HF-W CHRONOLOGY OF LARGE IGNEOUS INCLUSIONS FROM ORDINARY CHONDRITES. A.M. Ruzicka[1], J.L. Hellmann[2], and T. Kleine[2], [1]Cascadia Meteorite Laboratory, Department of Geology, 17 Cramer Hall, 1721 SW Broadway, Portland State University, Portland, OR, USA 97207 (ruzickaa@pdx.edu), [2]Institut für Planetologie, University of Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany.

Introduction: Large (mm-to-cm-sized) igneous inclusions represent a distinct lithology unique to ordinary chondrites whose origins may hold important clues for melting processes in the early solar system. Here we report the first Hf-W ages for eight inclusions from a suite that has also been studied for major and trace element compositions [1,2], oxygen-isotope compositions [3], and I-Xe systematics [4]. The short-lived ^{182}Hf-^{182}W system is well-suited for dating the igneous inclusions because their formation is associated with metal-silicate fractionation and hence Hf-W fractionation. As a result, the inclusions should exhibit elevated Hf/W ratios and radiogenic ^{182}W compositions, such that a model age of inclusion formation can be calculated relative to the bulk chondrite Hf-W composition. Our results suggest diverse formation times spanning both chondrule and later periods, with some inclusions forming as megachondrules, and some as impact melts.

Samples and Analytical Methods: Inclusions analyzed here include representatives of three different chemical types [1] from H, L, and LL chondrites of various petrographic types, including Dimmitt (H3), Lut 005 (LL3), NWA 869 (L3-6), NWA 4686 (H4), NWA 8231 (H4-6), NWA 4859 (LL5), NWA 8645 (L5), and NWA 7871 (L6). They include droplet inclusion Lut-I1 of the vapor-fractionated (*Vfr*) chemical type that shows evidence for evaporative melting, four inclusions of the unfractionated (*Unfr*) chemical type that have lithophile abundances similar to ordinary chondrites and which could have formed by melting of such material, and three inclusions of the generally unfractionated but K-enriched (*Unfr+K*) chemical type best explained as chondritic impact melts [1,3].

Aliquots of inclusions (~90-1200 mg, judged 100% pure *via* binocular observation) were separated from host chondrites by a combination of breaking, cutting, and abrading. For Hf-W isotope analyses the inclusions were digested in HF-HNO_3, and 10% aliquots were taken to determine Hf and W concentrations by isotope dilution. For unspiked samples, W was separated by anion exchange chromatography [5] and W isotope compositions were measured on a Neptune *Plus* MC-ICPMS at Münster. Results are reported as ε^{182}W values as the parts-per-10^4 deviation from the ^{182}W/^{184}W measured for terrestrial standards.

Results: Different inclusions have diverse Hf/W and ε^{182}W values (Fig. 1). Both Hf/W and ε^{182}W values range from quasi-chondritic to more elevated. Four inclusions (Lut-I1, 7871-I1, 4859-I18, and 8645-I1) plot along a ~2 Ma isochron that also passes through the bulk chondritic composition (Fig. 1). Other inclusions (Dim-I1, 869-I1, 4686-I1, 8231-I1) lie variably below this isochron suggesting a variety of younger ages.

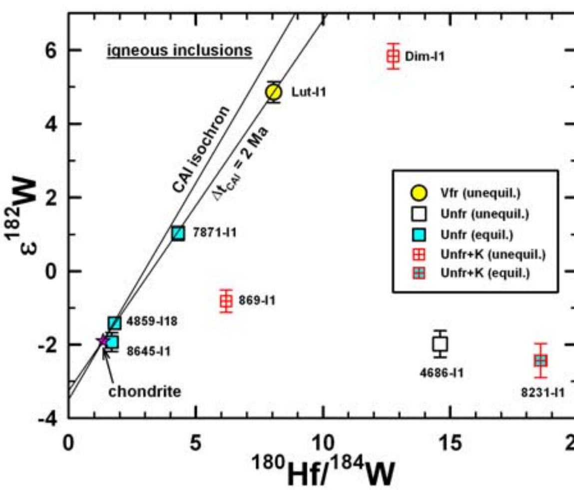

Fig. 1. Hf-W isochron diagram for large igneous inclusions. Inclusion symbols are coded by chemical type and by whether Fe-Mg in ferromagnesian silicates is chemically uniform (equil.) or variable (unequil.). Reference isochrons shown for CAIs [6] and Δt_{CAI} ~ 2 Ma; star indicates representative chondrite composition. Four inclusions plot on an apparent isochron with a model age of Δt_{CAI} ~ 2 Ma.

Fig. 2 shows model ages relative to CAIs (Δt_{CAI}). The model ages assume Hf-W fractionation from a representative chondritic bulk system. A lower limit model age of Δt_{CAI} >50 Ma is assigned to 4686-I1 and 8231-I1 as these inclusions have essentially no radiogenic ^{182}W despite high Hf/W. For 8645-I1, which has a nearly chondritic composition, the model age calculation is less useful than the observation that this inclusion could lie on a isochron with three other inclusions (Fig. 1). Model ages for inclusions thus range between Δt_{CAI} ~2 and >50 Ma (Fig. 2). This includes an old-age group of four inclusions (Lut-I1, 7871-I1, 4859-I18, 8645-I1) with Δt_{CAI} ~2 Ma; and a young-age group of four inclusions (4686-I1, Dim-I1, 869-I1, 8231-I1) with Δt_{CAI} ~7 to >50 Ma (Fig. 2).

Discussion:

Old-age group. The four inclusions comprising the old-age group could have formed at about the same time as chondrules (Δt_{CAI} ~2.0 Ma based on Al-Mg data for chondrules from primitive ordinary chondrites [7]) (Fig. 2). This includes the vapor-fractionated Lut-I1 droplet, as well as three *Unfr* inclusions (7871-I1, 4859-I18, 8645-I1) in type 5 or 6 hosts that have texturally blurred inclusion-host contacts and uniform Fe-Mg compositions in ferromagnesian silicates. The *Vfr* inclusion is best regarded as an unusually large chondrule (megachondrule), whereas the *Unfr* inclusions can be interpreted as melts of chondritic material that formed prior to thermal metamorphism in the host meteorites. Consistent with the latter possibility, these *Unfr* inclusions have Δt_{CAI} model ages (<3.0 Ma) that are older than those found for metal-silicate isochrons for H5-H6 chondrites (~6-10 Ma) [5]. The preservation of old ages for these *Unfr* inclusions implies that they did not all equilibrate with their host chondrites, and that they preserved an older age that was set during metal-silicate fractionation during formation of the inclusions. However, equilibration cannot be ruled out for 8645-I1 given its quasi-chondritic composition. A second aliquot analyzed for 4859-I18 gives a Δt_{CAI} model age of ~7 Ma, which can be interpreted as reflecting internal re-equilibration of the inclusion during metamorphism. Inclusions in the old-age group are best explained as having formed as large-volume melts during chondrule formation, involving evaporative melting as a droplet in one case (Lut-I1), and melting of chondritic material in the other cases (7871-I1, 4859-I18, 8645-I1).

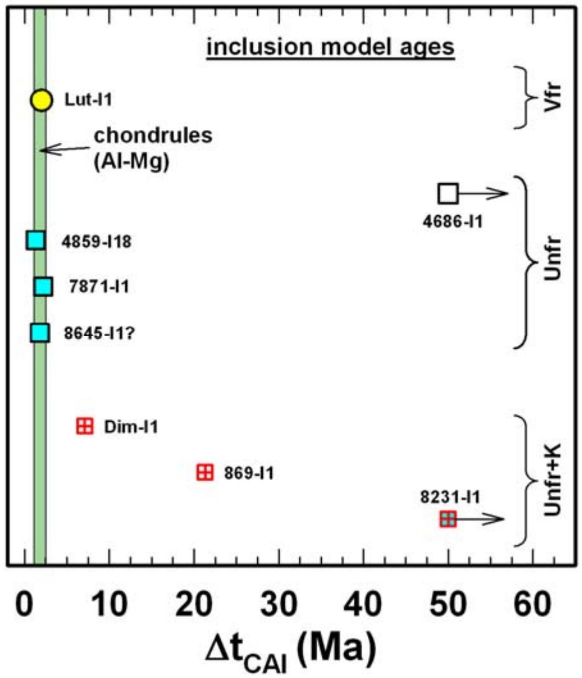

Fig. 2. Model ages for inclusions, assuming Hf-W evolution in a chondritic system. Chondrule age based on Al-Mg chronometry after Kita et al. [7]. Symbols same as in Fig. 1.

Young-age group. The four inclusions comprising the young-age group formed at times distinctly later than chondrules (Fig. 2). These inclusions are almost certainly impact melts. They include all three of the *Unfr+K* inclusions analyzed (Dim-I1, 869-I1, 8231-I1) whose chemistry is best explained by impact melting, as well as an *Unfr* inclusion (4686-I1). All these inclusions have oxygen-isotopic compositions consistent with melting of their hosts [3]. Three of the inclusions (869-I1, 4686-I1, Dim-I1) contain mesostasis glass and unequilibrated olivine, implying rapid cooling in a cool portion of their parent bodies. These petrographic-mineral chemistry indicators for fast cooling are consistent with Δt_{CAI} model ages for 869-I1 (~21 Ma) and 4686-I1 (>50 Ma) that are much later than the time of peak thermal metamorphism (~6-10 Ma [5]). 8231-I1 (Δt_{CAI} model age > 50 Ma) is holocrystalline and has chemically uniform olivine and pyroxene. Given the model age of this inclusion, well after peak thermal metamorphism, this inclusion may have cooled slowly in a larger batch of melt, possibly in a melt pool.

Summary: Large igneous inclusions in ordinary chondrites have a variety of Hf/W and $\varepsilon^{182}W$ values and model Hf-W ages. Variable ages including both old and young age groups as defined here are consistent with preliminary data for the I-Xe system on some of the same inclusions [4]. Older inclusions could have formed as large-volume melts potentially by the same process that formed chondrules at about the same time. Lut-I1 almost certainly formed as an unusually large chondrule (megachondrule), given its droplet form and vapor-fractionated composition. The other old inclusions may or may not have formed as free-floating objects, at about the same time as Lut-I1 and typical ferrogmagnesian chondrules. Younger inclusions formed later than chondrules, some well after peak metamorphism on chondritic parent bodies, by impact melting. Such melting affected various chondritic lithologies, including H3 (Dim-I1), H4 (4686-I1), H4-6 (8231-I1) and L3-6 (869-I1).

References: [1] Armstrong K. and Ruzicka A.M. (2015) *LPS XXXXVI*, Abstract #1571. [2] Ruzicka A. et al. (2017) *LPS XXXXVIII*, Abstract #2477. [3] Ruzicka A.M et al. (2016) *LPS XXXXVII*, Abstract #2230. [4] Crowther S.A. et al. (2017) *Meteoritics & Planet. Sci.*, Abstract #6284 and S.A. Crowther pers. comm.. [5] Kleine T. et al. (2008) *EPSL 270*, 106-118. [6] Kruijer T.S. et al. (2014) *EPSL 403*, 317-327. [7] Kita N. et al. (2000) *GCA 64*, 3913-3922.