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Space history of the High Possil and Strathmore meteorites from Ne and Ar isotopes

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Abstract: The High Possil and Strathmore L6 chondrites fell in Scotland in 1804 and 1917 respectively. Unravelling their cosmic-ray exposure (CRE) ages provides crucial information about when they were ejected from the parent body, how they were delivered to Earth and is ultimately important for understanding the dynamics of small bodies in the solar system. Here we use new measurements of the Ne and Ar isotopic composition to determine CRE ages of both meteorites. Duplicated cosmogenic ^{21}Ne and ^{38}Ar concentrations yield CRE ages of 44.6 ± 4.6 Ma for High Possil and 15.4 ± 1.3 Ma for Strathmore. These coincide with well-established peaks in the ejection record for the L6 chondrites. They yield ^{40}Ar gas retention ages in excess of 3.15 Ga, which is consistent with both meteorites originating at depth within the parent body at the time of asteroidal break-up.

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The High Possil and Strathmore meteorites are two of the three meteorite falls recorded in Scotland (Bevan *et al.* 1985; Meteoritical Bulletin 110 (2021)). The fall of the High Possil (5 April 1804) meteorite was heard by the workers at Possil sandstone quarry (55° 4′ N, 4° 14′ W) and observed throughout Glasgow. The impact left a 38 cm diameter hole that filled with water leaving the meteorite fragments embedded into the soft sandy bedrock. Only two outer parts of the meteorite were recovered. Based on the reported dimensions from Prior and Hey (1923) the total weight of the meteorite was estimated to be 4.5 kg (Bevan *et al.* 1985 and references therein). The larger of the two recovered fragments was donated to the Hunterian Museum, University of Glasgow.

The Strathmore meteorite fell on 3 December 1917 around Coupar Angus and Blairgowrie. It consists of four stones totalling 13.2 kg. Three fragments were recovered in Perthshire, at Easter Essendy (56° 35′ N, 3° 15′ E) (two fragments: 9.911 and 0.021 kg), Carsie (1.085 kg) and Keithick (1.172 kg). One fragment was found at South Corston (1.066 kg) in Angus (Bevan *et al.* 1985). Detailed descriptions of the fall are available at https://www.nms.ac.uk/explore-our-collections/stories/natural-sciences/strathmore-meteorite/.

Both meteorites have petrographic, mineralogical and chemical compositions consistent with the L-group chondrites (McLintock and Ennos 1922; Bevan *et al.* 1985). They have abundant plagioclase feldspar which puts them in the petrologic type 6 of the Van Schmus and Wood (1967) classification. The L6 chondrites are characterized by low iron content and have been metamorphosed at P–T conditions sufficient to homogenize mineral chemical compositions. They likely originate in S-type asteroids. The level of silicate alteration due to shock-loading is variable, but not intense, suggesting that shock pressures were in the range of 10–25 GPa. Strathmore has a greater proportion of deformed grains than High Possil, consistent with shock loading to higher pressures (Bevan *et al.* 1985).

Cosmic-ray exposure (CRE) ages of meteorites provide fundamental constraints against which models for the origin and delivery of meteorites from the asteroid belt to Earth are tested (e.g. Nesvorny *et al.* 2009). Cosmogenic nuclides in meteorites are produced by nuclear interactions of high-energy galactic cosmic ray (GCR) protons from outside the solar system, and energetic solar cosmic ray (SCR) protons emitted by the Sun. Cosmogenic nuclide production rate is governed by the meteorite composition, the shape and size of the irradiated body and the position of the analysed sample within the parent body (Eugster 1988). L6 meteorites tend to originate from deep within their parent body so do not acquire a significant cosmogenic nuclide load prior to ejection into space. Consequently, the CRE age records the transit time of a small object from its parent body to Earth after parent body ejection.

Cosmogenic ^{21}Ne and ^{38}Ar are widely used to reconstruct the irradiation history of meteorites in space (Wieler 2002). Here we use new measurements of Ne and Ar isotopes to determine the concentration of the cosmogenic Ne and Ar in the High Possil and Strathmore L6 chondrites in order to estimate the pre-atmospheric size of the meteorites and to reconstruct the exposure time in space. The concentration of radiogenic ^{40}Ar provides an insight into the thermal history of the parent body.

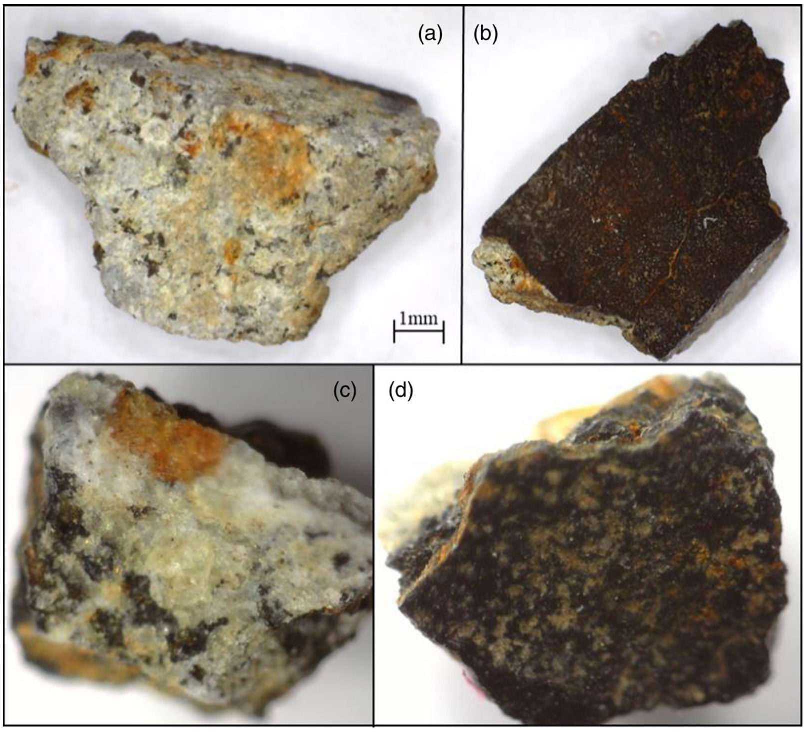

Fig. 1. Photographs of the interior (**a**, **c**) and the fusion crust (**b**, **d**) of the High Possil (a, b) and Strathmore (c, d) meteorites in this study. Scale in (a) applies to all photographs.

Samples and experimental techniques

In this study we report data on samples of the larger High Possil stone, provided by the Hunterian Museum, and the Keithick fragment of Strathmore, which was from the National Museum of Scotland collection. The specimens looked fresh under the binocular microscope and preserved fusion crust (Fig. 1). Chips (4.6 to 6.7 mg) were prised from the larger sample using tweezers taking care to avoid fusion crust. They were encapsulated in Pt packets, placed in recesses in a Cu pan then evacuated to ultra-high vacuum and baked for 12 h at *c.* 80°C to remove adsorbed atmospheric gases. The samples were degassed at *c.* 1300°C for 30 minutes using a 75 W 808 nm diode laser in apparatus identical to that described in Stuart *et al.* (1999). The gas released was purified by two SAES GP50 getters operated at 250°C and one at room temperature. Argon was trapped for 20 minutes on an activated charcoal-filled stainless-steel finger cooled to −196°C using liquid nitrogen. Neon was then trapped on activated charcoal in a cryostatic cold head at 30 K for 10 minutes; the unabsorbed He was pumped out then the Ne was released at 100 K prior to isotope analysis in static mode in a MAP-215-50 mass spectrometer (Williams *et al.* 2005). The Ar was subsequently released from the charcoal trap at room temperature and analysed using the same instrument.

System blanks were determined by heating an empty platinum tube to *c.* 1300°C. They never exceeded more than 0.2% of any isotope in the sample so blank corrections were not made. The sample packets were reheated and in all cases Ne and Ar concentrations did not exceed 1% of the gas released in the main step. Sensitivity and instrument mass discrimination are based on repeated measurements of an air standard. Neon isotopes have been corrected from isobaric interferences from $H_2^{18}O^+$, HF^+ and $^{40}Ar^{2+}$ at $^{20}Ne^+$, CO_2^{2+} at $^{22}Ne^+$ and $^{66}Cu^{3+}$ at $^{21}Ne^+$ following procedures in Codilean *et al.* (2008). Ne and Ar isotopes were determined in several splits of homogenized powder of the Millbillillie eucrite before and after these samples as a secondary check on mass spectrometer sensitivity and mass discrimination.

Results and discussion

Cosmogenic Ne and Ar

Neon isotopes were measured in three chips of High Possil and two chips of Strathmore (Table 1). The $^{20}Ne/^{22}Ne$ and $^{21}Ne/^{22}Ne$ ratios in each sample overlap within uncertainty (Fig. 2) and overlap the composition of cosmogenic Ne in chondrites (Eugster *et al.* 2007). This suggests that the contribution from atmospheric, solar or primordial Ne is negligible, and the Ne inventory is dominantly cosmogenic in origin.

Argon isotopes were measured in two aliquots of both meteorites (Table 2). $^{36}Ar/^{38}Ar$ of 0.88 ± 0.07 and 1.63 ± 0.33 for High Possil and Strathmore respectively are higher than the cosmogenic $^{36}Ar/^{38}Ar$ of L chondrites (*c.* 0.63; Wieler 2002). This is likely a consequence of the presence of significant contributions of solar wind and/or atmosphere-derived Ar, more so in the case of Strathmore. The low solar wind Ne and Ar content of L6 chondrites (Alexeev 2005) leads us to assume that the non-cosmogenic component is atmospheric in origin ($^{36}Ar/^{38}Ar = 5.319$) perhaps a consequence of incomplete degassing of adsorbed air prior to analysis. The correction for air-derived ^{38}Ar is *c.* 5% in the case of High Possil and 14–28% for the two Strathmore splits. Variation in $^{40}Ar/^{36}Ar$ is also consistent with a minor atmospheric contribution. For the component deconvolution we did not consider the contribution of ^{36}Ar generated by the decay of neutron-capture produced ^{36}Cl. This will tend to increase the $^{36}Ar/^{38}Ar$ and reduce the cosmogenic ^{38}Ar concentration (e.g. Huber *et al.* 2008).

The noble gas data alone are not sufficient to determine the pre-atmospheric size of the meteorite and so determine the

Table 1. *Measured Ne concentrations and isotope ratios, and calculated cosmogenic Ne concentrations, in bulk samples of the High Possil and Strathmore L6 chondrites*

Sample	Mass*	^{20}Ne†	1σ	^{21}Ne$_{cos}^{\dagger}$	1σ	^{20}Ne/^{22}Ne	1σ	^{21}Ne/^{22}Ne	1σ
High Possil #1	4.6	10.50	0.85	10.80	1.60	0.835	0.049	0.862	0.064
High Possil #2	6.3	11.56	0.96	11.94	1.74	0.836	0.049	0.866	0.064
High Possil #3	6.4	10.97	0.89	11.43	1.64	0.831	0.049	0.870	0.064
Average		**11.01**	**0.43**	**11.39**	**0.47**	**0.834**	**0.002**	**0.866**	**0.003**
Strathmore #1	6.7	5.69	0.48	6.15	0.90	0.833	0.049	0.903	0.067
Strathmore #2	6.6	5.94	0.48	6.35	0.93	0.816	0.048	0.924	0.068
Average		**5.82**	**0.12**	**6.25**	**0.10**	**0.825**	**0.009**	**0.914**	**0.011**

*Sample mass in mg.
†Concentrations in 10^{-8} cm^{3}STP g^{-1}.

sample depth. The empirical correlation of Bhandari *et al.* (1980) facilitates the determination of the pre-atmospheric mass and radius although it is only valid for samples that are from the interior of the meteorites where the variations of Ne ratios are relatively small. The relatively high ^{21}Ne/^{22}Ne of High Possil (0.87) and Strathmore (0.91), in combination with the cosmogenic ^{20}Ne/^{22}Ne ratio, is consistent with only a few centimetres of shielding (Garrison *et al.* 1995) and legitimizes the use of the empirical correlation between the cosmogenic ^{22}Ne/^{21}Ne and the pre-atmospheric mass of the meteorite developed by Bhandari *et al.* (1980). Using the average density for L-chondrites of 3.35 g cm^{-3} (Britt and Consolmagno 2003), we calculate pre-atmospheric radii of 14 and 19 cm for High Possil and Strathmore respectively (Table 3). The recovered masses for High Possil and Strathmore (4.5 and 13 kg, respectively; Bevan *et al.* 1985) suggest mass loss of around 89 and 87% during atmospheric entry. This is in line with the typical mass ablation for L-chondrites (Bhandari *et al.* 1980; Alexeev 2004). In this case the pre-atmospheric masses are *c.* 40 and 100 kg for High Possil and Strathmore, respectively.

As the pre-atmospheric radii of both meteorites was less than 65 cm we can apply the calculation method of Dalcher *et al.* (2013) to determine the CRE ages of both meteorites. This uses the empirical correlations between the cosmogenic ^{21}Ne (^{21}Ne$_{cos}$) and ^{38}Ar (^{38}Ar$_{cos}$) production rates and the (^{22}Ne/^{21}Ne)$_{cos}$ ratio as a shielding indicator. From the measured (^{22}Ne/^{21}Ne)$_{cos}$ (Table 1) we obtain ^{21}Ne production rates of 0.28 and 0.39 × 10^{-8} cm^{3}STP g^{-1} Ma^{-1} for High Possil and Strathmore, respectively. This leads to average

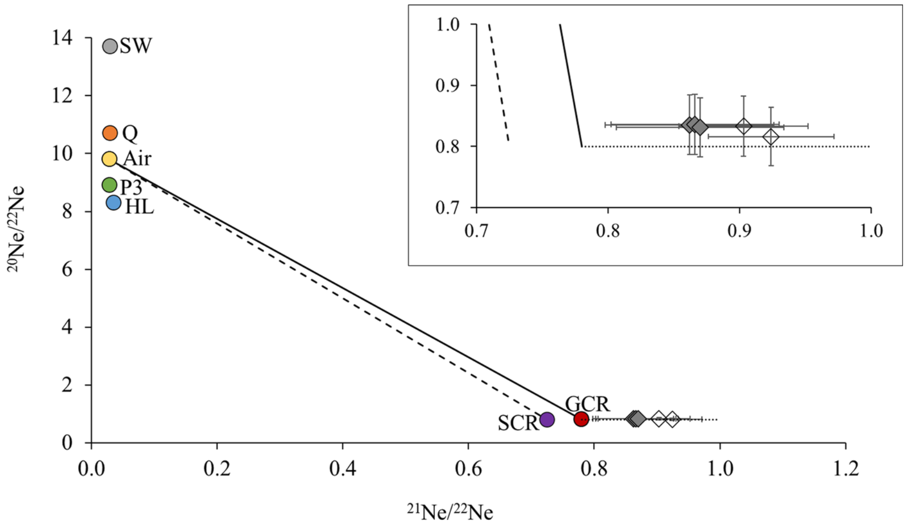

Fig. 2. Neon isotope data from the analysis of bulk material from High Possil (filled diamonds) and Strathmore (open diamonds) L6 chondrites. Solar wind (SW) Ne is taken from Geiss *et al.* (2004), P3 and HL endmembers are from Huss and Lewis (1994) and the Ne-Q is from Wieler *et al.* (1992) . Mixing lines between air and galactic cosmic ray (GCR; full line) and solar cosmic ray (SCR; dashed line) produced Ne isotope compositions are taken from Garrison *et al.* (1995). The theoretical shielding line (dotted line) is taken from Hohenberg *et al.* (1978).

Table 2. *Measured Ar concentrations and isotope ratios, and calculated cosmogenic Ne concentrations, in bulk samples of the High Possil and Strathmore L6 chondrites*

Sample	^{40}Ar*	1σ	^{36}Ar*	1σ	^{36}Ar/^{38}Ar	1σ	^{38}Ar$_{cos}$*	1σ
High Possil #2	4016	6	1.71	0.10	0.90	0.07	1.81	0.02
High Possil #3	5406	4	1.83	0.11	0.87	0.07	2.00	0.02
Average	**4711**	**695**	**1.77**	**0.06**	**0.88**	**0.01**	**1.90**	**0.09**
Strathmore #1	3814	1	1.69	0.10	1.30	0.11	1.12	0.01
Strathmore #2	3246	2	1.86	0.11	1.95	0.16	0.69	0.01
Average	**3530**	**284**	**1.78**	**0.09**	**1.63**	**0.33**	**0.90**	**0.21**

*Concentrations in 10^{-8} cm^{3}STP g^{-1}.

Table 3. *Pre-atmospheric mass (M_0) and radius (R_0) of High Possil and Strathmore L6 chondrites, calculated using the empirical correlation of Bhandari et al. (1980)*

Sample	^{22}Ne/^{21}Ne	*d*	M_0 (Kg)	R_0 (cm)	M_R (kg)	% Ablation
High Possil	1.155	0.004	40	14	4.5	89%
Strathmore	1.095	0.013	100	19	13	87%

The radii are calculated using the average density for L-chondrites of 3.35 g cm^{-3} (Britt and Consolmagno 2003) and the % of mass ablation uses the recovered masses (M_R) reported by Bevan *et al.* (1985).

Table 4. *Cosmogenic production rates of ^{21}Ne (P(^{21}Ne)) and ^{38}Ar (P(^{38}Ar)) (10^{-8} cm^{3}STP g^{-1} Ma^{-1}) are calculated using the correlation of Dalcher et al. (2013) and the (^{22}Ne/^{21}Ne)$_{cos}$ ratio for High Possil and Strathmore L6 chondrites*

Sample	$P(^{21}$Ne)	1σ	T_{CRE} (^{21}Ne)	1σ	$P(^{38}$Ar)	1σ	T_{CRE} (^{38}Ar)	1σ	T_{ret} (^{40}Ar)	1σ
High Possil #1	0.269	0.027	40.14	4.014						
High Possil #2	0.277	0.028	43.05	4.305	0.038	0.004	47.92	4.792	3467	520
High Possil #3	0.286	0.029	40.01	4.001	0.038	0.004	51.9	5.19	3935	590
Average	**0.277**	**0.007**	**41.066**	**1.405**	**0.038**	**0.00**	**49.91**	**1.987**	**3701**	**234**
Strathmore #1	0.362	0.036	16.98	1.698	0.045	0.004	24.92	2.492	3389	508
Strathmore #2	0.416	0.042	15.26	1.526	0.05	0.005	13.82	1.382	3145	472
Average	**0.39**	**0.027**	**16.12**	**0.861**	**0.047**	**0.002**	**19.37**	**5.549**	**3267**	**122**

The CRE ages (T_{CRE}) (Ma) are calculated using the ^{21}Ne$_{cos}$ and ^{38}Ar$_{cos}$ concentrations from Tables 1 and 2. The ^{40}Ar retention ages (T_{ret}) (Ma) are calculated using the measured ^{40}Ar concentrations reported in Table 2.

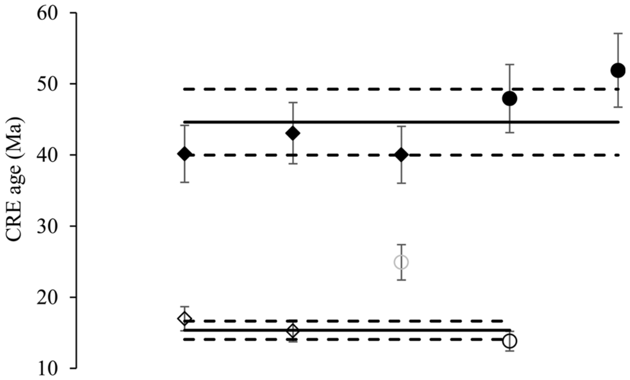

Fig. 3. Calculated CRE ages for High Possil (filled symbols) and Strathmore (open symbols) L6 chondrites based on cosmogenic ^{21}Ne (diamonds) and ^{38}Ar (circles). The average ages (continuous lines) and standard deviation (dashed lines) are calculated using the five ages determined for High Possil and three ages of Strathmore. The oldest Strathmore CRE age (grey circle) is not included in the mean exposure age calculation.

CRE ages of 41.1 ± 1.4 and 16.1 ± 0.9 Ma (Table 4). Applying the (^{22}Ne/^{21}Ne)$_{cos}$ to the calculation of the ^{38}Ar production rate we obtain production rates of 0.038 and 0.047 × 10^{-8} cm^{3}STP g^{-1} Ma^{-1} for High Possil and Strathmore, respectively. This produces CRE ages of 49.9 ± 1.9 for High Possil and 24.9 ± 2.5 to 13.8 ± 1.4 Ma for Strathmore (Table 4).

In the case of High Possil the five CRE ages agree within 1σ uncertainty and yield an average age of 44.6 ± 4.6 (Fig. 3). This overlaps the large *c.* 40 Ma peak in CRE ages of L6 chondrites that indicate a major collisional event on the L-chondrite parent body (Wieler 2002; Herzog and Caffee 2014). Three of the four CRE ages of Strathmore overlap a mean age of 15.4 ± 1.3 Ma (Fig. 3). The single old cosmogenic ^{38}Ar exposure age is a statistical outlier and is excluded. The mean Strathmore CRE age overlaps the major 15 Ma peak in the L chondrite CRE age inventory (Wieler 2002; Herzog and Caffee 2014).

Radiogenic ^{40}Ar

The K–Ar gas retention age of chondrites records the time since the meteorite experienced a thermal event causing leakage and provides an indication of the position of the meteorite within the parent body. Radiogenic ^{40}Ar concentrations can be combined with previously published K concentrations to determine the Ar retention age. Bevan *et al.* (1985) reported K concentrations of 1000 and 1200 ppm for High Possil and Strathmore, respectively. These values are slightly higher than the average for L-chondrites of 858 ppm (Kallemeyn *et al.* 1989). Using a K concentration of 1000 ± 200 ppm and the measured ^{40}Ar concentration (Table 2) the gas retention ages of the two High Possil splits are 3467 and 3935 Ma, and for Strathmore are 3389 and 3145 Ma (1σ uncertainties are 20% predicated on the uncertainty in the assumed K content). More precise K concentration data are required in order to distinguish whether the two meteorites have different gas retention ages. In any case, both meteorites have high gas retention ages that imply they were not close to the surface of the parental body when the asteroidal break-up event occurred at 470 Ma (e.g. Swindle and Kring 2008; Terfelt and Schmitz 2021).

Conclusions

The ^{21}Ne and ^{38}Ar CRE ages of the High Possil and Strathmore meteorites are both consistent with major peaks in the L6 chondrite age record that are indicative of impact events that led to the ejection of meteorites from the parent body (e.g. Wieler 2002; Herzog and Caffee 2014).

The low CRE age of Strathmore coincides with an old gas retention age. This is an exception to the general trend observed in L6 chondrites where the young CRE ages are associated with low gas retention ages that are indicative of relatively recent catastrophic disruption events on the L chondrite parent body. The high ^{40}Ar gas retention ages are an indication of the internal location within the parental body when the asteroidal break-up occurred.

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Author contributions **AC**: data curation (lead), formal analysis (lead), investigation (lead), methodology (lead), writing – original draft (lead); **FMS**: project administration (lead), supervision (lead), writing – review & editing (equal); **LDN**: formal analysis (supporting), methodology (supporting), writing – review & editing (equal); **JWF**: resources (supporting), writing – review & editing (supporting)

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Data availability All data generated or analysed during this study are included in this published article.

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