I-Xe ages of enstatite chondrites

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Abstract

In order to elucidate the early thermal history of enstatite chondrite parent bodies we determined ^{129}I - ^{129}Xe whole rock ages of enstatite chondrites (5 EH, 2 EL, one EH impact melt) relative to the Shallowater reference meteorite (4562.3 ± 0.4 Ma, all errors are 1σ). I-Xe ages of both EL6 chondrites (LON 94100: -4.38 ± 0.60 Ma and Neuschwanstein: -3.87 ± 0.73 Ma - negative sign indicates ages younger than Shallowater) agree well with data of other EL6 chondrites. LON 94100 displayed a second isochron at lower temperatures equivalent to a younger age of -5.25 ± 1.17 Ma, perhaps reflecting different retention temperatures of respective carrier phases during sequential cooling. The enstatite chondrites Abee (EH4), Indarch (EH4), EET 96135 (EH4/5) and St. Marks (EH5) encompass a I-Xe age range of

+0.57±1.05 Ma (EET 96135 #1) to -0.45±0.72 Ma (Abee), again in agreement with previously reported ages of EH chondrites. Only the age of St. Marks differs strongly from previously reported younger ages, now being more in accordance with other members of the EH clan. The EH3 chondrite Sahara 97096 showed the youngest I-Xe age of -7.87±0.46 Ma distinctly younger than other I-Xe ages of EH chondrites, including other EH3s. Due to the apparent high retention temperature of the I-Xe system in enstatite (estimated >800°C) this young age implies a later resetting of the I-Xe system by a severe thermal, likely impact-induced, event. The EH impact melt LAP 02225 records a similarly young thermal event. Though no isochron relationship could be established, the data fall within an apparent I-Xe age range of +5 to +15 Ma, similar to Sahara 97096. Overall, EH chondrite parent body experienced a thermal history determined by a complex interplay between impact disturbances and parent body metamorphism.

Keywords: I-Xe ages, enstatite chondrites, thermochronology

1 Introduction

Enstatite chondrites represent samples from parent bodies which formed in an environment of low oxygen fugacity. This is mirrored in their mineralogy. The dominant Mg-silicate phase is essentially Fe-free enstatite instead of Fe bearing olivine and pyroxene in ordinary chondrites. Other important minerals are plagioclase, kamacite (with several percent Si) and troilite. Besides these phases enstatite chondrites contain numerous rare sulfides. Some mineralogical and chemical differences (e.g. *Mason, 1966; Keil, 1968; Wasson and Wai, 1970; Sears et al., 1982*) led to the acceptance of two subgroups divided in EH (high Fe) and EL (low Fe) chondrites representing distinct parent bodies (e.g. *Baedecker and Wasson, 1975; Sears et al.,*

1982; Kallemeyn and Wasson, 1986; Keil, 1989) though alternative models are also advocated (Kong *et al.* 1997; Patzer and Schultz, 2002). The occurrence of niningerite, (Mg,Fe,Mn)S, in EH-type and of alabandite, (Mn,Mg,Fe)S, in EL-chondrites serves to distinguish between these two major enstatite chondrite groups (e.g. Sears *et al.*, 1982; Ehlers and El Goresy, 1988; Kimura and Lin, 1999). After the first identification of an EL5 (Sears *et al.*, 1984) it became clear that both enstatite suites follow a separate petrologic sequence. The EL-chondrite record is dominated by higher metamorphic grade EL6-chondrites, whereas the lower metamorphic grades 4 and 5 dominate the EH-chondrite record.

The EH-chondrites show a range in shock stages from S2 to S4, whereas EL-chondrites predominantly are classified into the lower shock stage 2 (Rubin *et al.*, 1997; Rubin, 2015). In spite of this lower shock-stage existence of relict phases points to an initially higher shock stage also in EL-chondrites (Rubin *et al.*, 1997). Most signs of an early impact history subsequently were erased during and after prograde metamorphism on the EL-chondrite parent body. A difference in impact history is also documented in the Ar-Ar age pattern. For example, Ar-Ar ages of many EL-chondrites (including both EL chondrites included in this study) show a rather uniform age range of 4.48-4.50 Ga (Hopp *et al.*, 2014), still in agreement with metamorphic cooling. In contrast, Ar-Ar ages of most EH-chondrites are more variable (Bogard *et al.*, 1983; 2010; Hopp *et al.*, 2014), and seem not necessarily related to metamorphism. This is also the case for a few of the EL chondrites, which indicates Ar loss and redistribution during thermal events or hydrothermal processes subsequent to the metamorphic cooling history of the respective parent bodies.

I-Xe ages of enstatite chondrites are consistently older than Ar-Ar ages. For example, I-Xe ages of EH chondrites fall into the range of ca. 4558-4564 Ma (Hohenberg *et al.*, 1967; Kennedy *et al.*, 1988; Whitby *et al.*, 2002; Busfield *et al.*, 2008), and of EL 6 chondrites in the range of ca. 4557-4559 Ma (Kennedy *et al.*, 1988; Busfield *et al.*, 2008). Hence, the retention

temperature of the I-Xe system in enstatite chondrites is relatively high compared to that of the K-Ar system. Xenon from iodine carrier phases seems to be associated with higher temperature minerals like enstatite (*Hohenberg, 1967; Hohenberg et al., 1967; Podosek, 1970; Kennedy et al., 1988; McCoy et al., 1995; Gilmour et al., 2006*) or is hosted in minute inclusions in enstatite (*Kehm et al., 1994*). This potentially allows an age determination of early thermal events (impact-induced, metamorphism), which can be compared with other potentially suited short-lived decay systems with similarly high retention temperatures, most notably the ^{53}Mn - ^{53}Cr system (half-life 3.7 Ma). Previously reported Mn-Cr ages of enstatite chondrites show substantial variation even within an individual meteorite (e.g., *Birck and Allégre, 1988; Wadhwa et al., 1997; Shukolyukov and Lugmair, 2004*) which in part might be related to the different experimental approaches and in part is attributed to re-equilibration processes of the Mn-Cr system in sulfides. For example, *Wadhwa et al. (1997)* observed variable initial $^{53}\text{Mn}/^{55}\text{Mn}$ -ratios in sulfides within individual meteorite specimens of EL 3 chondrites that are equivalent to relative age variations of ca. 14 Ma (MAC 88136). The same authors determined the relative Mn-Cr age difference between sulfide in Indarch and the more ancient Mn-Cr ages of the EL 3 meteorites as ca. 3Ma. *Shukolyukov and Lugmair (2004)* reported a slightly larger age difference of 4.5 to 5 Ma between EH 4 chondrites (Abee and Indarch) and the EL 6 chondrite Khairpur, and a similar range of initial $^{53}\text{Mn}/^{55}\text{Mn}$ -ratios as reported by *Wadhwa et al. (1997)*. Relative to the angrite LEW 86010 (initial $^{53}\text{Mn}/^{55}\text{Mn} = (1.25 \pm 0.07) \cdot 10^{-6}$ and absolute Pb-Pb age of 4557.8 ± 0.5 Ma, *Lugmair and Galer, 1992*) the corresponding initial $^{53}\text{Mn}/^{55}\text{Mn}$ -ratios reported by *Shukolyukov and Lugmair (2004)* refer to absolute ages of Khairpur (EL6) (4557.6 ± 0.3 Ma), Indarch (EH4) (4562.1 ± 1.3 Ma) and Abee (EH4) (4562.5 ± 0.8 Ma), which agree well with their I-Xe ages (*Hohenberg et al., 1967; Kennedy et al., 1988; Busfield et al., 2008*; relative to absolute age of Shallowater reference meteorite of 4562.3 ± 0.4 Ma, *Gilmour et al., 2009*). Hence, both decay systems

seem to document the same thermal events. In this study we present new I-Xe ages of a suite of enstatite chondrites which may help constraining the early thermal histories of the enstatite parent bodies and setting I-Xe ages in relation to other early solar system chronometers.

2 Meteorite samples

This I-Xe dating study is part of a still continuing chronological study of a more extended suite of enstatite chondrites and dominantly focusses on EH chondrites. The investigated meteorite suite encompasses one EH 3 (Sahara 97096), two EH 4 (Abee, Indarch), one EH 4/5 (EET 96135), one EH 5 (St. Marks) and two EL 6 chondrites (LON 94100, Neuschwanstein). In addition, we analysed one EH-impact melt (LAP 02225). The Antarctic samples were provided by the Meteorite Working Group (ANSMET section of NASA/JPL, Houston, U.S.), while the remaining samples were obtained from Jutta Zipfel (Senckenberg Museum, Frankfurt, Germany). A piece of the Shallowater meteorite was supplied by the Smithsonian Institution, (Washington D.C., U.S). For all of these meteorites Ar-Ar ages were previously reported (*Bogard et al., 1983; Bogard et al., 2010; Hopp et al., 2014*). In addition, the EH chondrites Abee, Indarch and St. Marks had been part of previous I-Xe studies (*Hohenberg et al., 1967; Podosek, 1970; Kennedy et al., 1988; Busfield et al., 2008*).

All meteorite falls included in this study had been previously investigated for their chemistry, mineralogy and petrology (e.g., among others, *Fuchs, 1966; Fuchs et al., 1966; Mason, 1966; Sears et al., 1982; Sears et al., 1983; Rubin and Keil, 1983; Keil, 1989; Rubin and Scott, 1997; Hsu, 1998; Zipfel et al., 2010; Rubin, 2015*). For EET 96135 and LAP 02225 basic petrographic informations can be found in *Izawa et al. (2011)*. A comprehensive lithophile trace element record of all meteorites, except EET 96135 and Neuschwanstein, is reported in *Barrat et al. (2014)*. Note that the major carrier phase(s) of iodine in enstatite chondrites

is/are still not well known and a more detailed petrographic subsection thus will not add much to our chronologic discussion presented below.

All meteorites show no or only minor signs of weathering (occasional presence of Fe-oxide and carbonate bearing veins, decomposition of oldhamite in LAP 02225 presumably by contact with water).

The EL 6 chondrites are classified as shock stage S2 (*Rubin et al., 1997*), but the existence of subordinate indicator phases of severe shock may point to a higher shock event predating the S2-event, at a time coeval to thermal metamorphism allowing for partial annealing of these shock effects (*Rubin et al., 1997*). The EH chondrite Abee is classified as an impact melt breccia, comprising a range of shock stages from S2 to S4 (*Rubin and Keil, 1983; Sears et al., 1983; Rubin and Scott, 1997*). Indarch, St. Marks and EET 96135 are classified as shock stage S3 (*Rubin et al., 1997; Izawa et 2011; Rubin, 2015*). Sahara 97096 is classified as stage S2 in the Meteoritical Bulletin Database (MBD), but a more recent investigation assigns a shock stage S3-S4 (*Quirico et al., 2011*). The higher shock stage better agrees with the highly disturbed Ar-Ar age spectrum of this meteorite (*Hopp et al., 2014*). EH-impact melt LAP 02225 is essentially unshocked (stage S1, MBD), indicating no further processing after re-crystallization. Finally, the Shallowater enstatite achondrite is classified as shock stage S2 (*Rubin, 2015*).

3 Experimental methods

The meteorites were gently crushed into smaller, mm-sized pieces, and cleaned with ethanol in an ultrasonic bath. Only in case of Shallowater we prepared a smaller grain size fraction (80-250 μm). Care was taken to avoid any contact with water in order to keep water-soluble minerals intact. Subsequently, about 150 – 200 mg whole rock material was wrapped in high-purity Al-foil.

Two irradiation series were performed. Details of irradiation and standardization, and details of and potential caveats with neutron flux correction procedure are discussed in Supplementary Material section 1.

After irradiation all meteorites were placed into an ultrahigh vacuum line. Xenon gas release was achieved by a stepwise heating procedure in an inductively heated Mo crucible (10 min heating time at nominal temperature). Furnace temperatures given in Table S1 are nominal temperatures and are lower than real temperatures. This is indicated by a subsequent cross-calibration with other furnace systems having a Pt-Rh or W-Re thermocouples, which indicates a relation between real and nominal temperatures (in °C) given by $T(\text{real}) (\pm 50) \sim 1.3 \cdot T(\text{nominal}) - 100$, valid in the T-range up to ca. 1650°C (real). We kept the (nominal) working temperatures in the text to facilitate reading (and cross-referencing of our raw data files), but added the calculated real temperatures in Supplementary Material Table S1.

During and after heating the released gas was cleaned, transferred to a charcoal held at the temperature of liquid nitrogen and after transfer heated up to -100°C. We shortly pumped the residual gas load (notably argon) in order to reduce a potential source of noise and minimize release of memory Xe in the mass spectrometer. Nonetheless, several extractions (but not the extractions of major Xe release defining the isochron relations) were still affected by memory and required a correction (details in Supplementary Material section 2). This led to a lower precision in the respective extractions.

Measurements were performed with a VG 3600 mass spectrometer at the Institut für Geowissenschaften, Universität Heidelberg, Germany. Frequent analyses of calibration gas were used for correction of measurement-induced mass fractionation and determination of sensitivity factors. Furnace blank measurements were performed routinely before each sample analysis and adequately corrected for. Total blanks ($< 1.5 \cdot 10^{-13}$ cm³ STP ¹²⁹Xe) were negligible in most cases (in particular in extractions of major Xe release). The isotopic

composition of the blanks mostly was atmospheric within uncertainties, except for some enhanced signal of ^{128}Xe presumably as a consequence of degassing from the samples in the line. Raw data after mass fractionation and blank corrections are given in Supplementary Material Table S1. Final data evaluation (necessary for evaluation of isochron relations) also included correction for spallation and fission contributions. Again, these corrections were low or negligible in all cases, with highest percentage of spallogenic ^{130}Xe and fissiogenic ^{132}Xe of 1.1% and dominantly values below 0.5 % (see Supplementary Material Table S2). More details on mass spectrometry can be found in Supplementary Material section 3.

4 Results

Calculation of I-Xe ages requires comparison of the $^{128}\text{Xe}_\text{I}/^{129}\text{Xe}_\text{I}$ ratios (i.e. essentially: $^{127}\text{I}/^{129}\text{I}$ initial ratio) between the meteorite of unknown age and a standard meteorite of known age (the currently used reference meteorite is Shallowater with an age of 4562.3 ± 0.4 Ma, *Gilmour et al. 2009*). In case of preservation of an age relationship the amount of $^{128}\text{Xe}_\text{I}$ should correlate with $^{129}\text{Xe}_\text{I}$. Thus, in a three-isotope diagram of type $^{129}\text{Xe}/^{132}\text{Xe}$ versus $^{128}\text{Xe}/^{132}\text{Xe}$ (normal isochron diagram) or alternatively, $^{128}\text{Xe}/^{129}\text{Xe}$ versus $^{132}\text{Xe}/^{129}\text{Xe}$ (inverse isochron diagram) we should find linear relations that can be interpreted as isochrons. We used the York regression method (*York et al., 2004*) for linear regression analyses that is implemented in the Isoplot 4.15 software, which is a Microsoft Excel 2007 compatible version of Isoplot 3.70 (*Ludwig, 2008*). We also included error correlation factors (for more details see Supplementary Material section 4). In the normal isochron diagram the age information ($^{128}\text{Xe}_\text{I}/^{129}\text{Xe}_\text{I}$ ratio) is contained within the slope, whereas in the inverse isochron diagram the $^{128}\text{Xe}_\text{I}/^{129}\text{Xe}_\text{I}$ ratio is given by the intercept. The respective linear relations are listed in Supplementary Table S3. To calculate an age difference relative to another meteorite (here: Shallowater) we have to apply the relation $\Delta t = \tau \cdot \ln([^{128}\text{Xe}_\text{I}/^{129}\text{Xe}_\text{I}]_{\text{met1}} -$

[$^{128}\text{Xe}/^{129}\text{Xe}_{\text{met2}}$], with life-time $\tau_{129} = 22.65$ Ma (corresponding to a 15.7 Ma half-life of ^{129}I). Since ^{129}Xe is more abundant than ^{132}Xe normalization to ^{129}Xe will improve the precision of the data and hence, a more precise age difference is derived via the inverse isochron relationship. All ages in this study refer to results for inverse isochrons. Nonetheless, age differences relative to Shallowater calculated from both approaches are indistinguishable within 1σ -uncertainty (Table 1 and Table S3). Release patterns of ^{128}Xe and ^{129}Xe and inverse isochron diagrams are shown in Fig. 1a-l and Fig. 2a-l, respectively. The normal isochron diagrams are shown in ‘Supplementary Material Fig. S4a-l’. The isochron diagrams derived via the Isoplot software are added in ‘Supplementary Material Fig. S5a-n and Fig. S6a-n’. All given uncertainties correspond to 1σ -uncertainties, and all I-Xe ages have been corrected for neutron flux variations (see section 3 and Supplementary Material section 1).

4.1 *Shallowater*

To ensure reproducible results from the Shallowater age monitor we prepared a whole rock grain size fraction of 80-250 μm . From this grain size fraction several Shallowater whole rock aliquots were measured during this project, two aliquots per irradiation (#3 and #4 in irradiation 1; #5 and #6 in irradiation 2). The precision of the isochron data for Shallowater wr#3 is poor because of memory problems as discussed above (Section 3 and Supplementary Material section 2) and hence, we do not use this aliquot for the calculation of I-Xe ages. Shallowater wr#4-wr#6 showed well-defined isochron relations at ~ 1000 - 1350°C (~ 1200 - 1650°C real temperature). The release patterns (Fig. 1a-c) exhibit one prominent and one minor release peak, at $\sim 1050^\circ\text{C}$ and $\sim 1150^\circ\text{C}$ (nominal temperatures), respectively. In both normal and inverse isochron diagrams (Fig. 2a-c and Fig. S4a-c) for all Shallowater analyses the data define isochrons which do not pass the OC- $^{129}\text{Xe}/^{132}\text{Xe}$ ($= 1.0399 \pm 0.0025$) reference composition (*Lavielle and Marti, 1992*), but at the OC $^{128}\text{Xe}/^{132}\text{Xe}$ (0.08271 ± 0.00050) value

the respective $^{129}\text{Xe}/^{132}\text{Xe}$ ratio is lower (0.8-0.9). We will discuss possible reasons for this discrepancy in Subsection 5.1 in more depth and only note here that the slopes are considered as isochrons.

4.2 *EL 6 chondrites LON 94100 and Neuschwanstein*

I-Xe ages of EL-chondrites are confined to type 6 at this time. The release patterns of $^{128}\text{Xe}_I$ and $^{129}\text{Xe}_I^*$ in LON 94100 and Neuschwanstein show two major peaks within the degassing range of 1000°C and 1200°C (Fig. 1d+e). There are also hints for two or three more minor release peaks, pointing to the existence of more than two carrier phases of iodine. Both EL chondrites included in this study showed well-defined isochrons (Fig. 2d+e; Fig. S4d+e; Fig. S5d-f and Fig. S6d-f) corresponding to I-Xe ages of -4.38 ± 0.60 Ma (LON 94100; 1085 - 1280°C) and -3.87 ± 0.73 Ma (Neuschwanstein; 960 – 1500°C) more recent than Shallowater. We observe an additional lower temperature isochron for LON 94100 (990 - 1055°C) corresponding to an age of -5.25 ± 1.17 Ma younger than Shallowater. The respective internal age difference calculated from the different intercepts of the isochrons is 0.86 ± 1.21 Ma.

4.3 EH chondrites

Release patterns of $^{128}\text{Xe}_I$ and $^{129}\text{Xe}_I^*$ (Fig. 1f-l) for the EH chondrites and the EH impact melt are all similar and resemble the patterns obtained for Shallowater and the EL chondrites. The only (minor) differences arise from height of the various peaks. For example, except for EET 96135 the major Xe release in EH chondrites occurs between 1000°C and 1100°C (nominal temperatures, distributed at two or more peaks). In contrast, EET 96135 and both EL 6 chondrites tend to show their dominant degassing peak at slightly higher temperatures (nominal 1100°C to 1200°C, Fig. 1a-e and Fig. 1g+h). This difference likely reflects the distinct abundances of the carrier minerals for Xe and point to some basic differences between EH and EL chondrites (with exception of EET 96135).

All EH-chondrites are characterized by well-defined linear relations between $^{128}\text{Xe}_i$ and $^{129}\text{Xe}_i^*$, which in case of extractions from major xenon release temperatures can be interpreted as isochrons (Fig. 2f-k; Fig. S4f-k; Fig. S5g-n; Fig. S6g-n). Commonly, the isochrons pass the OC-Xe composition considered as initial xenon composition. The only significant exception is Sahara 97096 (see below). In the inverse isochron diagram of Abee (Fig. S4f) the isochron also misses the OC-Xe composition. However, respective data precision still allows OC-Xe as valid trapped composition. In a few cases more than one linear relationship is observed, but an interpretation as isochron relation might be not justified (see below). Abee (EH 4), Indarch (EH 4), EET 96135 (EH 4/5) and St. Marks (EH 5) share a rather old I-Xe isochron age similar to or slightly younger than Shallowater (Table 1). The ages of Abee (-0.45 ± 0.72 Ma younger than Shallowater) and Indarch ($+0.16 \pm 0.50$ Ma older than Shallowater) agree with previous results (*Podosek, 1970; Kennedy et al., 1988; Busfield et al., 2008*), whereas the I-Xe age of St. Marks (-1.02 ± 0.66 Ma younger than Shallowater) in this study is 3-4 Ma older than reported by *Podosek (1970)* and *Kennedy et al. (1988)* and closer to those of the other EH 4, EH 4/5 chondrites. The ages of the two whole rock splits of EET 96135, included in different irradiation series, are slightly different, which may be a consequence of an imperfect neutron flux correction. Whereas EET 96135 wr#1 is about -0.57 ± 1.05 Ma older than Shallowater, the age of EET 96135 wr#3 is -0.61 ± 0.60 Ma younger than Shallowater. Both values agree within their uncertainties, however.

Indarch and St. Marks both show evidence of a second linear trend at slightly lower degassing temperatures compared to the isochron extractions (Fig. 2i+k; Fig. S4i+k; Fig. S5j+m; Fig. S6j+m). In case of Indarch this line would correspond to a I-Xe age which is 0.40 ± 0.68 Ma older compared to the isochron age of major extractions. Though, given the uncertainty, this seems not significant, closer inspection clearly shows that the line has a different intercept, at lower $^{129}\text{Xe}/^{132}\text{Xe}$ ratios and not passing the OC-Xe composition. The same applies to the

second linear trend observed for St. Marks, which corresponds to a 1.01 ± 0.38 Ma older I-Xe age compared with the higher temperature isochron age. We tentatively attribute these trends to a thermally-induced (maybe impact-related) redistribution of I and Xe in respective lower temperature phases (probably sulfides) and hence, we do not consider these trends as carrying a reliable age signal (see subsection 5.1).

Sahara 97096 is part of a large group of paired specimens of EH 3 chondrites. In a previous contribution (*Hopp et al., 2014*) we showed that the Ar-Ar age of this meteorite is strongly disturbed by a thermal or late metamorphic event, maybe as late as 2 Ga ago. From these results one might expect a severe disturbance of the I-Xe system. However, for this meteorite we also observed a well-defined isochron, corresponding to an age -7.87 ± 0.46 Ma younger than Shallowater (Fig. 2j; Fig. S4j; Fig. S5l; Fig. S6l). No discernable second linear trend could be detected. However note, that the isochron obtained for Sahara 97096 also does not pass the initial OC-Xe value, similar to second isochrons of Indarch and St. Marks and to the Shallowater isochrons.

Finally, we analysed LAP 02225, which is classified as EH-impact melt. A general feature of this meteorite is its rather low xenon abundance (both trapped and radiogenic). Because of this and because of relatively high abundance of radiogenic argon (*Hopp et al., 2014*) the measurements suffered from strong memory problems which introduced large uncertainties. Only two extractions required no correction and these two may form a ‘two-point isochron’ corresponding to an age about 5 Ma younger than Shallowater (Fig. 2l; Fig. S4l). The other data plot between isochrons corresponding to 5 Ma and 15 Ma, if interpreted in chronological terms. Since the most reliable data are those without correction, one may argue that our treatment of memory xenon might have introduced a large systematic error. Accordingly, the 5 Ma I-Xe age would be a best chronologic estimate provided the data of these two extractions were indeed part of an isochron.

5 Discussion

5.1 On potential origins of a trapped sub-OC Xe component

Commonly, the composition of trapped $^{128}\text{Xe}/^{132}\text{Xe}$ and $^{129}\text{Xe}/^{132}\text{Xe}$ should correspond to the planetary Xe component observed in ordinary chondrites designated as OC-Xe (*Lavielle and Marti, 1992*). In several cases apparent lower sub-OC-Xe values were observed in meteorites of various types and some models that could explain these observations were discussed (e.g. *Caffee et al., 1982a; Gilmour et al., 2001; Hohenberg et al., 2004*). However, there is no evidence from previously reported data of Shallowater for a trapped sub-OC- $^{129}\text{Xe}/^{132}\text{Xe}$ value no matter if whole rock pieces or large enstatite crystals were used for analysis (*Hohenberg, 1967; McCoy et al., 1995; Brazzle et al., 1999; Gilmour et al., 2006*). Thus, observed lower than OC- $^{129}\text{Xe}/^{132}\text{Xe}$ values for Shallowater require more discussion. We can exclude an unrecognized systematic error introduced during the experiment because other meteorites included in this study definitely pass the OC-Xe composition. In addition, energetic / kinetic considerations essentially rule out noticeable recoil of $^{128}\text{Xe}_\text{I}$ and $^{129}\text{Xe}_\text{I}^*$ during the neutron irradiation process and, in fact, have never been reported by other studies (e.g. *Gilmour et al., 2006*). Hence, we need to regard alternative scenarios that potentially could explain a sub-OC Xe composition in Shallowater. The problem of sub-OC xenon has been addressed in some previous studies already (e.g. *Caffee et al., 1982a; Gilmour et al., 2001; Hohenberg et al., 2004*). Various interpretations are summarized below.

1) A I-Xe study of artificially shocked Bjurböle aliquots demonstrated that shock can redistribute iodine from lower to higher temperature sites (*Caffee et al., 1982a*). These sites however, do not reflect the initial iodine-xenon distribution and thus disturb any potential isochron relations. Furthermore, the xenon isotope record within the meteorite is increasingly homogenized with increase in shock, resulting from enhanced mobility of the trapped and

radiogenic xenon components. In case of Bjurböle it was shown by *Caffee et al.* (1982a) that the $^{128}\text{Xe}/^{129}\text{Xe}^*$ ratios of high temperature extractions rise with increasing shock pressures, shifting the resulting isochron at lower shock pressure (70 kb) in a similar manner as observed for our Shallowater aliquots. If a shock-scenario applies to Shallowater, respective isochrons may not define a real age reference line. However, Shallowater is classified as shock stage S2 (*Rubin, 2015*) which precludes a severe shock-induced redistribution of iodine and xenon, and its unbrecciated character (*Keil et al., 1989*) make significant differences in shock stage between the variously analyzed clasts unlikely.

2) Sub-planetary trapped $^{129}\text{Xe}/^{132}\text{Xe}$ -ratios were also reported for some carbonaceous chondrites (*Hohenberg et al., 2004*) which were explained by an incorporation of a pseudo-trapped component consisting of an admixture of Xe and iodine. The addition of iodine in a trapped component would result in an apparent increase of the trapped $^{128}\text{Xe}/^{132}\text{Xe}$ ratio due to neutron-induced formation of ^{128}Xe from iodine during reactor irradiation. If iodine still contained some undecayed ^{129}I during incorporation an additional increase in respective trapped $^{129}\text{Xe}/^{132}\text{Xe}$ would be expected. In an isochron diagram both scenarios would result in linear trends which carry a real age signal but would not pass OC-Xe composition. In case of Shallowater, incorporation of such a pseudo-trapped component could only have occurred very recently (maybe during sample preparation) since other studies show no evidence of sub-OC Xe in Shallowater. But it remains unclear how this incorporation should have taken place.

3) Linear trends need not to carry a chronologic information but may also arise from mixing of two components, each having different trapped Xe and I compositions. This has been demonstrated by *Gilmour et al.* (2001) who found a linear correlation for the martian Nakhla meteorite. Since Nakhla is too young for dating with the I-Xe method, this linear relation must be due to mixing processes. *Gilmour et al.* (2001) could attribute one component to planetary Xe whereas the second component consisted of iodine that was mixed with martian

atmospheric Xe in constant proportions. Still, mixing requires some addition of iodine similar to the scenario of *Hohenberg et al.* (2004) that we described above, but no age information would be necessarily associated with the resulting linear relation.

To summarize, we tentatively consider the age information contained in the $^{128}\text{Xe}_\text{I}/^{129}\text{Xe}_\text{I}^*$ of Shallowater as valid, but are aware that this explanation is still not satisfactory. Future work should address this observation in detail.

The observed isochron relation of Sahara 97096 is similar to Shallowater, pointing to an apparent trapped sub-planetary Xe component. . The relatively young I-Xe age defined by the high temperature phases in Sahara 97096, which is opposite to older I-Xe ages of other EH 3 chondrites (*Whitby et al.*, 2002), may indicate an impact-induced resetting of the I-Xe system and a remobilization of iodine within this meteorite. In this respect, the isochron might in fact mirror a real age characterized by an altered, re-homogenized trapped Xe composition, similar to the model described by *Caffee et al.* (1982a) and *Hohenberg et al.* (2004).

5.2 Comparison of I-Xe ages with literature ages: Bjurböle (L4) versus

Shallowater reference meteorites

In the past most I-Xe ages of enstatite chondrites were reported relative to the Bjurböle L4 chondrite. Only in recent years the Shallowater meteorite became the major age reference for the I-Xe system. This is justified by the much better reproducibility of the $^{128}\text{Xe}_\text{I}/^{129}\text{Xe}_\text{I}^*$ -ratio in Shallowater compared with Bjurböle, as demonstrated by *Gilmour et al.* (2006). In part, this might reflect the larger age range of the chondrules within Bjurböle (about 6.5 % variation of initial $^{129}\text{I}/^{127}\text{I}$ representing an age range of ca. 1.1 Ma, *Caffee et al.*, 1982b, *recalculated with $t_{1/2}(^{129}\text{I})=15.7\text{ Ma}$*) that potentially causes a larger spread in ages. Actually, this still leaves the problem of cross-calibration between both reference meteorites. The

reported relative age differences changed during various studies of the past decades by about 2 Ma. First Bjurböle was suggested to post-date Shallowater by ca. 1 Ma (*Hohenberg, 1967*), 1.2 ± 1.2 Ma (*McCoy et al., 1995*) and, based on $^{129}\text{I}/^{127}\text{I}$ -initial values of $1.095 \cdot 10^{-4}$ (Bjurböle) and $1.12 \cdot 10^{-4}$ (Shallowater), about 0.5 Ma (values taken from *Hohenberg and Kennedy, 1981*). More recent investigations indicate that instead Shallowater is post-dating Bjurböle, by 0.46 ± 0.15 Ma (*Brazzle et al., 1999*) or by about 1.1 Ma (*Gilmour et al., 2006*, based on $^{129}\text{I}/^{127}\text{I}$ -initial values of $1.125 \cdot 10^{-4}$ for Bjurböle and $1.072 \cdot 10^{-4}$ for Shallowater). The overall age uncertainty, if linked with the Shallowater reference, may thus be as large as 1 Ma. As can be seen in Fig. 3a+b, I-Xe ages measured relative to Bjurböle show a systematic offset relative to the (few) I-Xe ages determined relative to the Shallowater meteorite if plotted with no age offset assumed between both meteorites (i.e. age of Shallowater = age of Bjurböle). In particular, the group of EL6 chondrites (vs Bjurböle) appears slightly older than our data and the only other EL6 Khairpur (*Busfield et al., 2008*) dated against the Shallowater reference. Furthermore, our result for Indarch is identical to the result in *Busfield et al. (2008)* (both determined against Shallowater), whereas the older Bjurböle-referenced data show an offset of about 1-1.5 Ma towards older ages. Finally, the EH3 chondrule ages (measured against Shallowater, *Whitby et al., 2002*) encompass a similar age range than our I-Xe ages of EH4-5 chondrites, whereas again a slight offset towards older ages is detected for EH4-5 chondrites measured against Bjurböle. To conclude, the most likely age difference between Bjurböle and Shallowater is in the range of 1 ± 0.5 Ma, with Bjurböle being *younger* as Shallowater. However, this subject requires more work. In the following, for the purpose of intercomparison of both I-Xe age suites (referenced against Bjurböle and Shallowater) we tentatively assume that Bjurböle is coeval with Shallowater, with all uncertainties associated with this value as noted above.

5.3 I-Xe ages and metamorphic cooling

5.3.1 Retention temperatures T_C of I-Xe in enstatite

The closure temperatures of the I-Xe system in enstatite and for many other minerals are not known yet. For assessing retention temperatures we may utilize a cooling model for the H-chondrite parent body (*Trieloff et al., 2003; Henke et al., 2013*) which based on Pb-Pb, fission track and Ar-Ar ages of a subset of H chondrites with low shock-stage and for which I-Xe ages of feldspar and phosphates are available (*Brazzle et al., 1999; Gilmour et al. 2006*). This results in I-Xe closure temperatures of ca. 770 ± 60 K in feldspar and 650 ± 50 K in phosphates. Because T_C depends strongly on cooling rate, these retention temperatures are only valid at cooling rates of ca. 10-100 K/Ma. Retention temperatures in enstatite are expected to be higher, given its higher xenon release temperature. If we assume a 250 ± 50 K difference between feldspar and enstatite (corresponding to the difference in release temperatures) we end up with $T_C = \text{ca. } 1020 \text{ K } (\pm 100 \text{ K})$. Again, this value strongly depends on cooling rate: Fast cooling rates that would occur for example, during an impact-induced thermal heating event may raise the actual T_C by several 100 K. In addition, it is possible to calculate diffusion parameters from individual meteorites by application of an Arrhenius diagram $\ln(D/a^2)$ versus $1/T$ for $^{128}\text{Xe}_i$ if single degassing peaks correspond to individual phases. For determination of D/a^2 values we applied the approximations given in *Pravdivtseva et al. (2013)*. Only few meteorites in this study are suited for this purpose (Fig. S7a-e in Supplementary Material). T_C values were calculated after the formulation of *Dodson (1973)* for spherical geometry. For the EH chondrites EET 96135 (wr 1 and 3) and Indarch the activation energies are 72-79 kcal/mole for $^{128}\text{Xe}_i$, and the calculated retention temperatures were > 700 K at a cooling rate of 1 K/Ma. St. Marks provides a lower activation energy (36 kcal/mole for $^{128}\text{Xe}_i$) and T_C of 428 K at 1 K/Ma. LON 94100 yields a very high activation energy (264 kcal/mole for $^{128}\text{Xe}_i$) and high T_C (>1220 K for cooling rates above 1 K/Ma).

Again, calculated retention temperatures vary with cooling rate and thus serve only as a lower limit at relatively fast cooling rates. The I-Xe retention temperature in enstatite of EL6 appears higher than in EH4 / EH5 chondrites and even within EH chondrites a variation is obvious. Hence, the precondition of single phase diffusion appears to be not sufficiently well fulfilled precluding calculation of a well-defined T_C for the I-Xe system in enstatite. Irrespective of this, our first estimate of 1020 ± 100 K may be a good approximation for relatively fast cooling rates.

5.3.2 EL 6 chondrites

EL 6 chondrites appear to be 3-6 Ma younger than Shallowater (Fig. 3a, Table 1) and the EH 4-5 chondrite suite, and both I-Xe ages of EL 6 chondrites in our study are in good accord with previous EL 6 I-Xe ages. Obviously, irrespective of the offset in age between the reference meteorites Bjurböle and Shallowater we observe a very coherent age pattern. The apparent variation could be solely due to statistical variation, thus representing a single formation / cooling age. Estimates of peak temperatures recorded in enstatite chondrites are in the range of 800-1000°C (e.g. *Zhang and Sears, 1996*), i.e. very close to the estimated retention temperature of 650-850°C. However, peak temperatures were considered to pre-date parent body assembly (*Zhang and Sears, 1996*). Based on sulfide thermometry the peak metamorphic temperatures assessed for the EH and EL parent bodies are lower, <800°C (EH) and <400°C (EL) (*Zhang and Sears, 1996*). Apparently, the enstatite retention temperature never would have been reached in the EL-chondrite parent body. In this case, the I-Xe age of EL 6 chondrites would correspond to the formation of enstatite within the solar nebula or during a severe impact-induced thermal event which could raise temperatures above T_C after parent body formation. The age difference between formation of first solids (Ca-Al-rich inclusions (CAI), 4567.18 ± 0.50 (2 σ) Ma, *Amelin et al., 2010*) and EL 6 chondrites is ca. 10 ± 1 Ma. It seems doubtful whether temperatures could be kept sufficiently high for such a late

enstatite formation within the early Solar System unless formation was very close to the Sun. An impact-induced thermal reset of the I-Xe system in enstatite by impact heating could be a viable explanation, therefore. In addition, metamorphic annealing of previously established high pressure phases is documented in EL 6 chondrites (*Rubin et al., 1997*) which likely requires temperatures above 400°C. Hence, during parent body metamorphism temperatures above T_C may have been reached, high enough for resetting the I-Xe system. If true, a metamorphic cooling model for EL 6 chondrites requires a relatively fast drop in temperature after reaching peak temperature conditions because otherwise the enstatite retention temperature would be crossed much later than 10 Ma after CAI formation. This differs from H 6 chondrite cooling trajectories, in which hot conditions prevail longer and cooling is slower, and resembling the cooling histories of H5 or H4 chondrites. From this we may conclude that the parent body of EL 6 chondrites may have been significantly smaller than the H chondrite parent body. A final clue to distinguish between the different models requires I-Xe ages of EL chondrites with lower petrologic type.

5.3.3 EH chondrites

Most I-Xe ages presently known for EH chondrites are old, i.e. show evidence of closure of the I-Xe system within the first ca. 4-7 million years after CAI-formation (Fig. 3b). With the exception of Sahara 97096 (EH 3) (this study) Yamato-691 (EH 3, *Honda et al., 1983*) and St. Marks (*Hohenberg et al., 1967; Kennedy et al., 1988*) all EH-chondrites fall within an I-Xe age range of about 1 Ma older to 2 Ma younger than Shallowater, which corresponds to absolute ages of about 4560 to 4563 Ma (Fig. 3b). Within uncertainties, there is no evidence for a systematic trend with petrologic type. For example, Indarch (EH 4), Abee (EH 4) and EET 96135 (EH 4/5) agree well within their errors. The I-Xe age of St. Marks (EH 5) appears slightly more recent (though not significant within 2σ -uncertainties), but differs from the ~3 Ma more recent ages reported previously by *Hohenberg et al. (1967)* and *Kennedy et al.*

(1988). Irrespective of minor differences, closure of the I-Xe system for these EH 4, EH 4/5 and EH 5 chondrites can be regarded as approximately simultaneous. The only EH 3 chondrite, Sahara 97096, shows the youngest I-Xe age (-7.87 ± 0.46 Ma more recent than Shallowater). This is not expected from a simple metamorphic cooling history of an onion-shell layered parent body, for which the outermost layer is cooling fastest. On the other hand, this outer layer is more likely to be disturbed by an impact-induced thermal event. Furthermore, the fine-grained nature of type 3 meteorites makes the I-Xe system more prone to thermal effects. It is thus not too surprising that our EH 3 meteorite does not fit a simple prograde metamorphic cooling scheme. More recent I-Xe ages relative to Shallowater for unequilibrated chondrites are not unusual and have been reported for both carbonaceous and ordinary chondrites (e.g. *Podosek, 1970; Podosek and Hohenberg, 1970; Swindle et al., 1991; Pravdivtseva et al., 2003; Hohenberg et al., 2004; Holland et al., 2005*) and the EH 3 chondrite Yamato-691 (16 Ma more recent to Bjurböle, *Honda et al., 1983*). However, our EH 3 I-Xe age differs markedly from the older I-Xe ages obtained for single chondrules from EH 3 chondrites Kota-Kota and Qingzhen (Fig. 3b, *Whitby et al., 2002*).

We here note a basic problem with the ages of EH chondrites of low petrologic type: As low petrologic types experienced the mildest degree of metamorphic heating, it is questionable if metamorphism caused a total reset by exceeding the closure temperature of the high temperature I-Xe phase. To solve this problem, one may argue that all EH I-Xe ages could represent chondrule formation ages, although chondrule formation 4-7 Ma after CAIs only marginally coincides with the chondrule ages known from other chondrite groups. We tentatively consider the possibility that the actual closure temperature of the I carrier phases may have been much lower during prograde metamorphism, thus allowing a reset of the I-Xe system, and that during low temperature metamorphism, part of the iodine carrier phases were poikilitically encapsulated into enstatite by low temperature surface diffusion. Such iodine

carrier phases would become effectively isolated and keep their xenon until high release temperatures, and would be resistant against subsequent reset, thereby mimicking the high closure temperature of the I-Xe system defined by the enstatite. This hypothesis could also explain that there are always some disturbed low temperature data points deviating from the high temperature isochron and indicating later disturbances of the I-Xe clock: the low temperature phases are iodine carrier phases that never managed to be encapsulated in a “protective” enstatite container.

Concerning other chronometric systems, Qingzhen shows a younger Ar-Ar and Rb-Sr age of ca. 2-3 Ga (*Jessberger, 1983; Torigoye and Shima, 1993*) and mineral decomposition features (Qingzhen-reaction, *El Goresy et al., 1988*) which both has been attributed to hydrothermal processes. This may similarly apply to Sahara 97096 which also showed a disturbed Ar-Ar age spectrum with ages down to ca. 1.5- 2 Ga (*Hopp et al., 2014*). This seems in contradiction to the observed older I-Xe ages of the EH 3 chondrites. However, Ar-Ar ages obtained from individual djerfisherite grains show a large age range from 0.8 – 4.4 Ga (*Müller and Jessberger, 1985*) which may point to a considerable variability in mineral ages even within an individual meteorite. For example, the ^{53}Mn - ^{53}Cr age of sphalerites in Sahara 97158, paired with Sahara 97096, was found to be 4562.7 ± 0.5 Ma (*Trieloff et al., 2013*), i.e. ~8 Ma older than the Sahara 97096 I-Xe age. The retention temperatures of the Mn-Cr and I-Xe systems are not expected to differ much, as is evident from other Mn-Cr ages reported from enstatite chondrites (Indarch (EH 4) 4562.1 ± 1.3 Ma; Abee (EH 4) 4562.5 ± 0.8 Ma; Khairpur (EL 6) 4557.6 ± 0.3 Ma; *Shukolyukov and Lugmair, 2004*, recalculated relative to LEW 86010 Pb-Pb age of 4557.8 ± 0.5 Ma and initial $^{53}\text{Mn}/^{55}\text{Mn} = (1.25 \pm 0.07) \cdot 10^{-6}$ and half-life of ^{53}Mn of 3.7 Ma, *Lugmair and Galer, 1992*) which fit well the corresponding I-Xe ages (this study; *Hohenberg, 1967; Kennedy et al., 1988; Busfield et al., 2008*). It appears that due to the brecciated nature of the various paired Sahara EH 3 specimens some parts may

have been more and others less affected by thermal or hydrothermal events. Sahara 97096 investigated in our study may have experienced a more extensive processing.

6 Summary and conclusions

We report I-Xe ages of a suite of EH 3-5 and EL 6 chondrites, and a EH impact melt, relative to the Shallowater reference meteorite (positive age: more recent / negative age: more ancient, than the Shallowater age of 4562.3 ± 0.4 Ma, *Gilmour et al., 2009*). Both EL 6 chondrites, LON 94100 and Neuschwanstein, yield more recent isochron ages of -4.38 ± 0.60 Ma and -3.87 ± 0.73 Ma, respectively, for high temperature extractions likely related to degassing of enstatite and/or inclusions enclosed in enstatite. Both EL 6 chondrites are well in the range of previously reported I-Xe ages for EL 6 chondrites. The relatively fast cooling rate and the I-Xe age of about 10 Ma after CAI would demand a smaller parent body compared with the H chondrite parent body. However, important information to further support this speculation is missing, in particular I-Xe ages of lower petrologic types and the retention temperatures of the I-Xe carrier minerals. Thus, the age patterns can be equivalently explained by a large-scale impact-induced thermal event relatively early in the history of the EL parent body allowing for annealing of high pressure phases during still ongoing metamorphism.

The I-Xe ages of the EH 4 chondrites Abee (-0.45 ± 0.72 Ma) and Indarch ($+0.16 \pm 0.50$ Ma) also agree with previously reported ages (*Hohenberg et al., 1967; Kennedy et al., 1988; Whitby et al., 2002; Busfield et al., 2008*). Two splits of the EH 4/5 chondrite EET 96135, irradiated at different reactor sites, were analyzed and gave I-Xe ages of $+0.57 \pm 1.05$ Ma and -0.61 ± 0.60 Ma. Finally, we determined an I-Xe age for St. Marks (EH 5) of -1.02 ± 0.66 Ma, which is coeval to the other EH chondrites, but differs from a previously reported 3-4 Ma younger age (*Hohenberg et al., 1967; Kennedy et al., 1988*). The most primitive meteorite in

our study, EH 3 chondrite Sahara 97096, yielded the most recent I-Xe age of -7.87 ± 0.46 Ma, documenting a severe thermal event early in the history of the EH parent body. This is contrary to I-Xe ages of chondrules in the EH 3 chondrites Kota Kota and Qingzhen (*Whitby et al.*, 2002), and to a ^{53}Mn - ^{53}Cr age of sphalerite in (the paired with Sahara 97096) meteorite Sahara 97158 (*Trieloff et al.*, 2013), which are similar to other EH chondrites with ages between +1 and -2 Ma relative to Shallowater.

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9 Figure captions

Figure 1: a) – l) Release patterns of $^{128}\text{Xe}_I$ and $^{129}\text{Xe}_I^*$ in all analyzed meteorites, normalized to total respective concentration and temperature step (nominal temperatures, $T^\circ\text{C}(\text{real}) \sim 1.3 \cdot T^\circ\text{C}(\text{nominal}) - 100$). Initial pre-degassing step was 300°C (chondrites) and 400°C (Shallowater), respectively. Errors are 1σ -uncertainties.

Figure 2: a) – l) Three-isotope diagram of $^{128}\text{Xe}/^{129}\text{Xe}$ versus $^{132}\text{Xe}/^{129}\text{Xe}$. Except for LAP 02225 (Fig. 2l) all meteorites exhibit well-defined isochron relationships (black lines, data assigned to isochron are shown as filled black circles, other data as open black circles). LON 94100 (Fig. 2d), Indarch (Fig. 2i) and St. Marks (Fig. 2k) show a second linear trend at lower temperatures. The second line is shown in grey, and the respective data are represented as grey circles. Errors are 1σ -uncertainties.

Figure 3: Compilation of I-Xe ages of this study (black circles) and of literature data (grey squares). Open squares denote I-Xe ages measured relative to the Bjurböle age reference, filled symbols refer to ages measured relative to the Shallowater reference meteorite. *We tentatively assume that Bjurböle is coeval with Shallowater.* Ages after CAI-formation refer to CAI-age of 4567.18 Ma (Amelin *et al.*, 2010). See discussion in subsection 5.1. a) I-Xe ages of EL chondrites and EL impact melts. b) I-Xe ages of EH chondrites and EH impact melt. Errors are 1σ -uncertainties. Data sources: Podosek (1970); Kennedy *et al.* (1988); McCoy *et al.* (1995); Whitby *et al.* (2002); Busfield *et al.* (2008); *this study*.

10 Table caption

Table 1: I-Xe ages and results of isochron regression analyses

Table 1: I-Xe ages and results of (inverse) isochron regression analyses

Meteorite	Type	Weight (mg)	Isochron extractions (°C)	n ^a	I-Xe age (Ma) relative to Shallowater ^b	MSWD-value ^c	Probability ^c
Shallowater, USNM 1206 wr #4	Enstatite achondrite	154.9	1030 - 1100	6	$\equiv 0$	0.73	0.57
Shallowater, USNM 1206 wr #5	Enstatite achondrite	171.8	1030 - 1350	8	$\equiv 0$	0.48	0.82
Shallowater, USNM 1206 wr #6	Enstatite achondrite	169.3	1030 - 1350	8	$\equiv 0$	0.34	0.91
Abee	EH 4	238.1	820 - 1340	11	-0.45 ± 0.72	1.02	0.42
EET 96135,18 wr #1	EH 4/5	240.6	1000 - 1300	8	$+0.57 \pm 1.05$	0.26	0.96
EET 96135,18 wr #3	EH 4/5	216.9	1005 - 1215	18	-0.61 ± 0.60	0.13	1.00
Indarch, 436/1	EH 4	203.1	1085 - 1280	12	$+0.16 \pm 0.50$	0.45	0.92
			1030 - 1070	4	$+0.56 \pm 0.68$	0.031	0.97
LAP 02225,21	EH-impact melt	187.0	no isochron, estimate only	---	-5 to -15	---	---
LON 94100,33	EL 6	186.3	1085 - 1280	15	-4.38 ± 0.60	0.10	1.00
			990 - 1055	5	-5.25 ± 1.17	0.21	0.81
Neuschwanstein	EL 6	218.3	960 - 1500	21	-3.87 ± 0.73	0.39	0.991
Sahara 97096 (1233/2)	EH 3	186.0	1040 - 1225	11	-7.87 ± 0.46	0.19	0.995
St. Marks	EH 5	201.2	1005 - 1500	14	-1.02 ± 0.66	0.39	0.97
			900 - 990	5	-0.01 ± 0.69	0.74	0.53

Errors are 1 σ -uncertainties.

^a Number of extractions defining the isochron.

^b Positive ages are older and negative ages are younger than Shallowater (= 4562.3 $\pm$ 0.4 Ma, *Gilmour et al. 2009*). Ages in italics are considered as not reliable (see main text). All isochron ages are calculated from intercept in $^{128}\text{Xe}/^{129}\text{Xe}$ versus $^{132}\text{Xe}/^{129}\text{Xe}$ (inverse) isotope diagrams.

^c MSWD- and probability values of isochron regression calculated with Isoplot 4.15 (*Ludwig, BGC*)

Figure 1a-f

Figure 1g-l

Figure 2a-f

Figure 2g-l

Figure 3a

Figure 3b