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

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Abstract The GRV 024516 and GRV 024517 meteorite samples collected from Grove Montains, Antactica 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 determinated 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 C, which are mainly carrier of noble gases indicating obviously shock metamorphism effects, which induced ^{40}Ar partial loss. The H5 chondrite indicates thermal metamorphism of parent body, its gas retention age fall the range between 3220 Ma and 4510 Ma of the least shocked H5 chondrites.

Key words 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, 3 polymict, and the diamond-free ureilite ALH 78019 and their acid-resistant, C-rich residues. ^{21}Ne-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 gas carried. In addition, production rates of He, Ne and Ar for H chondrites are also all attention. Laya *et al.*[7, 8] 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 nonmagnetic fraction and bulk samples of 17 H chondrites and their ^{36}Cl-^{36}Ar exposure ages, ^{21}Ne production rates as a function of $^{22}Ne/^{21}Ne$ and mean ^{38}Ar production rates are determined. They gave production rate ratios P(^{38}Ar from Ca) /P(^{38}Ar from Fe). The radio varies between 10 and 77, and is not correlated with the absolute ^{38}Ar production or with $^{22}Ne/^{21}Ne$. Because of ^{3}He deficits in the metal phase is much more pronounced than that in the silicate minerals. Eugster and Lorenzetti[9] systematically studied production rates of cosmogenic nuclides of achondrites, especially of howardite, eucrite and diogenite (HED meteorite——4 Vesta), and the break-up events of asteroids. They also concludes experience formula for calculating production rates. Recently, Eugster and Lorenzetti[10] 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.*[11, 12] studied netron capture effects and pre-atmospheric sizes of meteoroids and determinated the cosmic ray exposure history of two Antarctic meteorites.

GRV 024516 is ureilitte with weighing 24.7 g. GRV 024517 is H5 ordinary chondrite with weighing 40.5 g. They were collected in the Grove Mountains region, 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 nuber of carbon polymorphs[13]. GRV 024516 (ureilite) composed mainly of pigeonite ($En_{77.1\pm0.4}Wo_{9.3\pm0.1}Fs_{13.6\pm0.4}$) and olive ($Fo_{84.0\pm0.4}$). The chemical compositions of olivine and pigeonite are homogeneous. In the reduced rim of olivine grains there are inclusions of Ni-poor Ni metal and sulfide. Limonite veins are common and shock stage is S2/S3[13]. GRV 024517(H5 chondrite) consist 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 studing 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 ℃ for about 10 days to remove atmospheric gases. Noble gases extraction and mass spectrometric measurements were performed using our standard procedure[14]. Two different system of extraction and mass spectrometer were used. System A contains two 60 ℃ 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[15,16]. Analysis errors correspond to a 95% confidence level. Isotope analyses of noble gases were conducted in the Institute of Physics of the University of Bern.

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 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: $T_s = C^s/P^s$, T_s for the age (Ma), C^s for concentrations (10^{-8} cm^3 STP/g) of stable cosmogenic nuclides (^3He, ^{21}Ne, ^{38}Ar), and P^s for production rates of the nuclides (10^{-8} cm^3 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 experiential isotopic ratios. Calculated method of ordinary chondrites

referred to refs [11]. 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 1.

Table 1. Methods for calculating concentrations of cosmogenic(c),, trapped(tr) and radiogenic(r) nuclids and production rates

isotopes	Calculated formula of concentrations of of cosmogenic(c), trapped(tr) and radiogenic(r) nuclides
$^{22}Ne_c$, $^{21}Ne_c$, $^{20}Ne_{tr}$, $^{38}Ar_c$, $^{36}Ar_{tr}$, T_{40}	(1) $^{22}Ne_c = {}^{22}Ne_m \times [1-(^{20}Ne/^{22}Ne)_m/(^{20}Ne/^{22}Ne)_{tr}]/[1-(^{20}Ne/^{22}Ne)_c/(^{20}Ne/^{22}Ne)_{tr}]$ (2) $^{21}Ne_c = {}^{21}Ne_m - (^{21}Ne/^{22}Ne)_{tr}[^{22}Ne_m - {}^{22}Ne_c]$ (3) $^{20}Ne_{tr} = {}^{20}Ne_m - {}^{22}Ne_c(^{20}Ne/^{22}Ne)_c$ m is measured concentratios of He, Ne, Ar and their ratios. If $(^{20}Ne/^{36}Ar)_{tr} < 1$, assumption: $(^{20}Ne/^{22}Ne)_{tr} = 8.46$, $(^{21}Ne/^{22}Ne)_{tr} = 0.035$, $(20Ne/^{22}Ne)_c = 0.8$; If ④Ne, assumption: $(^{20}Ne/^{22}Ne)_{tr} = 9.80$, $(^{21}Ne/^{22}Ne)_{tr} = 0.0290$, $(^{20}Ne/^{22}Ne)_c = 0.8$; If ㈣ $(^{20}Ne/^{36}Ar)_{tr} > 1$, assumption: $(^{20}Ne/^{22}Ne)_{tr} = 12.4$, $(^{21}Ne/^{22}Ne)_{tr} = 0.0310$, $(^{20}Ne/^{22}Ne)_c = 0.8$. $^{22}Ne_c$, $^{21}Ne_c$ and $^{20}Ne_{tr}$ are obtained from (1), (2) and (3). (4) calculation of $^{38}Ar_c$ and $^{36}Ar_{tr}$: $(^{36}Ar/^{38}Ar)_c = 0.65$, $^{38}Ar_c = {}^{38}Ar_m[1.1392 - 0.2141(^{36}Ar/^{38}Ar)_m]$; $^{36}Ar_{tr} = 0.65 \times {}^{38}Ar_c$ $(^{36}Ar/^{38}Ar)_c = 0.63$, $^{38}Ar_c = {}^{38}Ar_m[1.1343 - 0.2132(^{36}Ar/^{38}Ar)_m]$; $^{36}Ar_{tr} = 0.63 \times {}^{38}Ar_c$ (5) $T_{40} = 1.805 \ln[^{40}Ar_r/0.701 \times K + 1]$, K = ppm
isotopes	Production rates (p) are a function of shielding parameter (22Ne/21Ne) c and target elements(HED meteorites and ureilites)

^{3}He	(6) $P'_3 = 1.15[Ti+Cr+Mn+Fe+Ni] + 1.75\{100-[Ti+Cr+Mn+Fe+Ni]\}$ [x] is element(wt%), $P'_3 = 10^{-10}$ cm^3 STP/(g Ma)] (7) P(^{3}He) vs (^{22}Ne/^{21}Ne)$_c$ $P_3 = 0.62 P'_3[2.09 - 0.43(^{22}Ne/^{21}Ne)]$ [x] is element(wt%), $P_3 = 10^{-10}$ cm^3 STP/(g Ma)]
^{21}Ne	(8) $P'_{21} = 1.63[Mg] + 0.6[Al] + 0.32[Si] + 0.22[S] + 0.07[Ca] + 0.021[Fe+Ni]$ [x] is element(wt%), $P'_{21} = 10^{-10}$ cm^3 STP/(g Ma)] P(^{21}Ne) vs (^{22}Ne/^{21}Ne)$_c$ $P_{21} = 4.8P'_{21}[25.7(^{22}Ne/^{21}Ne) - 23.7]^{-1}$ [x] is element(wt%), $P_{21} = 10^{-10}$ cm^3 STP/(g Ma)]
^{38}Ar	(9) $P'_{38} = 1.81[Ca] + 0.098[Fe+Ni] + 0.38[Ti+Cr+Mn] + 2.9[K] = $ [x] is element(wt%), $P'_{38} = 10^{-10}$ cm^3 STP/(g Ma)] Calculation of production rate of GRV 024516(ureilite) is using $P'_{38} = 3.0 \times 10^{-10}$ cm^3 STP/(g Ma) and mean production rate(0.0440) of H5 chondrite, but the concentrations of these elements in ureilites are about a factor of 1.9 lower than that in H-chondrites its production rate of ^{38}Arc is 0.0440/1.9= 0.0232 × 10^{-8} cm^3 STP/(g Ma)
isotopes	Production rates (p) are a function of shielding parameter (^{22}Ne/^{21}Ne) c(H, L and LL chondrites)
^{3}He, ^{21}Ne, ^{38}Ar	(10) $P_3 = F[2.09 - 0.43(^{22}Ne/^{21}Ne)_c]$ $F_H = 0.98$; $F_{L,LL} = 1.00$ (11) $P_{21} = 1.61F[21.77(^{22}Ne/^{21}Ne)_c - 19.32]^{-1}$ $F_H = 0.93$; $F_{L,LL} = 1.00$ (12) $P_{38} = F[0.125 - 0.071(^{22}Ne/^{21}Ne)_c]$ $F_H = 1.08$; $F_{L,LL} = 1.00$ F is chemical correction factor, P_3, P_{21}, $P_{38} = 10^{-8}$ cm^3 STP/(g Ma)

The mean chemical compositions of ureilites are compared with mean chemical compositons of Changde(H5) and Mianchi (H5) chondrites, and are given in table 2.

Table 2 Mean elemental compositios(wt%) by calculation of cosmic-ray exposure ages for ureilites

meteorite	Mg	Al	Si	S	Ca	Fe	Cr	Ti	Mn	Ni
ureilite(n=9) [6]	21.81	0.25	18.60	0.330	0.71	14.62	0.508	0.07	0.290	0.131
Changde chondrite (H5) [16]	13.79	1.15	17.58	2.04	1.37	28.21	0.36	0.05	0.139	1.8
Mianchi chondrite (H5) [16]	14.03	1.11	18.08	2.01	1.28	28.38	0.32	0.08	0.271	1.69
Mean chemical Composition of the 8 H5 chondrites [16]	14.1	1.15	–	–	1.26	27.4	0.36	–	0.23	1.64

It must point out, the determination of the production rate for ^{38}Ar in the ureilite is very difficult. Up to date, there yet no data of the production rate for ^{38}Ar in ureilites. Rai *et al.* [6] only obtain ^{3}He$_c$ (T_3) and ^{21}Ne$_c$ (T_{21}) cosmic-ray exposure ages of 10 ureilites. Eugster and Michel [17] investigated production rates of cosmogenic nuclides of HED meteorites and they also suggested that although the ^{22}Ne/^{21}Ne ratio of eucrites are variable the observed ^{38}Ar production rates are consistant 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 age, versus as calculated from chemical abundances[17] all data, allowing for the experiment errors, fall on the correlation line. They, therefore, estimate the 2σ 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 $^{38}Ar_c$ (T_{38}) age is 41.6Ma ($^{38}Ar_c/P_{38}$ = 125.05/3.0= 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)[8] and its shielding parameter ($^{22}Ne/^{21}Ne$= 1.15) is close to GRV 024516 ($^{22}Ne/^{21}Ne$= 1.16). In stoy meteorites ^{38}Ar is produced exclusively by reaction on Ca, Fe, 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 $\times 10^{-8}$ cm^3 STP/ (g Ma), which gives exposure age of T(^{38}Ar) = 52.7 ±5.8Ma(E-mail 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 $\times 10^{-6}$; for ureilite (GRV 024516), K 80 $\times 10^{-6}$[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 ^3He, ^{21}Ne and ^{38}Ar, their exposure ages, and the gas retention ages.

Table 3. Results of He, Ne and Ar measurements(10^{-8} cm^3 STP/g) for ureilite(GRV 024516) and ordinary chondrite(GRV 024517).

meteorites	Sample weight (mg)	^4He	^3He	^{20}Ne	^{40}Ar	$^4He/^3He$	$^{20}Ne/^{22}Ne$	$^{22}Ne/^{21}Ne$	$^{36}Ar/^{38}Ar$	$^{40}Ar/^{36}Ar$	^{36}Ar
GRV 024516 (ureilite)	110.77	303 ± 13	54.5 ± 2.4	10.7 ± 0.4	108 ± 5	5.5596	1.09 ± 0.02	1.20 ± 0.02	5.27 ± 0.22	0.1785	605 ± 31
GRV 024517 (ordinary chondrite, H5)	177.36	n.d	75.9 ± 3.2	19.2 ± 0.8	4330 ± 180		1.01 ± 0.02	1.12 ± 0.02	1.92 ± 0.08		3.64 ± 0.17

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

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

This correlation is valid in the range for the ($^{22}Ne/^{21}Ne$)$_c$

Table 4. Cosmogenic, trapped and radiogenic noble gases (concentrations in 10^{-8} cm^3 STP/g) for ureilite (GRV 024516) and ordinary chondrite (GRV 024517)

meteorites	^3He_c	$^{21}Ne_c$	$^{22}Ne_c$	$^{38}Ar_c$	$\frac{^{22}Ne}{^{21}Ne}$	$^{20}Ne_{tr}$	$^{36}Ar_{tr}$	^4He_r	$^{40}Ar_r$
GRV 024516 (ureilite)	54.5 ± 2.4	8.17 ± 0.17	9.445	1.224 ± 0.12	1.16	3.144	0.8128	30.5 1)	83.0
GRV 024517 (ordinary chondrite, H5)	–	16.9 ± 0.4	18.46	1.374 ± 0.01	1.094	4.416	0.899	–	4330–0.28= 4329.72 2)

Note: 1) If take ($^3He/^4He$) c= 0.2[6], then ^4He_c= 54.5/0.2= 272.5, ^4He_r = 303– 272.5= 30.5
2) If take ($^{40}Ar/^{38}Ar$)$_c$ = 0.2, then $^{40}Ar_c$= 1.374 × 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} cm^3 STP/g Ma) for ureilite (GRV 024516) and ordinary chondrite (GRV 024517)

meteorites	P_3	P_{21}	P_{38}	$\frac{T_3}{(Ma)}$	$\frac{T_{21}}{(Ma)}$	$\frac{T_{38}}{(Ma)}$	$\frac{T_{40}}{(Ma)}$
GRV 024516 (ureilite)	1.639 [6] (P'_3 = 1.633)	0.282 [6] (P'_{21} = 0.421) 0.25[7,8]	0.030 [6] 0.0232 ± 0.0012[7,8]	33.8[6]	29.[6] 32.7 ± 6.5[7,8]	40.8 [6] 52.7 ± 5.8[7,8]	1936.8
GRV 024517 (ordinary chondrite, H5)	–	0.328 ± 0.045[7,8]	0.0440 ± 0.0022[7,8]		51.5 ± 7.4[7,8]	31.2 ± 2.0[7,8]	3720

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 ^3He diffusion loss, as they fall below the correlation line. The ($^{22}Ne/^{21}Ne$) c ratio is 1.16 for GRV 024516 (ureilite) and it has no diffusion loss. The ^3He_c (T_3) age is 33.8 Ma consisting with $^{21}Ne_c$ (T_{21}) age (32.7 Ma), but its $^{38}Ar_c$ (T_{38}) age (40.8 Ma or 52.7 Ma) is different from ^3He_c and $^{21}Ne_c$ ages. The probably errors caused by heterogeneous of concentrations of target elements. In general, $^{21}Ne_c$ (T_{21}) age is more reliable than the $^{38}Ar_c$ (T_{38}) age (possible trapped ^{38}Ar= 0.15 × 10^{-6} STP/g). Therefore, the average exposure age of this ureilite is 33.3 Ma.

There no diffusion loss for ^3He_c in the GRV 024517 (H5 chondrite), but ^4He content exceed detection limit, so the ^3He_c cosmic-ray exposure agecan not be caculated without data of ^4He. The determined ($^{22}Ne/^{21}Ne$) ratio is 1.12 closed to cosmogenic ($^{22}Ne/^{21}Ne$)$_c$ ratio (1.094). Thus, the assumption whether the trapped component is of atmospheric or planetary compositions does not change the results. The $^{21}Ne_c$ (T_{21}) age of GRV 024517 (H5 chondrite) is 51.5 ± 7.4 Ma. But ages determined via $^{21}Ne_c$ and $^{38}Ar_c$ disagree with it, one probable reason is, that ^{38}Ar is not homogeneously distributed in meteorites. In addition, gas retention age falls bewteen 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 vein 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.*[6] point out, in diamond-bearing ureilites, diamond is the principal gas carrier and graphite is virtually free of trapped gases[22]. The diamond-free ureilite 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[6]. Except for two small clusters as at 1 ± 1 Ma(n = 6) and 10 ± 1 Ma(n = 5), for the rest the exposure ages are distributed between 1Ma and 47Ma, indicating no obvious single event thar all the ureilites ejected from their parent bodies. Whereas the diamond-free monomict ureilite (ALH78019) has the lowest exposure age (0.1Ma), but the polymict ureilite which is also diamond-free has the largest exposure age of 47Ma. About 60% of ureilites are having cosmic-ray exposure ages less than 10Ma. This indicats that ureilites, in general, has low cosmic-ray exposure ages. The cosmic-ray exposure ages of four polymict ureilites (EET83309: 47Ma, EET87720: 8.9Ma, Nilpena: 9.8Ma, DaG319: 21.5Ma) are different. And reveal that they were ejected from their parent body[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 clinoaugite 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[23]. In addition, the composition of nitrogen in diamond is very similar to other cases of diamond-bearing ureilites. Thus, mere presence of diamond in ALH 82130 of low shock grade and in the almost unshock ureilite DaG 868[24] provides anather agrumemt 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[23]. 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[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 [$(Fe, Ni)_3C$] is present inside metallic spherules which occur within olivine and pigeonite grains in several ureilites[26], indicating that the melts from which ureilites formed were carbon rich. It demonstrates that carbon was indigenous to the ureilite parent body[27]. The carbon polymorphs are present in many ureilites, Haverö contains chaoite (C) along with diamond and lonsdaleite (Vdovykin 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 major carrier of noble gases. Is 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.

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