Exposure ages and radiogenic ages of ureilite (GRV 024516) and ordinary chondrite (GRV 024517) from Antarctica

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Received January 5, 2007

Abstract The GRV 024516 and GRV 024517 meteorite samples collected from Grieve Mountains, Antarctica are ureilite and H5 ordinary chondrite, respectively. Based on the study of mineralogy-petrology, the cosmic-ray exposure ages and gas retention ages of these two meteorites were determined and calculated. Their cosmic-ray exposure ages are 33.3 Ma, 51.7 Ma and gas retention ages are 1936.8 Ma and 3720 Ma, respectively. The ureilite contains diamond, graphite and amorphous G, which are mainly carrier of noble gases indicating obviously shock metamorphism effects which induced 40Ar partial loss. The H5 chondrite indicates thermal metamorphism of parent body, its gas retention age fall in the range between 3220 Ma and 4510 Ma of the least shocked H5 chondrites

Keywords meteorite, achondrite, noble gases, cosmogenic nuclide

1 Introduction

Cosmic-ray produced nuclides provide important constraints on meteorite origin, orbital evolution and parent body histories. Especially understanding origin of diamond in ureilites have important significance. Ureilites show signs of both igneous crystallization and primitive nebular condensation. On the one hand, in the aspects of mineralogy, texture, lithophile element chemistry, and Sm-Nd systematics, they appear as highly fractionated rocks either magmatic cumulates [1,2] or partial melt residues [3], and thus the product of planetary differentiation processes. On the other hand, they contain high abundance of carbon which contains large amount of fractionated primordial noble gases and metal with high abundance of trace siderophile elements, both of which are typical of undifferentiated chondritic material [4]. In addition, ureilites contain the oxygen isotope signature of primitive chondrites [5].

Recently, Rai et al. [6] investigated abundances and isotopic compositions of Ne, Ar, Kr
and Xe in 6 monomict polymict and the diamond-free ureilite ALH 78019 and their acid-resistant C-rich residues ²¹Ne-based cosmic-ray exposure ages for these 10 ureilites studied range from 0.1 Ma to 47 Ma indicating that no single conspicuous event ejected all the ureilites from their parent bodies Diamond and amorphous carbon are main noble gases carried. In addition, production rates of He, Ne and Ar for H chondrites are also all attention. Lay et al. investigated production rates of cosmogenic nuclides in H chondrites and other stony meteorites and suggested a purely physical model for the calculation of depth- and size-dependent production rates of cosmogenic nuclides by galactic cosmic-ray particles. Based on the concentrations and isotopic compositions of He, Ne, and Ar for normal magnetic fraction and bulk samples of 17 H chondrites and their ³⁶Cl/²⁶Ar exposure ages, ²¹Ne production rates as a function of ²²Ne/²¹Ne and mean ³⁸Ar production rates are determined. They gave production rate ratios P(³⁸Ar from Ca)/P(³⁸Ar from Fe). The radio varies between 10 and 77 and is not correlated with the absolute ³⁸Ar production or with ²²Ne/²¹Ne. Because of He deficits in the metal phase is much more pronounced than that in the silicate minerals. Eugster and Lorenzetti systematically studied production rates of cosmogenic nuclides of achondrites, especially of howardite, eucrite, and diogenite (HED meteorite—Vesta), and the break-up events of asteroids. They also concludes experience formula for calculating production rates. Recently, Eugster and Lorenzetti determined the He, Ne and Ar isotopic abundances and cosmic ray exposure ages in two differentiated acapulcoites and lodranites. They suggested evidence for a two-layer structure of the acapulcoite/lodranite parent asteroid. The acapulcoites correspond to the H3 and H4 chondrites and originated from exterior whereas the lodranites similar to H5 and H6 chondrites represent the inner regions of their parent body. Wang et al. studied neutron capture effects and pre-atmospheric sizes of meteoroids and determined the cosmic ray exposure history of two Antarctic meteorites.

GRV 024516 is ureilite with weighing 24.7 g GRV 024517 is H5 ordinary chondrite with weighing 40.5 g. They were collected in the Grombo Mountains region of Antarctica by the 19th Chinese Antarctic Expedition Team, on Jan. 2003. Ureilites are the rare type in achondrites and consist of olivine and pigeonite (1-3 mm) with interstitial and vein material that contains a number of carbon polymorphs. GRV 024516 (ureilite) composed mainly of pigeonite (En₉₇₁ ± 3 W₃₀₃ ± 4 Fs₆₆ ± 4) and olivine (Fo₈₄ ± 0.₅ 0.₄). The chemical compositions of olivine and pigeonite are homogeneous. In the reduced rim of olivine grains there are inclusions of Ni-poor metal and sulfide. Limonite veins are common and shock stage is S2/S3. GRV 024517 (H5 chondrite) consists mainly of olivine [(16.0 ± 0.₄) mol% Fa] and pyroxene [(16.0 ± 0.₄) mol% Fs].

In this paper, on the bases of the studied mineralogic-petrographic features of GRV 024516 (ureilite) and GRV 024517 (H5 chondrite) we report cosmic-ray exposure ages and retention ages of these two meteorites and discuss their cosmic ray exposure history.

2 Experimental procedure

Crushed meteorite samples were heated in vacuum at 90 °C for about 10 days to remove atmospheric gases. Noble gases extraction and mass spectrometric measurements were performed using our standard procedure. Two different systems of extraction and mass spec-
were used. System A contains two 60 °C sector-extraction mass spectrometers with glass tubes. The spectrometer for analyses of He, Ne, and Ar has a Faraday collector whereas the Kr/Xe spectrometer is equipped with an additional secondary electron multiplier. System B has a different gas extraction line and two metal-tube mass spectrometers equipped with secondary electron multipliers. One of the mass spectrometers was used for analyses of He and Ne and the other for Ar. The detailed analytical procedure, including background and blank correction, is referred to refs. Analysis errors correspond to a 95% confidence level. Isotope analyses of noble gases were conducted in the Institute of Physics of the University of Bem.

3 Calculation of cosmic-ray exposure age and retention age

One of the main goals of analysis and determination of cosmic-ray irradiation produced nuclides is the calculation of cosmic-ray exposure age. With concentrations of cosmogenic nuclides of meteorites, the cosmic-ray exposure ages can be calculated based on below equation: \( T_e = \frac{C}{P} \), where \( T_e \) for the age (Ma), \( C \) for concentrations \( (10^{-8} \text{ am}^3 \text{ STP/g}) \) of stable cosmogenic nuclides \( ^{1}H_e, ^{2}N_e, ^{3}R_{e}, ^{38}A_r \), and \( P \) for production rates of the nuclides \( (10^{-8} \text{ am}^3 \text{ STP/g* Ma}) \). The concentrations of cosmogenic \((c)\), trapped \((tr)\), and radiogenic \((r)\) nuclides can be determined from the analyses of the noble gases using some experimental isotopic ratios. Calculated method of ordinary chondrites is referred to refs. The calculation of concentrations of cosmogenic \((c)\), trapped \((tr)\), and radiogenic \((r)\) nuclides determined from the analyses of the noble gases for ureilites is somewhat different; their calculated methods are given in table I.

### Table I. Methods for calculating concentrations of cosmogenic \((c)\), trapped \((tr)\) and radiogenic \((r)\) nuclides and production rates

<table>
<thead>
<tr>
<th>isotopes</th>
<th>Calculated formula of concentrations of cosmogenic ((c)), trapped ((tr)) and radiogenic ((r)) nuclides</th>
</tr>
</thead>
</table>
| \( ^{22}N_{e}, ^{21}N_{e}, ^{36}A_{r}, ^{38}A_{r}, ^{38}A_{r} \) | \begin{align*}
(1) \quad ^{22}N_{e} &= ^{22}N_{e} \times \left[ 1 - \left( ^{20}N_{e}/^{22}N_{e} \right)_{m} / \left( ^{20}N_{e}/^{22}N_{e} \right)_{n} \right] / \left[ 1 - \left( ^{20}N_{e}/^{22}N_{e} \right)_{c} / \left( ^{20}N_{e}/^{22}N_{e} \right)_{n} \right] \\
(2) \quad ^{21}N_{e} &= ^{21}N_{e} - \left( ^{21}N_{e}/^{22}N_{e} \right)_{n} \left[ ^{22}N_{e} - ^{22}N_{e} \right] \\
(3) \quad ^{36}A_{r} &= ^{36}A_{r} - ^{36}A_{r} \left( ^{38}N_{e}/^{36}N_{e} \right)_{c}
\end{align*} |

\( m \) is measured concentration of He, Ne, Ar, and their ratios \( (^{20}N_{e}/^{36}A_{r})_{m} < 1 \), assumption \( (^{20}N_{e}/^{36}A_{r})_{n} = 8 \), \( 4G \) \( (^{21}N_{e}/^{22}N_{e})_{n} = 0.035 \), \( (^{20}N_{e}/^{22}N_{e})_{c} = 8 \) if \( ^{36}N_{e} \) assumption \( (^{20}N_{e}/^{36}A_{r})_{n} = 9.80 \), \( ^{21}N_{e}/^{22}N_{e})_{n} = 0.0290 \), \( (^{36}N_{e}/^{36}A_{r})_{c} = 8 \) if \( ^{38}N_{e} \) assumption \( (^{20}N_{e}/^{36}A_{r})_{n} = 12.4 \), \( ^{21}N_{e}/^{22}N_{e})_{n} = 0.0310 \), \( (^{36}N_{e}/^{36}A_{r})_{c} = 8 \) if \( ^{22}N_{e}, ^{21}N_{e}, \) and \( ^{36}N_{e} \) are obtained from (1), (2) and (3).

(4) calculation of \( ^{38}A_{r} \) and \( ^{36}A_{r} \):
\begin{align*}
^{36}A_{r}/^{38}A_{r} &= 0.65 \quad ^{36}A_{r} = ^{36}A_{r} \left[ 1, 1392 - 0.2141 \left( ^{36}A_{r}/^{38}A_{r} \right)_{n} \right] ; \quad ^{36}A_{r} = 0.65 \times ^{38}A_{r} \\
^{38}A_{r}/^{36}A_{r} &= 0.63 \quad ^{38}A_{r} = ^{38}A_{r} \left[ 1, 1343 - 0.2132 \left( ^{38}A_{r}/^{36}A_{r} \right)_{n} \right] ; \quad ^{38}A_{r} = 0.63 \times ^{38}A_{r}
\end{align*}

(5) \( T_{40} = 1.805 \ln \left( ^{40}A_{r}/0.701 \times K + 1 \right) \), \( K = \text{ ppm} \)

<table>
<thead>
<tr>
<th>isotopes</th>
<th>Production rates ((p)) are a function of shielding parameter ((22N_{e}/21N_{e})_{c}) and target elements (HED meteorites and ureilites)</th>
</tr>
</thead>
</table>
Table 2  Mean elemental compositions (wt %) by calculation of cosmic ray exposure ages for ureilites

<table>
<thead>
<tr>
<th>meteorite</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>Ca</th>
<th>Fe</th>
<th>Cr</th>
<th>Ti</th>
<th>Mn</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>ureilite (n = 9)(^{[6]})</td>
<td>21</td>
<td>81</td>
<td>0</td>
<td>25</td>
<td>18</td>
<td>60</td>
<td>0</td>
<td>330</td>
<td>0</td>
<td>71</td>
</tr>
<tr>
<td>Changde (H5)(^{[16]}) chondrite</td>
<td>13</td>
<td>79</td>
<td>1</td>
<td>15</td>
<td>17</td>
<td>58</td>
<td>2</td>
<td>04</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>M i an chi (H5)(^{[16]}) chondrite</td>
<td>14</td>
<td>03</td>
<td>1</td>
<td>11</td>
<td>18</td>
<td>08</td>
<td>2</td>
<td>01</td>
<td>1</td>
<td>28</td>
</tr>
</tbody>
</table>
Mean chemical Composition of the H5 chondrites\(^{[16]}\) | 8   | 14  | 1   | 1   | 15  | 1   | 26  | 27  | 4   | 0   | 36  |

The mean chemical compositions of ureilites are compared with mean chemical compositions of Changde (H5) and M i an chi (H5) chondrites, and are given in Table 2.

It must be pointed out that the determination of the production rate for \(^{38}\)Ar in the ureilite is very difficult. Up to date, there is yet no data on the production rate for \(^{38}\)Ar in ureilites. R a i e t al \(^{[6]}\) only obtain \(^{3}\)He, \((T_{3})\) and \(^{21}\)Ne, \((T_{21})\) cosmic ray exposure ages of 10 ureilites. E u g e ster and M ich e l \(^{[17]}\) investigated production rates of cosmogenic nuclides of H E D meteorites and they also suggested that although the \(^{22}\)Ne, \(^{21}\)Ne ratio of eucrites are variable the ob-
served $^{38}$Ar production rates are consistent with the shielding independent formula (table 1). Considering the present precision production rate calibration it is not justified to invoke a shielding dependency for $^{38}$Ar. But on the graph of $^{38}$Ar production rate $P_{38}$ calculated from cosmogenic $^{38}$Ar and $^{81}$Kr-$Kr$ exposure ages versus as calculated from chemical abundances all data allowing for the experiment errors fall on the correlation line. They therefore estimate the error for $^{38}$Ar to be about 10%. When $^{38}$Ar production rate $P_{38}$ of GRV 024516 (ureilite) is calculated if $P_{38} = 3.0 \times 10^{-10}$ cm$^3$/STP/(g Ma) chosen then $^{38}$Ar (T$_{38}$) age is 41.6 Ma ($^{38}$Ar $/P_{38} = 125.05/3 = 41.6$ Ma). But the average $^{38}$Ar production rate for H-chondrites is (0.0440 ± 0.0022) $\times 10^{-8}$ cm$^3$/STP/(g Ma) and its shielding parameter ($^{22}$Ne/$^{21}$Ne = 1.15) is close to GRV 024516 ($^{22}$Ne/$^{21}$Ne = 1.16). In stony meteorites $^{38}$Ar is produced exclusively by reaction on Ca, Mg, and Ni. The concentrations of these elements in ureilites are about a factor of 1.9 lower than those in H-chondrites; therefore, the production rate for $^{38}$Ar.

In ureilites must also be a factor of 1.9 lower than in H-chondrites. Therefore $P(^{38}$Ar) $= 0.0440/1.9 = 0.0232 ± 0.0012 × 10^{-8}$ cm$^3$/STP/(g Ma), which gives exposure age of T($^{38}$Ar) = 52 ± 5.8 Ma (email communication). The retention age of $^{40}$Ar (radiogenic $^{40}$Ar age) is calculated from $T_{40} = 1.805 ln(40Ar_r/0.701 × K(ppm) + 1).$ For H5 ordinary chondrite (GRV 024517), K $900 × 10^{-6}$, for ureilite (GRV 024516), K $80 × 10^{-6}$. [18]

4 Results and discussion

The analyses of isotope of He, Ne and Ar and their ratios of ureilite (GRV 024516) and H-5 chondrite (GRV 024517) are listed in table 3. Table 4 shows their calculated concentrations of the cosmogenic trapped and radiogenic nuclides and table 5 shows the determined production rates ($P_3$, $P_{21}$, $P_{38}$) of cosmogenic $^3$He, $^{21}$Ne and $^{38}$Ar their exposure ages and the gas retention ages.

<table>
<thead>
<tr>
<th>meteorites</th>
<th>Sample weight (mg)</th>
<th>$^4$He</th>
<th>$^3$He</th>
<th>$^{20}$Ne</th>
<th>$^{40}$Ar</th>
<th>$^3$He/ $^4$He</th>
<th>$^{20}$Ne/$^{21}$Ne</th>
<th>$^{21}$Ne/$^{38}$Ar</th>
<th>$^{36}$Ar/$^{38}$Ar</th>
<th>$^3$Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRV 024516</td>
<td>110.77</td>
<td>303±13</td>
<td>54±5</td>
<td>10±7</td>
<td>108±5</td>
<td>5.596</td>
<td>1.09±0.02</td>
<td>1.20±0.02</td>
<td>1.27±0.02</td>
<td>1.785</td>
</tr>
<tr>
<td>(ureilite)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRV 024517</td>
<td>177.36</td>
<td>n.d</td>
<td>75.9±19</td>
<td>2±4330</td>
<td>1.01±1</td>
<td>1.12±1</td>
<td>1.92±1</td>
<td>0.08±0.02</td>
<td>0.08±0.02</td>
<td>3.64±1</td>
</tr>
<tr>
<td>(ordinary</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>chondrite H5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The most widely used shielding indicator is ($^{22}$Ne/$^{21}$Ne) which correlates with ($^{3}$He/$^{21}$Ne) with least squares fit for 138 chondrites been calculated and the aquation resulted as following

($^{3}$He/$^{21}$Ne) = 21.77($^{22}$Ne/$^{21}$Ne) - 19.32 ($^{19}$) 

This correlation is valid in the range for the ($^{22}$Ne/$^{21}$Ne).
Table 4  Cosmogenic trapped and radiogenic noble gases (concentrations in \(10^{-8} \text{ cm}^3 \text{STP/g}\)) for ureilite (GRV 024516) and ordinary chondrite (GRV 024517)

<table>
<thead>
<tr>
<th>meteorites</th>
<th>(^3\text{He})</th>
<th>(^{21}\text{Ne})</th>
<th>(^{22}\text{Ne})</th>
<th>(^{38}\text{Ar})</th>
<th>(^{22}\text{Ne}/^{21}\text{Ne})</th>
<th>(^{20}\text{Ne})</th>
<th>(^{38}\text{Ar})</th>
<th>(^4\text{He})</th>
<th>(^{40}\text{Ar})</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRV 024516 (ureilite)</td>
<td>54 5 ± 2</td>
<td>4 8 17 ± 1</td>
<td>17 9 445 1 224 ± 12 1 16</td>
<td>3 144</td>
<td>0 8128</td>
<td>30 5</td>
<td>83 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRV 024517 (ordinary chondrite, H5)</td>
<td>16 9 ± 4</td>
<td>18 46 1 374 ± 01 1 094</td>
<td>4 416</td>
<td>0 899</td>
<td>—</td>
<td>4330 −</td>
<td>0 28 +</td>
<td>4329 72 &amp;superscript{2}</td>
<td></td>
</tr>
</tbody>
</table>

Note 1) If take \(\frac{^{3}\text{He}}{^{4}\text{He}}\) = 0 2 &superscript{61}, then \(\frac{^{3}\text{He}}{^{4}\text{He}}\) = 54 5/0 2 = 272 5, \(\frac{^{3}\text{He}}{^{4}\text{He}}\) = 303 &minus; 272 5 = 30 5
2) If take \(\frac{^{38}\text{Ar}}{^{20}\text{Ne}}\) = 0 2, then 40A = 1 374 &times; 0 2 = 0 275

Table 5  Cosmic ray exposure ages and gas retention ages, and production rates \(P_3, P_{21}, P_{38} = 10^{-8} \text{ cm}^3 \text{STP/g M a}\) for ureilite (GRV 024516) and ordinary chondrite (GRV 024517)

<table>
<thead>
<tr>
<th>meteorites</th>
<th>(P_3)</th>
<th>(P_{21})</th>
<th>(P_{38})</th>
<th>(T_3) (Ma)</th>
<th>(T_{21}) (Ma)</th>
<th>(T_{38}) (Ma)</th>
<th>(T_{38}) (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRV 024516 (ureilite)</td>
<td>1 639 [16]</td>
<td>0 282 [16]</td>
<td>0 030 [16]</td>
<td>29 [16]</td>
<td>32 7 ± 5</td>
<td>40 8 [16]</td>
<td>1936 8</td>
</tr>
<tr>
<td>GRV 024517 (ordinary chondrite, H5)</td>
<td>−</td>
<td>0 328 ± 2 [8]</td>
<td>0 0440 ± 2 [8]</td>
<td>51 5 ± 7</td>
<td>31 2 ± 2</td>
<td>3720</td>
<td></td>
</tr>
</tbody>
</table>

ratio between about 1 06 and 1 30. It may used for calculation of the cosmic ray exposure ages and allows to recognize meteorites which might have suffered \(^{3}\text{He}\) diffusion loss as they fall below the correlation line. The \(\frac{^{22}\text{Ne}/^{21}\text{Ne}}{_{c}}\) ratio is 1 16 for GRV 024516 (ureilite) and it has no diffusion loss. The \(^{3}\text{He}\) \((T_3)\) age is 33 8 Ma consisting with \(^{21}\text{Ne}\) \((T_{21})\) age (32 7 Ma), but its \(^{38}\text{Ar}\) \((T_{38})\) age (40 8 Ma or 52 7 Ma) is different from \(^{3}\text{He}\) and \(^{21}\text{Ne}\) ages. The probably errors caused by heterogeneous of concentrations of target elements. In general, \(^{21}\text{Ne}\) \((T_{21})\) age is more reliable than the \(^{38}\text{Ar}\) \((T_{38})\) age (possible trapped \(^{38}\text{Ar}\) = 0 15 &times; 10^{-6} STP/g). Therefore, the average exposure age of this ureilite is 33 3 Ma.

There no diffusion loss for \(^{3}\text{He}\) in the GRV 024517 (H5 chondrite), but \(^{4}\text{He}\) content exceed detection limit so the \(^{3}\text{He}\) cosmic ray exposure age cannot be calculated without data of \(^{4}\text{He}\). The determined \(\frac{^{22}\text{Ne}/^{21}\text{Ne}}{_{c}}\) ratio is 1 12 close to cosmogenic \(\frac{^{22}\text{Ne}/^{21}\text{Ne}}{_{c}}\) ratio (1 094). Thus the assumption whether the trapped component is of atmospheric or planetary compositions does not change the result. The \(^{21}\text{Ne}\) \((T_{21})\) age of GRV 024517 (H5 chondrite) is 51 5 &pm; 7 4 Ma. But ages determined via \(^{21}\text{Ne}\) and \(^{38}\text{Ar}\) disagree with it; one probable reason is that \(^{38}\text{Ar}\) is not homogeneously distributed in meteorites. In addition, gas retention age falls between 3220 Ma and 4510 Ma of the least shocked H5 chondrites.

The relative abundance pattern of noble gases in ureilites is of the fractionated planetary type, the same as in carbonaceous chondrites \(^{20, 21}\), though gas content vary considerable
(for example, Xe content vary by a factor of ~100) in bulk samples. Analysis of the carbonaceous matrix or ve in material showed the noble gases to be enriched at least 600 fold relative to the silicates and indicated that the gases are largely contained in carbon. Rai et al.\textsuperscript{[6]} point out in diamond-bearing ureilites diamond is the principal gas carrier and graphite is virtually free of trapped gases\textsuperscript{[22]}. The diamond-free ureilites has also trapped noble gases, which are carried by fine-grained carbon whose structural state is unknown. The distribution of cosmic-ray exposure ages of 28 ureilites are as follows\textsuperscript{[6]}. Except for two small clusters as at 1 ±1M a (n = 6) and 10 ±1M a (n = 5), for the rest the exposure ages are distributed between 1M a and 47M a, indicating no obvious single event that all the ureilites ejected from their parent bodies. Whereas, the diamond-free monomict ureilite (ALH 78019) has the lowest exposure age (0.1M a), but the polymict ureilite which is also diamond-free has the largest exposure age of 47M a. About 60% of ureilites are having cosmic-ray exposure ages less than 10M a. This indicates that ureilites in general has low cosmic-ray exposure ages. The cosmic-ray exposure ages of four polymict ureilites (EET83309 47M a EET87720 8 9M a Nilpena 9 8M a DaG319 21 5M a) are different and reveal that they were ejected from their parent body.\textsuperscript{[6]} in separate events. The most of the Ne is cosmogenic in origin. The small amount of trapped Ne could be mostly due to the Ne component from diamond and amorphous carbon, the main noble gas carriers. Thus, the trapped Ne content and its variable amount among bulk ureilites might be a direct reflection of fractional abundance of the carbon.

GRV 024516 is a ureilite with diamond and amorphous carbon. Graphite, diamond and amorphous carbon are a nebular condensate under reduced condition. Olivine and clinopyroxene are a directly condensed from gas phase at same location or the different location and at same time; but their condensations are later than that of carbon. All three carbon phases have been produced from the gas phase in the nebula and later have been incorporated into ureilites. That is to say, the diamond formation is unrelated to parent body processes and hence that the diamond is not produced in situ\textsuperscript{[23]}. In addition, the composition of nitrogen in diamond is very similar to other cases of diamond-bearing ureilites. Thus, the presence of diamond in ALH 82130 of low shock grade and in the almost unshocked ureilite DaG 868\textsuperscript{[24]} provides another argument against the role of shock in the formation of diamond.

Since diamond discovered in ureilites, its origin has been puzzle. Many of the features of ureilites indicate that the diamond was produced in situ by shock conversion of graphite\textsuperscript{[25]}. Although most ureilites show evidence of shock, it is not clear whether the shock is really responsible for diamond formation or whether the diamond was already present when ureilites underwent the shock event. Fukunaga and Matsuda\textsuperscript{[25]} have interpreted the diamond as a nebular origin for it can be produced by chemical vapor deposition in an artificial noble gas atmosphere under low-pressure plasma condition.

Ureilites contain coarse (millimeter-size) olivine and pyroxene grains that either crystallized from or equilibrated with melts at high temperatures. Cohenite [(Fe, Ni)\textsubscript{3}C] is present inside metal spherules which occur with olivine and pigeonite growths in several ureilites\textsuperscript{[26]}, indicating that the melts from which ureilites formed were carbon rich. It demonstrates that carbon was indigenous to the ureilite parent body\textsuperscript{[27]}. The carbon polymorphs are present in many ureilites. Haveri contains chaoite (C) along with diamond and lonsdalite.
leite (V dovyk in 1972). All three carbon polymorphs were formed by shock\[28\,29\]. Shock pressure of at least 100 GPa appear to have been involved (Carter et al. 1968). High concentrations of planetary-type noble gases are present in chondrites but not in basaltic achondrites. The high concentrations of planetary-type noble gases in ureilites \[21\,30\,31\] are consistent with very brief heating episodes and rapid burial minimizing the time available for noble gases to escape \[27\].

As can be seen, the diamond is the major carrier of noble gases. Its origin has been a topic of great debate which is still not settled. The diamonds are probably either produced from gas-rich amorphous carbon (nebular condensation origin) or converted from graphite into diamond phase by shock effect.

Acknowledgments We are very grateful to Prof. Ingo Leya and his group in the Institute of Physics of the University of Bremen for help in noble gas isotope measurements. This work was supported by the National Natural Science Foundation of China (Grant No. 40473037).

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