

**THE DURATION OF ORDINARY CHONDRITE METAMORPHISM INFERRED FROM TUNGSTEN MICRODISTRIBUTION IN OC METAL.** M. Humayun<sup>1</sup> and A. J. Campbell<sup>2</sup>, <sup>2</sup>Dept. of the Geophysical Sciences, The University of Chicago, Chicago, IL 60637, USA (hum8@midway.uchicago.edu).

**Introduction:** We showed that individual metal grains in equilibrated ordinary chondrites (EOC) exhibited large variations of Re/Os and Re/Ir ratios, with chondritic Os/Ir ratios [1]. This was found to be the result of a greater depletion of Os and Ir relative to Re in such metal. This distribution was postulated to represent a redox signature rather than solid metal-liquid metal fractionation proposed by [2]. We have added tungsten, an element that strongly reflects redox and subsolidus metamorphic processes, to our microanalytical procedures, the preliminary results of which were presented by [3]. Here we report precise W/Ir and Re/Ir ratios determined on individual metal grains from Weston H4, Allegan H5, Kernouve H6, Soko Banja LL4 and Alfianello L6 (EOC), and from Tieschitz H3.4-3.6, Mezö-Madaras L3.7, and Parnallee LL3.6 (UOC). These data are used to infer the behavior of these siderophile elements during metamorphism, with implications for the <sup>182</sup>Hf-<sup>182</sup>W and <sup>187</sup>Re-<sup>187</sup>Os chronometers.

**Experimental:** Prior to laser ablation, thin sections and/or polished slabs of these chondrites were mapped by SEM, and metal grains were selected for trace element microanalysis by laser ablation ICP-MS [1, 3, 4]. The analytical procedure of [1] was modified to include W. Each point was analyzed twice: first, a 20-50 pulse laser burst was used to measure the isotopes <sup>182</sup>W, <sup>185</sup>Re, <sup>190</sup>Os, <sup>193</sup>Ir, and <sup>195</sup>Pt; then, an additional 5-10 pulse burst was used for <sup>57</sup>Fe, <sup>59</sup>Co, and <sup>60</sup>Ni measurements for metal phase identification. Analyzing these two mass ranges separately improved precision of the interelement ratios (typically 5%, 1σ). The laser-ablated pit produced was ~30 μm in diameter and ~25 μm deep.

**Results and Discussion:** Data are shown in Fig. 1. In kamacite grains from Tieschitz, the W/Ir ratios vary by over two orders of magnitude, mostly to subchondritic values. In kamacite from Allegan, there is little variation with W/Ir=0.53±0.08 (1σ), compared with W/Ir=0.33 in H chondrites [5]. Further W/Ir ratios both in kamacite and in taenite from Weston and Allegan are correlated with Re/Ir ratios, with chondritic W/Re. In Allegan, W preferentially concentrates in kamacite by a factor of about 3 relative to taenite, consistent with the bcc structure of metallic W. This data indicates the complete control of both W and Re distribution in OC metal by metamorphic processes, and W is known to enter EOC chondritic metal with increasing degrees of metamorphism [6,7]. In the L and LL chondrites, Parnallee LL3.6 and Mezö-Madaras L3.7 exhibit a similarly broad range of W/Ir ratios. Soko-Banja LL4 exhibits a behavior intermediate between the UOC and Alfianello L6, which exhibits a tight

W/Ir vs. Re/Ir correlation. The kamacite-taenite partitioning exhibited by equilibrated H chondrites is not evident in Alfianello, where both kamacite and taenite define the same trend in Fig. 1. Alfianello kamacite compositions cluster tightly around separated bulk metal reported by [8] for Alfianello. Bulk metal W/Ir of Mezö-Madaras and Parnallee are significantly lower than those reported for Alfianello [8], indicating that metamorphism resulted in a net transfer of W from oxidized phases to OC metal, in addition to reducing the spread in W/Ir ratios.

Thus, in EOC metal, W/Re ratios are chondritic, while Ir and Os are variably depleted, as observed by [2] in their Re-Os isotopic studies. It is conceivable that Ir and Os were present in both Fe-Ni alloy and as refractory metal nuggets in UOC. During metamorphism, reduction of FeO from the silicates contributed further Fe to pre-existing metal grains, resulting in dilution of Ir and Os abundances. The presence of W and Re in chondritic relative proportions is possibly related to their original presence in an oxidized form in silicates, which either directly contributed to their abundances during reduction, or facilitated the diffusive transport of these elements to the sites of incorporation into metal. The Ir-Os deficiency in OC metal ranges from chondritic to about a factor of two lower than chondritic.

The direct implication of these findings to <sup>187</sup>Re-<sup>187</sup>Os dating of EOC metal is that the observed variations of Re/Os occurred during metamorphic processes affecting the OC parent body and not during nebular processes. A ΔT=60 m.y. of metamorphism was independently established from U-Pb systematics of EOC phosphates [9]. This estimate of timing is in conflict with recent data based on the short-lived <sup>182</sup>Hf-<sup>182</sup>W chronometer that indicate that metal separated from ordinary chondrites of all metamorphic grades exhibited the same ε<sup>182</sup>W [10], distinct from from OC silicate phases. This is surprising given the degree of re-equilibration observed here. We propose that these seemingly contradictory findings can be reconciled if 1) the onset of metamorphism in the OC parent body occurred at a very early time in solar system history, shortly after accretion, and b) reduction took place during the initial stages of metamorphism (prior to grade 4), and that all the reductant was consumed in this phase, so that further exchange of unradiogenic W from metal with radiogenic W in silicate was inhibited. By contrast, the U-Pb chronometer was set during cooling from peak metamorphic temperatures, as phosphates reached their Pb closure temperatures. Thus, the Hf-W chronometer and the U-Pb chronometer date fundamentally different processes, the former

marking the onset of metamorphism and the later marking its termination. The combination of the two chronometers yields the duration of metamorphism. This interval of metamorphism varies according to metamorphic grade, with the grade 6 chondrites having the longest duration of metamorphism, about 60 m.y.

*The nature of the reductant:* Ordinary chondrites contain a few thousand ppm C, including both terrestrial contaminants and indigenous phases, and exhibit a decrease in C content with increasing metamorphic grade as measured by petrologic type [11]. Certain tracers such as presolar grains and interstellar organic molecules provide proxy measures of reductants. D/H ratios (a proxy for the presence of interstellar molecules) were observed to decrease with increasing metamorphic grade in UOC [12]. Huss [13] noted that the abundances of presolar diamond and SiC grains decreased during the initial stages of OC metamorphism in UOC, generally vanishing at about metamorphic grades 3.6-3.8. This was attributed to oxidation of these reduced phases during incipient metamorphism by reaction with FeO in silicates. This process added Fe to OC metal, and based on our data also added W and Re. Likewise, [7] noted that W and Ga were added to bulk OC metal during metamorphism. It is essential to terminate this reduction process, or W would equilibrate throughout the metamorphic episode, contrary to the findings of [10]. Given the consumption of C-bearing phases (presolar grains, interstellar organic molecules) in the earliest stages of metamorphism, we propose that exhaustion of the available reductant terminates the process, setting the Hf-W chronometer.

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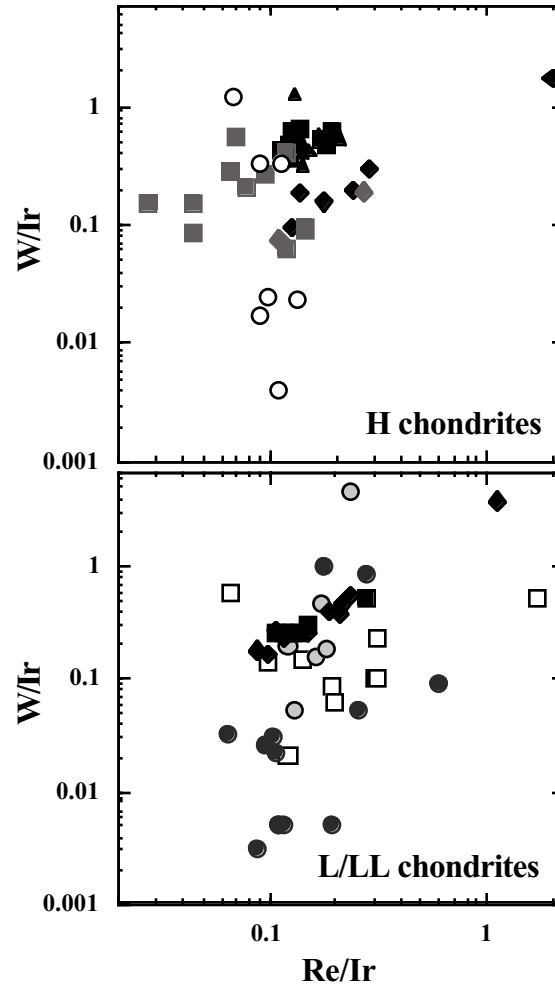


Figure 1: W/Ir vs. Re/Ir for ordinary chondrite metal. EOC metal: kamacite: squares, taenite: diamonds (except Kernouve H6 depicted by dark triangles); UOC metal is shown as circles. H chondrites: Tieschitz H3.4 (open), Weston H4 (gray), Allegan H5 (dark); L/LL chondrites: Parnallee LL3.6 (light gray), Mezö-Madaras LL3.7 (dark gray), Soko-Banja LL4 (open), Alfianello L6 (dark).