VOLATILE LOSS AND RETENTION DURING IMPACT MELTING IN THE CHICO L6 CHONDRITE.

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Introduction: Chondritic impact melt can inform on how impact melt processing affected the chemistry of bodies in the early inner Solar System. Our study aims to understand volatile redistribution during impact melting, focusing on noble gas and halogen behavior in the unmelted chondritic host (OC) and impact melt (IM) fractions of ordinary chondrites. Volatile behavior is considered in relation to impact histories, in the context of ^{40}Ar-^{39}Ar chronology, as well as bulk and individual phase chemistry and petrology.

Here we report our results on volatile distribution in the highly shocked Chico L6 chondrite [1]. Chico contains ~60 vol% highly vesiculated clast-free IM in ~5-10 cm zones within S6 OC [2]. Vesiculated chondritic impact melt implies volatile redistribution during melting [3] with S suggested as the main degassed species [4]. Our study aims to determine if other volatiles, specifically halogens and noble gases, have been degassed from the IM. Our results show not all volatiles have been degassed from the Chico IM as expected. Chico's volatile signature is complicated by cosmogenic noble gas addition after parent-body breakup.

Methods: For noble gas and halogen analyses, 3 OC and 3 IM chips were selected, with masses of ~10 mg. Noble gas concentrations were determined through step heating with a 75 W diode laser to full fusion, with sample gases analyzed on a Thermo Scientific Helix MC^{TM} noble gas mass spectrometer (NGMS). The neutron irradiation noble gas mass spectrometric (NI-NGMS) technique of [5] was used to determine sample Cl, K and Ca contents. Samples were step heated with a 55 W CO_2 laser to full fusion. Sample gases were analyzed on a Thermo Scientific Argus VI^{TM} NGMS. The technique outlined in [6] was used to determine Cl abundances. High and low temperature (T) steps were excluded from Cl totals as these were assumed to be mainly terrestrial contamination and cosmogenic components respectively. Energy Dispersive X-Ray mapping on polished sections of OC and IM was used to locate and estimate the apatite abundance of each fraction. Apatite chemistries were determined using a Cameca SX100 Electron Microprobe (EPMA).

Results: The IM yields a ^{40}Ar-^{39}Ar plateau age of 622±11 Ma (1σ, Fig. 1) and an isochron age of 581±60 Ma. The OC defines no plateau age but three release steps (~45% of the ^{39}Ar) agree with the IM plateau (Fig. 1) and isochron age.

Apatite ($Ca_5(PO_4)_3$(F,Cl,OH)), present in both fractions, is more abundant in the Chico OC (~0.1 vol%) than the IM (~0.025 vol%). The OC apatites are larger, up to ~280 µm, than those in the IM, up to ~80 µm. OC and IM apatites are Cl rich and have similar Cl and F contents with Cl# (atomic (Cl+Fl)/Cl) of 0.9 ± 0.02 and 0.9 ± 0.06 respectively.

We determined Cl contents of ~200 ppm in the OC and ~50 ppm in the IM, consistent with the higher apatite abundance in the OC. Most Cl in the OC comes from a lower T release, not observed in the IM. The Ca content is also higher in the OC which contains 1.54 wt% versus 0.42 wt% in the IM.

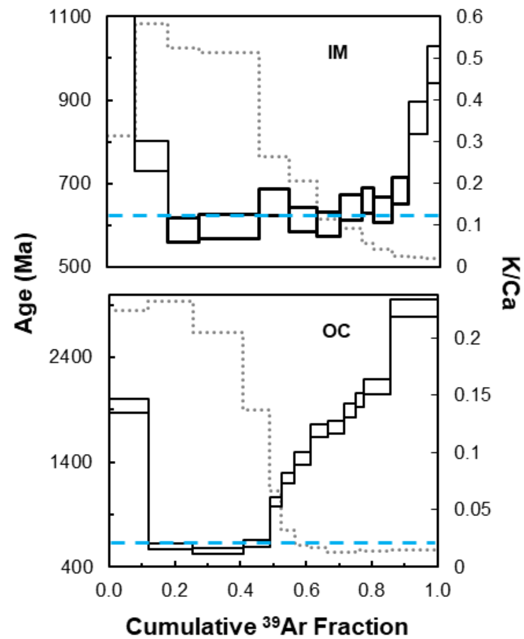

Fig. 1. ^{40}Ar-^{39}Ar ages (rectangles; left scale) and K/Ca (dotted lines; right scale) as a function of ^{39}Ar cumulative release for stepwise T extractions of the Chico IM and OC. The blue dashed line represents an age of 622 Ma. Bold release steps constrain a plateau age.

The Chico IM has higher Ne, Ar, Kr and Xe isotopic concentrations than the OC by ~40-80% except for ^{36}Ar, higher in the OC by ~10%. Fig. 2 shows the release patterns of ^{36}Ar and ^{37}Ar, and the ^{38}Ar/^{37}Ar ratio as a function of T step from irradiated OC and IM. ^{37}Ar is formed solely in the reactor from ^{40}Ca. The main ^{38}Ar release from each T step is Cl derived, produced in the reactor through slow neutron capture. Both fractions begin with a high ^{38}Ar/^{37}Ar and increasing ^{36,37}Ar before trending to low ^{38}Ar/^{37}Ar where ^{37}Ar peaks (Fig. 2). At moderate T only the OC exhibits ^{38}Ar/^{37}Ar and ^{36}Ar peaks with no significant ^{37}Ar elevation (Fig. 2).

Discussion: Our Chico ^{40}Ar-^{39}Ar ages agree with the range of literature ages taken to represent a large ~500 Ma L chondrite parent-body collision which formed the Chico IM (Fig. 1) [e.g. 2]. A consistent IM plateau age regardless of K/Ca shows that this event reset all IM mineral ages (Fig. 1). Outlying low and high T steps are attributed to terrestrial Ar contamination (uncorrected) and residual undegassed ^{40}Ar respectively (Fig. 1). Only low T phases in the OC, with K/Ca ~0.1-0.2, were completely degassed (Fig. 1). Higher T steps show diffusive loss and partial degassing from minerals with a lower K/Ca ratio (Fig. 1).

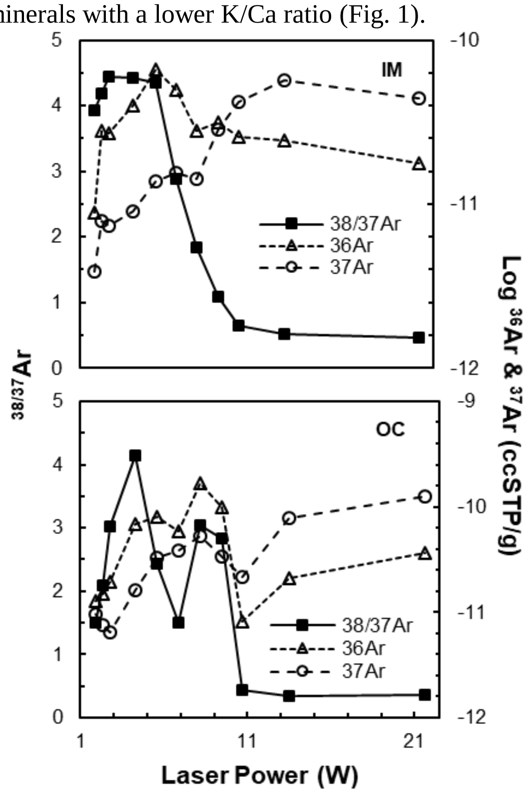

Fig. 2. $^{38}Ar/^{37}Ar$ (left scale) and $^{36,37}Ar$ concentrations (right scale) as a function of stepwise laser power extractions from irradiated Chico IM and OC.

Apatite is likely the main host of Cl in Chico as the OC and IM have Cl contents consistent with apatite abundances. Impact melting appears to have caused Cl loss from the IM, evident in the lower abundance of apatites in the IM relative to the OC. However, previous studies did not show a consistently higher Cl content in OC compared with IM [e.g. 6]. OC apatites may be larger as they grew during the longer timescales of parent body thermal equilibration while IM apatites grew during the shorter timescales of the impact event. Similar Cl# in the OC and IM shows that Cl and F were not fractionated relative to each other during degassing.

The higher noble gas content in Chico IM is surprising as we would expect degassing of the IM noble gases relative to the OC. The difference between the two may be diffusion related as during shock, OC volatiles only have to diffuse through grain-lengths but IM volatiles have to diffuse through the entire melt-length [4]. Alternatively, as the Chico IM likely formed as part of a crater floor or wall dike complex [7], the OC and IM precursors may have had different original noble gas contents, reflected in their current compositions.

The OC ^{36}Ar enrichment is likely due to addition of a cosmogenic component ($^{36}Ar_n$) post parent-body breakup. Slow neutron capture ($^{35}Cl(n,\gamma)^{36}Cl(\beta-)^{36}Ar$) produces $^{36}Ar_n$ in large meteoroids such as Chico (pre-atmospheric radius of >70 cm [8]) with long exposure histories (~65 Ma [8]). Fig. 2 shows this component, as $^{38}Ar/^{37}Ar$ relates to the transition from the release of predominantly Cl-derived ^{38}Ar phases (the low-T elevated $^{38}Ar/^{37}Ar$ in both fractions) to spallation ^{38}Ar dominated Ca-rich phases (the higher-T low $^{38}Ar/^{37}Ar$ in both fractions). Conversely ^{37}Ar reveals the Ar release from Ca-rich phases (the main sources of spallation derived cosmogenic $^{36,38}Ar$) seen in the elevated ^{37}Ar at higher-T (Fig. 2). Therefore, the secondary ^{36}Ar coinciding with a $^{38}Ar/^{37}Ar$ peak and low ^{37}Ar in the OC is likely dominated by $^{36}Ar_n$ (Fig. 2). This $^{36}Ar_n$ was previously reported in Chico [9]. However, we only observe it in the OC, possibly due to the lower Cl abundance in the IM we analyzed.

Conclusions: The vesiculation and larger diffusive loss of ^{40}Ar from the Chico IM relative to the OC (Fig. 1) suggests that it is volatile poor and degassed during melting. This is true for Cl and F but not the majority of noble gases. The higher IM noble gas content may be related to diffusion [4] or differences in the IM and OC precursor noble gas contents. ^{36}Ar is enriched in the Chico OC as $^{36}Ar_n$ has preferentially formed in the OC relative to the IM after parent-body breakup (Fig. 2). Chico's volatile signature is interesting as numerous species do not behave as predicted during impact melting, while volatile redistributions after IM formation are evident. Our further investigations of volatile redistribution during impact melting will examine a broader selection of impact-melted ordinary chondrites.

Acknowledgments: Chico samples were from the Institute of Meteoritics, University of New Mexico.

References: [1] Urey H. and Craig H. (1953) *GCA, 4,* 36. [2] Bogard D. et al. (1995) *GCA, 59,* 1383. [3] Ashworth J. (1985) *EPSL, 73,* 17. [4] Begemann F. et al. (1992) *MAPS, 27,* 174. [5] Ruzié-Hamilton L. et al. (2016) *Chem. Geol., 437,* 77. [6] Garrison D. et al. (2000) *MAPS, 35,* 419. [7] Scott E. et al. (1986) *LPSC Proceedings, 17,* 785. [8] Garrison D. et al. (1992) *MAPS, 27,* 371. [9] Bogard D. et al. (1995) *Journal of Geophys. Res., 100,* 9401.