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Citation

Krietsch, Daniela; Busemann, Henner; Riebe, My E.I.; King, Ashley J.; M.O'D. Alexander, Conel and Maden, Colin (2021). Noble gases in CM carbonaceous chondrites: Effect of parent body aqueous and thermal alteration and cosmic ray exposure ages. *Geochimica et Cosmochimica Acta*, 310 pp. 240–280.

URL

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PII: S0016-7037(21)00331-8
DOI: <https://doi.org/10.1016/j.gca.2021.05.050>
Reference: GCA 12234

To appear in: *Geochimica et Cosmochimica Acta*

Received Date: 15 October 2020
Revised Date: 22 May 2021
Accepted Date: 25 May 2021

Please cite this article as: Krietsch, D., Busemann, H., Riebe, M.E.I., King, A.J., M.O'D. Alexander, C., Maden, C., Noble gases in CM carbonaceous chondrites: Effect of parent body aqueous and thermal alteration and cosmic ray exposure ages, *Geochimica et Cosmochimica Acta* (2021), doi: <https://doi.org/10.1016/j.gca.2021.05.050>

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Noble gases in CM carbonaceous chondrites: Effect of parent body aqueous and thermal alteration and cosmic ray exposure ages.

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Abstract

Like most primitive carbonaceous chondrites, the CM chondrites experienced varying degrees of asteroidal aqueous alteration, which may have overprinted pre-accretionary processing. Several aqueous alteration scales for CM chondrites (and other carbonaceous chondrites) have been proposed based on alteration-dependent changes in various petrological and geochemical characteristics. Given the possibility that the intensity of aqueous alteration could be recorded in the primordial noble gas compositions, we test potential correlations between petrologic, geochemical and noble gas characteristics in a detailed study on 39 CM chondrites, including some of the most pristine CM chondrites identified to date, and 4 CM-related carbonaceous chondrites. We mainly compare our noble gas data with the alteration schemes proposed by Alexander et al. (2013) and Howard et al. (2015). In addition to the noble gas analyses, we determined the phyllosilicate fractions of 17 of the CM chondrites using X-ray diffraction (XRD) to complement missing data points in the Howard alteration scheme. The influence of post-hydration thermal modification on noble gases in CM chondrites is investigated by comparison of heated and unheated samples. Cosmic-ray exposure (CRE) ages are determined for all samples in this study as well as for 26 more samples based on CM chondrite literature noble gas data.

The noble gas inventory in CM chondrites represents a mixture of cosmogenic, radiogenic, and abundant primordially trapped noble gases. Additionally, about 50 % of our CM bulk samples contain detectable solar wind (SW), which implies that many but not all CM chondrites are regolith breccias or carry SW from a pre-accretion irradiation phase. Aqueous alteration affects primordial noble gas abundances and elemental and isotopic compositions in CM chondrites. In particular, the process causes loss of an Ar-rich component, different in elemental and isotopic composition to known noble gas components. This component is lost during the early stages of aqueous alteration until complete degassing of its carrier material (possibly upon at least partial destruction) below petrologic type of ~1.5 on the Howard et al. (2015) scale. Likely, small amounts of Q gases were additionally released by

aqueous alteration. Strong thermal modification at >750 °C results in a significant additional loss of noble gases, whereas peak temperatures <500 °C likely have minor effects on the noble gas inventories of CM chondrites. Some of the described trends of noble gas contents and elemental and isotopic ratios in this study are observable across multiple carbonaceous chondrite groups, in particular also the CR chondrites. Hence, these carbonaceous chondrites may have started with similar initial noble gas inventories due to accretion of material from a common reservoir. The CRE ages of most of our CM samples fall within the typical range of <10 Myr previously observed for CM chondrites. A few CM chondrites, however, show longer CRE ages, with the longest CRE age of ~ 20 Myr determined for the SW-rich CM Allan Hills (ALH) 85013. The degree of aqueous and thermal alteration is variable among CM chondrites with similar CRE ages.

1 Introduction

Aqueous alteration played an important role in the evolution of the early Solar System. Studying this widespread process is crucial for understanding the early processing of Solar System materials and to decipher their unaltered compositions. During aqueous alteration, fluids interact with anhydrous materials at low temperatures (typically <120 °C, occasionally perhaps up to 275 °C; e.g., Nakamura (2005); Verdier-Paoletti et al. (2017)) within asteroidal parent bodies, and/or possibly in the solar nebula (Brearley, 2006). Early aqueous alteration between ~ 4.3 - 5.3 Myr after the formation of Calcium-aluminium-rich inclusions (CAI) was common on chondritic parent bodies and was likely driven by internal heating from radioactive decay of ^{26}Al after accretion (Fujiya et al., 2012; 2013; Jilly-Rehak et al., 2017; Jilly et al., 2014). Aqueous alteration results in various changes to the original materials, e.g., changes in mineralogy, texture, and elemental and isotopic compositions. Variable degrees of aqueous alteration within and between the different chondrite groups show that conditions such as time, pressure, temperature, and fluid/rock ratio varied between asteroid types as well as within individual asteroids. Like most primitive carbonaceous chondrites (CCs), the Mighei-type carbonaceous (CM) chondrites experienced varying degrees of aqueous alteration. In particular, the CMs show various petrologic types and well-populated sub-classifications in a large range of aqueous alteration. Understanding the range and sequence of aqueous alteration experienced by the CMs and other hydrous chondrites has been the focus of many researchers (e.g., Alexander et al., 2013; Browning et al., 1996; Howard et al., 2015; Rubin et al., 2007; Zolensky and McSween, 1988).

The first petrologic classification scheme for meteorites was proposed by Van Schmus and Wood (1967). In developing their classification scheme, a key intention of Van Schmus and Wood was that petrologic type should be independent of chemical group. In the current use of the Van Schmus and Wood scheme, the CMs span a petrologic range from mildly/moderately altered type 2 (low/intermediate degree of aqueous alteration indicated by abundant hydrated minerals, abundant fine-grained matrix, presence of chondrules, and Ni-bearing sulphides) to fully hydrated type 1 meteorites

(high degree of aqueous alteration, most primary minerals are replaced by secondary ones, absence of chondrules) (Zolensky et al., 1997).

Since the establishment of the Van Schmus and Wood classification scheme, several aqueous alteration scales have been proposed (Alexander et al., 2013; Browning et al., 1996; Howard et al., 2015; Rubin et al., 2007) that use different petrologic and geochemical characteristics to infer the degree of hydration, and that in some cases have abandoned the original 1-3 scale for alteration. Browning et al. (1996) proposed a relative alteration scale for CMs based on three parameters: (1) the *mineralogical alteration index* (MAI) that represents the changing matrix phyllosilicate compositions from cronstedtite (Fe-rich serpentine) to Mg-serpentine as Mg-rich chondrules became increasingly altered. The MAI ranges between 0.0 and 2.0 and increases with alteration. (2) The volume percent of isolated matrix silicates, which decreases with progressive alteration, and (3) the volume percent of chondrule alteration that increases with extent of alteration. Browning et al. (1996) also noted that H contents increased and ^{36}Ar contents decreased with their estimated order of alteration. Rubin et al. (2007) preferred a classification scheme with petrologic subtypes between 3.0 and 2.0 based on changes to various petrographic and mineralogical properties that are observable in thin sections. The Rubin et al. scheme requires that either there no longer be a petrologic type 1, or that petrologic classification of the chondrites no longer be independent of chemical group (e.g., if CIs are to be classified as type 1). Alexander et al. (2013) proposed an alteration scheme on a scale of 1.0 to 3.0 based on the degree of hydration (wt. % H in water and OH in hydrous minerals) determined from the bulk H and C contents, as well as noting systematic changes in bulk H and N isotopes that reflect variations in the relative abundances of H in water/OH and organics and modification of the organics. Finally, Howard et al. (2015) proposed a scale, also from 1.0 to 3.0, based on the normalized *phyllosilicate fraction* ($\text{PSF} = [\text{total abundance of phyllosilicates}]/[\text{total anhydrous silicate} + \text{total phyllosilicate abundance}]$) as determined by X-ray diffraction (XRD) of bulk meteorite powders. The increasing replacement of anhydrous minerals by phyllosilicates can also be seen in the infrared spectra of CM chondrites (Beck et al., 2014).

These classification schemes broadly organize the CMs in similar ways. However, there are several discrepancies between the different alteration scales. As aqueous alteration processes are highly complex, describing the degree of aqueous alteration with a single classification scheme is challenging. Deviations between the alteration scales can result from uncertainties related to the classification parameters used, terrestrial weathering, and/or isotopic anomalies, e.g., as observed for Bells (Alexander et al., 2013; Howard et al., 2015). In addition, CM chondrites are breccias and different lithologies within the same meteorite can have different degrees of aqueous alteration (Bischoff et al., 2017; Lentfort et al., 2020). According to these authors, the differences can be significant on a micrometre scale, e.g., sub-classifications ranging from 2.2-2.5 (on the Rubin et al. (2007) scale) can be observed in a single thin section of Nogoya. Also, diverse lithologies in Jbilet Winselwan were

altered to petrologic type $\leq 2.3-2.7$ on the Rubin et al. (2007) scale (King et al., 2019b). Hence, the characterization of a meteorite sample (independent of the classification scheme chosen) might not be representative for the whole meteorite and the ideal method for comparing and correlating various characteristics is to perform different analyses on the very same aliquot.

Browning et al. (1996) suggested that the intensity of aqueous alteration can be deduced from the primordial noble gas contents in CMs. They observed a negative correlation between the bulk ^{36}Ar content (data from compilation by Schultz and Kruse (1989)) and the MAI of eight CMs. Based on this finding they proposed: (1) a similar unaltered primordial noble gas composition in all CMs, (2) a loss of primordial noble gases with increasing aqueous alteration (^{84}Kr and ^{132}Xe were expected to produce similar trends as ^{36}Ar), and (3) only a minor effect of sample heterogeneity as systematic variations between the CMs are still evident. Recently, it has been observed that the degrees of aqueous alteration of CR chondrites also vary with their ^{36}Ar concentration (Busemann et al., 2019; 2021).

Some CMs experienced additional thermal modification after aqueous alteration, resulting in dehydration of the phyllosilicates formed during aqueous alteration (e.g., Nakamura, 2005; Tonui et al., 2014). Evidence for thermal modification that occurred before aqueous alteration is, to our knowledge, generally yet lacking, although recently in situ alkali-halogen metasomatism (high temperature water-rock interaction) prior to lower temperature aqueous alteration has been proposed to explain the presence of sodalite in CM Miller Range (MIL) 01075 (paired with MIL 01072; Lee et al., 2019a). Nakamura (2005) classified heated hydrous carbonaceous chondrites based on their matrix mineralogy and proposed four different heating stages: stage I $<300\text{ }^\circ\text{C}$, stage II $300-500\text{ }^\circ\text{C}$, stage III $500-750\text{ }^\circ\text{C}$, and stage IV $>750\text{ }^\circ\text{C}$. The source and exact timing of the heating, however, remain debated. Possible heat sources are internal radiogenic heating due to the decay of ^{26}Al , impact heating, or heating due to solar radiation (e.g., Nakamura, 2005). The heating must have occurred after the final stage of hydration in order for the phyllosilicates to be dehydrated. Recently, Amsellem et al. (2020) modelled the timing of the heating of altered chondrites using Rb-Sr chronology and applied this model to five CMs. They found these meteorites were heated during the two last Ga, which excludes radioactive decay of ^{26}Al as possible heat source and favours heating due to collisions. Based on the structure of insoluble organic matter (IOM) in one heated CM, Cody et al. (2008) also favoured short duration heating, which is further supported by Nakato et al. (2008) based on the diffusion time required to achieve Fe-Mg zoning in olivine in (heated) CM chondrites. The effect of thermal modification is visible in XRD patterns caused by the lower abundance and the disordered nature of phyllosilicates in heated meteorites (King et al., 2015a; 2019b; Nakamura, 2005). Quirico et al. (2018) proposed a C-based classification scheme of heated C2 chondrites as the composition and structure of IOM records the extent of thermal heating in these meteorites. Alexander et al. (2013) observed that heated meteorites generally do not follow the same trends as unheated samples with respect to their bulk H, C and N abundances and isotopic

compositions. It remains to be determined if differences caused by thermal modification are also traceable in the noble gas compositions of CMs.

In this study, we present noble gas data (He-Xe) from 40 CM chondrites and 3 closely related (see section 2.1) ungrouped CCs that experienced variable degrees of aqueous and thermal alteration to produce a comprehensive data set that spans the full range of alteration conditions experienced by CMs. We investigate if the effects of aqueous alteration on primordial noble gases, suggested by previous studies based on much smaller data sets, hold true for the full range of aqueous alteration and perhaps can be used to determine the degree of aqueous alteration. We mainly compare our noble gas data with the alteration schemes proposed by Alexander et al. (2013) and Howard et al. (2015) as most of the samples in this study were previously analysed by these authors: Noble gas analysis could be performed on small aliquots of the same homogenised meteoritic powders of ~1 g that were used for XRD and bulk H, C and N analyses. To complement missing data points in the Howard alteration scheme, we determined the PSF of 17 CMs for which data was previously unavailable, using XRD. When possible, XRD and noble gas analyses were performed on the same aliquot to avoid heterogeneity effects. Some of the most pristine CMs, e.g., Paris (Bekaert et al., 2019; Hewins et al., 2014) are included in our study, providing additional information about the initial composition of primitive asteroids. Although primordial noble gas components identified to date are typically associated with HCl/HF-resistant carrier phases, such as organics and presolar diamonds/SiC, potential changes in noble gas composition with increasing aqueous alteration may be related to other carriers, e.g., the acid-soluble mineral phases of a meteorite. The influence of thermal alteration on primordial noble gases is investigated by comparison of unheated and heated meteorites. Cosmic ray exposure (CRE) ages are determined for all samples to allow a link to collisional ejection events and potential common source areas in the parent body(ies). We also test whether there is a correlation between CRE ages and petrologic types as suggested by several authors (King et al., 2020; Takenouchi et al., 2013; Zolensky et al., 2017; 2021), and investigate if there are systematic differences in the CRE ages of heated and unheated CMs. Our findings will help to further constrain the conditions prevailing during aqueous alteration, the modification of the noble gas carrier phases and the CM parent body(ies) as a whole.

2 Methods

2.1 Samples

We analysed the noble gases in 50 bulk samples of CCs: 40 CM chondrites (in 46 samples) and three ungrouped carbonaceous chondrites (including two aliquots of Bells; Table 1). One of the meteorites, Meteorite Hills (MET) 00432, classified as a CM, is associated with Tagish Lake (C2-ung; Nakamura et al., 2013). Each of the non-CMs included in this study is related to the CMs: Bells was initially classified as a CM2 but has been reclassified as a C2-ung (Meteoritical Bulletin Database). Bells is often described in the literature as an anomalous CM as its bulk oxygen isotopic and elemental

compositions, and IOM structure are CM-like (Alexander et al., 2007; Mittlefehldt, 2002). However, it is also a heavily brecciated meteorite that shows anomalies in N isotopes and an unusual alteration mineralogy compared to other CMs (e.g., Alexander et al., 2013; Brearley, 1995; Mittlefehldt, 2002). Elephant Moraine (EET) 83355 has been reported as a heated CM by Alexander et al. (2013) and was recently described as likely related to CM or CO chondrites, i.e., it may be a heated CM or CO (Torrano et al., 2020). Finally, NWA 5958 has been described as a weakly altered CM-related C-ung by Jacquet et al. (2016). Note that we analysed more than one sample of some CCs because (i) we received several samples that could be different lithologies (Paris, Mukundpura, NWA 10574), (ii) stones from the same shower have different terrestrial histories (Bells), or (iii) for analytical reasons (Lewis Cliff (LEW) 85312, NWA 10827, see below). We received two samples each of Paris and Mukundpura without any information and noticeable macro- and microscopic differences. The two samples of NWA 10574 were different in colour (see section 3.2.5). The sample set comprises falls and (mainly Antarctic) finds, spanning a petrologic range from mildly altered type 2 to fully hydrated type 1 samples according to the Van Schmus and Wood (1967) scale. Terrestrial weathering ranges from pristine to heavily modified. All details and references are summarized in Table 1. Also given in Table 1 are the petrologic types of samples that were previously analysed by Alexander et al. (2013) for their bulk H, C, and N elemental abundances and isotopic compositions, by Rubin et al. (2007) for their mineralogy, and/or by Howard et al. (2015) for their PSF.

2.2 Noble gas mass spectrometry (NGMS)

We analysed ~20 mg samples of each meteorite (see Table 2 for exceptions), which were mostly taken from larger, homogenised powders of ~50 mg to ~1 g, for their noble gas (He to Xe) abundances and isotopes, following the methods described by Riebe et al. (2017c). The 50 samples were analysed over a period of about three years as part of six separate furnace loads. Each sample (powder or fragments, see Table 2) was weighed and wrapped in commercial Al foil, and then pre-heated to 110 °C in ultra-high vacuum for several days to remove absorbed atmospheric noble gases. For the noble gas analyses, the samples were heated to ~1700 °C in a Mo crucible in one step for about 30 minutes. Reactive gases were subsequently removed by chemical reactions in various getters (see Riebe et al., 2017c). The noble gases were cryogenically separated into three fractions (He and Ne, Ar, and Kr and Xe) utilizing their different boiling points. Typically, we measured 3 % of the total Ar in the Kr-Xe phase and 1 % of the total Kr in the Ar phase, which was monitored and corrected for, whereas Xe in the Ar phase was generally negligible. The three fractions were sequentially analysed using the ETH Zurich in-house-built magnetic sector-field noble gas mass spectrometer (“Albatros”). This mass spectrometer is equipped with a Baur-Signer ion source (Baur, 1980), an electron multiplier operated in counting mode (up to ~1 Mcps), and a Faraday cup for measurement of ion beam currents typically larger than 1.6×10^{-14} A (corresponding to 100 kcps). If the $^{36,38}\text{Ar}$ amounts were too high to be detected fully with the electron multiplier in the main measurement, we performed and measured an additional Ar dilution

step. In particular, ^{38}Ar cannot properly be measured with the Faraday cup on this instrument due to interference of scattered particles from the ^{36}Ar beam hitting a component of the vacuum chamber (unfortunate beam separation between ^{36}Ar and ^{38}Ar). During the course of this study, the amount of background ^{40}Ar in the system increased due to an accident that was independent of this project, which resulted in i) variable and more sizable ^{40}Ar blank corrections and ii) variable and more sizable precisions on ^{40}Ar amounts than are normally observed. To minimize the $^{40}\text{Ar}^{++}$ that interferes with ^{20}Ne , we switched to a lower electron energy for the last two runs, i.e., 45 eV instead of 100 eV used for the previous ones. Typical electron-impact ionisation cross section ratios of double to single ionisation are $\sigma(^{40}\text{Ar}^{++})/\sigma(^{40}\text{Ar}^+)_{45\text{eV}} = 0.0012 \pm 0.0006$ and $\sigma(^{40}\text{Ar}^{++})/\sigma(^{40}\text{Ar}^+)_{100\text{eV}} = 0.072 \pm 0.018$, respectively (Busemann, 1998). With the reduction of the electron energy, we could reduce interference of $^{40}\text{Ar}^{++}$ on the measured ^{20}Ne to negligible levels.

In addition to the main sample measurements, we measured re-extractions for all samples at a slightly elevated temperature (nominal ~ 1750 °C) to verify full gas extraction. The re-extractions yielded negligible gas amounts for all samples in all elements, except Ar. For Ar, the gases measured in the re-extractions (Q-like composition) were added to the gas amounts in the main extraction step, if the former exceeded the uncertainty and ~ 3 % of the Ar amount in the main step (marked with * in Table 3).

Blanks were measured frequently (every three to four samples) by analysing empty Al foil following the same procedure as for the sample measurements. Blank corrections amounted to <1.7 % for He, <4.2 % for Ne, <1.9 % for $^{36,38}\text{Ar}$, <43 % for ^{40}Ar , <2.3 % for Kr, and <1.4 % for Xe. For some samples blank corrections were significantly higher, i.e., for the two NWA 10574 samples and LEW 85312 C due to low sample masses, and the CM chondrite Pecora Escarpment (PCA) 02010 due to its gas-poor composition. Values in percentage of the respective sample gas amounts as well as typical absolute blank values are given in the respective table captions (Table 2 and Table 4). Noble gas standard aliquots with known amounts and isotopic compositions were measured frequently to determine the mass discrimination and sensitivity of the instrument and, hence, to allow the conversion of ion currents into absolute gas amounts (Heber et al., 2009; Riebe et al., 2017c).

2.3 Deconvolution of trapped and cosmogenic components

We differentiate between trapped (mostly primordial components, but also solar and atmospheric gases incorporated into the material) and in situ produced noble gases (cosmogenic, radiogenic, and fissionogenic). The samples show a wide range of Ne ratios resulting from variable relative abundances of trapped (tr) and cosmogenic (cos) Ne. Trapped Ne that is typically mostly carried by presolar grains (i.e., the primordially trapped noble gases such as HL, Ne-E, and Q; see section 3.2 and, e.g., Ott, 2014 for details) tends to dominate the Ne inventory in these types of meteorites (e.g., Eugster et al., 1998; Mazor et al., 1970; Scherer and Schultz, 2000), but cosmogenic Ne is resolvable in most of the samples. A two-component deconvolution was performed to determine the $^{21}\text{Ne}_{\text{cos}}$ concentration (Table 2). We

used typical Ne_{cos} endmember ranges ($(^{20}\text{Ne}/^{22}\text{Ne})_{\text{cos}} = 0.819 \pm 0.115$ and $(^{21}\text{Ne}/^{22}\text{Ne})_{\text{cos}} = 0.876 \pm 0.076$; Wieler, 2002) and variable trapped endmember compositions depending on the meteorite's position in the Ne-three-isotope diagram (Fig. 1). We distinguish three different trapped endmember groups: (1) for meteorites whose compositions plot in the area defined by cosmogenic Ne, Ne-Q, and solar wind (SW)-Ne (Heber et al., 2012; orange area), we assumed a trapped endmember covering Q and SW ($(^{20}\text{Ne}/^{22}\text{Ne})_{\text{tr}} = 11.695 \pm 1.305$ and $(^{21}\text{Ne}/^{22}\text{Ne})_{\text{tr}} = 0.03115 \pm 0.00175$); (2) for meteorites plotting within the triangle formed by cosmogenic Ne, Ne-Q, and Ne-HL (grey area), we used a ratio covering Q and HL composition (Busemann et al., 2000; Huss and Lewis, 1994; $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{tr}} = 9.445 \pm 0.945$ and $(^{21}\text{Ne}/^{22}\text{Ne})_{\text{tr}} = 0.0327 \pm 0.0033$); (3) several CCs plot on a mixing line between cosmogenic Ne and Ne with $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{tr}}$ that is slightly below that of Ne-HL ($(^{20}\text{Ne}/^{22}\text{Ne})_{\text{HL}} \sim 8.5$; Huss and Lewis, 1994; purple area). For these meteorites, we used the intersection of the linear regression through these data points and Ne_{cos} and the line through Ne-E and Ne-HL (Amari et al., 1995; Huss and Lewis, 1994; $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{tr}} = 7.98 \pm 1.00$ and $(^{21}\text{Ne}/^{22}\text{Ne})_{\text{tr}} = 0.0338 \pm 0.0042$) to define the trapped endmember. Note that these three trapped endmember ranges were used *only* to determine $^{21}\text{Ne}_{\text{cos}}$ in each sample and its uncertainty, which covers all possible combinations of the selected trapped and cosmogenic Ne ranges. We used these concentrations and the typical Ne_{cos} endmember ratios given above to calculate $^{22,20}\text{Ne}_{\text{cos}}$ and subtracted those values from the measured concentrations to determine the $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios that are hence not constrained a priori any further (Table 2). The low $^3\text{He}/^4\text{He}$ ratios ($\leq 30 \times 10^{-4}$ for all CCs measured in this work, except for EET 83355) and unknown abundances of radiogenic ^4He prevent us from a decomposition of the measured He into cosmogenic and trapped (and radiogenic) abundances. The same holds true for Ar, where the $^{36}\text{Ar}/^{38}\text{Ar}$ ratios of all samples are too close to the trapped components to resolve cosmogenic Ar.

2.4 Correction for air contamination in Xenon

For many samples, additionally trapped air Xe (Basford et al., 1973) was discernible and we had to correct the measured ^{132}Xe concentrations ($^{132}\text{Xe}_{\text{corr}}$ in Table 4, also see section 3.2.3). For the correction, we considered the $^{128,130,131}\text{Xe}/^{132}\text{Xe}$ ratios as their deviations from the expected Q-Xe ratios are most likely only due to air contamination. Other Xe isotopes might be affected by HL, ^{129}I -derived ^{129}Xe , and/or Xe_{cos} or fission Xe. We performed a two component deconvolution between Q and air (Basford et al., 1973; Busemann et al., 2000) using each of these three measured $^x\text{Xe}/^{132}\text{Xe}$ ratios to determine the relative amount of $^{132}\text{Xe}_{\text{air}}$ in all samples. The average of these three values obtained for the fraction of $^{132}\text{Xe}_{\text{air}}$, relative to the measured ^{132}Xe , was used to correct the measured ^{132}Xe concentration for all samples in which its 2σ uncertainty did not exceed the correction.

2.5 Production rates and CRE ages

The production rates for $^{21}\text{Ne}_{\text{cos}}$ used for the calculation of CRE ages (Table 5) were determined using the models for CCs by Leya and Masarik (2009) and, if available, the bulk chemical composition of the

individual CC (Table A 1, references given in Table 5). In addition (to check for consistency), and for meteorites where the chemistry was not given in the literature, we used the average elemental abundances in CMs given by Alexander (2019). We assumed pre-atmospheric meteoroid radii of 10 cm to 65 cm, and give ranges for the production rates that cover the full range of shielding depths. Whereas the lowest possible meteoroid radius of 10 cm is predefined in the model, constraining the upper limit of allowed meteoroid radii is challenging. Since trapped Ne is abundant in CMs, we cannot precisely determine the $(^{22}\text{Ne}/^{21}\text{Ne})_{\text{cos}}$ ratio that is commonly used as a shielding indicator. Instead, we took the largest mass found amongst the CMs in this study as a starting point (Murchison, 100 kg) and assumed that the recovered mass represents 50 % of the mass that reached the Earth's surface. We roughly estimated the original mass of the meteoroid based on an average value for ablation mass loss of ordinary chondrites during atmospheric entry determined by Alexeev (2003). This value of ~91.5 % ablation loss is of the same order as those determined by other authors for various kinds of meteorites (e.g., Bhandari et al., 1980; Zeng et al., 2018). Using the average bulk density for CMs of 2.2 g cm^{-3} (Macke et al., 2011) and assuming a spherical shape for the meteoroid, we calculated an upper limit of ~65 cm for the pre-atmospheric radius.

2.6 XRD analysis

We analysed seventeen of the meteoritic samples (Table 6) for their mineralogy by position sensitive detector (PSD) XRD analysis at the Natural History Museum (NHM), London, to complement the data base of aqueous and thermal alteration degrees based on PSF according to the Howard et al. (2015) scheme. Note that for most samples the degree of aqueous alteration and thermal modification can be disentangled, i.e., the degree of aqueous alteration prior to heating can be estimated (King et al., 2015a; 2019b; 2021). For determining the pre-heating degree of aqueous alteration of samples heated to <500 °C, the PSF is used as normal but the total phyllosilicate amount represents the sum of hydrated and dehydrated phyllosilicates. For samples heated to >500 °C up to ~1000 °C, the determination of the alteration degree is more challenging. Nevertheless, the amounts of primary (leftover after hydration) and secondary (formed during heating) olivine can be estimated and used to constrain the alteration history. The bulk mineralogy and the derived PSF in vol. % of samples analysed here are given in Table 6. Uncertainties are typically <0.5 vol% for crystalline phases and <1 vol% for non-crystalline phases, resulting in PSF errors of ~0.01 – 0.02 (for details see King et al., 2015a; 2021). We used an Enraf-Nonius PDS 120 X-ray diffractometer equipped with an INEL curved 120° PSD. Samples were powdered to a grain size of <50 µm and ~50 mg of each sample was loaded into Al sample holders. XRD patterns were collected using Cu $K\alpha_1$ radiation for ~16 hours to achieve good signal-to-noise ratios. Standards of typical minerals found in hydrated meteorites were measured under the same analytical conditions as the meteorites for ~30 min. The XRD patterns of the standards were used to quantify the mineral abundances in the meteorites using a profile-stripping technique. The diffraction pattern of the mineral standard is thereby scaled to the measurement time of the sample and then reduced

in intensity by a factor until it matches the intensity of the respective peak in the sample diffraction pattern. This is repeated for each mineral standard. In the end, the sum of all fit factors should be one and subtraction of the mineral standards from the meteorite patterns should produce a residual with zero counts. The final mineral abundances in vol. % can be derived from the fit factors of the mineral standards. For full details of the XRD methods used see King et al. (2015a).

3 Results

3.1 XRD data and effects of heating

The PSD-XRD patterns of Banten, Dominion Range (DOM) 08003, EET 96006, EET 96016, LEW 85312, Maribo and Nogoya are typical of CM chondrites (e.g., Howard et al., 2015). Diffraction peaks at $\sim 12^\circ$ and $\sim 25^\circ$, and broader features at $\sim 19^\circ$ and $\sim 61^\circ$, are attributed to relatively crystalline Fe-rich serpentine (cronstedtite) and fine-grained, poorly crystalline Mg-Fe serpentine, respectively (e.g., Howard et al., 2015; King et al., 2017). Other crystalline phases identified in the patterns (not all phases are present in every meteorite) include gypsum, olivine, enstatite, magnetite, calcite, tochilinite, Fe-sulphides (pyrrhotite and pentlandite) and metal (see Fig. 2). The abundances of phyllosilicates (60–87 vol. %) and anhydrous silicates (olivine and enstatite, 8–35 vol. %) in these meteorites are consistent with the range reported in other CM chondrites (e.g., Howard et al., 2015; King et al., 2017) and result in PSFs of 0.64–0.91 corresponding to petrologic types of 1.2–1.8. All other phases are present at < 5 vol. % (Table 6). We also note that the abundances for Nogoya are in agreement with two separate aliquots of this meteorite analysed using PSD-XRD by Howard et al. (2009). All three XRD analyses were performed on samples that were aliquots from the same meteoritic powder (~ 1 g in total) allocated from C. Alexander and also used for analysis in Alexander et al. (2012; 2013). This demonstrates that ~ 50 mg aliquots are representative of the homogenized meteorite powders and that the XRD analyses are reproducible.

The PSD-XRD patterns for the two Paris lithologies were similar to each other and consistent with other CM chondrites. However, Paris A contains more phyllosilicates (70 vol. %) and fewer anhydrous silicates (26 vol. %) than Paris B (62 and 32 vol. %, respectively). In addition, tochilinite was identified in Paris A but not Paris B; we are unable to determine the abundance of tochilinite due to the lack of a suitable standard, but it is likely removed during the profile-stripping (see section 2.6) of Fe-serpentine and present at < 5 vol. % (e.g., King et al., 2017). PSD-XRD patterns for the Mukundpura lithologies were also consistent with CM chondrites, although Mukundpura A is more altered, containing ~ 83 vol. % phyllosilicate and ~ 9 vol. % anhydrous silicate (PSF = 0.90, petrologic type = 1.2) compared to ~ 74 vol. % phyllosilicate and ~ 20 vol. % anhydrous silicate in Mukundpura B (PSF = 0.79, petrologic type = 1.5).

The diffraction patterns of Allan Hills (ALH) 84033, MIL 05152 and NWA 10827 contained peaks from gypsum, olivine, enstatite, magnetite, calcite, Fe-sulphides and metal. However, unlike the other analysed samples we did not observe phyllosilicate diffraction peaks at $\sim 12^\circ$, $\sim 25^\circ$, $\sim 19^\circ$ and $\sim 61^\circ$. The absence of these peaks is typical of CM chondrites that experienced short-lived, post-hydration thermal modification at temperatures $>300^\circ\text{C}$ (e.g., King et al., 2019a; Nakamura, 2005). Dehydration and dehydroxylation cause the loss of interlayer H_2O and structural $-\text{OH}$ resulting in the collapse of the phyllosilicate structure to form a highly disordered phase that does not produce coherent diffraction. For these meteorites, we found that following the subtraction of the crystalline phases from the diffraction pattern we were left with a residual pattern that was in good agreement with the overall shape and intensity of our phyllosilicate standards (excluding the diffraction peaks). We therefore attributed the remaining counts in the residual patterns to a highly disordered, dehydrated phase with remaining phyllosilicate structure present in ALH 84033, MIL 05152 and NWA 10827 at $\sim 57\text{--}80$ vol. %.

At peak temperatures of $>500^\circ\text{C}$, dehydrated phyllosilicates start to recrystallize back into olivine. If the duration of heating was short, as was the case for CM chondrites, this secondary olivine is fine-grained and poorly crystalline resulting in broad peaks in diffraction patterns (King et al., 2015a; Nakamura, 2005). We did not observe such peaks in the PSD-XRD patterns of ALH 84033, MIL 05152 and NWA 10827, allowing us to constrain their peak metamorphic temperatures at $300\text{--}500^\circ\text{C}$, i.e. stage II in the Nakamura (2005) scheme. In contrast, we identified abundant (~ 53 vol. %) secondary olivine in NWA 11024, but found no evidence for a highly disordered, dehydrated “phyllosilicate” suggesting that it experienced higher peak temperatures, likely $>750^\circ\text{C}$, i.e. stage IV in the Nakamura (2005) scheme. NWA 11024 also contains unaltered primary olivine (sharp diffraction peaks, ~ 21 vol. %), so if we assume that all the secondary olivine was originally phyllosilicate then we can infer that it had a PSF of 0.62 (petrologic type = 1.8) prior to the heating event.

The PSD-XRD patterns of Graves Nunataks (GRA) 98005 and MET 01072 differed from the other samples in having peaks at $\sim 12^\circ$ and $\sim 25^\circ$ from Fe-rich serpentine that, although present, were significantly lower in intensity than those typically seen in CM chondrites. The intensity of these peaks is influenced by preferred crystal alignments, but all the samples were of similar grain size and packed into the sample holders using the same method. Instead, we suggest that the lower intensity of the $\sim 12^\circ$ and $\sim 25^\circ$ peaks for GRA 98005 and MET 01072 reflects partial dehydration of the Fe-rich serpentines, which start to lose $-\text{OH}$ at lower temperatures than Mg-bearing phyllosilicates (King et al., 2015b). As we do not observe a complete collapse of the Fe-serpentine structure in GRA 98005 and MET 01072, the peak metamorphic temperature likely was $<300^\circ\text{C}$.

3.2 Noble gas data

In the following, the noble gas data of all our CCs are described first for each element separately. Also discussed is the elemental composition of the CCs. In addition to cosmogenic (used to determine

exposure ages) and radiogenic noble gases, we discuss the presence (or absence) of specific trapped noble gas components. Amongst the trapped components there are the most dominant primordial noble gases, some of which are carried by presolar grains. The HL component resides in presolar nanodiamonds (Huss and Lewis, 1994), whereas Ne-E, essentially pure ^{22}Ne , is carried by presolar graphite and/or SiC (Lewis et al., 1994; Amari et al., 1995). A less well constrained carrier is the so called “phase Q”, a likely carbonaceous phase and carrier of the Q gases, dominating the heavier noble gases Ar-Xe (e.g., Busemann et al., 2000; and references therein). We are also interested in trapped solar-type noble gases that were implanted by solar wind irradiation, typically while the samples were part of a regolith, or, perhaps, by processes operating in the nebula. Solar wind only penetrates the top 100 nm of rocky material (Grimberg et al., 2006).

3.2.1 Neon and Helium

Neon concentrations, including $^{20}\text{Ne}_{\text{tr}}$ and $^{21}\text{Ne}_{\text{cos}}$, and isotopic ratios are given in Table 2. The Ne isotopic ratios are highly variable in all samples (Fig. 1), an effect of varying *relative* abundances of trapped and cosmogenic Ne. Nevertheless, trapped Ne is predominant in all samples; >85 % of the measured ^{20}Ne concentration is trapped, with the exception of C-ung EET 83355 (~60 %).

The trapped Ne is a mixture of typically dominant HL, Ne-E, and Q. Some CCs clearly carry SW in addition (Fig. 1, orange area “1”). We have indicated these samples with an “X” in Table 1. However, many samples plot on a mixing line between cosmogenic Ne and Ne that is slightly below HL, suggesting that they contain negligible SW-Ne. This is also visible in Fig. 3: here, all samples that plot below the HL-cosmogenic mixing line in Fig. 1 (purple area “3”) consistently show relatively high $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios of ~0.13. This ratio is slightly higher than the value for pure HL of ~0.118 (Huss and Lewis (1994)), and marginally trending towards the Ne-E composition with $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{E}} > 10$ (Lewis et al., 1994; Amari et al., 1995). This implies a roughly constant mixing ratio of presolar diamonds (carrying HL) and graphite/SiC (carriers of Ne-E) in these samples. Figure 4 shows the $^{20}\text{Ne}_{\text{tr}}$ and ^4He concentrations of all CCs in this study. The concentrations of $^{20}\text{Ne}_{\text{tr}}$ and ^4He in the samples without clear evidence for SW (purple data points) fall in narrow ranges of ~6-15 x 10^{-8} cm³ STP/g and ~1950-4325 x 10^{-8} cm³ STP/g, respectively, forming the “baselines” (light blue ranges) in Fig. 4.

All CCs with clear SW contributions according to Fig. 1 (orange area “1”) have significantly lower $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios and consistently higher amounts of $^{20}\text{Ne}_{\text{tr}}$ (lower $1/^{20}\text{Ne}_{\text{tr}}$) and ^4He than the samples without SW (Fig. 3 and 4, orange data points), including the heated CM chondrite EET 96029 (Alexander et al., 2012; 2013; Lee et al., 2016).

Samples that plot with intermediate compositions in the triangle constrained by Q-, HL-, and cosmogenic Ne in Fig. 1 (grey area “2”) have lower $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios than HL composition. This could be due to an addition of Q, SW, or both, to HL as these components have lower $^{22}\text{Ne}/^{20}\text{Ne}$ ratios than HL. Another option is that these samples contain an abundant, so far unidentified, Ne component with

a $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{tr}}$ ratio that is higher than 8.5 and that resides in the acid-soluble phases of bulk CCs (Krietsch et al., 2019). The $^{20}\text{Ne}_{\text{tr}}$ and ^4He concentrations of these samples with intermediate Ne compositions typically are above the baseline concentrations constrained by samples without evidence for SW (Fig. 4, grey data points). One of the heated samples, PCA 02010, is characterized by remarkably low $^{20}\text{Ne}_{\text{tr}}$ and ^4He concentrations and, hence, is separated from all other samples in Fig. 3 and Fig. 4. The concentrations in PCA 02010 are, in fact, remarkably low in all noble gas elements compared to all other meteorites in this study.

The He concentrations and isotopic compositions of all samples are given in Table 2. The ^4He concentration is highly variable amongst the CCs measured here ($\sim 70\text{-}790000 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$), but within the range previously determined for CMs (Haack et al., 2012; Hewins et al., 2014; Nakamura, 2006; Okazaki and Nagao, 2017; Schultz and Franke, 2004). Compared to the typical cosmogenic value ($(^4\text{He}/^3\text{He})_{\text{cos}} \sim 5.65$; Wieler, 2002), the $^3\text{He}/^4\text{He}$ ratios are low for all the measured CCs, i.e., $\leq 30 \times 10^{-4}$, except for C-ung EET 83355 that has a $^3\text{He}/^4\text{He}$ ratio of $\sim 189 \times 10^{-4}$. Thus, He in all the samples is a mixture of the dominant trapped and some cosmogenic He with additional radiogenic ^4He of unknown concentration. For comparison, a typical CM (U ~ 10 ppb, Th ~ 39 ppb; Alexander, 2019) would accumulate $1755 \times 10^{-8} \text{ cm}^3 \text{ STP/g } ^4\text{He}_{\text{rad}}$ in 4.55 Ga. The trapped He could be of Q/HL composition ($^3\text{He}/^4\text{He} = \sim 1.2\text{-}1.7 \times 10^{-4}$; Busemann et al., 2000; Huss and Lewis, 1994). A significant number of the samples probably also contain SW-He ($(^3\text{He}/^4\text{He})_{\text{SW}} = (4.64 \pm 0.09) \times 10^{-4}$; Heber et al., 2009) based on their Ne isotopic compositions (see above) that are more diagnostic for distinguishing between the different components.

3.2.2 Argon

Table 3 summarizes the Ar concentrations and isotopic compositions in the measured samples. The $^{40}\text{Ar}/^{36}\text{Ar}$ ratios are between 0.8 and 27, reflecting the dominance of primordial trapped Ar. The small spread towards higher $^{40}\text{Ar}/^{36}\text{Ar}$ ratios up to 27 may result from radiogenic ^{40}Ar or, perhaps, a small contribution of Ar-air ($(^{40}\text{Ar}/^{36}\text{Ar})_{\text{air}} = 295.5$; Steiger and Jäger, 1977). Even if we assume all ^{40}Ar to be air, $\leq 9\%$ of the measured ^{36}Ar would be air. Furthermore, the measured ^{40}Ar concentrations ($\leq 1265 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$) are generally lower than the concentrations of $\sim 1645\text{-}4640 \times 10^{-8} \text{ cm}^3 \text{ STP/g } ^{40}\text{Ar}$ we would expect to be produced by radioactive decay from K (206-581 ppm, see Table 1) within 4.55 Ga, which makes significant Ar-air contributions even less likely. Nominal K-Ar gas retention ages for the CCs in this study where the K concentrations are given (noble gases and K measurements performed on different aliquots; Table 1) are highly variable between 0.7-3.4 Ga. All samples have $^{36}\text{Ar}/^{38}\text{Ar}$ ratios between 5.2 and 5.4, indicating abundant contributions from Ar-Q ($(^{36}\text{Ar}/^{38}\text{Ar})_{\text{Q}} = 5.34 \pm 0.02$; Busemann et al., 2000) and possibly minor Ar-HL ($(^{36}\text{Ar}/^{38}\text{Ar})_{\text{HL}} = 4.41 \pm 0.06$; Huss and Lewis, 1994). Cosmogenic Ar is negligible in all samples.

3.2.3 Krypton and Xenon

The Kr data for our samples are given in Table 3. Krypton in our analysed CCs has a Q-like composition. The $^{86}\text{Kr}/^{84}\text{Kr}$ ratios determined for some of the bulk samples (e.g., LaPaz Ice Field (LAP) 02277, ALH 84033, EET 96016, and perhaps NWA 10574 B) are slightly elevated compared to those of Kr-Q/air which could be due to small amounts of Kr-HL. Krypton is lighter than Xe and, hence, less easily adsorbed onto grain surfaces, however, it is more abundant in the terrestrial atmosphere. For this reason, some samples, especially those with the highest Xe-air contents, might have incorporated some atmospheric Kr.

All Xe results are summarized in Table 4. The Xe in all samples is, as expected, dominated by the Q component. A few meteorites show significant contributions of Xe-air, however. The extent of air contamination in the CCs is illustrated in Fig. 5, which shows the $^x\text{Xe}/^{132}\text{Xe}$ ratios, normalized to Q composition, for all Xe isotopes. About 50 % of the meteorites' Xe compositions scatter around Q ($\equiv 1$). However, the other 50 % of the CCs show a clear air contribution. The ten samples most affected by air contamination in Xe are: MET 00432 (~80 % of the measured ^{132}Xe is air), MIL 07689 (~60 %), Scott Glacier (SCO) 06043 (~55 %), PCA 91008 (~50 %), GRA 98005 (~45 %), EET 96029 (~40 %), LEW 85312 A (~40 %), MIL 05152 (~40 %), EET 83355 (~40 %), and Lonewolf Nunataks (LON) 94102 (~35 %). The extent of Xe-air contamination correlates with the terrestrial weathering grade, as is clearly shown for $^{128}\text{Xe}/^{132}\text{Xe}$ in Fig. 6. The samples most affected by air are labelled in Fig. 6.

In some samples (e.g., NWA 10574 B, NWA 5958, LAP 02277), we observe slightly elevated $^{136}\text{Xe}/^{132}\text{Xe}$ ratios relative to Xe-Q/air which could indicate small contributions from Xe-HL (Table 4, Fig. 7). Indeed, their patterns slightly tend towards HL composition (high $^{124,126,134,136}\text{Xe}/^{132}\text{Xe}$ relative to Q) in Fig. 5 (most pronounced in NWA 5958). Except for NWA 10574 B and LAP 02277, there is no overlap of samples that show indications for Kr- and Xe-HL. The $^{129}\text{Xe}/^{132}\text{Xe}$ ratios in about half of the samples are higher than in the components Q, air and HL, showing these samples contain some excess ^{129}I -derived Xe (Fig. 7). A correction of Xe-air will increase the number of meteorites having a ^{129}Xe excess. The cosmogenic contributions are negligible in all the meteorites with respect to both Kr and Xe. Based on $^{21}\text{Ne}_{\text{cos}}$ and the production rate equations by Eugster (1988) for CM chondrites $^{126}\text{Xe}_{\text{cos}}$ amounts to <1 % of the measured concentration in all samples. Nevertheless, a few meteorites show elevated $^{126}\text{Xe}/^{132}\text{Xe}$ (e.g., CMs NWA 10574 B, PCA 02010 (very little Xe_{tr}) and Murchison, C-ung NWA 5958; Fig. 5). Perhaps there is some production of monoisotopic excess of ^{126}Xe in Te in these samples as observed earlier (Maddox, 1990; Begemann and Mathew, 1996; Mathew, 2003). We use ^{132}Xe concentrations corrected for air ($^{132}\text{Xe}_{\text{corr}}$, Table 4) in all the following plots and related discussions. For some of the samples, the measured ^{132}Xe concentrations are considerably higher than the corrected ^{132}Xe concentrations due to abundant Xe-air contamination (Fig. A 1).

3.2.4 Elemental compositions

Figure 8 shows the $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ elemental ratios for the samples, and we observe two main trends.

(1) The majority of the CMs in this study plot close to Q ($(^{36}\text{Ar}/^{132}\text{Xe})_{\text{Q}} = 76 \pm 7$; $(^{84}\text{Kr}/^{132}\text{Xe})_{\text{Q}} = 0.81 \pm 0.05$; Busemann et al., 2000), but their compositions indicate that they also contain minor amounts of air (shaded in yellow). The ^{132}Xe abundances have been corrected for air based on Xe isotopes (see section 2.4; only done for samples where the 2σ uncertainty of the measured ^{132}Xe did not exceed the correction) which leads to substantially higher uncertainties. The samples with the highest air corrections for Xe (see section 3.2.3) tend towards higher $^{84}\text{Kr}/^{132}\text{Xe}$. It is likely that Kr-air contamination is also significant in these samples, which will have shifted their compositions to the right in Fig. 8. However, for Kr an air correction is not possible due to the very similar Kr isotopic compositions of Q and air, and the unknown extent of elemental fractionation of air during weathering (Mohapatra et al., 2009; Schwenger et al., 2012).

(2) Approximately 30 % of the CM samples we measured have significantly higher $^{36}\text{Ar}/^{132}\text{Xe}$ ratios than the mixing line between Q and air (LEW 85312 B, Queen Alexandra Range (QUE) 97990, NWA 10827 A/B, NWA 10574 A, PCA 91008, GRA 98005, Paris A/B, NWA 11024, Banten, and LAP 04796; shaded in light blue). Also, the $^{84}\text{Kr}/^{132}\text{Xe}$ ratios tend to increase with increasing $^{36}\text{Ar}/^{132}\text{Xe}$ ratios among those samples. The non-CMs of this study plot well within the range of the CMs, with EET 83355 and NWA 5958 showing high $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios that are similar to or even higher than the most primitive CMs.

3.2.5 Sample homogeneity

A few of the meteorites contain distinct lithologies that were separately analysed for their noble gas compositions. We received two fragments of Mukundpura, which turned out to be different lithologies with different petrologic types (A = 1.2 and B = 1.5 on the Howard et al. (2015) scale, Table 1). The concentrations of ^4He and ^{20}Ne (Table 2) in Mukundpura B are about a factor of three higher than in Mukundpura A. The Ne isotopic ratios (Fig. 1, Table 2) indicate a higher relative amount of trapped Ne and a more significant SW component in Mukundpura B compared to A. Nevertheless, the Ne_{cos} concentration in Mukundpura B is slightly higher than in Mukundpura A (Table 2). Also Mukundpura B is slightly more Ar-, Kr-, and Xe-rich (~10 %). The two samples of NWA 10574 were slightly different in colour. The matrix of NWA 10574 A looked dark which is usual for primitive matrix material while the matrix of NWA 10574 B appeared lighter and, hence, slightly more terrestrially altered. Nevertheless, all results are broadly consistent amongst the two samples except for deviations in some Xe isotopes (e.g., ^{126}Xe). We received two samples of Bells, one “clean” (Bells C) which was recovered shortly after the fall and one sample, Bells W (“water”), that was recovered after a storm (Alexander et al., 2012). Isotopic ratios are mostly consistent in both samples of Bells. However, the

concentrations in all noble gases are higher (factor of ~ 1.4) in Bells C than in Bells W. In contrast, the $^{21}\text{Ne}_{\text{cos}}$ concentration is significantly ($\sim 60\%$) higher in Bells W than in Bells C. Our XRD analysis of the two samples of Paris showed that they differ in petrologic type ($A = 1.6, B = 1.7$). The concentrations of ^4He and ^{20}Ne in Paris B are 4-5 times higher than in Paris A. In Paris B, Ne_{tr} is characterized by a pronounced SW component (more pronounced than in Paris A). The $^{36,38}\text{Ar}$, ^{84}Kr , and ^{132}Xe concentrations are 1.7-1.3 times higher and the $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ are 1.3-1.1 times higher in Paris A than in B, while the isotopic compositions of Ar-Xe are mostly similar.

The petrology and noble gas compositions of Paris and Maribo have been described in previous publications (Haack et al., 2012; Hewins et al., 2014; Bekaert et al., 2019). Hewins et al. (2014) analysed two different aliquots (from two different lithologies that are probably different from the two lithologies we analysed) of Paris for their noble gas composition, their Paris A and Paris B are here referred to as Paris C and Paris D, respectively. The ^4He concentration of our Paris B is similar to that of Paris C, whereas it is significantly higher than in Paris D (factor of ~ 2) and Paris A (factor of ~ 4). The concentration of ^{20}Ne is highest in Paris B ($> \text{Paris C} > \text{Paris D} > \text{Paris A}$). The Ne isotopic ratios are roughly similar in Paris B/Paris C (pronounced SW) and Paris A/Paris D, respectively. In contrast to the lighter noble gases, primordial Ar is highest in Paris A ($> \text{Paris C} > \text{Paris D} > \text{Paris B}$), whereas $^{40}\text{Ar}/^{36}\text{Ar}$ is higher (9.2-9.7) in both samples analysed by Hewins et al. (2014) compared to Paris B (3.9) and Paris A (2.1). In Hewins et al. (2014), Xe data is only available for Paris D, in which the ^{132}Xe concentration is strikingly lower (factor of $\sim 0.2-0.3$) than in our samples. As a result, the $^{36}\text{Ar}/^{132}\text{Xe}$ elemental ratio is also completely different from that observed in our Paris samples: ~ 585 for Paris D compared to $\sim 135/180$ for Paris B/A. Krypton data are not given in Hewins et al. (2014). Bekaert et al. (2019) report Ar, Kr, and Xe isotopic compositions within two different lithologies of Paris. They observe that the ^{36}Ar concentrations (no substantial correction for $^{36}\text{Ar}_{\text{cos}}$ required) and $^{36}\text{Ar}/^{132}\text{Xe}$ ratios are lower in their samples of type 2.7 than in their samples of type 2.9 (on the Rubin et al. (2007) scale; which corresponds to type ~ 1.8 and ~ 2.0 , respectively, on the Howard et al. (2015) scale). In comparison, their ^{36}Ar concentrations (between 148 and 187 $\times 10^{-8}$ cm^3 STP/g), independent of the lithology, are between those of Paris A and Paris B in our study (224 and 133 $\times 10^{-8}$ cm^3 STP/g, respectively). Their $^{36}\text{Ar}/^{132}\text{Xe}$ ratios (between 79 and 115) are lower than in our samples (A: 179, B: 136), i.e., close to Q composition due to relatively high ^{132}Xe concentrations (between 162 and 188 $\times 10^{-10}$ cm^3 STP/g instead of 125 and 98 $\times 10^{-10}$ cm^3 STP/g in our Paris A and B, respectively). Possibly, this results from a contribution of atmospheric Xe that is not corrected for in their study. From the above, it is clear that the noble gas compositions are highly variable amongst the samples of Paris, reflecting distinct lithologies in this meteorite. By contrast, the noble gas compositions of the Maribo sample measured here are in remarkably good agreement with the results given by Haack et al. (2012), likely related to the mono-lithologic character of this meteorite (Lentfort et al., 2020).

We repeated the measurement of two meteorites, LEW 85312 and NWA 10827, for analytical reasons. The noble gas compositions of sample A of NWA 10827 pointed to a high petrologic type, but the sample was too small for phase quantification using the standard PSD-XRD set-up. We purchased another piece of this meteorite, sample B, from a second source to allow for both noble gas and XRD analyses on the same meteoritic powder. The He and Ne results for the two NWA 10827 samples are broadly consistent. Only Ne_{cos} is slightly elevated in NWA 10827 B compared to NWA 10827 A (Table 2), but the CRE age ranges determined for both samples still overlap (Table 5). Such a difference in the cosmogenic concentrations can arise when the samples originate from different depths within a meteoroid. However, the small mass of NWA 10827 (32.7 g, Meteoritical Bulletin Database) precludes differences in depths that are large enough to account for the difference in Ne_{cos} . Alternatively, small differences in the mineralogy, and thus in the abundance of the target elements, between the samples can be the reason for the small deviations in Ne_{cos} . The Ar, Kr, and Xe concentrations are slightly lower (by ~10 %) in NWA 10827 B than in A.

The Kr and Xe measurements of sample A of LEW 85312 were affected by high hydrocarbon contents in the system due to inefficient gettering. The extrapolation of Kr and Xe data to the time of the gas introduction into the mass spectrometer, thus, involved large uncertainties. To ensure precise Kr and Xe concentrations for LEW 85312 with reasonably small errors we repeated the measurement of this CM. Before analysing another sample with the typical mass of ~20 mg (sample B), we measured noble gases and contaminants in a smaller sample (C; ~5 mg; both samples from the same meteoritic powder as sample A). In this way, we aimed to avoid a repeated pollution of the system as the source of the abundant hydrocarbons remained unclear and may have come from the sample itself. However, the hydrocarbon contents stayed at blank levels in both measurements (sample B and C). The He and Ne concentrations and isotopic compositions agree well amongst the three samples of LEW 85312 (A, B, C). The Ar abundances and isotopic compositions are consistent between samples A and B, but not detectable in the smaller C sample. As mentioned above, the errors for the Kr and Xe concentrations (and less so also isotopic ratios) are high in LEW 85312 A. Nevertheless, the Kr and Xe concentrations and isotopic ratios are mostly consistent within the uncertainties for all three samples.

3.3 $^{21}\text{Ne}_{\text{cos}}$ production rates and CRE ages

The CRE age ranges (and the value of the centre of these ranges) for all samples with $^{21}\text{Ne}_{\text{cos}}$ concentrations that are resolvable from trapped Ne (Table 2), as well as corresponding production rate ranges used for the calculation, are summarized in Table 5. We used an average CM bulk chemical composition (Alexander, 2019) to determine the production rate ranges of meteorites for which (to our knowledge) no bulk major element chemistry is available. We applied both individual (where available) and average CM compositions to all other samples to estimate the accuracy of the CRE ages based on average chemistry compared to actual values. In many cases, the CRE age ranges were consistent between the two data sets, i.e., deviations turned out to be <5 % between the centre of the CRE age

ranges determined with production rates based on both, average and individual chemistries. For eight samples (ALH 84042, EET 96029, LAP 02333, LAP 04514, Mukundpura A/B, NWA 11024, and QUE 93005), the deviations were higher (21 % at maximum for EET 96029), but still within the possible exposure age range. In addition to the CRE age ranges of the CCs in this study that are listed in Table 5, we calculated CRE age ranges from the CM literature noble gas data compiled in Schultz and Franke (2004; Maribo from Haack et al., 2012; Paris from Hewins et al., 2014) for comparison, using the same approach as for our samples. The analytical uncertainties of the noble gas measurements from the literature were not included in our overall CRE error estimates, because of incompleteness. However, they are likely negligible compared to the uncertainty of the production rates. Figure 9 illustrates the calculated CRE age ranges of our CCs and the CMs in the literature (average values in case of multiple measurements of the same meteorite and paired specimens) as well as the probability density plot (PDP; calculated using “DensityPlotter” by Vermeesch, 2012) of CRE ages for the CMs in this study. For one of the C-ung, EET 83355, we calculated a CRE age range of 44-111 Myr, which is distinct from all CM chondrites and not shown in Fig. 9.

4 Discussion

4.1 Noble gas composition and components

4.1.1 Noble gases in CM chondrites

The noble gas inventories in CMs represent mixtures of cosmogenic (resolvable only in Ne), radiogenic (^4He , ^{40}Ar , ^{129}Xe), and trapped noble gases (primordial, SW, air). The measured ^{40}Ar concentrations were all lower than the expected radiogenic ^{40}Ar in all CMs and individual K-Ar nominal gas retention ages younger than 4.55 Ga (i.e., 0.7-3.4 Ga) indicating a loss of $^{40}\text{Ar}_{\text{rad}}$ due to impact processes or, perhaps, solar heating. Amongst the samples for which we could estimate K-Ar ages, the two heated CMs, EET 96029 and PCA 91008, have the lowest ages (~ 0.9 Ga and ~ 0.7 Ga, respectively; Figure A 2d). Also, the ^{40}Ar concentrations of the heated samples are between $109\text{-}655 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$, while those of the unheated samples cover a broader range from $218 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$ up to $1265 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$. Low K-Ar ages are typical for type 1-3 CCs, whereas an increase in K-Ar ages from type 1 to type 3 has been observed that is likely related to an increase in the grain size of the K-bearing phases associated with an increasing ^{40}Ar retention (Mazor et al., 1970). Meaningful K-Ar ages for CMs are, thus, difficult to determine, i.e., they do not date the actual event but reflect the extent of ^{40}Ar diffusive losses (Mazor et al., 1970; Eugster et al., 1998). Indeed, $^{40}\text{Ar}_{\text{rad}}$ is lost at relatively low temperatures (mainly at ≤ 500 °C) compared to $\text{He}_{\text{rad+tr}}$ and Ne_{tr} (mainly at ~ 750 °C; Eugster et al., 1998). With respect to the trapped noble gases, the CMs show abundant primordial noble gases, which is typical for primitive CCs and also in agreement with previous studies on CMs (Schultz and Franke, 2004; Nakamura, 2006; Haack et al., 2012; Hewins et al., 2014; Okazaki and Nagao, 2017). These primordial noble gases include mainly Q gases that dominate the heavier noble gases, Ar, Kr, and Xe, but also

presolar components like HL and Ne-E, and probably still unidentified components (see following discussion). We also observe some air contributions, which is most significant in Xe as demonstrated by the isotopic compositions (section 3.2.3). Additionally, about 50 % of the samples likely contain a SW component that is typically interpreted to indicate that these are regolith samples (e.g., Bischoff et al., 2006; Riebe et al., 2017b), but pre-irradiation of some pristine phases prior to parent body accretion cannot be entirely excluded (e.g., Kööp et al., 2018).

For some samples, SW contributions are visible in the Ne isotopes, and are indicated by $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios that are lower than the ratio of Ne-Q (Fig. 3). Also, the concentrations of $^{20}\text{Ne}_{\text{tr}}$ and ^4He are high (up to ~ 3110 and $\sim 789900 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$, respectively) in the SW-rich samples. QUE 97990 shows by far the highest concentrations in both elements and, hence, is the most SW-rich sample in this study. Based on the fact that one of the heated CMs, EET 96029, has a low $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratio, we can exclude the possibility that all samples with higher $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios lost significant amounts of their $^{20}\text{Ne}_{\text{tr}}$ content due to heating. Thus, loss of Ne_{tr} due to heating cannot account for the higher $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios of the samples in the grey and purple area relative to those in the orange area in Fig. 3. A characterisation of the Ne_{tr} component(s) contained in EET 83355 is challenging because of the relatively high abundances of Ne_{cos} .

Samples that show $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios that are lower than Ne-HL have to contain some combination of SW, an unknown Ne-rich component or Ne-Q in addition to HL and Ne-E. While Ne-Q is present in all samples, including in those with higher $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios than Ne-HL, in contrast to SW, Q dominates the inventory of the heavier noble gases Ar, Kr, and Xe, but less so the inventory of He and Ne. For this reason, we find a decrease of $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ below Ne-HL being due to Ne-Q excess the least likely explanation. Note that, e.g., only ~ 6 % of the ^{20}Ne measured in Murray is $^{20}\text{Ne}_{\text{Q}}$, assuming the total amount of ^{132}Xe is Q and $(^{20}\text{Ne}/^{132}\text{Xe})_{\text{Q}} \sim 3.2$ (Busemann et al., 2000). Thus, we argue that samples with $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ between Ne-HL and Ne-Q and concentrations of $^{20}\text{Ne}_{\text{tr}}$ and ^4He that are higher than the “baselines” in Fig. 4 also likely incorporated some SW. We indicated those samples with “(X)” in Table 1. In contrast to the $^{20}\text{Ne}_{\text{tr}}$ concentrations, the ^4He concentrations of the NWA 10827 samples and ALH 84033 are in the range for samples without evidence for SW. Both meteorites are amongst the most primitive CMs. The same can be observed, based on the noble gases, for the primitive C-ung EET 83355. Furthermore, the $^{20}\text{Ne}_{\text{tr}}$ concentrations of the LEW 85312 samples (the most primitive CM in this study) are the highest amongst all meteorites shown as grey data points in Fig. 4, whereas the ^4He concentrations are similar to other meteorites of this group. A SW contribution usually increases the concentrations in both $^{20}\text{Ne}_{\text{tr}}$ and ^4He . Possibly, the elevated $^{20}\text{Ne}_{\text{tr}}$ concentrations in these samples result from an additional, yet unknown, Ne-rich component, that is only present in the most primitive CMs (and other CCs). We marked these samples with “Ne” in Table 1. The $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios of Nogoya, ALH 84042, PCA 02010, and NWA 10574 A/B are between those of HL and Q (Fig. 3). However, the

relatively low $^{20}\text{Ne}_{\text{tr}}$ and ^4He concentrations (within the “baselines” in Fig. 4) do not provide any evidence for SW in these samples.

For half of the CMs in this study, we infer a constant mixing ratio of HL from presolar diamonds and Ne-E carried by presolar graphite or SiC and negligible SW-Ne ($(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}} \sim 0.13$). Such a constant mixing ratio of different primordial components is expected if we assume an initially homogeneous distribution of their carriers and similar losses (if any) due to secondary processes in the CM parent body. The only alternative explanation for their compositions is a scenario in which all these CMs incorporated the same amounts of SW relative to primordial Ne_{tr} , which is very unlikely because their absolute Ne (and also He) contents indicate that they were exposed to the SW for different periods (if at all). Also, the low $^{20}\text{Ne}_{\text{tr}}$ and ^4He concentration (max. ~ 15 and $\sim 4325 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$, respectively) and $^{20}\text{Ne}/^{36}\text{Ar}$ ratios (< 0.36) in these meteorites do not provide any hint of SW. This is in disagreement with a previous study by Bischoff and Schultz (2004) that concluded that 100 % of the CMs in their sample suite (19 CMs in total) contained SW (further discussed in the review by Bischoff et al., 2006). Their investigations were also mainly based on noble gases. The main difference between the two studies, however, is the inclusion of HL-He and -Ne as significant components in CMs in our deconvolution of the noble gas compositions. When we apply our criteria for the presence of SW in CMs (i.e., when $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}} < (^{22}\text{Ne}/^{20}\text{Ne})_{\text{HL}}$ and $^{20}\text{Ne}_{\text{tr}}$ and ^4He concentrations are elevated compared to those in samples with $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}} > (^{22}\text{Ne}/^{20}\text{Ne})_{\text{HL}}$), only ~ 55 % of the CMs analysed by Bischoff and Schultz (2004) incorporated SW. This fraction is very similar to what we find for our sample suite. The result that many samples examined here and in the literature do not show detectable SW (-Ne) does not support the claim that all CMs are regolith breccias (Bischoff and Schultz, 2004; Bischoff et al., 2006), unless brecciation predated dissipation of the solar nebula or was so rapid that little SW was implanted. It may, instead, support a link between the CMs and a rubble-pile asteroid, such as, or similar, to Bennu and Ryugu (Lauretta et al., 2019; Watanabe et al., 2019). Also, SW-Ne from a pre-accretion irradiation phase, that likely had a similar Ne signature as “regular” SW, would not be detectable in many *bulk* CMs. However, we cannot exclude a pre-accretion exposure to SW for very minor phases (below the detection limit of SW in bulk samples). This can only be tested by stepwise etching or heating with many steps for each meteorite (e.g., Riebe et al., 2017a). Note that generally we can only describe the characteristics of the samples we analysed, while other samples of the same meteorite may show different characteristics due to the brecciation of CMs.

4.1.2 Noble gases in CM-related carbonaceous chondrites analysed in this study and implications for their classification

With a few exceptions, the non-CMs analysed in this study show noble gas characteristics that are similar to the CMs. The two Bells samples are distinct from the trend defined by most CMs in Fig. 10 (B, D, F) where we show noble gas concentrations (^{36}Ar , ^{84}Kr , and ^{132}Xe) versus petrologic types

according to Alexander et al. (2013) (see section 4.2.1.1). This is, however, likely attributed to the petrologic assignment of this meteorite, i.e., the petrologic type may be overestimated in Alexander et al. (2013). Both samples of Bells are distinct outliers in the plots of δD vs. H content or C/H shown by Alexander et al. (2013) and the authors questioned the respective petrologic assignments. According to its PSF (Howard et al., 2015), Bells shows an alteration degree similar to the more aqueously altered CMs that are also characterised by noble gas concentrations similar to those measured in Bells (Fig. 10 A, C, E). Hence, noble gas analysis supports that Bells may be a moderately to highly altered CM that is anomalous in some characteristics (see section 2.1). Leaving aside the fact that Xe-HL is slightly more pronounced in NWA 5958 than in most CMs, its noble gas composition agrees well with typical characteristics for CMs. As a determination of its petrologic type is pending (not determined here, due to insufficient mass for the PSD-XRD set-up used), a comparison of NWA 5958 with CMs of similar alteration degree is not feasible. Jacquet et al. (2016) describe NWA 5958 to be most similar to a CM chondrite with low degree of alteration. Indeed, the noble gas elemental composition of NWA 5958 (i.e., $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$) is in agreement with that of primitive CMs. The absolute abundances in ^{36}Ar , ^{84}Kr , and ^{132}Xe , however, resemble those of the highly altered CMs that could result from larger abundances of gas-poor chondrules and/or CAIs compared to CMs. So far, the noble gas composition of NWA 5958 supports a classification as a C-ung that is related to the CM group as previously suggested by Jacquet et al. (2016) and Nittler et al. (2020). Among all samples in this study, EET 83355 is the meteorite with the highest $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios (Fig. 8), which are similar to those of the most primitive CRs, suggesting a low degree of aqueous alteration and no intense modification above ~ 750 °C, where noble gases carried in presolar phases might be significantly affected (see section 4.2.2). King et al. (2021) determined a heating stage III (500-750 °C) for EET 83355 based on XRD patterns. Quirico et al. (2018) classified EET 83355 as a strongly heated C2-ung, albeit without giving a peak temperature, based on Raman and infrared studies of IOM. Alexander et al. (2012; 2013) also listed this meteorite as heated based on bulk H and C abundances and ratios, which was, however, based on the assumption that it is a CM. EET 83355 exhibits a significantly higher cosmogenic noble gas contribution compared to all other samples that is reflected in its old CRE age of ~ 78 Myr. This CRE age is clearly distinct from all CM CRE ages measured here or previously reported, and is long compared to exposure ages determined for most CCs. Only a few of the COs have similarly long CRE ages (Scherer and Schultz, 2000; Herzog and Caffee, 2014) as EET 83355.

4.2 Effect of secondary processes on noble gases in the parent body(ies)

In principle, an investigation of the effect of thermal alteration prior to looking at variations in noble gases due to aqueous alteration is reasonable as the heating is believed to postdate aqueous alteration processes in the parent body(ies) (e.g., Nakamura, 2005; Tonui et al., 2014). However, the effect of aqueous alteration on noble gases in CM chondritic material turns out to be dominant, whereas thermal alteration apparently in most cases has minor effects (in particular, heating stage I (< 300 °C) and II

(300-500 °C) that involves most of the heated CMs in this study; Table 1). Indeed, none of the heated CMs show noble gas concentrations significantly lower than the typical range of the unheated samples except for PCA 02010 (heating stage IV, >750 °C). For this reason, we will first focus on the effects of aqueous alteration on noble gases in CCs before we discuss the details of possible heating-dependent noble gas variations. Also, as we can determine reliable pre-heating aqueous alteration degrees by XRD and heating has minor effects on the noble gas composition of most meteorites, we consider heated as well as unheated samples to investigate the effect of aqueous alteration on primordial noble gases; keeping in mind that deviations of very strongly heated (e.g., >750 °C, see above) samples from the trends formed by the unheated specimens may be related to an additional loss of noble gases due to heating.

Note that we do not expect to find statistically valid correlations between noble gases and other parameters, such as the degree of aqueous alteration, as these parameters are not necessarily quantifiably linked to noble gas concentrations and isotopic or elemental noble gas ratios. Changes at *macroscopic* scale (at mg-g level), such as changes in the phyllosilicate fraction, will not necessarily statistically correlate with *microscopic* changes in the noble gas carriers (perhaps at ppb to ppm level). In principle, *all* trapped noble gases could easily be carried by phases totalling not even a wt. % of a meteorite's mass. Nevertheless, a qualitative comparison of changes in noble gases and other features with the alteration degree will be valuable as both react upon alteration. When we use terms like “trends” and “correlations” it means that we observe rough trends between noble gas compositions and, e.g., high/low alteration degree, not necessarily a causal relationship between both parameters.

4.2.1 Effect of aqueous alteration on noble gases

4.2.1.1 *Effect of aqueous alteration on noble gases in CM chondrites*

Here, we focus on the relationship between aqueous alteration and the noble gas contents in CM chondrites to better understand the effect of parent body secondary processing on their primordial noble gas inventories. The investigation of the effects of alteration on the lighter noble gases is challenging: we cannot resolve the various primordially trapped He and Ne components with our bulk sample analyses, and in some samples these components could be superimposed by SW (which is a problem for many of the most primitive CMs). Hence, for the purposes of this section we concentrate on the heavier noble gases, Ar, Kr, and Xe. Figure 11 shows the relation between the measured ^{36}Ar concentrations and the petrologic types determined by Rubin et al. (2007) based on petrographic and mineralogical properties. The Rubin et al. (2007) classification is currently the most commonly used scheme to characterize individual CMs (e.g., new falls). Nevertheless, the number of meteorites that have been classified according to this scheme is still relatively small compared to the many CMs in the collections, and there is not much overlap between meteorites classified in this way and those analysed

for their noble gases in this study (see Table 1). Nevertheless, meteorites with higher petrologic types tend to have a higher ^{36}Ar concentration (similar trends can be observed for ^{84}Kr and ^{132}Xe).

Figure 10 shows the concentrations of ^{36}Ar , ^{84}Kr , and ^{132}Xe versus their petrologic type according to Howard et al. (2015) (A, C, E, on the left, based on the phyllosilicate fraction) and Alexander et al. (2013) (B, D, F, right, based on the abundance of H in water and OH), respectively. Except for a few meteorites (Bells, LON 94102, MET 00432, and Thiel Mountains (TIL) 91722), the two different approaches to classification of CMs agree very well for unheated samples. For heated samples, the Alexander et al. (2013) method cannot be used because it depends on the H content as a measure of the degree of alteration/hydration, and the heating will have driven off some or all H. Note that not even all unheated meteorites studied in this work have been classified using both classification techniques. Hence, there are differences in the numbers of meteorites shown in the left and right of Fig. 10. Figure 10A, C, E include several NWA samples, namely NWA 10827 (A/B), NWA 11024, and NWA 10574 (A/B). Work by Ash and Pillinger (1995) and Alexander et al. (2007) shows that hot desert weathering can intensely attack the organics in such meteorites. To our knowledge the organics have not been studied in our NWA meteorites. The weathering grade is low for NWA 10827 and NWA 10574, although NWA 10574 B appears more terrestrially altered based on its colour (lighter than sample A). The weathering grade for NWA 11024 is high (Table 1). However, the Xe-air content is not extraordinarily high in all three NWA specimens, while primordial noble gas contents in NWA 10827 are higher than average contents in our CCs. Accordingly, there is no indication for more pronounced changes in noble gas composition due to hot desert weathering of the NWA samples compared to all other samples analysed in this study. Plotting the NWA samples together with all other samples is hence reasonable, even if the noble gases potentially affected by aqueous alteration should be carried in organics.

In agreement with Browning et al. (1996), we observe that meteorites with the highest petrologic types and, hence, the lowest degrees of aqueous alteration, contain much higher concentrations of Ar, Kr, and Xe than the highly altered samples (Fig. 10). The ^{36}Ar concentrations in the most primitive CCs (petrologic classifications do not exist for all samples) are on the order of 20 times higher than the concentrations in the most altered (unheated) samples; ^{84}Kr and ^{132}Xe concentrations are roughly eight times higher.

The CMs gain mass during aqueous alteration, which dilutes the initial noble gas concentrations. The amounts of $\text{H}_2\text{O}/\text{OH}$ present in CMs increase with increasing degree of aqueous alteration (on the order of ~4 to 13 wt. %; Alexander et al., 2013; Garenne et al., 2014). The mass gain with aqueous alteration may be even higher than the mass of the $\text{H}_2\text{O}/\text{OH}$ as the water is partly consumed in oxidizing Fe and S (H is lost but O is retained) (e.g., Alexander, 2019; Alexander et al., 2010; Sutton et al., 2017). However, while this addition of mass can have a modest effect on the noble gas concentrations (decrease

them by up to 30 %), it cannot account for the huge differences in concentrations between the most primitive and the highly altered CMs.

One of the purposes of this study was to assess the different classification schemes. However, an assessment of the schemes based on noble gas data turns out to be difficult as only a fraction of the meteorites discussed in this study have been classified according to all of the proposed schemes. In addition, because of the brecciation of CMs, the petrologic types given in the literature do not always perfectly represent the degree of alteration of the samples we analysed for their noble gas composition. Although the petrologic types defined according to the Rubin et al. (2007) scheme show trends with the ^{36}Ar concentrations of CMs (Fig. 11), only 10 of our CMs have been classified according to this scheme. Furthermore, the petrologic and noble gas analyses were not performed on the same samples, which as discussed above, does introduce additional uncertainties. The number of meteorites in this study classified according to Alexander et al. (2013) and Howard et al. (2015) schemes are significantly higher (29 and 41, respectively). A comparison of Fig. 10A, C, E with Fig. 10B, D, F shows that trends of Ar with petrologic types are similar, independent of the applied alteration scale (Alexander et al., 2013; Howard et al., 2015), whereas Kr and Xe concentrations particularly correlate well with the petrologic types defined according to Howard et al. (2015). Although both alteration schemes, proposed by Alexander et al. (2013) and Howard et al. (2015), quantify the degree of aqueous alteration and illustrate the dependency between noble gas concentrations and the intensity of aqueous alteration, we focus on the Howard et al. (2015) scheme in the following paragraphs. Reasons for this choice are the larger number of samples classified, including several very primitive CMs (e.g., Paris, NWA 10827, ALH 84033) which are not classified according to Alexander et al. (2013), as well as the capability to determine the pre-heating aqueous alteration degree using XRD, whereas the bulk H and C contents utilised in the Alexander et al. (2013) scheme are more affected by heating following the aqueous alteration.

In Fig. 8, which shows $^{36}\text{Ar}/^{132}\text{Xe}$ versus $^{84}\text{Kr}/^{132}\text{Xe}$, the petrologic types of the CMs, according to the method proposed by Howard et al. (2015), are colour-coded. We observed ~30 % of the CMs have ratios higher than Q and plot above the mixing line between Q and air. Solar wind measured by the Genesis mission has a $^{36}\text{Ar}/^{132}\text{Xe}$ ratio of 22700 ± 2800 and a $^{84}\text{Kr}/^{132}\text{Xe}$ ratio of 9.5 ± 1.0 (Heber et al., 2009). An addition of unfractionated SW to the samples would therefore result in elevated values for these ratios compared to Q (Fig. 8). However, we can exclude this, as we calculated upper limits for the SW-Ar/Kr/Xe contents based on $^{20}\text{Ne}_{\text{tr}}$, assuming [unrealistically but] conservatively that all trapped Ne is SW. The resulting amount of SW-Xe and SW-Kr, relative to the measured ^{132}Xe and ^{84}Kr concentrations, is negligible, <0.5 % and <3 %, in all meteorites, which does not explain the observed trend. Also, the positions of the data points do not suggest a mixing between unfractionated SW and Q (Fig. 8). However, we cannot exclude the presence of an elementally strongly fractionated solar-like component, although the Xe isotopic compositions would not allow for a significant contribution of

SW-Xe to the dominant Q-like Xe isotope patterns (Fig. 5), i.e. even any potentially once present solar Xe must have been essentially lost. Instead, we argue that there is a correlation between high $^{36}\text{Ar}/^{132}\text{Xe}$ from another $^{36(,38)}\text{Ar}$ -rich (hereinafter referred to as “Ar-rich”) component and (less pronounced) $^{84}\text{Kr}/^{132}\text{Xe}$ ratios and the petrologic type of these meteorites (see in the following for a more detailed discussion). The samples with high ratios are some of the most primitive CMs, particularly NWA 10827, LEW 85312, PCA 91008, Paris, and QUE 97990 (Table 1).

Besides the degree of aqueous alteration, other parameters will inevitably also influence the abundance of primordial noble gases in a meteorite, among them the chondrule/matrix ratio. Chondrules were molten droplets before cooling and accretion and, hence, have significantly lower contents of primordial noble gases, as noble gases present in the chondrule precursors would have evaporated during chondrule formation (Vogel et al., 2004). Primordial noble gases mostly reside in the meteorite matrix. Hence, a higher chondrule/matrix ratio will result in lower primordial noble gas concentrations even if the meteorite is very primitive and did not experience intense secondary processing. According to Weisberg et al. (2006), the average matrix abundance in CMs is ~70 vol. % (chondrules ~20 vol. %; rest = CAIs/amoeboid olivine aggregates/metal), but variable within the CM group (from 55 vol. % in Paris to 85 vol. % in Nogoya; Braukmüller et al. (2018) and references therein) and between different meteorite groups (e.g., matrix in CRs = 30-50 vol. %). We do not observe any correlation between noble gas concentrations and matrix abundances given in the literature (McSween, 1979; Hewins et al., 2014). However, the number of CMs with measured matrix abundances is small and values given in the literature do not necessarily represent the primordial matrix abundance (i.e., the matrix abundance at the time of accretion may have changed due to alteration and brecciation), making the statistical significance of this conclusion uncertain. Alternatively, the bulk C content (given in Alexander et al., 2012; 2013) can be used as a proxy for the matrix abundances in CCs as organic C was exclusively accreted as part of the matrix. In Fig. A 3, we observe that some of the most pristine samples show the highest ^{36}Ar concentrations although they have moderate bulk C contents. Some of the most pristine CMs, such as NWA 10827, are not shown in the figure as the bulk C content has not yet been determined for these samples. Amongst the less primitive CCs, the primordial noble gas abundances may slightly increase with higher C contents. Although the matrix abundance has an influence on the primordial noble gas abundances, the dependence is minor compared to the strong dependence of primordial noble gas abundances from the degree of aqueous alteration.

To balance the effect of the chondrule/matrix ratios without having the actual values for all CMs, it is reasonable to plot elemental or isotope ratios instead of concentrations versus petrologic types to investigate the impact of aqueous alteration on noble gases. For example, plotting ^{36}Ar over another isotope that is mainly situated in the matrix (but preferably not influenced by parent body alteration) would be useful to cancel out different chondrule abundances. However, this turns out to be difficult as most trapped noble gas isotopes seem to be affected by secondary processes, such as aqueous alteration

and, possibly, shock heating. In Fig. 12, we plot $^{36}\text{Ar}/^{132}\text{Xe}$ ratios of all CMs versus their degree of aqueous alteration, i.e., their petrologic type according to Howard et al. (2015). Even if there is a considerable loss of ^{132}Xe during alteration, it is significantly less than the loss of ^{36}Ar over the full range of analysed CMs (compare with Table 3 and Table 4, Fig. 10). Hence, we expect lower $^{36}\text{Ar}/^{132}\text{Xe}$ ratios with increasing aqueous alteration if the previously identified trends in Fig. 10 are not controlled by the chondrule/matrix ratio in these meteorites. This is what we observe in Fig. 12, keeping in mind that this trend would be even more pronounced (and, hence, more similar to the trends of concentrations versus petrologic types) with an isotope in the denominator that is independent of the petrologic type (instead of ^{132}Xe). Hence, even though the matrix fraction generally has an influence on noble gas abundances in meteorites, variations due to the chondrule/matrix ratio are less significant within the CM chondrite group than changes due to the degree of aqueous alteration. Samples with petrologic types ≥ 1.5 tend to have higher $^{36}\text{Ar}/^{132}\text{Xe}$ ratios (up to ~ 325), whereas none of the samples with petrologic type < 1.5 exceed $^{36}\text{Ar}/^{132}\text{Xe}$ of ~ 125 (except for MET 00432, the sample with the highest Xe-air correction and a correspondingly large error). In fact, below petrologic types of ~ 1.5 , the $^{36}\text{Ar}/^{132}\text{Xe}$ ratios seem to stabilize in a range between 60 and 125. The CMs LEW 85312, NWA 10827, QUE 97990, and PCA 91008 (petrologic type 1.8-1.6) have the highest $^{36}\text{Ar}/^{132}\text{Xe}$ ratios among the samples shown in Fig. 12.

Based on our extensive data set, we can substantiate previously observed trends between decreasing primordial noble gases and the increasing degree of aqueous alteration of the CMs. This can be seen in the concentrations of the heavier noble gases, as demonstrated by ^{36}Ar , ^{84}Kr , and ^{132}Xe abundances (Fig. 10). Also, the $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios of the more primitive CMs (type ~ 1.8 -1.5) tend to be higher than those of the more altered samples (Fig. 12 and Fig. 8; similar trends can be observed for $^{36}\text{Ar}/^{40}\text{Ar}$, see Appendix and Fig. A 4). The noble gas compositions appear to be most pristine in LEW 85312 and NWA 10827 – they have the highest concentrations and $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios (e.g., Fig. 13) - in agreement with their high petrologic type (1.8 and 1.7, respectively). LEW 85312 is paired with LEW 85311 also assigned as a 1.7 by Lee et al. (2019b) (1.9 in the scheme of Alexander et al., 2013), although Lee et al. (2019b) speculated that it may originate from a different parent body to most other CMs.

Instead of continuously decreasing isotopic and elemental ratios and concentrations with increasing aqueous alteration, we observe a threshold at petrologic type ~ 1.5 below which concentrations and ratios approach roughly constant levels (Fig. A 5a). CMs with a petrologic type ≥ 1.5 are often characterised by distinctly higher primordial noble gas concentrations (Fig. A 5b) as well as $^{36}\text{Ar}/^{132}\text{Xe}$ ratios (Fig. 12). Thus, the most primitive CMs carry one or more noble-gas-rich components that were lost by the more altered samples. At least one carrier of primordial noble gases must, therefore, be susceptible to parent body aqueous alteration - and be attacked within the first stages of the aqueous alteration process. Possibly, the complete destruction of the carrier(s) in CMs with petrologic type < 1.5

is related to the temperature prevalent during aqueous alteration processes, i.e., these CMs were altered at higher temperatures (>120 °C) compared to CMs with petrologic type >1.5 . This has earlier been stated for CM1 chondrites (petrologic type 1.1-1.2) based on the absence of tochilinite in these meteorites (Zolensky et al., 1997; King et al., 2017 and references therein). However, higher fluid/rock ratios, longer durations of aqueous alteration, and/or changes in the fluid compositions might have also played roles.

Our conclusion that aqueous alteration does not result in further modification of the noble gases below petrologic types <1.5 is in disagreement with the findings of Browning et al. (1996). These authors proposed a progressive loss of primordial noble gases with increasing aqueous alteration based on their data set. However, they only had data for eight CMs with petrologic types equal to or lower than that of Murchison ($= 1.5$ based on the PSF). The alteration classification scheme used by Browning et al. (1996) depended largely on their MAI (see section 1). The petrologic types determined based on PSF and MAI roughly correlate for the small number of meteorites that have been classified with both schemes (except for Bells, which shows anomalies in a variety of characteristics). Hence, the application of different classification schemes cannot explain the different trends seen in the Ar concentrations. Another reason for the different trends below a petrologic type of 1.5 could be that Browning et al. (1996) exclusively considered falls, whereas our sample set comprises both falls and finds. However, when we plot the ^{36}Ar concentrations obtained in this work versus petrologic type for falls only, we still do not obtain such a good correlation as found by Browning et al. (1996). Particularly Murray falls off the trend as the ^{36}Ar concentration we determined for Murray ($\sim 50 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$) is lower than the one adopted in Browning et al. (1996) ($\sim 75 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$, mean from compilation by Schultz and Kruse, 1989). Their conclusions were based on a relatively small sample set, which seems fortuitous, particularly with regard to the small range of ^{36}Ar concentrations amongst their samples ($\sim 30\text{-}85 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$) – while our lowest abundances are similar, the maximum is $\sim 410 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$ in this work. Note that the variations in ^{36}Ar concentrations from several analyses of the same meteorite but different aliquots can be larger than the variations of the mean concentrations with petrologic type used in Browning et al. (1996) due to heterogeneities within CM chondrites. To illustrate this issue, we show ^{36}Ar ranges (based on minimum and maximum values given in the compilations by Schultz and Kruse (1989) and Schultz and Franke (2004)) instead of average values versus the MAI as given in Browning et al. (1996) in Fig. A 6. Here, the ^{36}Ar concentration of the CM with the lowest MAI (Murchison, least altered) tends to be even lower than concentrations measured in the CMs with higher MAI. If one still maintains that there is a trend of ^{36}Ar with MAI, the slope of this trend is much shallower than compared to the slope of the trend of ^{36}Ar versus alteration degrees of CMs with petrologic types that are higher than that of Murchison.

From the results of our study, we can confirm the overall conclusion of Browning et al. (1996) that some primordial noble gases, most obviously trapped ^{36}Ar , were lost during aqueous alteration.

However, our results show that the effects of aqueous alteration are most apparent amongst the most pristine members of the CMs, and that trapped ^{36}Ar abundances are essentially constant ($\sim 50 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$) for CMs with petrologic type < 1.5 , within the normal variation in concentrations observed for CMs with similar petrologic type.

This study shows that correlations between petrologic types and noble gases, where petrologic types and noble gas data were determined on different aliquots of a meteorite as in Browning et al. (1996), are not necessarily meaningful. To allow for comparisons between different parameters, such as petrologic type and noble gas compositions, ideally the various analyses (e.g., XRD and NGMS) should be performed on aliquots of the same homogenized powder prepared from a substantial fragment of the meteorite (i.e., 1-2 g) to ensure that the sample is representative (Morlok et al., 2006; Alexander et al., 2013). We could mostly meet these requirements in our study. As described above, we obtained the noble gas data plotted in Fig. 10 from material taken from the same powdered samples ($\sim 1 \text{ g}$) previously used for the analysis of the CM's bulk H, C and N contents in the study of Alexander et al. (2013). The XRD analyses of Howard et al. (2015) were also conducted on these same samples. Only for a few meteorites (EET 96029, LAP 04514, LAP 04796, NWA 10827 A, and Bells C) did we have to adopt petrologic types from the literature or determine them on second samples, which may add some uncertainty. However, the noble gas data of these samples is well within the range of the data for the other meteorites with similar petrologic type. We further conclude that while noble gases *alone* cannot be used for an exhaustive scale of alteration in chondrites, i.e., to differentiate their alteration degrees in 0.1 intervals, they can well be used to differentiate between primitive (close to type 3) and moderately to severely altered (type 1/2) specimens.

While our XRD analyses suggest that Paris A (1.6) is slightly more aqueously altered than Paris B (1.7) (Table 1 and 6; section 3.1), we observe consistently higher Ar, Kr, and Xe concentrations, as well as higher isotopic ($^{36}\text{Ar}/^{40}\text{Ar}$) and elemental ratios ($^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$), in Paris A. Only the concentrations of ^4He and $^{20}\text{Ne}_{\text{tr}}$ are higher in Paris B, likely the result of a higher contribution from SW in this lithology (see Fig. A 7). The lack of a tochilinite peak in the XRD pattern of Paris B, but its presence in Paris A (section 3.1), could indicate that Paris B experienced higher peak temperatures than Paris A as tochilinite is thought to break down at $> 120 \text{ }^\circ\text{C}$ (Zolensky et al., 1997; King et al., 2017). These slightly elevated temperatures during aqueous alteration could have initiated an additional loss of the heavier noble gases. If there was also a loss of the lighter noble gases, it has been overprinted by large amounts of SW-He/Ne. However, recently higher formation temperatures of tochilinite have been proposed (120-160 $^\circ\text{C}$; Vacher et al., 2019) and it is possible that tochilinite was never present in Paris B. The differences in the noble gas compositions might also well be explained by natural variations observed among the CMs with similar classification.

As described above, Maribo represents one of the more primitive CMs with a petrologic type of 1.6. However, with respect to the noble gases, Maribo often shows affinities to the more highly altered CMs mainly due to a low concentration in ^{36}Ar . The most unusual property of Maribo according to Haack et al. (2012) is a deficit in Na relative to that of typical CMs. The authors suggest that this Na depletion is likely to be a nebular feature reflecting heterogeneous accretion of the CM parent body, potentially reinforced by terrestrial weathering. It seems possible that the processes responsible for the Na depletion are also linked with the unusual noble gas compositions of Maribo. Alternatively, terrestrial weathering could have affected the noble gas compositions (preferential loss of the lighter elements) of Maribo as this meteorite suffered wet conditions between fall and recovery (Haack et al., 2012).

4.2.1.2 *Effect of aqueous alteration on noble gases across multiple carbonaceous chondrite groups*

Like the CMs, the CI, CY (the “Yamato-type” class meteorites have been introduced by King et al., 2019, by notifying significant differences to CI chondrites, their original classification) and CR chondrites are considered to be some of the most primitive chondrites. All four meteorite groups are thought to have originated from the volatile-rich C-type asteroids. Given the fact that the applied classification schemes are independent of the chemical group, the noble gas trends with the degree of alteration seen amongst the CMs may also be visible across these other primitive chondrite groups. Such group-independent noble gas trends are, however, not to be expected if the primordial matrix abundances were different for these CC groups and initial noble gas abundances depended on these primordial matrix abundances.

In Fig. 13, we have plotted the ^{36}Ar versus ^{132}Xe concentrations of our samples, with the degree of aqueous alteration according to the Howard et al. (2015) scheme indicated by the various colours of the points. Also shown are the ^{36}Ar and ^{132}Xe concentrations (Xe not corrected for air) of a number of CRs, CIs, and CYs (Mazor et al., 1970; Nagao et al., 1984; Riebe et al., 2017a; Busemann et al., 2019; 2021; King et al., 2019a). Busemann et al. (2021) previously identified two different trends of ^{36}Ar versus ^{132}Xe concentrations among the CRs indicated as straight lines in Fig. 13. The more primitive CR2-3s show a relatively flat positive trend ($^{36}\text{Ar}/^{132}\text{Xe} \sim 350$). In contrast, Grosvenor Mountains (GRO) 95577 (CR1) and the most aqueously altered CR2s (namely Al Rais, Renazzo, and GRA 06100; according to Schrader et al., 2014) plot on a significantly steeper slope (CR1-2), suggesting a loss of (mainly) ^{36}Ar with progressive aqueous alteration and, hence, lower Ar/Xe ratios (~ 60). All our samples plot in between or roughly on one of the two trends defined by the CRs. Many of the CMs plot close to the trend given by the highly altered CRs (CR1-2 line). In contrast, several of the least aqueously altered CMs like LEW 85312 B, NWA 10827 A/B, PCA 91008, and QUE 97990 as well as NWA 10574 A (petrologic type yet undefined) plot close to the trend produced by the majority of the CR2s (CR2-3 line). Also, ALH 84033 and Paris B (both petrologic type = 1.7), LAP 04796 and Banten (both 1.6), and Paris A (1.6) show ^{36}Ar concentrations that are clearly higher than samples that plot close to the CR1-2 line. Maribo (petrologic type = 1.6) with a comparatively low ^{36}Ar concentration does not follow

the CR2-3 trend. Two further CM samples with the same petrologic type of 1.6 (EET 96029 and LAP 04514) also plot close to the slope constrained by the CR1-2s. Thermal alteration might be responsible for the relatively low ^{36}Ar concentrations in these meteorites even though we do not observe any loss in the lighter noble gases compared to the unheated CMs. In general, a few of the thermally modified samples, especially some of those with a low degree of aqueous alteration and PCA 02010, are characterized by lower ^{36}Ar than what would be expected based on their petrologic types (further discussed in section 4.2.2). PCA 02010 is the most extreme sample with very low Ar and Xe concentrations, consistent with its extremely low Ne content (see above, Fig. 3). The CI/CYs mostly plot in the range of the mildly to highly altered CMs. Amongst the non-CMs in this study, EET 83355 (C-ung) plots close to the primitive CR (CR2-3) trend.

The range of $^{36}\text{Ar}/^{132}\text{Xe}$ ratios observed (Fig. 12) for the more altered CMs (~60 to 125 below petrologic type ~1.5) is similar to the range seen amongst the highly altered CRs (~50 to 120; Busemann et al., 2021) and CIs (~70 to 105; King et al., 2019a; Mazor et al., 1970; Riebe et al., 2017a). The CMs with the highest $^{36}\text{Ar}/^{132}\text{Xe}$ ratios among the CMs shown in Fig. 12 (NWA 10827 and QUE 97990; petrologic type 1.7-1.6) fall within the lower range constrained by the minimally altered CRs (265 to 445, Busemann et al., 2021). The $^{36}\text{Ar}/^{132}\text{Xe}$ ratios of most CR2-3s (Fig. 12), however, are higher than the ratios of CMs. Accordingly, the CMs fill the gap in the trend in Fig. 8 between the least altered CRs, characterized by higher $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios, and the highly altered CRs with lower ratios. The $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios of the few highly aqueously altered CI chondrites resemble the ratios of the most aqueously altered CMs (Mazor et al., 1970; Riebe et al., 2017a; King et al., 2019a). Extensive terrestrial weathering increased the (Kr and) Xe concentrations of the aqueously and thermally altered CYs (60-80 % of the total Xe is Xe-air; King et al., 2019a) and is, thus, likely responsible for the low $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios in these samples (Fig. 8 and 12).

The trends in noble gas concentrations and ratios with petrologic type often become even clearer when we include data for other primitive CCs. This may imply that the primordial matrix and initial noble gas abundances were similar for different CC groups. This observation is also supported by very similar presolar SiC grain abundances in the matrices of the most pristine members of the different carbonaceous chondrite groups (Davidson et al., 2014). Even though many of the CRs, CIs, and CYs analysed for noble gases are not classified by either of the alteration schemes used here, the CRs are, with a few exceptions, less affected by aqueous alteration than the CMs (Brearley, 2006), whereas CIs typically represent the most aqueously altered CCs (all type 1 according to the Van Schmus and Wood (1967) scheme). The CYs experienced varying degrees of aqueous alteration followed by thermal modification at temperatures of $>500\text{ }^\circ\text{C}$ (King et al., 2019a). The result is that the more primitive CCs (CMs, CRs, CIs, CYs, and C-ung) produce a roughly linear trend between $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios (Fig. 8), suggesting that there is an endmember component somewhere at the “end” of this trend

line. This Ar-rich endmember component, which apparently gets lost with increasing aqueous alteration grade, differs in composition compared to known noble gas components.

4.2.1.3 *Potential carrier phases of noble gases released with progressing aqueous alteration*

Aqueous alteration mostly results in a decrease in the ^{36}Ar concentration due to a loss of an Ar-rich component. Although the decrease in ^{36}Ar with progressive aqueous alteration is most pronounced, we also observe a loss of Kr and Xe (see above). However, it remains uncertain whether the gases released by aqueous alteration are all carried in the same phase or if there are small amounts of Q gases released from phase Q proper by aqueous alteration in addition to the main, poorly constrained, Ar-rich component. If we assume that the primordially trapped Ar, Kr, and Xe released by aqueous alteration are all carried in the same phase, there are two possible explanations for the more pronounced loss of ^{36}Ar with aqueous alteration compared to Kr and Xe, either: (i) this is the result of mass-dependent fractionation and the lighter Ar is easier to release by secondary processes, or (ii) the susceptible carrier is enriched in ^{36}Ar compared to Kr and Xe. Based on the roughly constant “baseline” noble gas contents of the more intensely aqueously altered CMs that are not affected by aqueous alteration, we argue that the second option is more likely and that the carrier(s) susceptible to aqueous alteration is(are) completely degassed at a certain stage (petrologic type ~ 1.5). Also, the low temperatures during parent body alteration favour a complete destruction of the carrier(s) rather than a diffusive process. Based on the decreases in Ar, Kr, and Xe concentrations from the most primitive to the highly altered CMs (in 10^{-8} cm³ STP/g: Ar ~ 360 , Kr ~ 1.7 , Xe ~ 1.5 ; Fig. 10A, C, E), we estimate $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios for the noble gases released by aqueous alteration to be ~ 240 and ~ 1.13 , respectively. These ratios are consistent with the trend defined by the primitive CMs and CRs in Fig. 8. However, many of the CRs and the most primitive CMs have higher $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios. Therefore, aqueous alteration likely causes a small release of Q gases from phase Q in addition to the unknown Ar-rich component from a distinct carrier, resulting in the estimated $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios being mixtures of both components. Release of some Q gases with aqueous alteration has previously been inferred by Busemann et al. (2000). These authors proposed that there are at least two phases carrying the Q gases, “Q₁” and “Q₂”, which both likely incorporated gases from a common reservoir but acquired or lost noble gases in different proportions. Both carriers are affected by parent body processes, thermal modification and aqueous alteration, but Q₂ is more susceptible to aqueous alteration (Busemann et al., 2000).

The carrier of the unknown Ar-rich component(s) is only present in the least altered CMs. This suggests that it might be a silicate phase. Amorphous silicates are probably good candidates as these are only abundant in the matrix of the most pristine CCs and are some of the first materials to be affected by aqueous alteration (e.g., Chizmadia and Brearley, 2008; Nakamura-Messenger et al., 2011; Floss and Stadermann, 2012; Leitner et al., 2012; Le Guillou et al., 2015; Leroux et al., 2015). DOM 08006 (CO3.00) is known to contain abundant amorphous silicates (15 vol. % Fe-bearing amorphous material;

Alexander et al., 2018) and also shows high concentrations in the heavier noble gases (Davidson et al., 2019). In Fig. 8, DOM 08006, assuming ~20 % of its Xe is terrestrial contamination (based on its Xe isotopic ratios), with $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios of $\sim 228 \pm 9$ and $\sim 1.07 \pm 0.03$, respectively, would plot in the range of the very pristine CMs. The same holds true for LL3.0 chondrite Semarkona that also contains amorphous silicates in its matrix (Dobrică and Brearley, 2020) with $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios of $\sim 164 \pm 6$ and $\sim 1.25 \pm 0.06$, respectively (assuming negligible Xe_{air} based on its Xe isotopic ratios; Schelhaas et al., 1990). Considering the low matrix abundance of Semarkona (~27 vol. %; Lobo et al., 2014), the matrix normalized Ar, Kr, and Xe concentrations of Semarkona approach those of the primitive CMs. Thus, data from DOM 08006 and Semarkona support the hypothesis of amorphous silicates being the carrier. Nevertheless, the carrier could also be metal, sulphide or other phases that are also readily altered by aqueous alteration processes (Nakamura-Messenger et al., 2011; King et al., 2017 and references therein). Also, the organic matter in CCs is a potential noble gas carrier of the Ar-rich component. However, based on the data at hand, we cannot prove that organic matter is the Ar-rich carrier susceptible to aqueous alteration. Figure A 3 shows a lack of clear trends between primordial ^{36}Ar and C contents (given in Alexander et al., 2012; 2013; Piani et al., 2018) in CMs. If we subtract the carbonate C from the bulk C (C-carb; Alexander et al., 2012; 2013; 2015), the correlation with ^{36}Ar is still poor. Argon-36 over C-carb decreases with decreasing petrologic type (Fig. A 8a). This, however, must be triggered by the loss of ^{36}Ar with progressing aqueous alteration as we do not observe any clear trend of C-carb either with the ^{36}Ar concentration (Fig. A 8b) or the petrologic type (Fig. A 8c). Nevertheless, our observations also do not exclude organics being the Ar-rich carrier susceptible to aqueous alteration: On the one hand, a potential carbonaceous carrier may represent only a very minor fraction of the total C (e.g., as expected for the likely carbonaceous carrier of the Q gases). A loss of such a fraction may well be below our detection limits and not visible in all the respective plots. On the other hand, even if we would observe a correlation between ^{36}Ar and C or C-carb contents in CMs, a causal correlation is not necessarily given.

In summary, our new CM data confirms trends previously observed in the CRs and extends the trends to the lower end of the petrologic range. Also, the CMs provide a high resolution of these trends as they cover a more complete range of petrologic types compared to the CRs. We were able to resolve the “threshold” at petrologic type ~1.5 on the Howard et al. (2015) scale when steep declines in noble gas abundances (>1.5 , due to a loss of noble gases with aqueous alteration) transform into relatively constant values (<1.5). The CRs and CMs (and possibly also CI/CYs) may have accreted the same noble gas carriers, including at least one newly recognized carrier (“Ar-rich”) that is very susceptible to aqueous alteration and whose nature is still poorly constrained. This supports the proposal that CM and CR chondrites (and other primitive CCs) were all formed from a common set of materials (e.g., Busemann et al., 2000; Alexander et al., 2007; 2010; 2013; 2017; Davidson et al., 2014; Alexander,

2019;) and, hence, started with similar, primordially trapped noble gas inventories that were subsequently modified by processing in the CC parent bodies.

4.2.2 Effect of thermal alteration on noble gases

The meteorites analysed in this work experienced various peak temperatures from $<120\text{ }^{\circ}\text{C}$ to $>750\text{ }^{\circ}\text{C}$. For this reason, we investigate if post-hydration heating influences the primordial noble gas inventory of a meteorite. Excluding SW-rich meteorites, He and Ne are suitable tracers for the effects of heating. If carried in the same phases, the lighter noble gases will have diffused out of their carriers faster than the heavier noble gases. PCA 02010 shows concentrations in the lighter noble gases (Fig. 4) that are significantly lower than in all other samples. This is in agreement with the high peak temperatures this meteorite has experienced ($>750\text{ }^{\circ}\text{C}$; Hanna et al., 2020; King et al., 2021). Only two other meteorites in this study, NWA 11024 and PCA 91008, have experienced temperatures in this range (see Table 1; updated minimum peak temperature used for PCA 91008; King et al., 2021). However, once PCA 02010 is excluded, we do not observe any clear differences in the He and Ne concentrations between the heated (including NWA 11024 and PCA 91008) and unheated samples in Fig. 4 that do not show evidence for containing significant SW (black data points). Hence, heating of material below temperatures of $\sim 750\text{ }^{\circ}\text{C}$ probably only has a weak effect (if any) on the light noble gas abundances, which is in agreement with stepwise heating experiments on the CM chondrite LEW 90500 (Eugster et al., 1998). Also with respect to the heavier noble gases Ar, Kr, and Xe, none of the heated CMs but PCA 02010 shows noble gas concentrations significantly lower than the most aqueously altered unheated samples.

It is, however, possible that the effect of heating is not clearly visible due to the concurrent changes in noble gas compositions associated with aqueous alteration. This is difficult to deduce from the lighter noble gases only as we do not consider SW-rich meteorites and, hence, the number of heated and unheated meteorites with a common degree of aqueous alteration is limited (especially amongst the very primitive CMs in which changes due to heating are expected to be most evident). Hence, to explore the interference of effects from aqueous and thermal alteration we focus on the concentrations of the heavier noble gases. Note that by XRD reliable pre-heating aqueous alteration degrees can be determined for heated samples (cf. section 2.6). It should also be borne in mind that heating may have different effects on the heavier noble gases compared to the light ones if they have distinct carrier phases with different heat resistance.

On the one hand, some of the heated CMs (LAP 02277, MET 01072, QUE 93005, GRA 98005, PCA 02010, LAP 04514, EET 96029, PCA 91008, NWA 11024) have lower noble gas concentrations (^{36}Ar , ^{84}Kr , ^{132}Xe) compared to (most) other meteorites of the same petrologic type (Fig. 10). In particular, PCA 02010, NWA 11024, and PCA 91008 (all heated to $>750\text{ }^{\circ}\text{C}$; Table 1) plot well below other CMs of similar petrologic type in Fig. 10. Trapped (and radiogenic) noble gas concentrations (He-Xe) in PCA 02010 are so low that it seems to have been almost completely degassed. Furthermore,

PCA 02010 has the lowest bulk H, C, and N contents, as well as C/H and C/N ratios, of any of the CMs analysed by Alexander et al. (2013). It seems likely that the high degree of thermal alteration of PCA 02010 was responsible for the observed features in this meteorite. While PCA 02010 lost most of its trapped components, it still contains significant cosmogenic noble gases, indicating that the heating event occurred long before its arrival on Earth (e.g., in the parent body).

On the other hand, MIL 05152, NWA 10827, and ALH 84033 experienced thermal alteration (all heating stage II, see Table 1) after being aqueously altered but still have relatively high concentrations of all three noble gases. Particularly for petrologic types <1.5, we observe little heating-related differences in the element concentrations as the concentrations in the heated samples do not drop much lower than the lowest concentrations already reached with moderate aqueous alteration. This implies that affected carriers of the more altered CMs have been efficiently degassed due to aqueous alteration prior to thermal alteration and/or heating <500 °C does not have an effect on the noble gas concentrations. The latter would also explain the high Ar, Kr, and Xe concentrations of NWA 10827, ALH 84033, and MIL 05152 (all heated to 300-500 °C) relative to the unheated samples with similar petrologic type. The primordial noble gases He-Xe in the CM chondrites studied here are discernibly affected at temperatures >750 °C, which is also consistent with stepwise heating experiments on LEW 90500 (Eugster et al., 1998). Also, in stepwise heating experiments on two CM chondrites by Nakamura (2006), a major part of the noble gases is released at temperatures ≥ 680 °C, while noble gases released at lower temperatures may be atmospheric. Altogether, our results indicate an additional volatile loss upon heating of CM chondrites to temperatures certainly >750 °C, possibly already above 500 °C (no stage III CM included in this study), which has been previously suggested for CY chondrites heated to >500 °C (King et al., 2019a).

The noble gas concentrations in NWA 11024 and PCA 91008 (both heated to >750 °C) are somewhat contradictory. The concentrations in the heavier noble gases are, as expected, significantly lower than those in CMs with similar petrologic types. However, the concentrations of the lighter noble gases, ^4He and $^{20}\text{Ne}_{\text{tr}}$, are in the typical range for unheated and mildly thermally altered CMs, different from the case of PCA 02010 (also heated to >750 °C). Potentially, we can expect different effects of thermal alteration on different noble gas elements as they are usually carried in distinct phases with individual heat resistance. For example, primordially trapped He and Ne might not be affected by short-period heating to ~ 750 °C as they are mostly carried by highly resistant presolar grains (Ott, 2014). In contrast, the heavier noble gases might react differently as some of their carriers are possibly less heat-resistant (e.g., metals, sulphides, amorphous silicates, organics). Although PCA 02010, NWA 11024, and PCA 91008 were all heated to >750 °C, lower peak temperatures within this range experienced by PCA 91008 and NWA 11024 compared to PCA 02010 or shorter durations of heating at peak temperature could explain our observations that PCA 91008 and NWA 11024 still contain significant He and Ne amounts, whereas PCA 02010 experienced a significant loss of the light noble gases.

To sum up, intense thermal modification with peak temperatures >750 °C affects the CM noble gas inventories. Within this range, heavy noble gases (mainly Q and the Ar-rich gases) may be released at lower temperatures than He and Ne (mainly residing in presolar grains) since they have different carriers with different heat resistance. For peak temperatures <500 °C, there is no significant effect on noble gas abundances. The effect of heating on CMs to 500-750 °C still needs to be investigated. The noble gases in CMs indeed seem to be less sensitive to heating than, e.g., organics (i.e., a loss of H and often C and N; Alexander et al., 2012; 2013) and infrared transmission spectra (i.e., reduction of the intensity of water-related absorption at 3 μm ; Fig. A 9; Beck et al., 2014). However, only 12 heated CMs are included in this study (and only three out of these have been analysed spectroscopically by Beck et al., 2014) and an increase of the data set or stepwise heating experiments might change the picture. A refinement of the heating scale (i.e., a division of stage III and IV into several sub-stages) may also facilitate more detailed investigations on the effect of thermal alteration on noble gases. Possibly, the duration of the heating and pressure, as well as the environment (e.g., $f\text{O}_2$, pH, mineralogy), about which we have little information, is also crucial to understanding the effects of thermal alteration.

As a side note, according to Black (1972), SW-Ne is mainly released from CM chondritic material at temperatures between 100 °C to 500 °C. EET 96029, heated to 300-600 °C, still contains abundant SW-Ne, which indicates that the heating event probably happened before SW incorporation. Hence, the timing of SW incorporation can be loosely constrained to a time after heating. Also, no other sample but EET 96029 in this study is heated and clearly contains SW-Ne which would confirm our observations. Nevertheless, an early irradiation to SW, before or around accretion of the CM parent body can be excluded (cf. also below).

4.3 Noble gas abundances in a CM parent body unaffected by parent body alteration processes

LEW 85312 and NWA 10827 are amongst the most pristine CMs identified to date and contain only minor (if any) SW. Based on the noble gas concentrations measured in LEW 85312 and NWA 10827, we have estimated the primordial noble gas concentrations in a CM parent body that was unaffected by parent body alteration and U/Th decay (Table 7). Helium-4 and ^{20}Ne ranges given in Table 7 also cover the concentrations of some more of the most primitive samples amongst the CMs that are certainly unaffected by SW (e.g., LAP 04514). The production of $^4\text{He}_{\text{rad}}$ within the first ~ 100 Ma of Solar System evolution is negligible. However, over 4.55 Ga, substantial amounts of $^4\text{He}_{\text{rad}}$ have accumulated in the CM chondrites. Here we subtracted 1755×10^{-8} cm³ STP/g $^4\text{He}_{\text{rad}}$ from the actual ^4He range of 3000-4500, based on the average CM U and Th concentrations of 10 ppb and 39 ppb, respectively (Alexander, 2019), and assuming no $^4\text{He}_{\text{rad}}$ loss. In the case of no aqueous alteration (a.a.) and no SW, corresponding ^3He concentrations were determined based on the ^4He concentrations and $(^3\text{He}/^4\text{He})_{\text{HL}} = (1.7 \pm 0.1) \times 10^{-4}$

(Huss and Lewis, 1994) as CMs that are unaffected by SW and only moderately altered (not dominated by ${}^4\text{He}_{\text{rad}}$) show ${}^3\text{He}/{}^4\text{He}$ ratios of ~HL composition.

The noble gas compositions of CM chondrites given here can be used to constrain contributions of CM chondritic material to the formation of the terrestrial planets (see, e.g., Marty, 2012; Halliday, 2013; Williams and Mukhopadhyay, 2019). The values given here are based on the so far detected concentrations in a large number of samples, and although the range given may obviously slightly change with newly found samples, this is the best (only?) way to determine them using the meteoritic database. However, the time of accretion of chondritic bodies by the planets, i.e., whether it took place before or after (1) aqueous alteration started and (2) SW was incorporated in the CM parent body, is unknown. This thus represents a major difficulty to determine the noble gas content of CM planetesimals potentially accreted by the terrestrial planets. Depending on whether accretion took place before or after aqueous alteration started, one has to use the primordial noble gas abundances of the most pristine or the more altered CM samples, respectively. Another unknown is the time and duration of SW incorporation in the CM parent body, although the heating that EET 96029 experienced must have occurred before SW incorporation (see section 4.2.2). It is possible that SW incorporation into small planetary bodies had already taken place within the first million years after CAI formation. In fact, SW in the upper tens of meters of a planetesimal (assuming 300 times more He and Ne, see e.g. QUE 97990 in Fig. 4) might be significant even for planetary bodies with radii of for example >50 km (20 m regolith with the concentration of QUE 97990 would contribute ~36 % of the gas of a body of 50.02 km radius with an average CM concentration; Fig. 4). Thus, depending on whether accretion took place before or after SW incorporation into chondritic material, one may have to consider primordial and SW noble gases in CMs to constrain CM chondritic contributions to terrestrial planet formation. For this reason, in addition to the primordial noble gas contents of CM chondritic material unaffected by parent body aqueous alteration in Table 7, we give (1) noble gas contents typical for highly altered CMs based on MIL 05137 and MIL 07689 (petrologic type 1.1) and (2) additional He and Ne concentrations typical for CM material strongly affected by SW (2a) based on the primitive CM chondrite QUE 97990 (petrologic type 1.6) and (2b) based on the highly altered CMs MET 00432, Mukundpura A, and ALH 85013 (petrologic type 1.1-1.3).

4.4 CRE ages

CRE ages represent the interval over which meteoroids were exposed to cosmic rays as a small object in interplanetary space, typically following ejection from their parent bodies. Clusters of CRE ages within a meteorite group indicate common ejection events. A pre-exposure to cosmic rays at the surface of the meteoroid's parent body before excavation is possible and needs to be considered, especially when SW is detected in the meteorite. The determination of CRE ages for CMs based on ${}^{21}\text{Ne}_{\text{cos}}$ entails significant uncertainties because of the high abundances of trapped Ne in these meteorites, and the resulting, large uncertainties associated with the ${}^{21}\text{Ne}$ production rates.

Previous studies have found that CM chondrites have relatively young CRE ages, i.e., typically ≤ 10 Myr (Herzog and Caffee, 2014), compared to other CC classes (except for CIs and CYs; Herzog and Caffee, 2014; King et al., 2019a). This is mostly consistent with our results (Table 5, Fig. 9). In this study, 35 of our 39 CMs have CRE ages of < 10 Myr (when we discuss CRE ages we refer to the centre of the possible CRE age range of a given meteorite). The CRE ages calculated from CM literature data are also all within this range. Only four CMs (NWA 10827, LAP 04796, QUE 97990, and ALH 85013) have CRE ages that are higher than previously observed for any CMs. The highest CRE age of ~ 20 Myr (ALH 85013) is about a factor of two higher than the highest ages determined from literature data, although the corresponding CRE age ranges are large. ALH 85013 and QUE 97990 contain abundant SW noble gases and for the other two high CRE age samples, LAP 04796 and NWA 10827, we cannot exclude some contributions from SW. Hence, we have to consider the possibility that they experienced pre-exposure to cosmic rays as part of a regolith at the surface of their parent body(ies).

According to the Meteoritical Bulletin Database, EET 96006, EET 96016, and EET 96029 (as well as several more Antarctic finds) are paired. The pairing between EET 96029 and other members of this pairing group has been questioned by Tyra et al. (2007) based on differences in carbonate abundances and O isotope compositions. Lee et al. (2016), however, argue the O isotope composition is more heterogeneous within EET 96029 than between the different meteorites and, hence, support pairing of these EET samples. The calculated CRE age ranges for EET 96006 and EET 96016 are very similar to each other (2.6-6.6 Myr and 2.7-6.8 Myr, respectively), which supports pairing of these two meteorites. The CRE age range determined for EET 96029, however, is significantly lower (0.4-1.3 Myr) than the ranges of the other two members of the pairing group. EET 96029 can therefore not be paired with EET 96006 and EET 96016 without suggesting more complex exposure scenarios, i.e. some pre-exposure of the latter two compared to EET 96029 on the parent body.

We observe the most pronounced cluster of CRE ages at ~ 0.2 Myr. This is in agreement with Zolensky et al. (2021, and references therein), who investigated the distributions of CRE ages determined by Nishiizumi and Caffee (2002) based on cosmogenic radionuclides. Our observation suggests that all the CMs (10 samples) forming the peak in the probability density plot (PDP; Fig. 9) were ejected in the course of one common impact event (assuming that the terrestrial ages of these meteorites are negligible as the ejection age represents the sum of the CRE age and the terrestrial age). There might be more clusters of CRE ages at ~ 1 , ~ 4.5 -6, and ~ 8 Myr indicating separate ejection events from one or multiple CM parent bodies. However, due to scatter in the CRE ages, the small number of available ages, and large uncertainties, these peaks are not very pronounced. Also, the CMs with CRE ages ≥ 11 Myr likely result from a separate collision(s) provided that pre-exposure to cosmic rays has a minor influence on the calculated ages.

Since we have several CMs in our sample suite with a CRE age of ~ 8 Myr, we also have a few candidates that possibly originate from the Veritas break-up 8.3 ± 0.5 Ma ago, which was probably the largest asteroid break-up event in the last 100 Myr (Nesvorný et al., 2003; Meier et al., 2016). The Veritas family is of the C type (Ch/C/Cg) that are spectrally similar to CM chondrites (Mothé-Diniz et al., 2005). The CRE ages of LEW 85312 and QUE 99355, in particular, correspond closely with the estimated formation age of the Veritas family.

It has previously been stated that all highly altered CMs have relatively low CRE ages, whereas many (but not all) of the primitive CMs show longer CRE ages (Zolensky et al., 2021, and references therein). King et al. (2020) also found short exposure ages of ~ 0.2 Myr to be characteristic for the highly altered CM1s, whereas the less altered CM2s show CRE ages in the range of 0.6-2 Myr and intermediately altered CMs tend to have CRE ages > 3 Myr. We cannot confirm these findings by our results. Figure 14 shows that the CRE ages determined for the CMs in this study do not show a clear trend with the petrologic type determined by PSF. For one of the highly altered (petrologic type 1.3) CMs, ALH 85013, we calculated a CRE age of ~ 20 Myr, the longest CRE age determined for any CM. However, we cannot exclude the possibility of a pre-exposure history for this meteorite. Several of the other highly altered CMs (petrologic type 1.1-1.3) have CRE ages of up to ~ 8 Myr. Indeed, the exposure ages of all CMs with petrologic type ≥ 1.7 ($n=5$) are greater than or equal to ~ 4.7 Myr. However, the number of CMs with such low degrees of alteration is too small to draw robust conclusions about trends between CRE ages and the petrologic types of CMs. Also, we do not observe any preferential CRE ages for heated and unheated CMs, respectively. Note that looking only at the centres of the T_{21} ranges instead of the unknown “true” CRE ages within these ranges may obscure any potential trend and we cannot definitely rule out the existence of a correlation with the alteration degree. Nevertheless, in Fig. 14, petrologic characteristics, both the degree of aqueous alteration and thermal modification, seem to be variable amongst meteorites with similar CRE ages.

Several scenarios can explain these observations: (1) excavation of surface material of a single parent body characterised by a heterogeneous mixing of lithologies with different degrees of alteration at the cm to m scale; (2) excavation of material from a large depth range (various alteration conditions) from a single parent body with well mixed lithologies at the cm to m scale, possibly but not necessarily due to a complete disruption of the asteroid; (3) delivery of material from more than one parent body with various characteristics (as previously proposed by Lee et al. (2019b) based on differences in the chemical composition of LEW 85311 compared to other members of the CM group) and the ejection occurred either due to separate collisions at about the same time or due to a single collision of the parent bodies themselves. The second scenario is less likely as heterogeneous mixing of lithologies in CM chondritic material is observed at the cm-scale, i.e., CMs often represent breccias that consist of various lithologies with different alteration degrees (e.g., Metzler et al., 1992; Lindgren et al., 2013; Bischoff et al., 2017; Lentfort et al., 2020). Although our results could be explained by the first scenario, we also

consider the CMs may originate from multiple CM parent bodies. Bischoff et al. (2006), e.g., suggested precursor CM parent bodies may have accreted from a similar starting material ~ 4.56 Ga ago. Subsequent impact processing may have caused a disruption and/or brecciation of these precursor bodies and the formation of the final CM parent bodies. Further evolution of these bodies in a similar environment, thus, can explain similar but not identical mineralogical and isotopic characteristics observed in CMs according to Bischoff et al. (2006). Secondary processing (aqueous and thermal alteration) may have started before accretion of the second generation parent body(ies) and continued in the final CM parent body(ies) (Brearley, 2006, and references therein).

5 Summary and conclusions

Within this work, we analysed the noble gas compositions of 50 bulk samples of CMs and some CM-related CCs that experienced varying degrees of aqueous and thermal alteration. In addition, we determined the petrologic type according to Howard et al. (2015) based on the volume fraction of phyllosilicates for 17 CM samples. Our main findings and conclusions are summarized in the following:

- Using XRD analysis, we identified/confirmed a number of least aqueously altered CMs with low phyllosilicate fraction (PSF), similar to the most primitive lithologies of Paris (Hewins et al., 2014): LEW 85312 (1.8), NWA 11024 (1.8), NWA 10827 (1.7), Paris B (1.7), ALH 84033 (1.7).
- Only about 50 % of the CMs contain detectable SW (-Ne) in bulk sample analysis and, hence, not all CMs can be defined as regolith breccias based on noble gases. We cannot exclude a pre-accretion exposure to SW of very minor phases in the other CMs, though, as resulting concentrations may be below the detection limit of SW in bulk samples.
- Aqueous alteration has an effect on noble gas abundances and elemental (and isotopic) compositions in CMs, i.e., causes a loss of an $^{36,38}\text{Ar}$ -rich, but otherwise still poorly constrained, component during the early stages of aqueous alteration until complete degassing of its carrier material (<1.5).
- While noble gases cannot be used for an exhaustive scale of alteration in chondrites, they can differentiate between highly primitive (close to type 3) and moderately to severely altered (type 1/2) specimens.
- It remains uncertain if *all* Ar and Kr and Xe lost upon parent body aqueous alteration share the same carrier phase. There might also be a small release of Q gases dominant in Kr and Xe, in addition to the Ar-rich component.
- The nature of the Ar-rich component as well as its carrier(s) still needs to be further constrained. We assume a component with high $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios, similar or higher than those of the most primitive CCs. Potential carriers are, e.g., amorphous silicates, metals, or sulphides as these phases tend to be modified quickly with aqueous alteration.

- Strong thermal modification >750 °C (possibly >500 °C as previously suggested for CY chondrites; King et al., 2019a) leads to an additional loss of noble gases in CM chondrites. For peak temperatures <500 °C, there is no clear pattern visible. Possibly, other factors such as duration of heating and environmental factors influence the behaviour of noble gases in addition to peak temperature.
- CMs extend and substantiate the alteration trends previously observed for CRs (Busemann et al., 2021). Hence, these (and probably also other carbonaceous) chondrites likely started with a similar initial noble gas inventory due to accretion of material from a common reservoir.
- Most of the CMs have CRE ages <10 Myr with a distinct peak in the probability density plot (PDP) at ~ 0.2 Myr. For four CMs we determined longer CRE ages between 11 and 20 Myr, exceeding all exposure ages for CMs given in (or calculated from) the literature. In addition to the clear peak at ~ 0.2 Myr, we observe three further minor peaks in the PDP at ~ 1 , ~ 4.5 -6, and ~ 8 Myr, respectively. All these peaks could represent individual ejection events. In addition, the CMs with exposure ages ≥ 11 Myr possibly were ejected in a separate event. However, as many CMs (including the ones with the highest CRE ages) carry SW, pre-exposure to cosmic rays might play a role. This prevents us from better constraining the number of ejection events responsible for the CMs found on Earth.
- We do not find a strong correlation between CRE ages and alteration grades of the CMs as stated earlier (e.g., Zolensky et al., 2021). In this work, meteorites with similar exposure ages show various degrees of aqueous and thermal alteration.

Acknowledgements

We thank Kieren Howard (American Museum of Natural History, New York), Martin Bizzarro (Natural History Museum of Denmark), Laurence Garvie and the Center for Meteorite Studies (Arizona State University), Yves Marrocchi (CRPG, CNRS, Nancy), Samuel Ebert (Westfälische Wilhelms-Universität Münster), Matthieu Gounelle (Muséum National d'Histoire Naturelle, Paris), and Knut Metzler (Westfälische Wilhelms-Universität Münster) for kindly providing some samples analysed in this study. For supplying the many Antarctic samples that were used in this work, the authors would like to thank: the members of the Meteorite Working Group, Cecilia Satterwhite and Kevin Righter (NASA, Johnson Space Center). US Antarctic meteorite samples are recovered by the Antarctic Search for Meteorites (ANSMET) program, which has been funded by NSF and NASA, and characterized and curated by the Department of Mineral Sciences of the Smithsonian Institution and Astromaterials Curation Office at NASA Johnson Space Center. The manuscript was significantly improved thanks to careful reading and detailed reviews by two anonymous reviewers and Jemma Davidson, as well as by comments from associate editor Anders Meibom. We thank Tomoki Nakamura for reading and

providing feedback on an earlier version of the manuscript. This research was supported by the Swiss National Science Foundation (SNSF), in parts through the NCCR “Planet S” (M. E. I. Riebe and H. Busemann). XRD analyses were partly carried out in the course of Europlanet 2020 RI, which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 654208. Jens Najorka is thanked for help with the PSD-XRD analyses, and A. J. King was supported by the Science and Technology Facilities Council (STFC), UK, through grant no. ST/R000727/1.

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Figure Captions

Fig. 1: Neon compositions of CCs in a Ne-three-isotope plot showing varying abundances of trapped (predominant in most samples) and cosmogenic Ne. We distinguish three different trapped endmember groups for the deconvolution of trapped and cosmogenic Ne (coloured areas, see section 2.3). The same figure with all meteorite names is given in the appendix (Fig. A 7).

Fig. 2: PSD-XRD patterns for a) non-heated CMs Maribo, Paris A, Mukundpura B, and b) for heated CMs MET 01072 (<300 °C), ALH 84033 (300-500 °C), and NWA 11024 (>750 °C). The main phases identified include phyllosilicates (cronstedtite and Mg-serpentine), olivine, pyroxene (enstatite), magnetite, calcite, Fe-sulphides (pyrrhotite and pentlandite), metal, and gypsum. Progressive aqueous alteration causes an increase in the phyllosilicate fraction of the meteorite. Subsequent thermal modification at peak temperatures >300 °C results in a dehydration and dehydroxylation of phyllosilicates and corresponding diffraction peaks are no longer present in the PSD-XRD patterns. Above 500 °C dehydrated phyllosilicates start to recrystallize back into olivine resulting in broad peaks in diffraction patterns (as observed in NWA 11024 but not in ALH 84033). As there is no evidence for dehydrated phyllosilicates but abundant secondary olivine in the pattern of NWA 11024 this meteorite was likely heated to >750 °C. The low intensity of the peaks at ~12° and ~25° from Fe-rich serpentine in the pattern of MET 01072 suggests that the peak metamorphic temperature was <300 °C (compared to a high intensity/absence of these peaks in patterns of meteorites that experienced no heating/peak temperatures >300 °C).

Fig. 3: Trapped Ne plot used to identify solar wind contribution in CCs summarized in Table 1. Samples that plot in the orange area clearly contain SW (marked with “X” in Table 1). All meteorites in the purple area do not contain detectable SW in bulk material (see discussion in section 4.1.1). Meteorites plotting in the grey area likely contain SW and/or another Ne-rich component similar to Ne-Q (marked with “(X)” in Table 1). The $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios of Nogoya, ALH 84042, PCA 02010, and the NWA 10574 (large uncertainties because of high blank corrections due to small sample masses; see Table 2) samples are between those of HL and Q. However, trapped Ne and He is within the “baselines” in Fig. 4 which argues against detectable solar wind in these meteorites. The same figure with all meteorite names is given in the appendix (Fig. A 10)

Fig. 4: ^4He (circles) and $^{20}\text{Ne}_{\text{tr}}$ (triangles) concentrations. Concentrations in samples that clearly show a SW component (orange; above Q-cos mixing line in Fig. 1 and $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}} < (^{22}\text{Ne}/^{20}\text{Ne})_{\text{Q}}$ in Fig. 3, indicated with “X” in Table 1) are higher than the “baselines” (light blue ranges) constrained by samples without evidence for SW (purple; on mixing line between Ne_{cos} and Ne with $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{tr}}$ slightly below that of Ne-HL in Fig. 1, purple area in Fig. 3). QUE 97990 shows the highest concentrations in both elements and, hence, is the most SW-rich sample. Samples that (1) plot in the triangle constrained by

Ne_{cos} , Q, and HL in Fig. 1, (2) have moderate $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}}$ ratios (Fig. 3), and (3) have concentrations higher than the “baselines” (shown in grey) likely contain a SW component and/or another He/Ne-rich component (we assigned these samples a “(X)” in Table 1). In contrast to the $^{20}\text{Ne}_{\text{tr}}$ concentration, the ^4He concentration of the NWA 10827 samples and ALH 84033 is in the range of those of the meteorites without evidence for SW. Both meteorites are amongst the most primitive CMs. The same can be observed for the primitive C-ung EET 83355. Furthermore, the $^{20}\text{Ne}_{\text{tr}}$ concentrations of the LEW 85312 samples (the most primitive CM in this study) are the highest amongst all meteorites that are shown as grey data points, whereas the ^4He concentrations are similar to other meteorites of this group. Samples with high $^{20}\text{Ne}_{\text{tr}}$ but comparably low ^4He are marked with “Ne” in Table 1. Heated meteorites are shown as open symbols. The most severely heated meteorite, PCA 02010, shows by far the lowest concentrations in both elements.

Fig. 5: Xe isotopic compositions of CCs and air (Basford et al., 1973) normalized to Xe-Q from Busemann et al. (2000). Many samples are affected by air contamination in Xe. About half of the CCs contain ^{129}I -derived Xe which is the reason for the peaks at mass 129. A contribution of HL results in higher normalized ratios for the lightest and heaviest Xe isotopes (e.g., NWA 5958). Furthermore, in a few meteorites (most distinct in NWA 10574 B and also PCA 02010) we observe a contribution of Xe_{cos} (due to low Xe_{tr} or high abundances of the target elements in the meteorite) responsible for the elevated ratios at mass 126.

Fig. 6: $^{128}\text{Xe}/^{132}\text{Xe}$ plotted versus terrestrial weathering grade (where available, see Table 1). Most samples scatter around the Q ratio (Busemann et al., 2000). Samples that experienced strong terrestrial weathering tend towards the air ratio (Basford et al., 1973), implying that the air contamination is related to the conditions and the residence time on Earth before recovery of the meteorites.

Fig. 7: The bulk Xe isotopic compositions of the analysed CCs in a Xe-three-isotope plot showing that their Xe contents are mainly mixtures of Q (dominant), HL, and air. About half of the samples also contain some ^{129}I -derived Xe.

Fig. 8: Three-element plot. We show the elemental ratios of the heavy noble gases in the measured samples, as well as CRs (Busemann et al., 2021) and CI/CYs (Mazor et al., 1970; Nagao et al., 1984; Riebe et al., 2017a; King et al., 2019a). The petrologic types according to Howard et al. (2015) are colour-coded. Many samples have ratios close to those of Q (shaded in yellow). The most primitive CCs tend to have higher $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ (shaded in blue). The red star represents the composition of the noble gases released by aqueous alteration which is a mixture of the Ar-rich component and Q gases. Samples for which the Xe-air correction was most significant often have higher $^{84}\text{Kr}/^{132}\text{Xe}$ ratios implying that Kr-air is also substantial in those samples. The CR, CI, and CY data are not corrected for Xe-air, which might lead to slightly underestimated $^{84}\text{Kr}/^{132}\text{Xe}$ ratios. A comparison

of this plot prior to and after Xe correction for air (except for the CRs, CIs, and CYs) is shown in the appendix (Fig. A 11).

Fig. 9: The CRE age ranges of the CCs analysed in this study and calculated for all CMs from bulk noble gas data in the literature (Schultz and Franke, 2004; Haack et al., 2012; Hewins et al., 2014) using the same approach. The symbol represents the centre of a CRE age range. Also shown is a probability density plot (PDP) for the CM exposure age ranges determined in this study (calculated using DensityPlotter by Vermeesch, 2012; we used the mean age ranges for meteorites with multiple measurements and paired specimens) and the range of the Veritas break-up (purple). The exposure age range of EET 83355 (C2-ung) is not shown (44-111 Myr). CRE age ranges determined in this study mostly agree with age ranges calculated from literature data. The main CRE age cluster of CMs is at ~0.2 Myr. We observe further minor peaks in the PDP at ~1, ~4.5-6, and ~8 Myr. The circles below the PDP represent the number of exposure ages considered. Some CMs in this study have their centre of the CRE age range at ≥ 11 Myr exceeding all values previously determined for CMs.

Fig. 10: The abundances of ^{36}Ar (top), ^{84}Kr (centre), and ^{132}Xe (bottom) of the CMs versus their petrologic type according to Howard et al. (2015) (left; A, C, E) and Alexander et al. (2013) (right; B, D, F). There are different meteorites shown in the left and right figures as not all of the samples have been classified according to both schemes. Also, heated samples are not shown in the figures on the right as the Alexander et al. (2013) method is not suitable for determining pre-heating aqueous alteration degrees. The concentrations of the heavy noble gases tend to decrease with increasing degree of aqueous alteration (lower petrologic type). The most primitive CMs have concentrations that are up to 20 and 8 times higher than highly altered samples for Ar and Kr and Xe, respectively. Correlations are slightly more pronounced when plotting concentrations versus petrologic types according to Howard et al. (2015), in particular for ^{84}Kr and ^{132}Xe . The same figure with all meteorite names is given in the appendix (Fig. A 12).

Fig. 11: The ^{36}Ar concentration of CMs versus their petrologic type on the Rubin et al. (2007) scale. Unheated CMs with higher petrologic types, meaning lower degree of aqueous alteration, tend to have higher ^{36}Ar concentrations compared to more aqueously altered samples. The petrologic type of Paris is 2.7-2.9 (see Table 1 for references).

Fig. 12: CMs with high petrologic types (≥ 1.5) according to Howard et al. (2015) tend to have higher $^{36}\text{Ar}/^{132}\text{Xe}$ ratios than samples with lower petrologic types. As ^{36}Ar and ^{132}Xe both mainly reside in the matrix of the meteorites, variations in the matrix/chondrule ratios of CMs are negligible and do not control previously identified trends of Ar concentrations decreasing with aqueous alteration. The $^{36}\text{Ar}/^{132}\text{Xe}$ ratios of the CMs with petrologic type < 1.5 are in agreement with ratios measured in the highly altered CRs (Busemann et al., 2021), whereas the most primitive CMs show ratios in the range

of $^{36}\text{Ar}/^{132}\text{Xe}$ ratios occupied by most of the CRs (Busemann et al., 2021). The same figure with all meteorite names is given in the appendix (Fig. A 13).

Fig. 13: The ^{36}Ar versus ^{132}Xe concentrations of the samples analysed here, as well as of CRs (Busemann et al., 2021) and CI/CYs (Mazor et al., 1970; Nagao et al., 1984; Riebe et al., 2017a; King et al., 2019a). Many of the most primitive CMs and other CCs tend towards the trend defined by the primitive CRs (CR2-3) analysed by Busemann et al. (2021). The concentrations of ^{36}Ar (and less so of ^{132}Xe) decrease with higher degrees of alteration. The majority of the CMs (highly altered) plot roughly on the trend formed by the highly altered CRs (CR1-2). PCA 02010 (severely heated) shows the lowest concentrations in ^{36}Ar and ^{132}Xe (but also other noble gases) amongst all samples analysed in this study. The CI/CYs mostly plot in the range of the mildly to highly altered CMs. A comparison of this plot prior to and after Xe correction for air is shown in the appendix (Fig. A 14).

Fig. 14: No obvious correlation between CRE ages and the petrologic type of CMs (and Bells). Petrologic characteristics are variable amongst meteorites with similar CRE ages. We calculated the longest CRE age (19.8 Myr) for ALH 85013, a highly altered CM of petrologic type 1.3. None of the CMs with petrologic type 1.7 and 1.8 has a CRE age < 4.7 Myr. For reasons of clarity we do not show most likely ranges of CRE ages.

Tables

Table 1: A list of all samples analysed here for their noble gas compositions. Also listed are their meteorite groups and weathering grades as given in the Meteoritical Bulletin Database, and the K concentrations (if available) of the meteorites. The degree of alteration (aqueous and thermal) is given according to various alteration scales. We indicate samples that clearly, “X” ($(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}} < (^{22}\text{Ne}/^{20}\text{Ne})_{\text{Q}}$), or very likely, “(X)” ($(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}} < (^{22}\text{Ne}/^{20}\text{Ne})_{\text{HL}}$) and trapped He and Ne above the

“baselines” in Fig. 4), carry SW in the last column. Samples with $(^{22}\text{Ne}/^{20}\text{Ne})_{\text{tr}} < (^{22}\text{Ne}/^{20}\text{Ne})_{\text{HL}}$ and high Ne_{tr} , but comparably low He_{tr} , are additionally marked with “Ne”.

Sample	Fall	Source	Groups*	Weathering grade*	K [ppm]**	Degree of aqueous alteration according to methods suggested by***			Degree of thermal metamorphism (peak temperatures)	Solar wind /Ne-rich ^o
						Rubin et al. (2007)	Alexander et al. (2013)	Howard et al. (2015)		
ALH 84033		C.A.	CM2	Ae				1.7	heated ^f /300-500 °C	(X)/Ne
ALH 84042		C.A.	CM2	A	415			1.2		
ALH 85013		C.A.	CM2	A	384			1.4	1.3	X
Banten	X	C.A.	CM2	Fall	581			1.7	1.6	X
DOM 08003		C.A.	CM2	B				1.1	1.2	
EET 96006		C.A.	CM2	Be				1.3	1.5	
EET 96016		C.A.	CM2	Be				1.4	1.4	
EET 96029 ⁺		C.A.	CM2	A/B	498	2.7 ^e		1.6 ^e	heated ^f /weakly ^g /~400-600 °C ^e /300-500 °C ^m	X
GRA 98005		C.A.	CM2	Ce				1.7	1.5	<300 °C (<120°C?)/heated ^f
GRO 95566		C.A.	CM-an	A/Be				1.6		
LAP 02277		C.A.	CM1	A		2.0		1.4	1.2 ^e	heated ^f
LAP 02333		A.K.	CM2	B	830			1.5	1.5	(X)
LAP 04514		A.K.	CM2	B	830			1.6 ^d	<300 °C	
LAP 04796		A.K.	CM2	A/B				1.6 ^d		(X)
LEW 85312 A		C.A.	CM2-an	B				1.8	1.8	(X)/Ne
LEW 85312 B		C.A.	CM2-an	B				1.8	1.8	(X)/Ne
LEW 85312 C		C.A.	CM2-an	B				1.8	1.8	(X)/Ne
LEW 90500		C.A.	CM2	B				1.6	1.4	
LON 94102		C.A.	CM2	Ce	368			1.8	1.3	(X)
Maribo	X	M.B.	CM2	Fall	372				1.6	(X)
MET 00432		C.A.	CM2	B				1.7	1.1	X
MET 01070		K.H.†	CM1	Be	233	2.0		1.2	1.2	
MET 01072		C.A.	CM2	B				1.5	1.2	if, <300 °C/heated ^f
Mighei	X	K.H.†	CM2	Fall	329			1.6	1.4	
MIL 05137		A.K.	CM1	Be					1.1 ^e	
MIL 05152		C.A.	CM2	B				1.4	1.4	heated ^f /300-500 °C
MIL 07689		A.K.	CM1	C					1.1 ^e	
Mukundpura A	X	L.G.	CM2	Fall	415				1.2	X
Mukundpura B	X	L.G.	CM2	Fall	415				1.5	X
Murchison [*]	X	C.A.	CM2	Fall	496	2.5	1.6	1.5	1.5	X
Murray	X	C.A.	CM2	Fall	323	2.4/2.5	1.5	1.5	1.5	(X)
Nogoya	X	C.A.	CM2	Fall	517	2.2	1.1	1.2	1.2	

Table 1. Continued.

Sample	Fall	Source	Class*	Weathering grade*	K [ppm]**	Degree of aqueous alteration according to methods suggested by***			Degree of thermal metamorphism (peak temperatures)	Solar wind /Ne-rich ^o
						Rubin et al. (2007)	Alexander et al. (2013)	Howard et al. (2015)		
						NWA 10574 A		K.M.		
NWA 10574 B		K.M.	CO	low						
NWA 10827 A		Y.M.	CM2	low			1.7 ^a	300-500 °C ^a	(X)/Ne	
NWA 10827 B		J.N.	CM2	low			1.7	300-500 °C	(X)/Ne	
NWA 11024		S.E.	CM-an	high	996 [#]		1.8	>750 °C/400-600 °C ^h		
Paris A		M.G.	CM	W0	332	2.7-2.9 ^{i,k,l}	1.6		X	
Paris B		M.G.	CM	W0	332	2.7-2.9 ^{i,k,l}	1.7		X	
PCA 02010 ⁺		C.A.	CM2	B			1.5 ^b	>750 °C ^{l,m} /severely heated ^f		
PCA 91008 ⁺		C.A.	CM2-an	B	404		1.8 ^b	strongly heated ^{f,g} /500-750 °C/updated: >750 °C ^m		
QUE 93005 ⁺		C.A.	CM2	A/Be	278	2.1	1.4	1.3	heated ^f /weakly heated ^g / <300 °C ^m	
QUE 97990		K.H.†	CM2	Be	377	2.6	1.7	1.6		X
QUE 99355		C.A.	CM2	B		2.3	1.5			
SCO 06043		C.A.	CM1	B/Ce	206		1.2	1.2		
TIL 91722		C.A.	CM2	B/Ce			1.9	1.5		(X)
Bells C	X	C.A.	C2-ung	Fall	<i>830</i>		2.3	1.4 ^a		
Bells W	X	C.A.	C2-ung	Fall, recovered after storm	<i>830</i>		1.9	1.4		
EET 83355 ⁺		C.A.	C2-ung	A/B					heated ^f /500-750 °C ^m	(X)/Ne
NWA 5958		Y.M.	C2-ung	W1	747					(X)

Samples that are not indicated as “Falls” are “Finds”. K concentrations in *italic* bear high uncertainties as the sources do not provide enough significant digits. Values not considered for the discussion. ^SC.A. = C. Alexander, A.K. = A. King, M.B. = M. Bizarro, K.H. = K. Howard, L.G. = L. Garvie, Y.M. = Y. Marrocchi, J.N. = J. Nauber, S.E. = S. Ebert, M.G. = M. Gounelle, K.M. = K. Metzler. *Meteoritical Bulletin Database. **See references for bulk chemistry in Table 5. ***Unless otherwise stated, the values are from Rubin et al. (2007), Alexander et al. (2013), and Howard et al. (2015), respectively. †Original source: C. Alexander. [#]High K concentration likely associated with strong terrestrial weathering (Ebert et al., 2019). Value not considered for the discussion. ^oCharacterisation only valid for the samples we analysed. Other samples of the same meteorite may show slightly different characteristics due to the brecciation of CMs. ⁺Meteorites included in a recent study by King et al. (2021). New petrologic types differ by maximum 0.1 from values used here. **Bold**: this study; **a**: taken from the second sample of this meteorite; **b**: determined based on data in Hanna et al., 2020. References [for petrologic type classification and peak temperatures]: **c**: King et al., 2017; **d**: Mason et al., 2018; **e**: Lee et al., 2016; **f**: Alexander et al., 2012, 2013; **g**: Quirico et al., 2018; **h**: Ebert et al., 2019; **i**: Hanna et al., 2020; **j**: Marrocchi et al., 2014; **k**: Rubin, 2015; **l**: Hewins et al., 2014; **m**: King et al., 2021..

Table 2: The He and Ne concentrations and isotopic ratios. Also given are the masses of the samples analysed and a short description of the condition of the samples used for noble gas analysis.

Sample	Mass [mg]	Condition	⁴ He	³ He/ ⁴ He x 10 ⁴	²⁰ Ne	²⁰ Ne/ ²² Ne	²¹ Ne/ ²² Ne	²⁰ Ne _{cr}	(²² Ne/ ²⁰ Ne) _{cr}	²¹ Ne _{cos}
			[10 ⁻⁸ cm ³ STP/g]		[10 ⁻⁸ cm ³ STP/g]			[10 ⁻⁸ cm ³ STP/g]		[10 ⁻⁸ cm ³ STP/g]
ALH 84033	18.22±0.02	powder	3562±36	7.667±0.080	18.165±0.081	5.531±0.019	0.34664±0.00090	17.171±0.098	0.11969±0.00086	1.068±0.013
ALH 84042	21.03±0.01	powder	2961±27	2.119±0.021	12.393±0.078	8.658±0.041	0.06135±0.00043	12.354±0.078	0.11191±0.00086	0.0426±0.0049
ALH 85013	21.03±0.01	powder	32437±43	5.140±0.016	164.7±7.4	9.78±0.44	0.22484±0.00078	161.6±7.4	0.0805±0.0037	3.330±0.034
Banten	20.70±0.01	powder	80400±110	3.731±0.011	402±18	12.42±0.56	0.046949±0.000075	402±18	0.0791±0.0035	0.515±0.058
DOM 08003	21.63±0.01	powder	2409±22	3.740±0.035	9.085±0.033	6.020±0.017	0.24630±0.00080	8.775±0.037	0.12829±0.00066	0.3335±0.0061
EET 96006	19.94±0.02	powder	3413±36	8.807±0.096	12.469±0.078	4.783±0.024	0.3315±0.0012	11.719±0.088	0.1432±0.0013	0.807±0.010
EET 96016	22.00±0.01	powder	3727±18	8.073±0.071	14.06±0.12	5.329±0.022	0.3372±0.0011	13.28±0.12	0.1265±0.0019	0.832±0.010
EET 96029	21.36±0.01	powder	6934±34	3.305±0.027	90.2±6.9	11.69±0.88	0.04498±0.00027	90.1±6.9	0.0843±0.0064	0.106±0.014
GRA 98005	30.20±0.02	powder	2204±20	29.66±0.28	11.600±0.072	4.881±0.026	0.3379±0.0014	10.901±0.082	0.1387±0.0012	0.7514±0.0093
GRO 95566	19.63±0.01	powder	3624±32	20.30±0.20	15.149±0.070	4.229±0.015	0.4379±0.0014	13.75±0.10	0.1346±0.0013	1.505±0.013
LAP 02277	18.39±0.01	powder	2456±13	1.502±0.013	7.990±0.071	7.823±0.039	0.05929±0.00054	7.965±0.071	0.1243±0.0015	0.0271±0.0045
LAP 02333	19.19±0.02	powder	8050±120	7.37±0.12	41.17±0.43	6.987±0.032	0.24633±0.00098	40.10±0.46	0.1094±0.0019	1.308±0.019
LAP 04514	19.28±0.02	powder	4324±53	1.654±0.025	14.81±0.17	7.620±0.048	0.04233±0.00025	14.80±0.17	0.1300±0.0020	0.0172±0.0085
LAP 04796	20.32±0.02	powder	9660±150	8.45±0.15	46.5±4.4	5.98±0.57	0.3289±0.0015	44.5±4.4	0.113±0.011	2.364±0.025
LEW 85312 A	24.31±0.02	powder	11754±65	7.597±0.048	79.8±3.6	8.33±0.38	0.16830±0.00048	78.6±3.6	0.1024±0.0047	1.334±0.032
LEW 85312 B	20.80±0.01	powder	9820±100	9.01±0.11	65.06±0.55	7.757±0.037	0.1958±0.0011	63.74±0.55	0.1060±0.0013	1.421±0.028
LEW 85312 C	5.21±0.02	powder	10520±120	8.52±0.12	68.53±0.68	7.752±0.045	0.1879±0.0013	67.20±0.68	0.1071±0.0015	1.425±0.030
LEW 90500	22.55±0.01	powder	2368±24	2.181±0.024	8.277±0.061	7.540±0.042	0.07792±0.00057	8.230±0.061	0.1263±0.0011	0.0504±0.0048
LON 94102	20.11±0.01	powder	11050±110	5.535±0.058	56.3±2.6	7.78±0.36	0.20185±0.00081	55.1±2.6	0.1046±0.0049	1.277±0.024
Maribo	20.67±0.01	powder	7611±56	1.792±0.020	36.13±0.32	8.726±0.051	0.06396±0.00085	36.01±0.32	0.1107±0.0012	0.134±0.014
MET 00432	24.28±0.01	powder	11935±65	4.024±0.027	31.96±0.14	9.743±0.034	0.12257±0.00046	31.67±0.14	0.09228±0.00049	0.3110±0.0063
MET 01070	21.65±0.01	fragments	3072±18	1.455±0.015	10.544±0.092	7.955±0.038	0.04885±0.00036	10.525±0.092	0.1237±0.0014	0.0207±0.0058
MET 01072	23.43±0.02	powder	2737±24	1.641±0.017	10.122±0.055	7.718±0.032	0.0455±0.0015	10.108±0.056	0.12795±0.00084	0.0160±0.0057
Mighei	19.21±0.01	powder	3291±20	6.926±0.055	12.70±0.10	5.292±0.019	0.3394±0.0012	11.99±0.11	0.1270±0.0019	0.7628±0.0094
MIL 05137	18.77±0.01	powder	2853±34	1.427±0.022	9.69±0.12	8.022±0.061	0.04441±0.00052	9.68±0.12	0.1232±0.0020	0.0133±0.0053
MIL 05152	24.61±0.02	powder	3456±42	2.418±0.031	15.241±0.095	7.382±0.037	0.09713±0.00100	15.114±0.096	0.12626±0.00095	0.1360±0.0089
MIL 07689	19.88±0.02	powder	2896±35	2.431±0.037	11.69±0.13	4.337±0.024	0.4528±0.0023	10.73±0.19	0.1253±0.0033	1.175±0.010
Mukundpura A	22.83±0.01	powder	7090±280	4.17±0.16	40.33±0.42	8.879±0.072	0.21565±0.00082	39.52±0.42	0.0896±0.0012	0.8690±0.0092
Mukundpura B	19.70±0.02	powder	19460±320	3.651±0.066	114.64±0.88	10.972±0.049	0.11668±0.00073	113.77±0.88	0.08246±0.00086	0.927±0.020
Murchison	18.90±0.01	powder	18210±280	3.405±0.053	73.0±3.7	10.99±0.56	0.07643±0.00033	72.7±3.7	0.0865±0.0044	0.303±0.012
Murray	26.09±0.02	powder	5404±66	4.402±0.055	30.17±0.18	8.156±0.041	0.17429±0.00049	29.67±0.18	0.10361±0.00073	0.544±0.012
Nogoya	19.74±0.02	powder	3028±31	1.670±0.019	11.843±0.040	8.304±0.021	0.04976±0.00049	11.819±0.040	0.11820±0.00048	0.0253±0.0049
NWA 10574 A	3.24±0.02 ⁺	fragments	2468±21	1.900±0.025	8.94±0.93	7.17±0.54	0.247±0.017	8.68±0.93	0.107±0.015	0.2770±0.0041
NWA 10574 B	2.71±0.02 ⁺	fragments	2284±18	1.823±0.030	8.3±1.1	7.29±0.72	0.208±0.020	8.1±1.1	0.111±0.021	0.2069±0.0038
NWA 10827 A	19.55±0.02	fragments	3100±14	4.593±0.041	30.21±0.22	5.821±0.042	0.3492±0.0021	28.62±0.23	0.1128±0.0033	1.706±0.017
NWA 10827 B	22.65±0.02	powder	3139±32	4.896±0.076	30.50±0.21	5.320±0.017	0.3939±0.0016	28.50±0.24	0.1144±0.0016	2.151±0.018
NWA 11024	19.48±0.02	powder	2709±29	15.14±0.19	10.993±0.088	4.030±0.018	0.4790±0.0019	9.82±0.11	0.1299±0.0023	1.263±0.010

Table 2. Continued.

Sample	Mass [mg]	Condition	⁴ He [10 ⁻⁸ cm ³ STP/g]	³ He/ ⁴ He x 10 ⁴	²⁰ Ne [10 ⁻⁸ cm ³ STP/g]	²⁰ Ne/ ²² Ne	²¹ Ne/ ²² Ne	²⁰ Ne _r [10 ⁻⁸ cm ³ STP/g]	(²² Ne/ ²⁰ Ne) _r	²¹ Ne _{cos} [10 ⁻⁸ cm ³ STP/g]
Paris A	19.65±0.02	powder	16380±170	4.912±0.056	71.83±0.45	9.327±0.022	0.13887±0.00063	71.03±0.45	0.09449±0.00087	0.8660±0.015
Paris B	21.90±0.02	powder	61500±710	3.654±0.047	331.3±3.4	11.95±0.27	0.05844±0.00028	330.5±3.4	0.08116±0.00099	0.785±0.051
PCA 02010	25.02±0.01	powder	70.1±7.2	25.7±2.7	0.873±0.061	6.15±0.34	0.390±0.017	0.824±0.061	0.099±0.010	0.05275±0.00046
PCA 91008	19.37±0.01	powder	2240±12	2.859±0.022	11.793±0.099	4.789±0.019	0.4175±0.0017	10.88±0.11	0.1225±0.0021	0.9825±0.0093
QUE 93005	18.10±0.02	powder	2589±12	4.297±0.035	9.675±0.070	4.639±0.010	0.4343±0.0013	8.867±0.082	0.1225±0.0020	0.8685±0.0078
QUE 97990	21.74±0.02	fragments	78990±3700	3.359±0.035	3110±230	12.63±0.58	0.04091±0.00050	3110±230	0.0783±0.0072	2.49±0.45
QUE 99355	19.92±0.01	powder	2648±24	16.38±0.16	10.476±0.046	3.607±0.013	0.5200±0.0014	9.110±0.087	0.1334±0.0015	1.469±0.011
SCO 06043	25.15±0.01	powder	2142±22	1.467±0.017	6.686±0.039	7.791±0.034	0.05369±0.00067	6.670±0.040	0.12561±0.00090	0.0177±0.0037
TIL 91722	25.09±0.01	powder	6036±61	12.24±0.13	30.32±0.15	6.168±0.023	0.27203±0.00095	29.19±0.17	0.12043±0.00090	1.218±0.020
Bells C	22.40±0.01	powder	2035±18	2.736±0.027	8.735±0.031	7.491±0.020	0.10892±0.00029	8.650±0.031	0.12269±0.00054	0.0911±0.0050
Bells W	19.69±0.01	powder	1950±12	3.577±0.026	6.616±0.022	6.769±0.018	0.18067±0.00096	6.478±0.023	0.12439±0.00053	0.1493±0.0041
EET 83355	25.22±0.01	powder	3301±40	188.6±4.7	33.26±0.20	1.8852±0.0085	0.7814±0.0039	20.50±0.72	0.0910±0.0048	13.718±0.053
NWA 5958	20.06±0.01	fragments	6335±41	8.710±0.066	27.52±0.17	5.656±0.034	0.3735±0.0019	25.92±0.19	0.1113±0.0034	1.722±0.016

Typical blanks (in 10⁻¹² cm³ STP): <1.2, <2850, and <55 for ³He, ⁴He, and ²⁰Ne, respectively. Exceptional higher blank corrections than given in the text were up to 18 % for He in PCA 02010 and up to 10 % and 22 % for Ne in PCA 02010 and NWA 10574 A/B, respectively. The reported uncertainties for the gas concentrations include those of counting statistics, sample masses, blank corrections, and detector sensitivity. The uncertainties for isotopic ratios include those of counting statistics, blank corrections, and instrumental mass discrimination. The uncertainties in the amounts of calibration gases are estimated to be ~2 % for He, Ne, and Ar, and ~5 % for Kr and Xe (Heber et al., 2009). Their contributions to the abundance uncertainties were not included in the reported values since we are mainly interested in comparing the samples within this study. The uncertainties in the calculated cosmogenic and trapped concentrations further include the uncertainties related to the deconvolution, i.e., the choice of the endmember components (section 2.3).

*Low sample masses as this meteorite was allocated with the information it could be a CO chondrite based on O isotope composition. See Appendix for a short discussion of the classification of NWA 10574.

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Table 3: Argon and Kr concentrations and isotopic ratios.

Sample	^{36}Ar	$^{36}\text{Ar}/^{38}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	^{84}Kr	$^{78}\text{Kr}/^{84}\text{Kr}$	$^{80}\text{Kr}/^{84}\text{Kr}$	$^{82}\text{Kr}/^{84}\text{Kr}$	$^{83}\text{Kr}/^{84}\text{Kr}$	$^{86}\text{Kr}/^{84}\text{Kr}$
	[10^{-8} cm ³ STP/g]	[10^{-10} cm ³ STP/g]			$^{84}\text{Kr} = 100$				
ALH 84033	189.9±1.5	5.376±0.028	0.9215±0.0079	139.3±2.3	0.6209±0.0051	4.212±0.033	20.14±0.16	20.07±0.18	31.48±0.23
ALH 84042	42.11±0.37	5.380±0.028	8.639±0.083	48.64±0.76	0.6014±0.0049	3.978±0.027	20.34±0.17	20.36±0.15	31.15±0.21
ALH 85013	62.38±0.49	5.360±0.024	9.815±0.087	63.71±0.99	0.5932±0.0066	4.013±0.027	20.06±0.11	19.96±0.11	30.87±0.17
Banten	96.48±0.80	5.366±0.032	4.392±0.041	68.6±1.0	0.6024±0.0047	3.933±0.027	20.145±0.096	20.17±0.11	31.22±0.14
DOM 08003	48.57±0.41	5.390±0.036	8.814±0.082	56.46±0.85	0.5951±0.0034	3.824±0.020	20.095±0.078	19.93±0.14	30.431±0.094
EET 96006*	60.09±0.68	5.356±0.019	4.786±0.067	69.2±1.1	0.5984±0.0046	3.919±0.026	20.13±0.14	20.00±0.12	30.73±0.20
EET 96016	65.3±1.4	5.288±0.023	6.30±0.15	74.5±1.9	0.6086±0.0056	3.955±0.023	20.35±0.11	20.472±0.086	31.46±0.17
EET 96029*	60.1±1.5	5.238±0.025	3.57±0.10	55.9±1.5	0.5906±0.0085	3.867±0.046	19.64±0.21	19.99±0.21	30.09±0.32
GRA 98005*	62.86±0.51	5.349±0.025	1.736±0.016	47.37±0.71	0.5879±0.0030	3.815±0.020	19.621±0.070	19.980±0.075	30.41±0.14
GRO 95566*	95.96±0.78	5.302±0.024	4.200±0.041	87.1±1.3	0.5903±0.0041	3.849±0.014	20.18±0.11	20.18±0.11	30.84±0.11
LAP 02277	24.72±0.53	5.354±0.023	14.31±0.37	28.24±0.72	0.6064±0.0044	3.922±0.027	20.04±0.11	20.16±0.16	31.67±0.15
LAP 02333	92.5±4.7	5.251±0.022	4.58±0.24	97.94±0.76	0.5881±0.0060	3.900±0.028	20.22±0.15	19.97±0.11	30.89±0.18
LAP 04514	52.0±2.7	5.381±0.024	9.61±0.54	62.89±0.53	0.6163±0.0098	3.916±0.035	20.22±0.16	19.98±0.12	31.03±0.20
LAP 04796	159.7±9.4	5.322±0.024	2.70±0.18	115.9±1.1	0.5932±0.0063	3.931±0.035	20.12±0.19	20.05±0.17	31.03±0.24
LEW 85312 A	409.9±3.6	5.387±0.025	1.389±0.014	192±83 ⁺	n.d.	n.d.	20.230±0.082 ⁺	20.05±0.14 ⁺	30.74±0.20 ⁺
LEW 85312 B*	404±12	5.308±0.015	1.809±0.069	215.9±2.5	0.5950±0.0054	3.894±0.023	20.025±0.080	19.980±0.072	30.78±0.11
LEW 85312 C	n.d.	5.331±0.024	n.d.	231.1±2.9	0.6051±0.0074	3.892±0.027	20.134±0.093	20.040±0.085	30.93±0.16
LEW 90500*	43.03±0.39	5.365±0.022	15.93±0.17	55.80±0.86	0.5903±0.0037	3.846±0.028	19.91±0.15	19.69±0.12	30.49±0.18
LON 94102*	107.88±0.99	5.346±0.019	4.298±0.047	104.0±1.6	0.5832±0.0038	3.853±0.024	19.98±0.12	20.15±0.12	30.70±0.18
Maribo	82.1±8.8	5.274±0.026	2.97±0.42	87.68±0.61	0.6163±0.0067	3.880±0.019	19.972±0.091	19.959±0.094	30.95±0.15
MET 00432*	46.73±0.40	5.297±0.024	27.06±0.26	80.9±1.3	0.6098±0.0051	3.937±0.023	20.185±0.099	19.97±0.13	30.82±0.15
MET 01070	39.93±0.93	5.347±0.021	22.10±0.58	46.6±1.2	0.6014±0.0046	3.895±0.025	20.13±0.14	20.17±0.14	30.85±0.19
MET 01072*	28.21±0.43	5.327±0.025	17.08±0.33	35.79±0.60	0.5880±0.0079	3.828±0.043	19.78±0.23	20.29±0.24	30.83±0.35
Mighei	60.3±1.3	5.290±0.024	16.56±0.41	69.3±1.8	0.5879±0.0037	3.889±0.024	19.93±0.10	19.77±0.10	30.43±0.10
MIL 05137	47.0±2.4	5.295±0.022	20.6±1.1	52.14±0.39	0.5992±0.0051	3.945±0.027	20.03±0.12	20.157±0.091	31.01±0.16
MIL 05152*	70.19±0.67	5.383±0.023	9.34±0.11	108.4±1.8	0.6028±0.0070	3.918±0.038	20.05±0.19	19.98±0.19	30.61±0.28
MIL 07689	62.5±3.1	5.327±0.026	15.59±0.81	70.46±0.57	0.5973±0.0061	3.914±0.030	19.85±0.12	20.03±0.11	31.30±0.17
Mukundpura A	57.5±1.6	5.263±0.026	19.69±0.70	68.77±0.46	0.5951±0.0058	3.901±0.033	20.00±0.12	20.175±0.088	30.98±0.13
Mukundpura B	66.9±1.7	5.274±0.022	17.08±0.58	79.04±0.57	0.6065±0.0057	3.931±0.025	20.21±0.13	19.98±0.14	30.86±0.17
Murchison*	74.02±0.63	5.352±0.027	9.590±0.092	75.7±1.2	0.5959±0.0062	3.947±0.025	20.05±0.13	20.37±0.15	31.11±0.18
Murray*	49.17±0.55	5.331±0.019	4.428±0.063	47.31±0.74	0.5949±0.0054	3.929±0.028	19.90±0.15	20.04±0.16	31.30±0.24
Nogoya*	54.01±0.58	5.363±0.020	17.85±0.24	70.7±1.1	0.6010±0.0041	3.977±0.015	20.064±0.083	20.207±0.083	31.01±0.15
NWA 10574 A*	76±30	5.380±0.022	1.03±0.50	35.88±0.96	0.594±0.076	3.881±0.032	20.18±0.15	21.09±0.26	31.06±0.31
NWA 10574 B*	n.d.	5.332±0.016	n.d.	37.0±1.3	0.633±0.030	3.82±0.14	19.20±0.70	20.95±0.73	31.4±1.1
NWA 10827 A	422±19	5.294±0.021	1.416±0.079	218.8±1.6	0.6017±0.0066	3.913±0.021	20.141±0.088	20.180±0.094	31.12±0.14
NWA 10827 B	412±48	5.276±0.024	0.98±0.14	196.0±2.3	0.5975±0.0055	3.874±0.026	20.072±0.080	20.005±0.068	30.77±0.13
NWA 11024*	64±10	5.238±0.025	6.1±1.2	45.03±0.53	0.5961±0.0090	3.929±0.029	20.13±0.11	19.994±0.096	30.94±0.16

Table 3. Continued.

Sample	^{36}Ar	$^{36}\text{Ar}/^{38}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	^{84}Kr	$^{78}\text{Kr}/^{84}\text{Kr}$	$^{80}\text{Kr}/^{84}\text{Kr}$	$^{82}\text{Kr}/^{84}\text{Kr}$	$^{83}\text{Kr}/^{84}\text{Kr}$	$^{86}\text{Kr}/^{84}\text{Kr}$
	$[10^{-8} \text{ cm}^3 \text{ STP/g}]$			$[10^{-10} \text{ cm}^3 \text{ STP/g}]$					
Paris A	223.9±1.2	5.343±0.017	2.066±0.013	136.7±1.6	0.6155±0.0061	3.883±0.021	20.095±0.069	20.063±0.067	30.793±0.100
Paris B	13.3±1.3	5.315±0.019	3.88±0.47	93.6±1.1	0.5959±0.0083	3.916±0.027	20.125±0.092	20.037±0.070	30.88±0.12
PCA 02010*	9.63±0.26	5.362±0.020	13.04±0.41	10.50±0.24	0.602±0.019	3.82±0.11	20.34±0.56	19.80±0.52	30.77±0.81
PCA 91008	169.3±5.7	5.299±0.023	8.850±0.035	105.4±2.7	0.6081±0.0068	3.933±0.019	20.225±0.074	20.180±0.086	31.11±0.11
QUE 93005	44.72±0.90	5.295±0.021	9.62±0.21	51.7±1.3	0.5948±0.0041	3.948±0.024	20.085±0.097	20.094±0.069	30.94±0.13
QUE 97990	221.6±4.7	5.274±0.022	2.133±0.050	93.6±2.4	0.5901±0.0053	3.899±0.037	19.89±0.15	20.10±0.15	30.77±0.23
QUE 99355*	49.39±0.44	5.333±0.019	4.797±0.050	55.70±0.89	0.6026±0.0056	3.919±0.029	20.21±0.15	20.31±0.14	30.99±0.23
SCO 06043*	21.06±0.18	5.397±0.022	10.64±0.12	44±25 ⁺	n.d.	n.d.	20.01±0.37 ⁺	20.374±0.093 ⁺	30.61±0.13 ⁺
TIL 91722	181.8±1.5	5.400±0.022	1.906±0.017	110±66 ⁺	n.d.	n.d.	19.829±0.024 ⁺	19.99±0.27 ⁺	30.76±0.19 ⁺
Bells C	53.75±0.54	5.391±0.025	14.67±0.19	59.61±0.89	0.6253±0.0064	3.883±0.015	20.158±0.083	20.248±0.095	31.00±0.12
Bells W*	40.04±0.35	5.387±0.026	10.70±0.11	46.22±0.70	0.5892±0.0044	3.893±0.020	20.34±0.10	20.19±0.11	30.83±0.14
EET 83355	308.8±2.4	5.268±0.023	1.1551±0.0099	138.1±2.1	0.6210±0.0033	4.023±0.015	20.060±0.090	20.026±0.090	30.80±0.11
NWA 5958	48.2±1.1	5.265±0.016	8.58±0.25	35.48±0.31	0.607±0.014	3.925±0.039	19.86±0.15	20.10±0.16	31.06±0.22

Typical blanks (in $10^{-12} \text{ cm}^3 \text{ STP}$): <165, <45900, and <3.4 for ^{36}Ar , ^{40}Ar , and ^{84}Kr , respectively. Exceptional higher blank corrections than given in the text were up to 5.2 % for $^{36,38}\text{Ar}$ in PCA 02010 and up to 88 % and 97 % for ^{40}Ar in NWA 10574 A/B and LEW 85312 C, respectively. Blank corrections for Kr were up to 5.5 %, 8.4 %, 3.3 % in PCA 02010, NWA 10574 A/B, LEW 85312 C, respectively. For information about uncertainties see Table 2.

* Minor gas amounts from re-extractions added to the gas amounts in the main extraction step.

⁺ Data less reliable due to analytical problems. The Kr and Xe measurement in these samples was affected by high hydrocarbon contents in the system due to inefficient gettering. Data points for these measurements are removed from Fig. 7, 8, 10, and 13.

Table 4: Xenon concentrations and isotopic ratios.

Sample	^{132}Xe	$^{124}\text{Xe}/^{132}\text{Xe}$	$^{126}\text{Xe}/^{132}\text{Xe}$	$^{128}\text{Xe}/^{132}\text{Xe}$	$^{129}\text{Xe}/^{132}\text{Xe}$	$^{130}\text{Xe}/^{132}\text{Xe}$	$^{131}\text{Xe}/^{132}\text{Xe}$	$^{134}\text{Xe}/^{132}\text{Xe}$	$^{136}\text{Xe}/^{132}\text{Xe}$	$^{132}\text{Xe}_{\text{corr}}$
	[10^{-10} cm ³ STP/g]	$^{132}\text{Xe} = 100$								
ALH 84033	202.5±2.3	0.4439±0.0059	0.3905±0.0040	7.907±0.042	101.5±1.0	15.969±0.084	81.86±0.40	38.52±0.21	32.52±0.20	202.5±2.3
ALH 84042	57.73±0.68	0.4747±0.0067	0.3995±0.0063	8.130±0.056	107.21±0.76	16.28±0.12	82.53±0.57	38.29±0.27	32.64±0.25	57.73±0.68
ALH 85013	68.02±0.76	0.4541±0.0035	0.4086±0.0031	8.301±0.045	107.15±0.59	16.322±0.081	82.46±0.43	38.74±0.19	32.72±0.20	68.02±0.76
Banten	69.34±0.79	0.4674±0.0036	0.4078±0.0068	8.077±0.051	106.42±0.88	16.048±0.095	82.02±0.40	38.26±0.27	32.22±0.21	69.34±0.79
DOM 08003	73.48±0.79	0.4506±0.0057	0.4046±0.0023	8.094±0.026	104.60±0.46	16.027±0.053	81.85±0.29	38.64±0.18	32.58±0.16	73.48±0.79
EET 96006	89.4±1.1	0.4604±0.0072	0.3982±0.0073	8.084±0.061	105.01±0.84	15.93±0.12	81.85±0.63	38.10±0.30	32.42±0.30	89.4±1.1
EET 96016	104.6±2.8	0.4419±0.0044	0.4072±0.0061	7.953±0.052	105.04±0.72	15.974±0.096	81.65±0.45	38.30±0.28	32.29±0.20	104.6±2.8
EET 96029	110.0±3.0	0.4033±0.0048	0.3557±0.0034	7.643±0.054	102.98±0.73	15.672±0.096	81.13±0.47	38.99±0.26	33.01±0.21	63±17
GRA 98005	51.85±0.60	0.4457±0.0039	0.3832±0.0023	7.900±0.048	101.93±0.63	15.673±0.086	80.35±0.48	38.17±0.24	32.34±0.19	29.4±6.1
GRO 95566	98.2±1.1	0.4611±0.0035	0.3950±0.0040	8.123±0.042	106.23±0.72	16.072±0.071	82.37±0.38	38.44±0.17	32.28±0.18	98.2±1.1
LAP 02277	43.0±1.2	0.4603±0.0035	0.4068±0.0030	8.035±0.039	106.83±0.46	15.909±0.099	80.85±0.34	39.01±0.20	33.15±0.21	31.8±3.7
LAP 02333	113.7±2.0	0.4562±0.0068	0.3987±0.0037	8.120±0.075	104.5±1.2	16.02±0.13	82.36±0.66	38.36±0.34	32.32±0.26	113.7±2.0
LAP 04514	76.5±1.3	0.4360±0.0061	0.3898±0.0048	7.890±0.057	102.88±0.96	15.87±0.11	81.01±0.50	38.27±0.25	32.45±0.21	53.7±1.3
LAP 04796	135.2±2.4	0.4449±0.0050	0.3896±0.0059	8.050±0.065	105.10±0.89	15.84±0.12	81.75±0.63	38.30±0.31	32.07±0.26	135.2±2.4
LEW 85312 A ⁺	210±69	0.464±0.022	0.399±0.030	7.91±0.26	106.250±0.070	15.84±0.47	80.96±0.90	37.66±0.40	31.58±0.44	123±42
LEW 85312 B	176.0±2.9	0.4592±0.0042	0.4092±0.0026	8.126±0.028	105.25±0.37	16.032±0.050	81.78±0.28	37.73±0.12	31.804±0.094	176.0±2.9
LEW 85312 C	193.4±3.3	0.4607±0.0086	0.3939±0.0077	8.124±0.044	105.37±0.52	16.114±0.083	82.54±0.39	38.00±0.18	31.90±0.17	193.4±3.3
LEW 90500	56.58±0.75	0.4586±0.0063	0.4083±0.0054	8.041±0.088	105.38±0.99	16.05±0.16	81.08±0.76	38.08±0.37	31.98±0.32	45.9±3.7
LON 94102	136.1±1.6	0.4265±0.0040	0.3940±0.0034	7.849±0.051	103.14±0.72	15.87±0.12	80.81±0.56	37.75±0.24	32.22±0.22	90.6±3.7
Maribo	113.4±1.0	0.4498±0.0043	0.3987±0.0050	8.098±0.046	102.69±0.54	16.189±0.076	81.37±0.44	38.09±0.18	31.88±0.15	113.4±1.0
MET 00432	135.8±1.6	0.3881±0.0046	0.3507±0.0029	7.440±0.050	101.35±0.81	15.216±0.092	79.47±0.48	38.40±0.25	32.69±0.23	25±14
MET 01070	56.0±1.6	0.4466±0.0043	0.4013±0.0060	8.022±0.078	108.1±1.1	15.73±0.14	80.75±0.82	37.62±0.32	31.69±0.27	37.5±7.4
MET 01072	38.62±0.48	0.4523±0.0083	0.4177±0.0094	7.982±0.088	102.0±1.1	15.83±0.15	81.17±0.82	38.92±0.40	32.66±0.33	28.4±2.7
Mighei	75.8±2.0	0.4687±0.0026	0.3990±0.0039	8.240±0.038	106.66±0.41	16.058±0.075	81.86±0.39	38.28±0.22	32.19±0.18	75.8±2.0
MIL 05137	66.3±1.1	0.4338±0.0037	0.4049±0.0078	7.922±0.058	105.47±0.98	15.784±0.096	81.53±0.50	37.88±0.27	32.27±0.21	66.3±1.1
MIL 05152	172.1±2.2	0.4163±0.0049	0.3729±0.0042	7.629±0.064	102.73±0.90	15.68±0.13	81.26±0.65	38.69±0.31	32.76±0.27	101±32
MIL 07689	133.9±2.2	0.3983±0.0042	0.3714±0.0034	7.539±0.038	102.46±0.83	15.458±0.086	80.27±0.42	38.20±0.21	32.19±0.16	51±11
Mukundpura A	73.16±0.70	0.4556±0.0084	0.4008±0.0052	8.049±0.049	105.48±0.60	16.044±0.086	81.06±0.47	38.19±0.21	32.06±0.19	59.2±5.0
Mukundpura B	84.26±0.78	0.4550±0.0026	0.4008±0.0038	8.112±0.052	105.96±0.59	16.015±0.088	81.77±0.38	38.15±0.21	32.08±0.17	84.26±0.78
Murchison	78.18±0.89	0.4639±0.0059	0.4346±0.0057	8.361±0.069	108.80±0.69	16.346±0.092	82.85±0.47	38.44±0.30	32.48±0.20	78.18±0.89
Murray	52.79±0.62	0.4870±0.0069	0.4149±0.0067	8.235±0.060	105.77±0.76	16.26±0.12	82.00±0.59	38.68±0.29	32.59±0.26	52.79±0.62
Nogoya	71.22±0.78	0.4518±0.0038	0.3914±0.0026	8.086±0.043	107.48±0.73	16.031±0.097	81.44±0.41	38.33±0.20	32.18±0.15	61.2±1.2
NWA 10574 A	26.74±0.75	0.495±0.011	0.384±0.013	8.68±0.15	105.38±0.93	16.38±0.16	83.87±0.74	39.08±0.39	32.93±0.55	26.74±0.75
NWA 10574 B	26.34±0.75	0.4580±0.0072	0.507±0.012	7.97±0.20	105.1±1.2	16.08±0.17	79.91±0.88	38.46±0.50	33.83±0.46	26.34±0.75
NWA 10827 A	174.8±4.4	0.4405±0.0044	0.3877±0.0044	8.035±0.071	102.7±1.0	15.98±0.14	82.01±0.72	38.34±0.33	32.20±0.29	174.8±4.4
NWA 10827 B	155.0±2.5	0.4498±0.0032	0.4031±0.0045	8.033±0.028	103.97±0.34	16.109±0.071	81.22±0.30	38.06±0.13	32.29±0.12	131±11
NWA 11024	41.24±0.68	0.4633±0.0082	0.3986±0.0071	8.112±0.037	104.60±0.36	16.120±0.096	82.08±0.39	38.32±0.16	32.74±0.14	41.24±0.68

Table 4. Continued.

Sample	^{132}Xe [10^{-10} cm 3 STP/g]	$^{132}\text{Xe} = 100$										$^{132}\text{Xe}_{\text{corr}}$ [10^{-10} cm 3 STP/g]
		$^{124}\text{Xe}/^{132}\text{Xe}$	$^{126}\text{Xe}/^{132}\text{Xe}$	$^{128}\text{Xe}/^{132}\text{Xe}$	$^{129}\text{Xe}/^{132}\text{Xe}$	$^{130}\text{Xe}/^{132}\text{Xe}$	$^{131}\text{Xe}/^{132}\text{Xe}$	$^{134}\text{Xe}/^{132}\text{Xe}$	$^{136}\text{Xe}/^{132}\text{Xe}$	$^{138}\text{Xe}/^{132}\text{Xe}$	$^{136}\text{Xe}/^{132}\text{Xe}$	
Paris A	124.9±2.0	0.4695±0.0044	0.4105±0.0018	8.318±0.029	105.98±0.35	16.172±0.058	81.87±0.23	38.73±0.12	32.39±0.10	32.39±0.10	124.9±2.0	
Paris B	97.8±1.6	0.4590±0.0019	0.4105±0.0035	8.171±0.027	104.33±0.25	16.075±0.030	83.08±0.24	38.02±0.13	32.059±0.081	32.059±0.081	97.8±1.6	
PCA 02010	10.76±0.26	0.434±0.014	0.445±0.015	8.06±0.26	102.7±3.2	15.85±0.51	82.1±2.6	37.6±1.2	31.5±1.0	31.5±1.0	10.76±0.26	
PCA 91008	156.5±4.3	0.4210±0.0038	0.3874±0.0043	7.728±0.061	102.14±0.80	15.63±0.11	80.40±0.58	38.13±0.30	32.25±0.26	32.25±0.26	79.0±6.8	
QUE 93005	64.5±1.7	0.4654±0.0074	0.4037±0.0054	8.107±0.050	110.45±0.63	16.194±0.096	82.29±0.50	38.81±0.26	32.70±0.24	32.70±0.24	64.5±1.7	
QUE 97990	99.5±2.8	0.4547±0.0060	0.3871±0.0039	8.002±0.073	102.83±0.90	15.82±0.14	80.54±0.74	37.62±0.36	31.61±0.30	31.61±0.30	66±1.2	
QUE 99355	71.93±0.85	0.4304±0.0037	0.3988±0.0038	7.998±0.057	103.10±0.85	15.80±0.12	81.02±0.53	38.15±0.25	31.99±0.26	31.99±0.26	51.3±6.0	
SCO 06043 ⁺	70±2.5	0.451±0.030	0.404±0.015	7.82±0.25	107.5±3.4	15.88±0.35	80.1±1.2	38.47±0.72	32.67±0.50	32.67±0.50	33±1.7	
TIL 91722 ⁺	128±5.4	0.4573±0.0089	0.390±0.022	7.877±0.059	105.29±0.87	15.94±0.25	82.142±0.028	37.819±0.011	31.96±0.10	31.96±0.10	128±5.4	
Bells C	74.80±0.80	0.4461±0.0032	0.3950±0.0055	8.060±0.033	103.40±0.43	15.868±0.047	80.82±0.32	37.79±0.13	31.844±0.090	31.844±0.090	54.7±7.9	
Bells W	61.57±0.67	0.4522±0.0028	0.3991±0.0037	7.946±0.037	102.37±0.42	15.926±0.073	81.17±0.28	38.35±0.17	31.76±0.16	31.76±0.16	46.38±0.95	
EET 83355	128.8±1.5	0.4289±0.0039	0.3814±0.0034	7.896±0.055	102.68±0.71	15.707±0.097	80.76±0.52	38.10±0.23	32.17±0.22	32.17±0.22	80±1.0	
NWA 5958	31.60±0.76	0.4683±0.0069	0.4246±0.0063	8.003±0.076	105.79±0.80	15.95±0.12	81.39±0.65	39.56±0.30	33.70±0.28	33.70±0.28	25.4±1.3	

Typical blank for ^{132}Xe was $<0.8 \times 10^{-12}$ cm 3 STP. Exceptional higher blank corrections than given in the text were up to 5.8 % and 2.1 % for Kr in PCA 02010 and NWA 10574 A/B, respectively. For information about uncertainties see Table 2. $^{132}\text{Xe}_{\text{corr}}$ represents measured ^{132}Xe corrected for air contamination (see text for details) used to test correlations with petrologic types.

⁺ Data less reliable due to analytical problems (see Table 3).

Table 5: Cosmic ray exposure (CRE) age ranges T_{21} determined from ^{21}Ne for all CCs. Production rate ranges P_{21} determined based on a pre-atmospheric radius of 10-65 cm, any shielding depth, and the chemistry given in Table A 1 using the model of Leya and Masarik (2009). Also listed are references for the individual bulk chemistry (if available), for all remaining CCs we used the mean CM chemistry given by Alexander (2019). We give mean CRE age ranges for meteorites with multiple measurements and paired specimens (based on the mean of the individual CRE ages and their 2σ).

Sample	Reference bulk chemistry	P_{21} [10^{-8} cm ³ STP/(g*Myr)]	T_{21} [Myr]	Centre of the T_{21} range [Myr]
CM mean	Alexander (2019)	0.124-0.308*		
ALH 84033			3.4-8.7	6.1
ALH 84042	Jarosewich, 1990	0.107-0.267	0.14-0.44	0.3
ALH 85013	Braukmüller et al., 2018	0.118-0.297	11.1-28.4	19.8
Banten	Jarosewich, 1990	0.115-0.294	1.6-5.0	3.3
DOM 08003			1.1-2.7	1.9
EET 96006			2.6-6.6	4.6
EET 96016			2.7-6.8	4.7
<i>EET 96006/16 mean</i>			<i>4.5-4.9</i>	<i>4.7</i>
EET 96029	Lee et al., 2016	0.094-0.219	0.42-1.27	0.8
GRA 98005			2.4-6.1	4.3
GRO 95566			4.9-12.3	8.6
LAP 02277			0.07-0.25	0.2
LAP 02333	Abreu et al., 2017	0.101-0.237	5.4-13.1	9.3
LAP 04514	Abreu et al., 2017	0.098-0.230	0.04-0.26	0.1
LAP 04796			7.6-19.3	13.4
LEW 85312 A			4.2-11.0	7.6
LEW 85312 B			4.5-11.7	8.1
LEW 85312 C			4.5-11.7	8.1
<i>LEW 85312 mean</i>			<i>7.4-8.5</i>	<i>8.0</i>
LEW 90500			0.15-0.44	0.3
LON 94102	Braukmüller et al., 2018	0.122-0.305	4.1-10.7	7.4
Maribo	Haack et al., 2012	0.117-0.297	0.4-1.3	0.8
MET 00432			1.0-2.6	1.8
MET 01070	Braukmüller et al., 2018	0.120-0.299	0.05-0.22	0.1
MET 01072			0.03-0.18	0.1
Mighei	Braukmüller et al., 2018	0.124-0.305	2.5-6.2	4.4
MIL 05137			0.03-0.15	0.1
MIL 05152			0.41-1.17	0.8
MIL 07689			3.8-9.6	6.7
Mukundpura A	Ray and Shukla, 2018	0.107-0.267	3.2-8.2	5.7
Mukundpura B	Ray and Shukla, 2018	0.107-0.267	3.4-8.9	6.1
<i>Mukundpura mean</i>			<i>5.3-6.5</i>	<i>5.9</i>

Table 5. Continued.

Sample	Reference bulk chemistry	P_{21} [10^{-8} cm ³ STP/(g*Myr)]	T_{21} [Myr]	Centre of the T_{21} range
Murchison	Braukmüller et al., 2018	0.122-0.304	1.0-2.6	1.8
Murray	Braukmüller et al., 2018	0.122-0.304	1.7-4.6	3.2
Nogoya	Braukmüller et al., 2018	0.116-0.291	0.07-0.26	0.2
NWA 10574 A			0.89-2.27	1.6
NWA 10574 B			0.66-1.70	1.2
<i>NWA 10574 mean</i>			<i>0.82-1.94</i>	<i>1.4</i>
NWA 10827 A			5.5-13.9	9.7
NWA 10827 B			6.9-17.5	12.2
<i>NWA 10827 mean</i>			<i>7.4-14.5</i>	<i>11.0</i>
NWA 11024	Ebert et al., 2019	0.132-0.340	3.7-9.6	6.7
Paris A	Hewins et al., 2014	0.119-0.300	2.8-7.4	5.1
Paris B	Hewins et al., 2014	0.119-0.300	2.4-7.0	4.7
<i>Paris mean</i>			<i>4.4-5.4</i>	<i>4.9</i>
PCA 02010			0.17-0.43	0.3
PCA 91008	Choe et al., 2010	0.114-0.291	3.3-8.7	6.0
QUE 93005	Rubin et al., 2007	0.111-0.276	3.1-7.9	5.5
QUE 97990	Rubin et al., 2007	0.113-0.283	7.2-26.0	16.6
QUE 99355			4.7-11.9	8.3
SCO 06043	Braukmüller et al., 2018	0.116-0.287	0.05-0.19	0.1
TIL 91722			3.9-10.0	6.9
Bells C	Davis et al., 1984	0.121-0.300	0.29-0.79	0.5
Bells W	Davis et al., 1984	0.121-0.300	0.48-1.27	0.9
<i>Bells mean</i>			<i>0.23-1.18</i>	<i>0.7</i>
EET 83355			44-111	78
NWA 5958	Jacquet et al., 2016	0.117-0.298	5.7-14.8	10.3

*Used to determine CRE age ranges for all CCs without individual bulk chemistry given in the literature.

The uncertainties in the production rates and corresponding CRE ages (i.e., the minimum and maximum of the ranges) include contributions from the measurement errors, the component deconvolution, and shielding. Not included are the uncertainties associated with the shielding model itself (as we mainly compare the CRE ages of the samples within this study) that are estimated to be 15-20 % (Leya and Masarik, 2009) as well as uncertainties in the chemical compositions of the meteorites. For the uncertainties of the mean CRE ages for meteorites with repeat measurements and paired specimens, we use 2σ of the mean of the individual CRE ages.

Table 6: The bulk mineralogy and derived phyllosilicate fraction (PSF) of samples analysed here by PSD-XRD.

Sample	Phyllosilicate		Olivine		Pyroxene		Magnetite		Fe-sulphide		Carbonate		Metal		Sulphate		PSF
	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	[vol. %]	
ALH 84033	61.3	17.1	16.4	2.0	2.1	0.5	0.3	0.4	0.65								
Banten	70.5	18.4	8.0	1.3	1.1	0.3	0.3	0.73									
DOM 08003	86.6	6.7	2.9	2.1	1.2	0.3	0.3	0.90									
EET 96006	74.2	17.5	4.5	1.4	0.9	0.4	0.2	0.77									
EET 96016	78.8	13.3	5.7	1.2	0.5	0.3	0.1	0.81									
GRA 98005	75.0	14.7	7.1	1.3	1.4	0.1	0.1	0.77									
LEW 85312	60.1	21.5	13.0	1.2	2.3	0.9	0.4	0.64									
Maribo	67.8	12.4	12.3	3.9	2.8	0.5	0.3	0.73									
MET 01072	88.8	7.2	1.2	0.9	1.4	0.4	0.91										
MIL 05152	80.1	11.7	4.3	1.1	2.2	0.4	0.1	0.83									
Mukundpura A	83.0	5.9	3.4	4.0	2.7	1.0	0.90										
Mukundpura B	73.5	14.0	6.0	3.0	1.8	1.8	0.79										
Nogoya	86.5	6.7	1.5	3.0	1.4	0.9	0.91										
NWA 10827	56.6	14.9	16.1	5.8	6.1	0.5	0.65										
Paris A	70.1	14.9	10.8	2.5	0.8	0.5	0.73										
Paris B	62.4	17.1	15.0	3.6	1.0	0.9	0.66										
Sample	Olivine (primary)		Olivine (secondary)														
	[vol. %]	[vol. %]	[vol. %]	[vol. %]													
NWA 11024	21.2	53.3	11.8	12.3	0.8	0.7	0.62										

Uncertainties are typically <0.5 vol% for crystalline phases and <1 vol. % for non-crystalline phases, resulting in PSF errors of ~0.01-0.02 (King et al., 2015a; 2021).

Table 7: Estimated primordial noble gas contents of a CM parent body unaffected by U/Th decay. Helium, Ne, and Ar concentrations are given in 10^{-8} cm³ STP/g, Kr and Xe concentrations in 10^{-10} cm³ STP/g. Values for pristine CM material unaffected by parent body aqueous alteration (“a.a.”) and SW (a.a. = no, SW = no) are based on some of the most pristine CMs, LEW 85312 and NWA 10827. We also give primordial noble gas contents typical for highly altered CMs (a.a. = yes) and additional He and Ne concentrations typical for CM material affected by SW (SW = yes). See text for details. Q composition (Busemann et al., 2000) is a suitable approximation for Kr and Xe isotopic ratios.

a.a.	SW	³ He	⁴ He	²⁰ Ne	²² Ne/ ²⁰ Ne	³⁶ Ar	³⁶ Ar/ ³⁸ Ar*	⁸⁴ Kr	¹³² Xe
No	No	0.2-0.4	1245-2745	15-65	0.106-0.114	400-425	5.28-5.31	195-220	130-180
No	Yes	~265	~790000	~3100	~0.078		~5.27		
Yes	No	0.4-0.7	1095-1140	~10	0.123-0.125	45-60	5.30-5.33	50-70	50-65
Yes	Yes	3-17	5340-30680	30-160	0.082-0.092		5.26-5.36		

*Ratios as measured in the respective samples. Essentially similar in SW-bearing and SW-lacking CM chondrites. Small deviations likely of statistic nature.

Appendix

Variations in Ar isotopic ratios with petrologic type

In section 4.2.1.1, we have shown that the matrix/chondrule ratio has a minor effect on noble gas abundances within the CM group compared to the degree of aqueous alteration of these meteorites. Thus, we can test trends between the degree of aqueous alteration and ^{36}Ar over ^{40}Ar (the latter is assumed to reside in both matrix and chondrules as K is present in both). Indeed, the $^{36}\text{Ar}/^{40}\text{Ar}$ ratio changes with petrologic type, i.e., $^{36}\text{Ar}/^{40}\text{Ar}$ roughly decreases with higher degree of aqueous alteration (Fig. A 3), whereas the $^{36}\text{Ar}/^{38}\text{Ar}$ ratio is roughly constant over the full range of petrologic types. The ^{40}Ar concentrations in GRA 98005 and ALH 84033 are well below the average for CMs, explaining their remarkably high values in Fig. A 3, although the ^{36}Ar concentration in ALH 84033 is also relatively high compared to many other CMs. The trend in Fig. A 3 indicates a predominant loss of trapped ^{36}Ar with lower petrologic type compared to radiogenic ^{40}Ar . The concentration of ^{40}Ar is highly variable among the samples ($\sim 80\text{-}1265 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$) but as expected rather independent of petrologic type (Fig. A 9a), although the highly altered CMs *may* tend towards ^{40}Ar concentrations slightly higher than the most primitive CMs. As there is no primordial ^{40}Ar , a potential gain of ^{40}Ar would be either associated with stronger air contamination or a higher presence of K with lower petrologic type. However, $^{40}\text{Ar}_{\text{air}}$ is most likely negligible and we also do not observe any correlation between petrologic types and the weathering grade of CMs. Also, no clear trend is visible when we plot petrologic types versus K concentrations of CMs (Fig. A 9b). Nevertheless, one *may* infer a small increase of ^{40}Ar over K with decreasing petrologic types (Fig. A 9c). As naturally associated with ^{40}Ar over K, the K-Ar ages determined for the CMs in this study show a similar *trend* with the petrologic type (Fig. A 9d). If this trend is real, CMs with higher petrologic type may originate from regions closer to the surface of the CM parent body compared to CMs with lower petrologic type as these regions were more affected by impacts. A larger impact rate may be responsible for a later reset of the K-Ar system and, hence, younger K-Ar ages of these CMs. However, there are no *clear* trends visible in Fig. A 9 and potential tendencies of the data shown with varying petrologic type may quickly change with the addition of new data. Even if these tendencies are real, they would only have a minor impact on the $^{36}\text{Ar}/^{40}\text{Ar}$ ratios shown in Fig. A 3. Hence, a loss of ^{36}Ar with decreasing petrologic types is clearly dominating the trend in Fig. A 3.

From the trend in Fig. A 3, we can infer that the main carriers of ^{36}Ar and ^{40}Ar are different. The fact that the ^{40}Ar concentrations are highly variable amongst the CMs (but most likely independent of the petrologic type and matrix abundances) implies an initially heterogeneous distribution of the ^{40}Ar carrier(s) and, hence, K abundances in the CM parent body and/or, more likely, randomly distributed gas retention ages. As we do observe trends between $^{36}\text{Ar}/^{40}\text{Ar}$ and the petrologic types, we infer that all CMs initially acquired both Ar carriers in constant mixing proportions. Thus, the carrier of ^{36}Ar is less stable against parent body alteration than the heat-susceptible K-rich carrier(s) of ^{40}Ar .

Classification of NWA 10574

NWA 10574 is classified as a CM2 in the Meteoritical Bulletin Database. The samples of this meteorite (NWA 10574 A/B) analysed in this study were allocated by K. Metzler, suggesting that it may be a CO chondrite, based on O isotope composition. The two samples of NWA 10574 were different in colour (section 3.2.5). However, our results were mostly consistent between sample A and B. The elemental ratios of the heavier noble gases in NWA 10574 fall within the ranges of compositions of the most pristine CMs (this study) that also overlaps with the typical ranges of COs (Scherer and Schultz, 2000; Bartoschewitz et al., 2010). However, NWA 10574 has low concentrations of ^{36}Ar , ^{84}Kr , and ^{132}Xe compared to the most pristine CMs, also slightly lower than most COs, suggesting that it either experienced (more) intense thermal modification ($>500\text{-}750^\circ\text{C}$ if CM; this study; $>$ type 3.7 if CO; Bonal et al., 2007) or contains larger abundances of gas-poor components, such as chondrules and/or CAIs, compared to other meteorites in these groups. The CRE age of NWA 10574 is ~ 1.4 Myr. This young exposure age, while not unique, is unusual for COs. So far, only one CO has been found with a comparably low CRE age (Isna ~ 0.15 Myr; Scherer and Schultz, 2000). All remaining COs have exposure ages ≥ 5 Myr and up to 63.5 Myr (Scherer and Schultz, 2000). Instead, the CRE age of NWA 10574 is in the typical range observed for CMs. Thus, noble gas results obtained for NWA 10574 are broadly consistent with both groups of CCs. A determination of the degree of aqueous and thermal alteration of NWA 10574 would help to clarify its classification.

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Figure captions

Fig. A 1: The plot shows Fig. 10E with the ^{132}Xe concentrations prior to the correction for Xe-air (light symbols) in addition to $^{132}\text{Xe}_{\text{corr}}$ to illustrate the large effects (up to 80 %, see main text) of the corrections necessary due to Xe adsorption probably mostly caused by terrestrial weathering. The correction clearly improves trends with the petrologic type.

Fig. A 2: a) The ^{40}Ar concentration is highly variable among all CCs in our study and most likely independent of petrologic type. b) K concentrations (Table 1) vary between $\sim 200\text{-}600$ ppm for the CMs in our study with a given bulk chemistry. We do not observe a clear correlation between K concentrations and petrologic type. ^{40}Ar over K (c) and thus K-Ar ages (d) may tend to be higher for

CMs more affected by aqueous alteration compared to the most primitive CM. A clear trend is, however, questionable.

Fig. A 3: The ^{36}Ar concentrations versus bulk C content given in Alexander et al. (2012, 2013) and Piani et al. (2018; Paris) as a proxy for the matrix abundances.

Fig. A 4: A plot of $^{36}\text{Ar}/^{40}\text{Ar}$ versus petrologic types according to Howard et al. (2015). See Table A 2 for full names.

Fig. A 5: Ar concentrations clearly decrease from type 1.8 to 1.5 (b), only NWA 11024 and PCA 91008 (type 1.8, strongly heated) fall off the trend and are not considered in the linear fit (linear fit with NWA 11024 and PCA 91008: slope ~ 732 , $R^2 = 0.38$). Argon concentrations for samples with petrologic type ≤ 1.4 tend to be roughly constant (a).

Fig. A 6: Plots of mineralogical alteration index (MAI) versus ^{36}Ar concentration modified after Browning et al. (1996). Instead of average values, we give ranges from minimum to maximum ^{36}Ar concentrations measured in CMs based on the compilation by Schultz and Kruse published in 1989 (top, as used by Browning et al., 1996) and based on the updated compilation by Schultz and Franke published in 2004 (bottom). Left column: plots include all ^{36}Ar data given in the compilations with consideration of outliers. Right column: Outliers are removed from the plot based on the approach by Browning et al. (1998) – any ^{36}Ar concentration beyond 2σ of the average of the remainder of values for that CM is excluded. Browning et al. (1996) in addition estimated another bulk ^{36}Ar value for Murchison, while the mean value of Nogoya is based on a weighting factor of light and dark material separates. Blue circles: ^{36}Ar concentrations extracted from Fig. 3b in Browning et al. (1996). Red squares: ^{36}Ar concentrations measured for these CMs in this study. Variations in the ^{36}Ar concentrations can be large within a single CM, i.e., they may be larger than the variations of the mean concentrations with MAI used in Browning et al. (1996). Even if one does infer a trend of ^{36}Ar concentration with the MAI, one would receive a flat slope compared to the slope of a trend of ^{36}Ar versus alteration degrees of CMs lower than that of Murchison.

Fig. A 7: Fig. 1 with all meteorite names (see Table A 2 for full names).

Fig. A 8: a) $^{36}\text{Ar}/\text{C-carb}$ is decreasing with lower petrologic type due to the loss of ^{36}Ar with progressing aqueous alteration as there is no clear correlation between C-carb and b) ^{36}Ar or c) petrologic type. C-carb determined from abundances given in Alexander et al. (2012, 2013, 2015).

Fig. A 9: ^{36}Ar tends to be higher in (unheated) CMs with low intensity of water-related absorption at $3\ \mu\text{m}$. The $3\ \mu\text{m}$ band intensity (Beck et al. 2014) is more sensitive to heating compared to ^{36}Ar as visible in the low $3\ \mu\text{m}$ band intensities of heated CMs, whereas ^{36}Ar is only strikingly low in one of

the heated CMs, PCA 02010 (heated at >750 °C). For a few CMs we used the 3 μm band intensity from paired specimens.

Fig. A 10: Fig. 3 with all meteorite names (see Table A 2 for full names).

Fig. A 11: Fig. 8 before (left) and after (right) correction for Xe-air.

Fig. A 12: Fig. 10 with all meteorite names (see Table A 2 for full names).

Fig. A 13: Fig. 12 with all meteorite names (see Table A 2 for full names).

Fig. A 14: Fig. 13 before (left) and after (right) correction for Xe-air.

Tables

Table A 1: Element abundances in wt. % for bulk CM chondrites used to determine $^{21}\text{Ne}_{\text{cos}}$ production rates with the model by Leya and Masarik (2009).

CM mean	ALH 84042**	ALH 85013	Banten	EET 96029	LAP 02333	LAP 04514	LON 94102	Maribo	MET 01070	Might	Mukundpura	Murchison	Murray	Nogoya	NWA 11024	Paris	PCA 91008	QUE 93005	QUE 97990	SCO 06043	Bells	NWA 5958	
C	1.94		1.78													3.29							
O	40.35	50.01	46.45	52.09	46.23	45.68	41.78	44.53	48.27	45.52	44.76	50.01	45.66	45.70	46.41	45.38	41.79	49.98	50.77	50.96	46.72	49.86	48.34
Na	0.41	0.44	0.45	0.45	0.44	0.37	0.67	0.13	0.21	0.11	0.36	0.44	0.09	0.20	0.44	0.28	0.50	0.18	0.28	0.42	0.14	0.19	0.40
Mg	11.70	10.50	12.08	11.95	7.30	8.26	8.26	12.44	12.11	12.15	11.77	10.50	12.12	12.24	11.88	14.23	11.96	12.20	10.80	11.00	11.51	11.46	12.11
Al	1.16	0.69	1.18	1.16	1.64	1.96	1.43	1.25	1.11	1.21	1.10	0.69	1.14	1.19	1.19	1.23	1.10	1.31	1.26	1.19	1.19	1.43	1.19
Si	13.00	13.79	12.13*	13.49	13.09	12.11	11.27	12.42*	13.72	12.02*	14.73*	13.79	13.90*	13.26*	11.56*	14.49	13.43	12.05**	13.98**	14.74**	12.06**	16.19	13.75
S	3.30	3.17	3.17	2.20	2.20	3.80	4.30	3.03	3.60	3.60	3.25	3.34	2.45	2.73	3.34						3.36	1.04	
Ca	1.24	1.22	1.29	1.35	0.22	0.64	0.43	1.29	1.30	1.08	1.35	1.22	1.18	1.24	1.17	1.18	1.15	1.34	1.28	1.17	1.27	0.45	0.94
K	0.04	0.04	0.04	0.06	0.05	0.08	0.08	0.04	0.04	0.02	0.03	0.04	0.05	0.03	0.05	0.10	0.03	0.04	0.03	0.04	0.02	0.08	0.07
Ti	0.06	0.08	0.06	0.07		0.06	0.06	0.06	0.07	0.06	0.05	0.08	0.06	0.06	0.06	0.06	0.06				0.06	0.02	0.07
Mn	0.17	0.17	0.18	0.22	0.12	0.15	0.15	0.19	0.18	0.19	0.17	0.17	0.18	0.18	0.18	0.19	0.17	0.15	0.18	0.17	0.18	0.17	0.17
Fe	21.20	22.66	21.69	17.01	26.67	24.57	30.01	23.21	21.53	22.63	21.17	22.66	21.88	21.85	22.30	22.55	22.42	21.50	20.10	19.20	22.18	18.91	21.57
Ni	1.21	0.00	1.29	1.67	1.67	2.20	1.50	1.40	1.25	1.40	1.24	1.42	1.29	1.32	1.42	1.42	1.25	1.33	1.12	1.32	1.02	1.25	
Rb	0.00017	0.00018	0.00017				0.00018	0.00018	0.00017	0.00017	0.00014	0.00018	0.00016	0.00015	0.00018	0.00013	0.00017				0.00014	0.00010	
Sr	0.00100	0.00103										0.00103				0.00521	0.00108					0.00398	
Y	0.00021	0.00022										0.00022				0.00026	0.00021					0.00023	
Zr	0.00048	0.00056	0.00048									0.00056				0.00047	0.00048				0.00047	0.00045	
Ba	0.00032	0.00024	0.00028									0.00024				0.00032	0.00029				0.00027	0.00219	
Te	0.00014		0.00015													0.00016	0.00015				0.00016		
Total	95.79	99.59	100.00	99.64	99.62	99.89	99.94	100.00	99.52	100.00	100.00	99.59	100.00	100.00	100.00	99.69	97.31	100.00	100.00	100.00	100.00	100.84	99.85

Bulk chemistry for CM mean from Alexander (2019). For references of individual bulk chemistries see Table 5.

*derived from SiO_2 [wt. %] = $100 - \text{SUM}(\text{major oxide abundances [wt. %]})$ by converting major element into corresponding oxide abundances. ⁺Assumption: $\text{H}_2\text{O} = 15$ wt. % (King et al., 2019). ^{**}from ALH 83100 (paired).

Table A 2: Abbreviations of meteorite names used in the following figures.

Name	Abbreviation	Name	Abbreviation
ALH 84033	ALH 1	MIL 05152	MIL 2
ALH 84042	ALH 2	MIL 07689	MIL 3
ALH 85013	ALH 3	Mukundpura A	MP A
Banten	BT	Mukundpura B	MP B
DOM 08003	DOM	Murchison	MC
EET 96006	EET 1	Murray	MY
EET 96016	EET 2	Nogoya	NG
EET 96029	EET 3	NWA 10827 A	NWA 1A
GRA 98005	GRA	NWA 10827 B	NWA 1B
GRO 95566	GRO	NWA 11024	NWA 2
LAP 02277	LAP 1	Paris A	PA A
LAP 02333	LAP 2	Paris B	PA B
LAP 04514	LAP 3	PCA 02010	PCA 1
LAP 04796	LAP 4	PCA 91008	PCA 2
LEW 85312 A	LEW 1A	QUE 93005	QUE 1
LEW 85312 B	LEW 1B	QUE 97990	QUE 2
LEW 85312 C	LEW 1C	QUE 99355	QUE 3
LEW 90500	LEW 2	SCO 06043	SCO
LON 94102	LON	TIL 91722	TIL
Maribo	MB	NWA 10574 A	NWA 3A
MET 00432	MET 1	NWA 10574 B	NWA 3B
MET 01070	MET 2	Bells C	BL C
MET 01072	MET 3	Bells W	BL W
Mighei	MI	EET 83355	EET 4
MIL 05137	MIL 1	NWA 5958	NWA 4

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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