

**IODINE-XENON SYSTEMATICS OF LARGE IGNEOUS INCLUSIONS IN ORDINARY CHONDRITE METEORITES.** S. A. Crowther<sup>1</sup>, J. D. Gilmour<sup>1</sup> and A. M. Ruzicka<sup>2</sup>, <sup>1</sup>School of Earth and Environmental Sciences, The University of Manchester, UK (sarah.crowther@manchester.ac.uk), <sup>2</sup>Portland State University, Department of Geology and Cascadia Meteorite Laboratory, USA.

**Introduction:** Large igneous inclusions, up to 4 cm across and with low metal and sulphide contents, are found in around 4 % of ordinary chondrite meteorites [1]. The oxygen and major element compositions of most inclusions are broadly similar to ordinary chondrites and chondrules, although not necessarily the same as that of the host meteorite [e.g. 2-4], whereas some have distinctly different compositions [e.g. 5]. Several mechanisms (summarised by [6]) have been proposed for the origins of these inclusions.

A new suite of 42 inclusions, extracted from H, L and LL ordinary chondrites, across a range of petrologic types (3-6), have been identified and characterised using a variety of techniques: their petrology, bulk chemical composition, trace element composition and oxygen isotope compositions have been studied in detail [6]. Hf-W ages have also been determined for a subset of the inclusions [7]. These inclusions formed by different processes at different times, both before and after metamorphism of their host meteorites, but the evidence suggests they did not form as a result of igneous differentiation. The majority of the inclusions fall into four main chemical types [4,6].

In this work we are examining the I-Xe ages and systematics of a subset of this new suite of inclusions. The I-Xe chronometer [8,9] enables us to examine the timing and sequence of events that occurred in the first ~70 millions of years of Solar System history with high resolution, and therefore shed new light on the timing of events in the early Solar System and the histories of these inclusions.

**Experimental:** I-Xe dating relies on the  $\beta$  decay of  $^{129}\text{I}$  to  $^{129}\text{Xe}$  (half-life = 16.1 Ma [10]). The aim is to determine the  $^{129}\text{I}/^{127}\text{I}$  ratio at the time of closure to loss of Xe. Samples are artificially neutron irradiated prior to analysis, which converts  $^{127}\text{I}$  to  $^{128}\text{Xe}$ . This allows for simultaneous measurement of  $^{129}\text{Xe}$  produced from  $^{129}\text{I}$ , and  $^{127}\text{I}$  as  $^{128}\text{Xe}$ . The  $^{129}\text{Xe}^*/^{128}\text{Xe}^*$  ratio (where \* denotes excess Xe produced either from  $^{127}\text{I}$  by neutron irradiation or from  $^{129}\text{I}$  by decay in the early Solar System) is directly proportional to the  $^{129}\text{I}/^{127}\text{I}$  ratio at the time of closure to Xe loss. A relative age in relation to other material is determined from this ratio. The absolute age is calculated with reference to Shallowater enstatite, the irradiation standard for I-Xe dating, which has an absolute age of  $4562.7 \pm 0.3$  Ma [11].

Following irradiation, the Xe isotopic composition of the samples is analysed using the RELAX mass

spectrometer [12,13]. Samples are laser step heated in a series of sequentially increasing powers. The gas extracted in each step is analysed to determine the Xe isotope ratios and the absolute amount of Xe released.

**Results and Discussion:** A subset of 10 inclusions was selected for I-Xe analyses (Table 1), seven of which have been analysed. All samples show excesses of uncorrelated  $^{128}\text{Xe}$  in low temperature heating steps, which is attributed to terrestrial contamination. Most also show  $^{131}\text{Xe}$  attributed to production via neutron capture on  $^{130}\text{Ba}$ .

*Unfr.* This chemical type has bulk chemistry that is essentially unfractionated with respect to bulk ordinary chondrite.

Mid temperature heating steps of 4686-I1 show a roughly constant, elevated  $^{129}\text{Xe}/^{132}\text{Xe}$  ratio (~1.3-1.5 vs 1.04 for Q-Xe [14]), although the excess  $^{129}\text{Xe}$  does not correlate with  $^{128}\text{Xe}^*$ . This inclusion is best described as an impact melt, which formed after metamorphism of the host meteorite. Its Hf-W age is >50 Ma, much later than the timing of peak metamorphism of the host meteorite [7]. Combining the I-Xe data with this Hf-W age suggests this inclusion formed late, from a source material that had a high I/Xe ratio, such that the  $^{129}\text{Xe}/^{132}\text{Xe}$  ratio evolved to the observed value over several 10s of millions of years prior to the formation/cooling of the inclusion.

4859-I18 was dominated by iodine, with very little trapped Xe. The data suggest an I-Xe age  $1.84 \pm 0.34$  Ma before Shallowater (absolute age  $4564.54 \pm 0.45$  Ma). This inclusion is thought to have formed from a melt of chondritic material, before host metamorphism and probably underwent metamorphism *in situ*. The preservation of an old Hf-W age (~2 Ma after CAIs [7]) implies that it did not equilibrate with the host meteorite and preserved an older age that was set during its formation. The I-Xe age is in good agreement with the Hf-W age and therefore was most likely also set during the formation of the inclusion. The old age implies that the I-Xe system was not reset by type 5 metamorphism in this instance.

Inclusion 7871-I1 was dominated by  $^{127}\text{I}$  ( $^{128}\text{Xe}$ ) and  $^{130}\text{Ba}$  ( $^{131}\text{Xe}$ ) in all heating steps, consistent with terrestrial contamination in calcite veins observed to be cutting through the inclusion. In most heating steps the other Xe isotopes were below the detection limit imposed by the dynamic range of the detector and the intensity of the signal from the abundant isotopes, and

unfortunately no I-Xe age can be inferred.

*Unfr + K*. This chemical type is similar to the *Unfr* type, except for being highly enriched in potassium.

Similar to 4686-I1, 8231-I1 has an elevated  $^{129}\text{Xe}/^{132}\text{Xe}$  ratio, but the excess  $^{129}\text{Xe}$  does not correlate with  $^{128}\text{Xe}^*$ . It also has a young Hf-W age, >50 Ma after CAI formation [7], well after peak thermal metamorphism. *Unfr + K* inclusions most likely formed by impact melting of chondritic material [6], and it has been suggested that this inclusion may have cooled slowly in a large batch of melt, possibly in a melt pool [7]. As for 4686-I1, it seems likely that this inclusion formed and cooled after the  $^{129}\text{Xe}/^{132}\text{Xe}$  ratio of the source material had evolved to the observed value.

Low temperature iodine contamination was not properly separated from high temperature correlated iodine in MET-I2. A lower limit of the age, no more than  $0.96 \pm 0.25$  Ma after Shallowater (absolute age at least  $4561.74 \pm 0.39$  Ma), can be estimated from heating steps with the lowest  $^{128}\text{Xe}/^{129}\text{Xe}$  ratios, i.e. those least affected by uncorrelated iodine. This inclusion is in a type 3 host, which shows no evidence of significant metamorphism, therefore this estimate may date the formation of the inclusion.

*Vfr*. These inclusions are thought to have formed primarily by evaporative melting of free-floating material in a 'nebular' (melt + gaseous) setting [6]. Their lithophile element abundances vary with volatility.

A well-defined I-Xe isochron is observed for MET-I1 (Fig. 1), giving a young age  $29.59 \pm 0.48$  Ma after Shallowater (absolute age  $4533.11 \pm 0.57$  Ma). There is no evidence this inclusion formed by melting of the host meteorite; it likely formed from a distinct body [6]. If this young age dates the formation of the inclusion, it is potentially very significant for both the formation mechanisms of inclusions and the timing of accretion of the chondrite parent bodies. An alternative explanation is that it reflects processing of the regolith of the parent body. Ages determined from other chronometers would assist in interpreting this age.

Similar to 4859-I18, Rfd-I1 is dominated by  $^{128}\text{Xe}^*$  and  $^{129}\text{Xe}$ , with only a negligible amount of trapped Xe. The inferred I/Xe ratios correspond to ages ~0.5-2.1 Ma after CAIs. This is consistent with rapid cooling at an early stage, and supports the hypothesis that this inclusion is an unusually large chondrule that formed around the same time as most other chondrules.

**Summary:** The various chemical types of inclusions (*Unfr*, *Unfr + K*, *Vfr*) show evidence for both early and late formation. Those which formed early perhaps date chondrule formation, whereas those which formed later are suggestive of impact melting and indicate multiple impact events at different times. Some, such as 4686-I1 and 8231-I1, formed several 10s of

Table 1. Summary of inclusions selected for I-Xe analyses. Further information about the individual inclusions is given by [6]. NWA = North West Africa; MET = Meteorite Hills.

Chemical Type	Inclusion	Host Meteorite	Host type	I-Xe done?
<i>Unfr</i>	4686-I1	NWA 4686	H4	✓
	4859-I18	NWA 4859	LL5	✓
	7871-I1	NWA 7871	LL6	✓
<i>Unfr + K</i>	8645-I1	NWA 8645	L5	
	869-I1	NWA 869	L3-6	
	8231-I1	NWA 8231	H4-6	✓
<i>Vfr</i>	MET-I2	MET 00489	L3.6	✓
	Lut-I1	Lut 005	LL3.7	
	MET-I1	MET 00489	L3.6	✓
	Rfd-I1	Richfield	LL3.7	✓

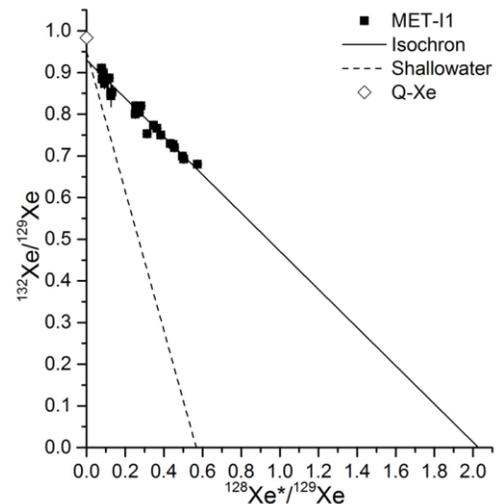


Fig. 1. High temperature steps for *Vfr* inclusion MET-I1.

millions of years after CAI formation, after significant decay of  $^{129}\text{I}$ . If the late age of MET-I1, an inclusion in a type 3 host meteorite, is interpreted as a formation age it has implications for the timing of accretion of the chondrite parent bodies, although further data are required for this and similar inclusions before drawing any firm conclusions.

**References:** [1] Bridges J.C. & Hutchison R. (1997) *MAPS* 32, 389-394. [2] Hutchison R. et al. (1988) *EPSL*, 90, 105-118. [3] Ruzicka A.M. et al. (2016) *LPSC XLVII* Abs #2230. [4] Armstrong K. & Ruzicka A.M. (2015) *LPSC XLVI* Abs #1572. [5] Ruzicka A.M. et al. (2012) *MAPS*, 47, 1809-1829. [6] Ruzicka A.M. et al. Petrology and oxygen isotope composition of large igneous inclusions in ordinary chondrites: Early solar system igneous processes and oxygen reservoirs. *GCA*, In Press. [7] Ruzicka A.M. et al. (2018) *LPSC XLIX* Abs #1714. [8] Gilmour J.D. et al. (2006) *MAPS*, 41, 19-31. [9] Pravdivtseva O. et al. (2017) *GCA*, 201, 320-330. [10] Chechev V.P. & Sergeev V.O. (2004) *Meas. Tech.*, 47, 402-406. [11] Gilmour J.D. & Crowther S.A. (2017) *Geochem. J.*, 51, 69-80. [12] Gilmour J.D. et al. (1994) *Rev. Sci. Instrum.*, 65, 617-625. [13] Crowther S.A. et al. (2008) *J. Anal. At. Spectrom.*, 23, 938-947. [14] Busemann, H. et al. (2000) *MAPS*, 35, 949-973.