Proc. NIPR. Symp. Antarct. Meteorites, 2, 288–295, 1989

NOBLE GAS DEGASSING FROM METEORITES AS INFERRED FROM ^{40}Ar-^{39}Ar ANALYTICAL DATA

Ichiro KANEOKA

Earthquake Research Institute, University of Tokyo, 1–1, Yayoi 1-chome, Bunkyo-ku, Tokyo 113

Abstract: 'Retention rate of radiogenic ^{40}Ar through a collisional event' (f_r) was estimated on the basis of ^{40}Ar-^{39}Ar analytical data for each meteorite reported. 'The amount of trapped ^{36}Ar' ($^{36}Ar_T$) seems to be roughly correlated with the determined Ar retention rate, 'f_r', for samples with f_r of less than 0.5. When we extend this correlation to $f_r=1$, the original amount of trapped ^{36}Ar in ordinary chondrites is estimated to be in the order of 10^{-7} cm^3 STP/g. Even meteorites with no clear sign of impact often show lower amounts of trapped ^{36}Ar, suggesting that the loss of trapped components might have occurred in a stage of meteorite formation for these meteorites.

The amounts of trapped ^{36}Ar and ^{84}Kr seem to be correlated with those of trapped ^{132}Xe, reflecting also the degree of equilibrium state of meteorites. Meteorites with signs of impact show lower amounts of trapped heavy noble gases. Such a correlation might be explained by degassing processes through diffusion at relatively high temperatures for prolonged periods of time.

1. Introduction

A meteorite contains noble gases of different origins, including primarily trapped components. To infer the compositions of primary components when the meteorite was formed, the trapped components are most significant. However, such components are often disturbed secondarily through impact (or collisional) processes and weathering on the Earth's surface (*e.g.*, BOGARD *et al.*, 1976; TURNER, 1969). Once disturbed, it is not easy to evaluate the original gas compositions of the meteorite, including the abundances of noble gases originally contained in it.

Based on the release patterns of Ar in neutron-irradiated meteorites, KANEOKA (1984) has tried to identify the kind of secondary effects such as a shock or weathering on the Earth's surface by showing some examples for Antarctic meteorites. However, it has not included the evaluation of the retention or degassing rate of noble gases.

Using ^{40}Ar-^{39}Ar analytical data, the author has tried to estimate the retention rate of noble gases after a meteorite experienced an impact. It requires some assumptions to get the retention rate, but it would still give us useful information about the state of noble gas degassing caused by an impact (or collisional) process(es).

2. Analytical Method and Examples for Antarctic Meteorites

The main purpose of this study is to estimate the retention rate of noble gases

Fig. 1(a). Schematic diagram to indicate events considered in this model. $({}^{40}Ar)^*_{Ta-Tc}$*: the amount of radiogenic* ${}^{40}Ar$ *accumulated during the period Ta-Tc.* $({}^{40}Ar)^*_{To-Tc}$*: the amount of radiogenic* ${}^{40}Ar$ *accumulated during the period To-Tc.* $({}^{40}Ar)^*_{Ta}$*: the amount of radiogenic* ${}^{40}Ar$ *accumulated from the time Ta to the present.* $({}^{40}Ar)^*_{To}$*: the amount of radiogenic* ${}^{40}Ar$ *accumulated from the time To to the present.*

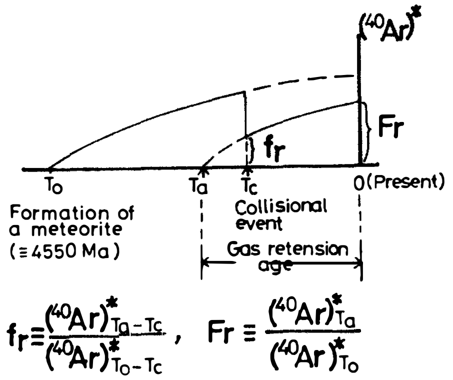
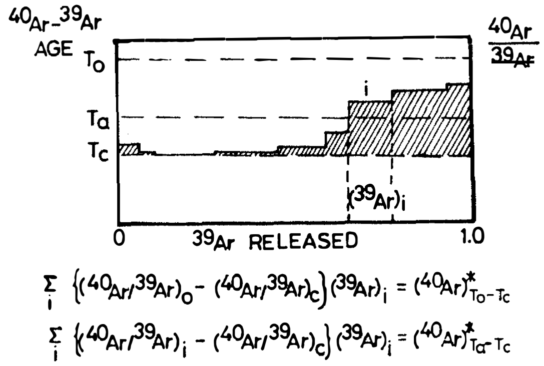


Fig. 1(b). Schematic diagram to indicate each component to calculate $({}^{40}Ar)^*_{To-Tc}$ *and* $({}^{40}Ar)^*_{Ta-Tc}$ *from the* ${}^{40}Ar$-${}^{39}Ar$ *analytical data.* $({}^{40}Ar/{}^{39}Ar)_0$*: the* ${}^{40}Ar/{}^{39}Ar$ *ratio which corresponds to the time To.* $({}^{40}Ar/{}^{39}Ar)_c$*: the* ${}^{40}Ar/{}^{39}Ar$ *ratio which corresponds to the time Tc.* $({}^{40}Ar/{}^{39}Ar)_i$*: the* ${}^{40}Ar/{}^{39}Ar$ *ratio observed in the 'i'-th temperature fraction.* $({}^{39}Ar)_i$*: the rate of the amount of* ${}^{39}Ar$ *released in the 'i'-th temperature fraction to the total amount of* ${}^{39}Ar$*.*



during a degassing process from a meteorite caused by an impact (or collisional) process(es). We utilize radiogenic ${}^{40}Ar$, though the trapping sites for radiogenic ${}^{40}Ar$ and for the other noble gases are not always the same.

A meteorite is assumed to have been formed at time 'To' and have degassed radiogenic ${}^{40}Ar$ together with other noble gases partially at time 'Tc'. Based on the ${}^{40}Ar$-${}^{39}Ar$ age spectra, we can assign the time Tc for the meteorite in a favourable condition. Further we can estimate the K-content of the meteorite from the ${}^{40}Ar$-${}^{39}Ar$ analytical data or by the direct K-measurement. Hence, if we know To, we can calculate the amount of radiogenic ${}^{40}Ar$ in the meteorite which has been accumulated during the period from To through Tc. On the other hand, we can calculate 'an apparent gas retention age' (Ta) from the present amount of radiogenic ${}^{40}Ar$ and the K-content of the meteorite. If we assume that the degassing occurred only at Tc and the meteorite was formed at To, we can calculate an apparent gas retention rate F_r from the following equation:

$$F_r = \frac{({}^{40}\mathrm{Ar})^*_{\mathrm{Ta}}}{({}^{40}\mathrm{Ar})^*_{\mathrm{Tc}}} \tag{1}$$

where $({}^{40}Ar)^*_{Ta}$ indicates the amount of radiogenic ${}^{40}Ar$ which should have been accumulated from Ta to the present and $({}^{40}Ar)^*_{To}$ the amount of radiogenic ${}^{40}Ar$ which should have been accumulated from To to the present.

As shown in Fig. 1(a), however, the retention rate of Ar at time 'Tc' (f_r) is different from F_r. 'f_r' is defined as follows:

$$f_r = \frac{({}^{40}\mathrm{Ar})^*_{\mathrm{Ta-Tc}}}{({}^{40}\mathrm{Ar})^*_{\mathrm{To-Tc}}} \tag{2}$$

where $(^{40}Ar)^*_{Ta-Tc}$ indicates the amount of radiogenic ^{40}Ar which should have been accumulated during the period of Ta and Tc and $(^{40}Ar)^*_{To-Tc}$ the amount of radiogenic ^{40}Ar during the period of To and Tc.

In the present study, it is essential to estimate f_r. To calculate this value on the basis of ^{40}Ar-^{39}Ar analytical data, the general scheme is shown in Fig. 1(b), schematically. $(^{40}Ar)^*_{To-Tc}$ and $(^{40}Ar)^*_{Ta-Tc}$ can be calculated as follows:

$$(^{40}Ar)^*_{To-Tc}=\sum_i \{(^{40}Ar/^{39}Ar)_0-(^{40}Ar/^{39}Ar)_C\}(^{39}Ar)_i \tag{3}$$

$$(^{40}Ar)^*_{Ta-Tc}=\sum_i \{(^{40}Ar/^{39}Ar)_i-(^{40}Ar/^{39}Ar)_C\}(^{39}Ar)_i \tag{4}$$

where $(^{40}Ar/^{39}Ar)_0$ indicates the ratio of radiogenic ^{40}Ar to K-derived ^{39}Ar for the meteorite with an age To, $(^{40}Ar/^{39}Ar)_C$ the ratio of radiogenic ^{40}Ar to K-derived ^{39}Ar for the meteorite which shows an age of Tc, $(^{40}Ar/^{39}Ar)_i$ the ratio of radiogenic ^{40}Ar to K-derived ^{39}Ar for the 'i'th temperature fraction of the meteorite and $(^{39}Ar)_i$ the rate of the amount of ^{39}Ar released in the 'i'th temperature fraction to that of the total ^{39}Ar released from the meteorite.

Some meteorites might have been affected secondarily in a more complicated way. In such a case, f_r should be interpreted to show a value as to have averaged them into a single event. As described above, it is essential to know Tc and To to calculate the value f_r. In the present study, To is assumed to be 4550 Ma on the

Table 1. Summary of the retention rate of radiogenic ^{40}Ar calculated for Antarctic meteorites.

Meteorite	Class	^{40}Ar-^{39}Ar age* (Ma) Plateau	Total	Tc (Ma)	F_r**	f_r**
Y-74640	H6	4407	4317	—	0.87	—
ALH-77288, 62	H6	4460	4759	—	(1.1)	—
63	H6	4497	4764	—	(1.1)	—
Y-74191	L3	—	3558	—	0.54	—
ALH-77015	L3	(4514)	4065	—	0.74	—
Y-74190	L6	357	443	357	0.02	0.006
ALH-761, 61	L6	—	4431	—	0.93	—
62	L6	—	4579	—	(1.0)	—
63	L6	4487	4417	—	0.92	—
ALH-77214	L3	—	3105	—	0.40	—
ALH-77304	LL3	4503	3680	—	0.58	—
Y-75258	LL6	4377	4381	4377	0.90	0.25
Y-74159	Eu	4075	4043	4075	0.73	0.08
Y-74450	Eu	4012	4045	4012	0.74	0.07
ALH-765	Eu	(3438)	3251	—	0.44	—
Y-7308	Ho	4480	4538	—	0.99	—
Y-74097	Di	(1100)	1190	(1100)	0.07	0
Y-75097	L6	489	583	489	0.03	0.006

* ^{40}Ar-^{39}Ar analytical data have been taken from the following references; KANEOKA (1980, 1981, 1983), KANEOKA *et al.* (1979, 1988).

** F_r and f_r were calculated after the definitions described in Fig. 1 and in the text. Numerical figures in parentheses are less reliable.

basis of radiometric age data reported for undisturbed meteorites (*e.g.*, TATSUMOTO *et al.*, 1973). Even if we assume it as 4500 Ma or 4600 Ma, however, it does not alter the value f_r significantly.

Examples are shown for Antarctic meteorites in Table 1, where f_r could be obtained only for limited samples, because we cannot determine Tc for the other samples definitely. From this result, it is pointed out that except for Y-75258 (LL6) most samples with signs of impact seem to have lost radiogenic ^{40}Ar seriously during the degassing event, though the value F_r is not always small.

Although details are not described, similar values have been reported in the paper by BOGARD *et al.* (1976).

3. Relationship between the Amount of Trapped ^{36}Ar and f_r in Disturbed Meteorites

By adopting the procedure described in the previous chapter, we can calculate f_r for each meteorite which has been analysed by the ^{40}Ar-^{39}Ar method. Based on the reported data, f_r is calculated for each meteorite and the amount of trapped ^{36}Ar ($^{36}Ar_T$) is plotted against f_r in order to examine the relationship between these components (Fig. 2). Reported values are used for $^{36}Ar_T$ in each paper, where cosmogenic ^{36}Ar is corrected.

In Fig. 2, as long as the meteorites with F_r of less than 0.5 are concerned, $^{36}Ar_T$ seems to increase roughly with the value of f_r. It is worth mentioning that f_r is derived from the amount of radiogenic ^{40}Ar alone. This implies that the trapped Ar would have also been lost from a meteorite together with radiogenic ^{40}Ar during an impact (or collisional) process(es). There seems to be no systematic difference among different kinds of meteorites, but meteorites with a relatively low f_r belong mostly to a

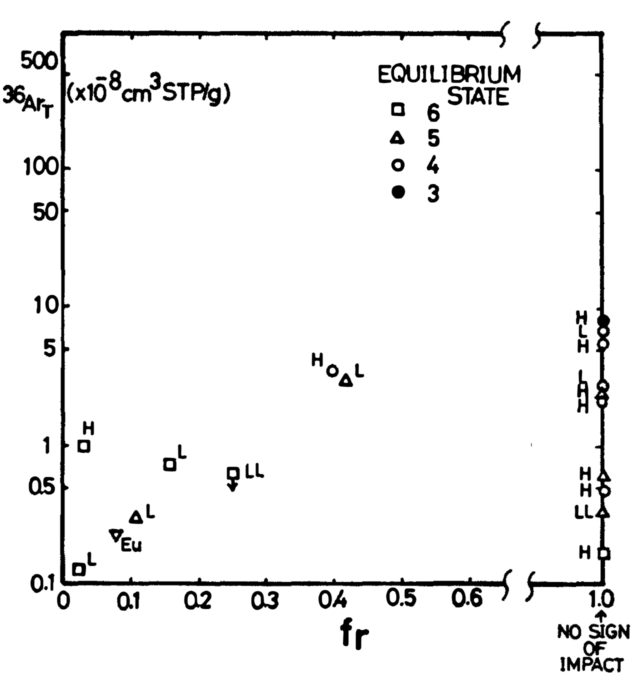


Fig. 2. The amount of trapped ^{36}Ar ($^{36}Ar_T$) vs. f_r. Equilibrium state is defined for each meteorite after VAN SCHMUS *and* WOOD *(1967). H, L, LL and Eu indicate H-, L-, LL-chondrites and eucrite, respectively. Data sources;* BOGARD *et al., 1976;* BOGARD *and* HIRSCH*, 1980;* KANEOKA*, 1981;* KANEOKA *et al., 1979, 1988;* TURNER*, 1969;* TURNER *et al., 1978.*

group of meteorites which show higher degrees of the equilibrium state (metamorphism defined by VAN SCHMUS and WOOD, 1967). If we could extend the trend to $f_r=1$, the amount of ^{36}Ar originally trapped in an oridinary chondrite is estimated to be in the order of 10^{-7} cm^3 STP/g for these meteorites.

On the other hand, even meteorites with no sign of impact show large variations in the observed $^{36}Ar_T$, which varies from 0.2 to 9 in the unit of 10^{-8} cm^3 STP/g. This suggests a possibility that trapped noble gases might have also been lost during the stage of meteorite formation, probably during accretion or soon after the meteorite formation. The time interval at this stage is much less compared with that of the later history of a meteorite. Hence, such an event does not affect the ^{40}Ar-^{39}Ar age spectrum apparently and we cannot evaluate the effect from their appearances. No systematic differences are observed among different kinds of meteorites, but there seems to be a trend that a meteorite with a lower degree of the equilibrium state keeps the larger amount of $^{36}Ar_T$. Thus we can argue that the degree of the equilibrium state of a meteorite defined by VAN SCHMUS and WOOD (1967) would reflect both effects caused during the meteorite formation and by a later thermal event including an impact (or collisional) process(es).

4. Noble Gas Degassing during an Impact (or Collisional) Process

It is well known that meteorites contain trapped components of noble gases in different amounts with large variations. An example is shown in Fig. 3, which is modified by adding some new data after the figure by HEYMANN (1971). A clear trend observed is that the amounts of trapped components are correlated with each other. The amounts of trapped ^{36}Ar ($^{36}Ar_T$) and ^{84}Kr ($^{84}Kr_T$) are correlated with that of ^{132}Xe ($^{132}Xe_T$), implying also the correlation between $^{36}Ar_T$ and $^{84}Kr_T$. In general, meteorites with a lower degree of the equilibrium state show larger amounts of trapped components (*e.g.*, ZÄHRINGER, 1966). Meteorites with a sign of impact show systematically lower amounts of trapped components. This suggests that the secondary impact would surely affect the degassing from a meteorite, reducing the original trapped noble gases.

In the present study, f_r is compared with $^{36}Ar_T$ only, because the number of meteorites which have sufficient data to get f_r and other noble gas data is limited. Combining the trends observed in Figs. 2 and 3, however, we can argue that f_r is also correlated with the amounts of $^{84}Kr_T$ and $^{132}Xe_T$ when such an impact process would occur secondarily.

The most important of the characteristics observed in Fig. 3 is the correlation among the amounts of trapped components of noble gases. This suggests that the degassing process of noble gases from a meteorite is controlled by a common process(es) which affects all noble gases or at least heavier noble gases. Although radiogenic ^{40}Ar is not always trapped in the same site as those of the trapped noble gases, the retention rates of these noble gases are correlated with each other. Hence, one of the main controlling factors for the degassing rate of noble gases seems to be thermal effects. During an impact process, the occurrence of microcracks would also cause degassing from the cracked regions. In such a case, however, the distribution

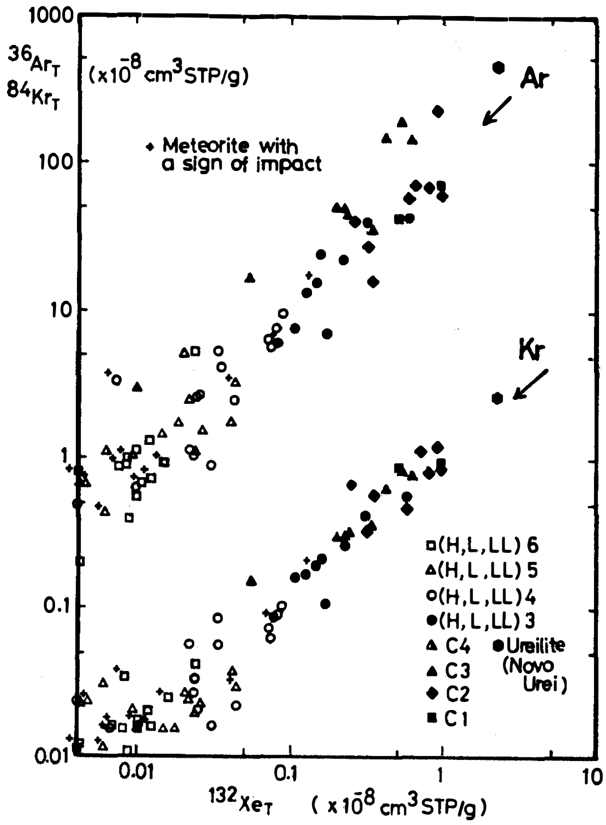


Fig. 3. The amount of trapped ^{36}Ar($^{36}Ar_T$) or ^{84}Kr($^{84}Kr_T$) vs. the amount of trapped ^{132}Xe($^{132}Xe_T$). Modified after Fig. 12 in HEYMANN *(1971). Meteorite with a cross indicates the one which shows a sign of impact. C indicates a carbonaceous chondrite.*

of each component would seriously affect the degassing rate and not always indicate a correlation between the trapped component and the radiogenic component which would be distributed in a different way. Although diffusion process is also controlled by the structures of samples, the degree of relative movement of each noble gas component would be held at a relatively similar value as long as the diffusion process is a main controlling factor.

In order to examine the degassing process during an impact, many experimental studies have been made (*e.g.*, BOGARD *et al.*, 1987; CAFFEE *et al.*, 1982; DAVIS, 1977; FREDRIKSSON *et al.*, 1964; JESSBERGER and OSTERTAG, 1982). However, most experiments indicate that the effect of pressure itself is not sufficient enough to degass from a meteorite significantly unless an elevated temperature also accompanies. Thus, to degas noble gases from a meteorite by an impact process through diffusion, it requires relatively elevated temperatures for prolonged time (*e.g.*, BOGARD *et al.*, 1987; KANEOKA *et al.*, 1988).

As mentioned before, even such meteorites which do not show any sign of impact seem to have often lost trapped components of noble gases. Thus, the amounts of trapped components of noble gases in meteorites would probably reflect the thermal metamorphism which occurred in the stage of meteorite formation and during the secondary processes of impact such as collision. Since the diffusion is considered to affect the degassing rate as one of the main factors, relatively elevated temperatures are indispensable to degas noble gases effectively from these meteorites. However, we do not observe the sign of melting in such meteorites in many cases. Hence, the temperature should be below the melting point of meteorites generally and rather prolonged periods of time are required to explain the degassing.

Acknowledgments

The author is grateful to the National Institute of Polar Research for supplying him with the Antarctic meteorites for ^{40}Ar-^{39}Ar analyses. The author is also grateful to two anonymous reviewers for their constructive criticism on this paper.

This study is financially supported in part by the Grant-in-Aid for Co-operative Research (No. 59390007) from the Ministry of Education, Science and Culture, Japan.

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(Received September 9, 1988; Revised manuscript received January 6, 1989)