M. P. Lucas[4]. [1]Department of Earth & Planetary Sciences, University of Tennessee, Knoxville, TN. [2]Lunar and Planetary Institute/USRA, Houston, TX. [3]ARES, NASA Johnson Space Center, Houston, TX. [4]University of Notre Dame, Notre Dame, IN. Email: brendan.a.anzures@nasa.gov

Introduction: Silicate inclusions in primitive achondrite winonaites and IAB iron meteorites record a complex history of heating, brecciation, fragmentation, and metamorphism. Stony winonaites and IAB irons are thought to come from the same parent asteroid because of their similar silicate mineralogy, mineral chemistry, and oxygen isotopic composition [1,2]. While both meteorite groups exhibit geochemical trends consistent with differentiation and partial melting, there are questions about whether the compositions of IAB silicate inclusions reflect precursor chondrites or parent body processes. The most common model of parent body evolution is that the winonaite-IAB parent asteroid underwent incomplete differentiation followed by catastrophic impact breakup and reassembly [3]. Application of thermometers sensitive to different temperature intervals place constraints on this process.

To understand the thermal evolution of winonaite-IAB parent bodies, we apply traditional two-pyroxene [4] and Ca-in-olivine thermometry [5] along with recently developed REE-in-two-pyroxene [6] and Mg-REE-in-plagioclase-clinopyroxene [7,8] thermometers that rely on relatively slow diffusive exchange of REEs between mineral pairs. These methods have recently been used to constrain thermal histories of ordinary chondrite parent bodies, suggesting early fragmentation and reassembly events [9]. We calculated temperatures using compositions of clinopyroxene (cpx) and orthopyroxene (opx), clinopyroxene (cpx) and plagioclase (plg), and olivine (ol). Textural analysis including grain size, petrographic texture, and modal mineralogy contextualizes these temperatures. We find that IAB meteorites may have undergone metamorphism, and perhaps mechanical phase mixing, before and/or during a fragmentation-reassembly event. Winonaites record more consistent thermal histories, and also record fast cooling rates suggesting a fragmentation-reassembly event.

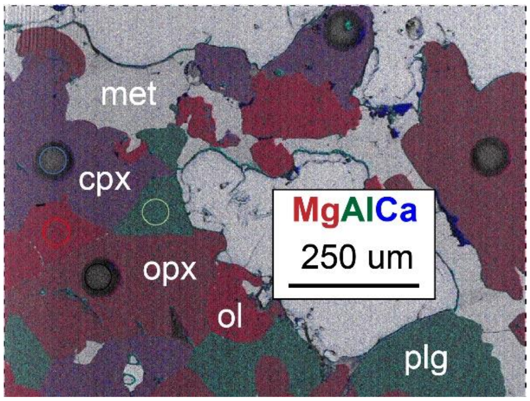

Figure 1. *1000 x 750 µm RGB (Mg:Al:Ca) image of IAB GRO 06050 showing coexisting cpx, opx, plg, and ol along with metal (met). 50 µm LA-ICP-MS spots are circled.*

Samples: We studied five winonaite meteorites (Graves Nunataks (GRA) 12510, Queen Alexandra Range (QUE) 94535, Northwest Africa (NWA) 4024, NWA 6448, NWA 725), and three IAB iron meteorites (Grosvenor Mountains (GRO) 06050, Larkman Nunatak (LAR) 06876, and Maslyanino) that all contain larger than 50 µm cpx, opx, plg, and ol crystals. Samples are thick sections provided by the NASA Meteorite Working Group (MWG) or were purchased, mounted in epoxy, and polished using 1.0 µm Al_2O_3.

Analyses: Cpx-opx and cpx-plg grain pairs, and ol were identified with a petrographic microscope and Phenom benchtop SEM in mapping mode (15 kV accelerating voltage and 9 mm working distance) as shown in **Figure 1**. Mineral major element compositions were measured using the SX100 electron microprobe at University of Tennessee. Grain sizes and modal mineralogy were calculated using X-ray elemental maps using the SX100 electron microprobe at Brown University. Mineral trace element compositions including REEs and Y were measured by LA-ICP-MS at University of Texas (laser fluence of ~6.2 J/cm^2 at 10 Hz and a spot size of 75 µm) and Brown University (3.8 J/cm^2 at 20 Hz and a spot size of 50-85 µm). Analytical precision for elements with concentrations greater than 10 ppm is 10-15% (relative), while elements below 1 ppm have a relative error of 20-35%.

Trace Element Results: Winonaite and IAB iron chondrite normalized REE+Y abundances are shown in **Figure 2**. Cpx REEs are typically above detection limit and exhibit a negative Eu anomaly. Opx light-REEs and plagioclase heavy-REEs(+Y) are not reported because they are typically below the detection limit. REE patterns are roughly consistent among meteorites, except larger variations are observed in paired minerals of IAB meteorites as shown in **Figure 2b** comparing GRA 12510 (win) with GRO 06050 (IAB).

Temperatures: REE diffusion is orders of magnitude slower than major element diffusion [10] meaning REE-based exchange thermometers potentially record peak, near-peak, or mineral growth temperatures, whereas Ca- and Mg-based exchange thermometers are more sensitive to diffusive resetting [6,8]. When monotonic cooling occurs and cooling rates are moderate to high, REE thermometers record higher temperatures relative to major element thermometers [6]. When quenching occurs, trace element and major element thermometers record similar temperatures. If the major element derived temperature is greater than the REE derived temperature, the sample may have been heated in a transient event, or chemically disturbed, such that cooling rates cannot be determined. Temperatures are summarized in **Table 1**.

Two-pyroxene: REE-in-two-pyroxene temperatures ($T_{REE\text{-}2px}$) are consistently lower than temperatures obtained from the major element two-pyroxene thermometer of Brey and Köhler (T_{BKN}) [4] (**Table 1)**. This suggests trace element disequilibrium between cpx and opx, or that these meteorites experienced reheating, which reset T_{BKN}. In comparison with IAB temperatures that exhibit intrasample variability indicative of thermochemical differences in silicate inclusions 5mm apart, winonaite temperatures are consistent among grain pairs (e.g. GRA 12510 and GRO 06050; **Table 1**, **Figure 2b**).

Plagioclase-clinopyroxene: $T_{REE\text{-}pxplg} > T_{Mg}$ for IABs and winonaite NWA 4024, suggesting cooling at moderate to fast rates. $T_{REE\text{-}pxplg} \approx T_{Mg}$ for one winonaite, NWA 725, consistent with rapid cooling. $T_{REE\text{-}pxplg} < T_{Mg}$ for winonaites GRA 12510, QUE 94535, and NWA 6448, suggesting reheating or chemical disturbance.

It is interesting that in general, $T_{BKN} \approx T_{REE\text{-}pxplg} \approx T_{Mg} \neq T_{REE\text{-}2px}$ (GRA 12510, QUE 94535, NWA 4024, NWA 725, Maslyanino), consistent with plagioclase forming later as a product of partial melting during metamorphism [1,11]. This would reset the faster diffusing major elements, but not the slower diffusing trace elements in pyroxenes.

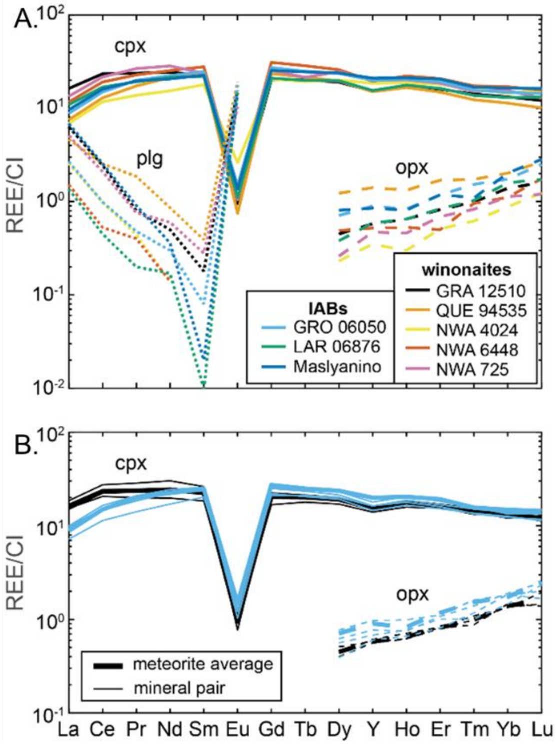

Figure 2. *Chondrite normalized REE+Y abundances in cpx (solid lines), opx (dashed lines), and plg (dotted lines) in winonaite and IAB meteorites. Meteorite averages are shown in a) and averages compared with individual grain pairs of GRA 12510 (win) and GRO 06050 (IAB) in b).*

Table 1. Closure temperatures (°C) for winonaite/IAB meteorites recovered by different thermometers

Sample	$T_{REE\text{-}2px}$	T_{BKN}	$T_{REE\text{-}pxplg}$	T_{Mg}	$T_{Ca\text{-}Ol}$
Winonaites					
GRA 12510	769±13	1000	911±2	1017±60	723±21
Pair A	759±33				
Pair B	760±18				
Pair D	775±9				
QUE 94535	885±87	1030	987±20	1063±44	750±53
NWA 4024	617±15	891	918±30	813±45	686±57
NWA 6448	694±53	935	883±14	1077±44	712±30
NWA 725	712±40	944	931±8	962±56	728±48
IABs					
GRO 06050	836±7	991	898±12	745±41	742±13
Pair A1	870±45				
Pair A2	851±28				
Pair B	906±27				
Pair C	783±49				
LAR 06876	766±20	942	905±3	824±46	670±35
Maslyanino	832±70	898	945±33	863±48	850±41

Cooling Rates: For meteorites with $T_{REE\text{-}pxplg} > T_{Mg}$, cooling rates may be calculated where the larger the ΔT, the slower the cooling rate. Winonaite NWA 4024 records a fast cooling rate of 0.68 °C/year from its initial $T_{REE\text{-}pxplg}$ temperature of 918 °C. IABs record fast cooling rates of 1.75, 0.48, and 0.52 °C/year from their initial $T_{REE\text{-}pxplg}$ temperatures of 898, 905, and 945 °C for GRO 06050, LAR 06876, and Maslyanino respectively. $T_{Ca\text{-}Ol}$ cooling rates through lower temperature intervals are consistent with 0.057-0.48 °C/year for winonaites (0.019 for NWA 4024) and from 0.064 to 0.28 °C/year for IABs LAR 06876 and GRO 06050 respectively.

Conclusions: For IABs, the high apparent temperature variability may suggest an exogenic origin for silicate inclusions in some meteorites. Where apparent cooling rates could be determined, the fast rates are many orders of magnitude more rapid than those anticipated for parent bodies with onion shell configurations [12]. We note the apparent rates obtained from the silicates are a few orders of magnitude faster than metallographic rates (3-7 x 10^{-5} °C/year [13]), which are recorded through lower temperature intervals (~500°C). Collectively, the data suggest metamorphism before and/or during a fragmentation and reassembly event.

Compared to IABs, winonaites record less intrasample variability in their apparent temperatures. The temperature distributions suggest fast cooling, consistent with IABs, but differ with thermochemical metamorphism occurring after fragmentation and reassembly.

References: [1] Benedix et al. (1998) *GCA 62*, 2535-2553. [2] Bild (1977) *GCA 41*, 1439-1456. [3] Benedix et al. (2000) *MPS 35*, 1127-1141. [4] Brey & Köhler (1990) *J. Pet. 31*, 1353-1378. [5] Köhler & Brey (1990) *GCA 54*, 2375-2388. [6] Liang et al. (2012) *GCA 102*, 246-260. [7] Sun & Liang (2017) *Contr. Min. Pet. 172*, 1-20. [8] Sun & Lissenberg (2018) *EPSL 487*, 165-178. [9] Lucas et al. (2020) *GCA 290*, 366-390. [10] Cherniak & Dimanov (2010) *RIMG 72*, 641-690. [11] Zeng et al. (2019) *EPS 71*. [12] Miyamoto et al. (1981) *Proc. LPSC*, 1145-1152. [13] Herpfer et al. (1994) *GCA 58*, 1353-1365.