Noble gases in Muong Nong-type tektites and their implications

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Abstract–We have measured the elemental abundances and isotopic compositions of noble gases in Muong Nong-type tektites from the Australasian strewn field by crushing and by total fusion of the samples. We found that the abundances of the heavy noble gases are significantly enriched in Muong Nong-type tektites compared to those in normal splash-form tektites from the same strewn field. Neon enrichments were also observed in the Muong Nong-type tektites, but the Ne/Ar ratios were lower than those in splash-form tektites because of the higher Ar contents in the former. The absolute concentrations of the heavy noble gases in Muong Nong-type tektites are similar to those in impact glasses. The isotopic ratios of the noble gases in Muong Nong-type tektites are mostly identical to those in air, except for the presence of radiogenic ^{40}Ar. The obtained K-Ar ages for Muong Nong-type tektites were about 0.7 Myr, similar to ages of other Australasian tektites. The crushing experiments suggest that the noble gases in the Muong Nong-type tektites reside mostly in vesicles, although Xe was largely affected by adsorbed atmosphere after crushing. We used the partial pressure of the heavy noble gases in vesicles to estimate the barometric pressure in the vesicles of the Muong Nong-type tektites. Likely, Muong Nong-type tektites solidified at the altitude (between the surface and a maximum height of 8–30 km) lower than that for splash-form tektites.

INTRODUCTION

Tektites are a group of natural glasses occurring in 4 different strewn fields (North American, Central European, Ivory Coast, and Australasian strewn fields) on the Earth. Numerous geochemical and isotopic studies have confirmed the terrestrial impact origin of the tektites (e.g., Taylor 1973; King 1977; Koeberl 1986, 1990, 1994; Glass 1990; Montanari and Koeberl 2000). Although tektites and impact glasses have both been produced by impact melting of terrestrial surface rocks, differences between tektites and impact glasses exist (e.g., impact glasses are found directly at a crater, while tektites are distal ejecta that occur in a strewn field away from the source crater).

Tektites can be divided into 3 groups. The first and second groups are splash-form tektites and aerodynamically shaped tektites. The third group is called Muong Nong-type tektites after the area in Laos from where they were first described by Lacroix (1935). Muong Nong-type tektites (also called "layered tektites") differ in their appearance from other tektites by having irregular, blocky shapes, layered structures, and by their larger sizes (e.g., Glass 1990; Wasson 1991; Koeberl 1992, 1994). Muong Nong-type tektites are mostly found in the Indochina part of the Australasian strewn field,

although, some of them have also been recovered from the Central European and North American strewn fields (e.g., Meisel et al. 1989; Glass et al. 1990, 1995). Chemically, Muong Nong-type tektites are enriched in volatile elements (e.g., Cl, Br, Zn, Cu, Pb) relative to splash-form and aerodynamically shaped tektites (e.g., Müller and Gentner 1973; Wasson 1991; Koeberl 1992). In addition to this compositional feature, petrographic evidence indicates a lower temperature origin for Muong Nong-type tektites than for other tektites (Glass and Barlow 1979; Barnes 1989; Koeberl 1992; Glass et al. 1995). However, uncertainty still exists regarding the formation mechanism of this particular type of tektite and its relation to the other tektite groups found in the Australasian strewn field.

Being chemically inert and volatile, noble gases in tektites and impact glasses provide valuable information about the conditions of their formation (e.g., Matsuda et al. 1993). Matsuda et al. (1989) measured noble gas contents in Darwin impact glasses and found significant enrichments of neon compared to air. Neon enrichments have been recorded from silica-rich glasses, such as tektites (Hennecke et al. 1975; Matsubara and Matsuda 1991; Matsuda et al. 1993; 1996; Palma et al. 1997), impact glasses (Matsuda et al. 1989; Matsubara et al. 1991), and obsidians (Matsuda et al. 1989;

Miura and Nagao 1991). A laboratory study clearly demonstrated that these neon enrichments are due to the faster diffusion of neon, compared with the heavier noble gases, in glasses after solidification (Matsubara and Matsuda 1995). Neon concentrations in these glasses are rather uniform, reflecting neon saturation in silica-rich glasses irrespective of their types. In contrast, there is a systematic difference in the concentration of the heavier noble gases between tektites and impact glasses—heavy noble gases are depleted in tektites compared to impact glasses and can be used as tracers to infer the height during their solidification (Matsuda et al. 1993). Later, Palma et al. (1997) reported that Xe concentrations in North American tektites were similar to those of impact glasses and that Kr concentrations in these tektites were between those in impact glasses and tektites from other strewn fields.

So far, our knowledge on noble gases in the Muong Nong-type tektites is based on a limited data set; only 4 samples had been analyzed by heating gas extraction (Jessberger and Gentner 1972; Murty 1997). Here we present the first comprehensive noble gas survey of Muong Nong-type tektites based on 16 total analyses. Because tektites have vesicles in which noble gases are likely to be trapped, we extracted the noble gases not only by heating but also by crushing to better understand the formation processes of tektites from their noble gas abundance and isotopic ratios. Muong Nong-type tektites are of particular interest because: 1) they are compositionally different from splash-form tektites; and 2) they are found only in a limited region in the Australasian strewn field without an identified source crater(s). Based on the new data, we discuss the formation of Muong Nong-type tektites and their relation to the splash-form Australasian tektites.

SAMPLES AND ANALYSES

We analyzed a well-documented suite of Muong Nong-type tektites from Ubon Ratchatani in East Thailand (7 samples), near the border of Laos, and one sample (MN X-103) from southern Laos. Detailed descriptions and chemical compositions for those and related samples were given in previous papers (Glass and Koeberl 1989; Blum et al. 1992; Koeberl 1992; Beran and Koeberl 1997).

To avoid (known) heterogeneities in the vesicle population, samples were coarsely crushed, and fragments with sizes between 1.18 to 1.70 mm were selected. The samples were subsequently washed in an ultrasonic bath with distilled water, acetone, and ethanol for 30 min each. After drying overnight in an oven at ~100°C, about 0.3 g of the crushed samples were loaded into stainless-steel sample containers in the crusher with 6 holders (Matsumoto et al. 2001). To determine the procedural blank levels, at least 1 container was loaded without a sample.

Details of gas handling and purification, as well as mass spectrometry by the VG5400 noble gas mass spectrometer,

are described in our previous publications (Wada and Matsuda 1998; Matsumoto et al. 2001). Sensitivity and isotope discrimination of the mass spectrometer were calibrated by analyzing known amounts of air aliquots (Ne, Ar, Kr, and Xe) and the synthetic mixture of ^{3}He and ^{4}He (HESJ Standard; ^{3}He/^{4}He = (2.888 ± 0.014) × 10^{-5}; Matsuda et al. 2002).

After the blank analysis, each sample was crushed in a vacuum by being hit by the piston for about 1000 strokes, and the elemental concentrations and isotopic ratios of noble gases were measured. The crushed samples were taken out of the vacuum line and were sieved under atmospheric pressure. The grains with sizes <150 μm were regarded as those that release gases from vesicles, and we normalized the elemental concentrations of the noble gases to the mass of the grains having sizes <150 μm (samples and data labeled "Crushing" in Tables 1–4). These crushed grains were again placed in the vacuum line and were subsequently heated to analyze the noble gases in the glass matrix (samples and data labeled "Heating"). Note that thin section observation revealed the presence of vesicles <150 μm, thus, the concentrations of the noble gases measured by melting the grains <150 μm should be regarded as the upper limit of gases trapped in glass matrix.

Typical crusher blank levels were $3.0 × 10^{-10}$, $3.4 × 10^{-11}$, $2.7 × 10^{-11}$, $1.2 × 10^{-12}$, and $1.2 × 10^{-14}$ cm^3 STP for ^{4}He, ^{20}Ne, ^{36}Ar, ^{84}Kr, and ^{130}Xe, respectively. The hot blanks for ^{4}He, ^{20}Ne, ^{36}Ar, ^{84}Kr, and ^{130}Xe were $1.3 × 10^{-8}$, $1.9 × 10^{-10}$, $2.9 × 10^{-10}$, $9.5 × 10^{-12}$, and $2.7 × 10^{-13}$ cm^3 STP, respectively. In many cases, the helium fraction released during the sample run was similar to the blank level. Typically, the crusher blank contributed only a few percent of the sample value for the heavy noble gases. Thus, blank corrections with isotopically atmospheric compositions were applied to all results obtained by crushing extraction. The hot blank contribution was slightly higher and was in many cases about 10% of the sample fraction. Blank corrections were applied to all samples, unless the corrections exceeded 30%, in which case, we only reported the uncorrected result of elemental abundance as an upper limit.

RESULTS

The elemental and isotopic compositions of the noble gases extracted from the Muong Nong-type tektites are reported in Tables 1–4.

Elemental Abundance

To compare the elemental abundance patterns of the Muong Nong-type tektites to those of air, fractionation factors (F[m]) are shown in Fig. 1. The fractionation factor is defined by the equation:

$$F(m) = (^mX/^{36}Ar)_{sample}/(^mX/^{36}Ar)_{air} \qquad (1)$$

Table 1. He and Ne concentrations and isotopic compositions in Muong Nong-type tektites.[a]

Sample	Weight[b]	Crushing[c]	^{4}He $(10^{-9}$ cm^3 STP/g)	^{3}He/^{4}He (10^{-6})	^{20}Ne $(10^{-8}$ cm^3 STP/g)	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne
Crushing							
MN 8301	0.135 g	×1000	<2.9	–	4.3	9.45 ± 0.16	0.0285 ± 0.0008
MN 8307	0.203 g	×1000	2.9	–	7.2	9.84 ± 0.03	0.0298 ± 0.0006
	–	×2000	<1.8	–	0.63	9.70 ± 0.11	0.0301 ± 0.0007
	–	Total	<4.7	–	7.9	9.82 ± 0.03	0.0298 ± 0.0006
MN 8309	0.150 g	×1000	<2.9	–	8.2	9.84 ± 0.10	0.0293 ± 0.0006
MN 8310	0.165 g	×1000	<4.1	–	3.9	9.75 ± 0.11	0.0290 ± 0.0006
MN 8311	0.128 g	×1000	<2.2	–	7.9	9.76 ± 0.11	0.0291 ± 0.0006
MN 8317	0.151 g	×1000	3.4	–	11	9.74 ± 0.11	0.0288 ± 0.0006
MN 8318	0.155 g	×900	2.9	–	11	10.0 ± 0.2	0.0289 ± 0.0009
MN X-103	0.223 g	×1000	57	1.60 ± 0.30	1.8	9.95 ± 0.12	0.0294 ± 0.0006
Heating							
MN 8301	0.110 g	1800°C	<22	–	1.9	9.55 ± 0.17	0.0272 ± 0.0008
MN 8307	0.189 g	800°C	37	–	2.0	9.57 ± 0.16	0.0292 ± 0.0007
	–	1200°C	<21	–	<0.008	–	–
	–	1600°C	<11	–	<0.011	–	–
	–	1800°C	11	–	<0.013	–	–
	–	Total	<80	–	<2.1	–	–
MN 8309	0.148 g	1800°C	15	–	2.0	9.71 ± 0.17	0.0312 ± 0.0008
MN 8310	0.135 g	1800°C	<20	–	2.3	9.69 ± 0.08	0.0288 ± 0.0004
MN 8311	0.128 g	1800°C	<18	–	2.4	9.51 ± 0.06	0.0290 ± 0.0002
MN 8317	0.121 g	1800°C	<21	–	3.1	9.55 ± 0.05	0.0288 ± 0.0002
MN 8318	0.144 g	1800°C	<17	–	2.1	9.48 ± 0.05	0.0281 ± 0.0003
MN X-103	0.181 g	1800°C	<13	–	0.28	9.83 ± 0.31	0.0296 ± 0.0010
Air	–	–	–	1.4	–	9.80	0.0290

[a]Concentrations of gases and isotopic ratios are corrected for procedural blank, but when blank levels exceed 30% of the sample signals, the concentrations are simply given as upper limits without blank correction.
[b]Weight of samples. For the crushing extractions, the weight is for the grains smaller than 150 μm.
[c]Number of crushing strokes for the crushing extraction. For the heating extractions, the temperatures to which the sample were heated are given.

where ^mX represents a noble gas isotope of mass "m." Helium data are not included because of their low abundances (possibly due to diffusive loss after tektite formation, and in the vacuum of the extraction system). As shown in Figs. 1a and 1b, the samples have F(20) values well above unity, indicating a neon enrichment relative to argon. No systematic difference exists in the degrees of neon enrichment in the crushing and heating experiments. Interestingly, the observed F(20) values in Muong Nong-type tektites (2.6 to 37) are significantly lower than those of normal tektites (200 to 7130; Matsubara and Matsuda 1991). In fact, the range of F(20) values for Muong Nong-type tektites agrees well with previously reported values for impact glasses (Matsuda et al. 1989; Matsubara et al. 1991). Note that the difference in the F(20) values is not due to differences in neon concentration between Muong Nong-type tektites and normal tektites. As shown in Fig. 2, both types of tektites have relatively uniform ^{20}Ne concentrations (~10^{-7} cm^3 STP/g). Matsubara and Matsuda (1995) concluded that neon in natural silica glasses has completely exchanged with atmospheric neon by rapid diffusion after their formation. Thus, a relatively uniform range of neon concentrations in these glasses reflects the saturation level that can be acquired by diffusive input.

Therefore, systematically smaller F(20) values in Muong Nong-type tektites should reflect their relatively high argon concentrations. As shown in Fig. 2, the range of ^{36}Ar concentrations in Muong Nong-type tektites are at least 1 order of magnitude larger than those in splash-form tektites and agree well with concentrations reported for impact glasses.

Values of F(84) and F(130) for gases released by crushing are consistent with atmospheric composition. In contrast, gases extracted by the heating of powdered samples yielded F(130) values significantly higher than unity, indicating that the released fraction is enriched in xenon with respect to the atmospheric composition. This is probably due to the adsorption of xenon onto the surface of the powdered grains, because xenon is the most easily adsorbed of all the noble gases (Matsubara and Matsuda 1995). The potential of "irreversible" adsorption is reported by Niedermann and Eugster (1992). However, the effect of adsorption of atmosphere is only shown in the heated samples. Our results indicate that noble gases in the Muong Nong-type tektite vesicles cannot have originated from atmospheric gases adsorbed on sediments that were released during the tektite-forming heating event. This is because fractionation values of
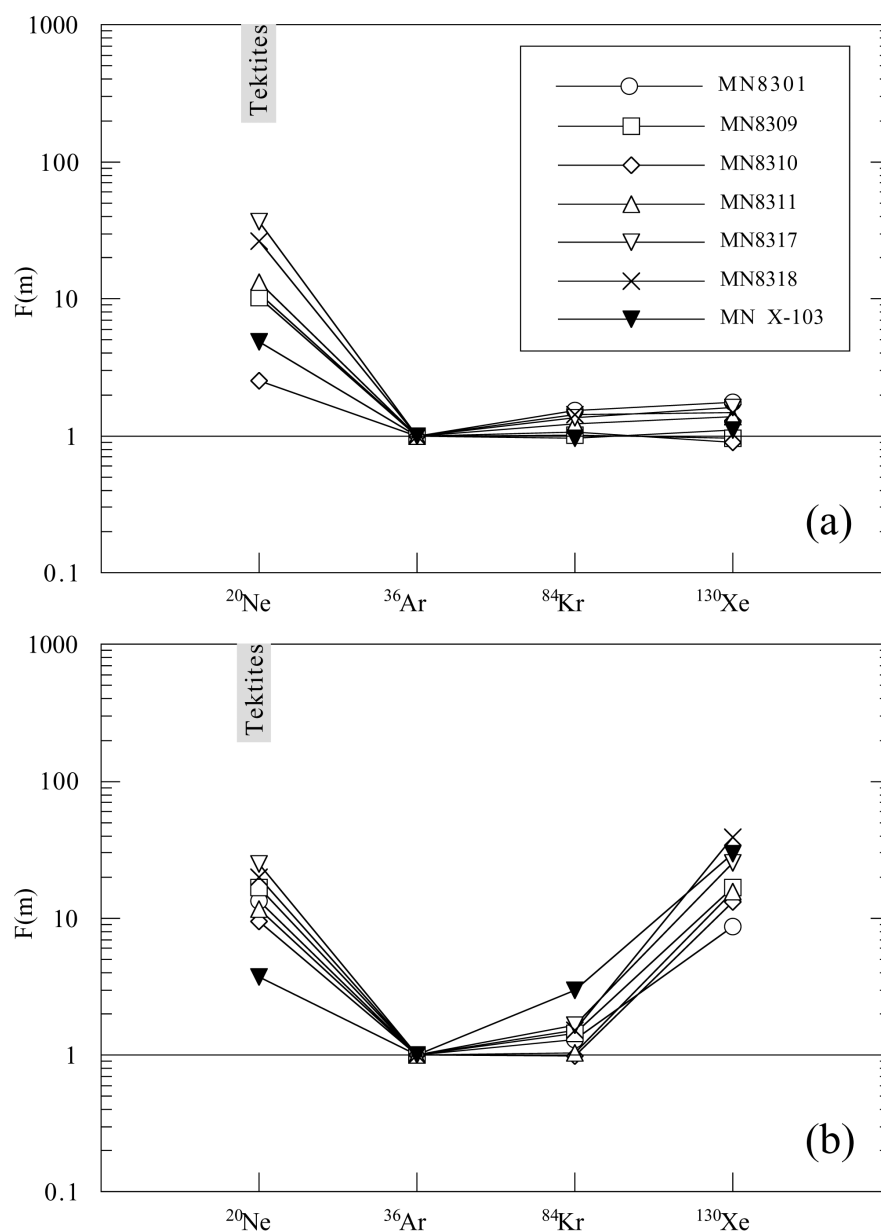
Fig. 1. Elemental abundance patterns of noble gases in Muong Nong-type tektites are plotted as the fractionation factor F(m) (see text for explanation) relative to the atmospheric composition: a) values obtained by the crushing method; b) data from the heating method. F(4) values are not shown, as helium abundances are as low as the procedural blank levels. The shaded area labeled "Tektites" shows the range of F(20) values (200 –7130) reported previously for splash-form tektites (Matsubara and Matsuda 1991).

the heavy noble gases (Kr, Xe) are almost unity (see Fig. 1a), in contrast to patterns for adsorbed gases. In the case of adsorption, the heavy noble gases are highly fractionated, and F(84) and F(130) values are about 10 or more (e.g., Matsuda and Nagao 1986).

Isotopic Ratios

As shown in Tables 1–4, almost all isotopic ratios, except the $^{40}Ar/^{36}Ar$ ratios, are consistent with atmospheric compositions within experimental uncertainties. The $^{20}Ne/$

^{22}Ne and $^{21}Ne/^{22}Ne$ ratios in the heated samples are slightly lower than the atmospheric values (Table 1), but the Ne ratios in the crushed samples are almost identical to the atmospheric values. The low Ne ratios in the heated samples may be due to the mass fractionation effect with the gas release by prior crushing. Up to about 80% of the Ne was released by crushing, and the Ne isotopic ratios are identical to atmospheric values. Thus, we can regard that Ne in the whole sample originated mostly from the air.

Such an occurrence of isotopically air-like noble gases is a common characteristic of glassy materials of terrestrial
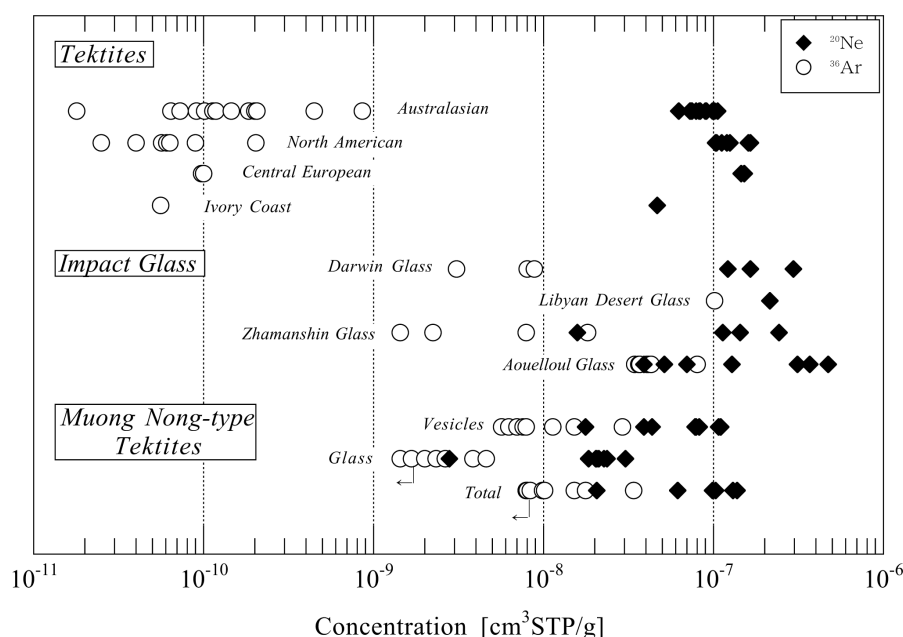
Fig. 2. Concentrations of [20]Ne (closed diamond) and [36]Ar (open circle) for tektites from 4 strewn fields (Hennecke et al. 1975; Matsubara and Matsuda 1991; Matsuda et al. 1993; Palma et al. 1997) and impact glasses: Darwin glass (Matsuda et al. 1989), Libyan Desert glass, Zhamanshin glass and Aouelloul glass (Matsubara et al. 1991). The neon concentrations in all samples are confined to a small range. The argon concentrations in Muong Nong-type tektites are close to those reported for impact glasses. The arrows indicate upper limits.

impact origin (such as tektites and impact glasses). Previous work on Muong Nong-type tektites also reported atmosphere-like isotopic compositions (Jessberger and Gentner 1972; Murty 1997). As to the $^{40}Ar/^{36}Ar$ ratios, note that $^{40}Ar/^{36}Ar$ ratios higher than the atmospheric ratio of 295.5 were found for gases released by crushing, suggesting that some radiogenic ^{40}Ar is also released by crushing from glass matrix. This is often observed in crushing experiments (e.g., Matsumoto et al. 2002).

K-Ar ages

By using the observed radiogenic ^{40}Ar in gases released by total fusion, as well as the potassium content of each sample (Koeberl 1992), calculating approximate K-Ar ages of the samples is possible. The ages with uncertainties smaller than 50% are 0.71 ± 0.34 Myr (MN 8309), 0.67 ± 0.14 Myr (MN 8311), 0.64 ± 0.14 Myr (MN 8317), and 0.73 ± 0.15 Myr (MN 8318) (other samples have significantly larger uncertainties due to low amounts of radiogenic ^{40}Ar). The obtained ages may give values lower than the real ages because some radiogenic ^{40}Ar was released by crushing before fusion. This may be the case for MN 8311 and MN 8317 which yielded relatively shorter ages, and is consistent with $^{40}Ar/^{36}Ar$ ratios greater than the atmospheric ratio at the crushing. However, applying corrections to K-Ar ages for such a loss of radiogenic ^{40}Ar by prior crushing is quite difficult because the radiogenic ^{40}Ar released by crushing cannot easily be expressed in units of cm³ STP/g. Note that

argon concentrations in Table 2 are calculated based on the assumption that the grains smaller than 150 μm had gases trapped in vesicles of >150 μm. Likely, the concentrations of radiogenic ^{40}Ar by crushing are overestimates because of the normalization to small masses.

At any rate, we assume the effect of radiogenic ^{40}Ar loss by crushing is negligible for correcting ages obtained from heating of the <150 μm fraction because the ages of ~0.7 Myr agreed with each other within their 2 sigma errors, and, more importantly, they agree with the reported Ar-Ar ages of Australasian tektites (0.77 ± 0.02 Myr; Izett and Obradovich 1992) and with fission track ages for Muong Nong-type indochinites—about 0.7 Myr (Storzer and Wagner 1977; Bigazzi and Michele 1996), implying that Muong Nong-type tektites are formed by a common event with other Australasian tektites. Note also that the K-Ar ages reported here are only a byproduct of our analyses and are not the main goal.

DISCUSSION

Noble Gas Distribution

Because we have analyzed the samples both by crushing and by total fusion, we can estimate the fractions of noble gases dissolved in the glass and trapped in the vesicles, respectively. We regard the amounts of Ne, Ar, Kr, and Xe released by crushing to represent the noble gases trapped in vesicles. Gases released from samples with grain sizes of <150 μm were regarded to represent the concentrations in the matrix

Table 2. Ar concentrations and isotopic compositions in Muong Nong-type tektites.[a]

Sample	Weight[b]	Crushing[c]	^{36}Ar $(10^{-9}\ cm^3/STP/g)$	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$
Crushing					
MN 8301	0.135 g	×1000	7.6	0.1909 ± 0.0033	311.0 ± 5.0
MN 8307	0.203 g	×1000	5.9	0.1928 ± 0.0043	301.9 ± 5.6
		×2000	0.4	0.1896 ± 0.0030	315.4 ± 6.8
		Total	6.3	0.1926 ± 0.0040	302.7 ± 5.3
MN 8309	0.150 g	×1000	15	0.1881 ± 0.0012	297.0 ± 3.2
MN 8310	0.165 g	×1000	29	0.1868 ± 0.0013	293.7 ± 3.2
MN 8311	0.128 g	×1000	11	0.1889 ± 0.0020	305.1 ± 3.6
MN 8317	0.151 g	×1000	5.6	0.1888 ± 0.0025	304.8 ± 4.6
MN 8318	0.155 g	×900	7.9	0.1809 ± 0.0017	282.3 ± 10.4
MN X-103	0.223 g	×1000	7.0	0.1881 ± 0.0012	307.4 ± 3.5
Heating					
MN 8301	0.110 g	1800°C	2.7	0.1869 ± 0.0012	304.9 ± 12.4
MN 8307	0.189 g	800°C	0.63	0.1874 ± 0.0012	412.5 ± 29.2
	–	1200°C	<0.39	–	–
	–	1600°C	<0.29	–	–
	–	1800°C	<0.36	–	–
	–	Total	<1.7	–	–
MN 8309	0.148 g	1800°C	2.3	0.1884 ± 0.0011	321.5 ± 12.0
MN 8310	0.135 g	1800°C	4.6	0.1884 ± 0.0031	304.9 ± 4.7
MN 8311	0.128 g	1800°C	3.9	0.1878 ± 0.0007	310.2 ± 2.4
MN 8317	0.121 g	1800°C	2.3	0.1888 ± 0.0019	319.7 ± 3.8
MN 8318	0.144 g	1800°C	2.0	0.1866 ± 0.0011	323.4 ± 4.1
MN X-103	0.181 g	1800°C	1.4	0.1889 ± 0.0023	333.5 ± 5.8
Air	–	–	–	0.1880	295.5

[a]Concentrations of gases and isotopic ratios are corrected for procedural blank, but when blank levels exceed 30% of the sample signals, the concentrations are simply given as upper limits without blank correction.
[b]Weight of samples. For the crushing extractions, the weight is for the grains smaller than 150 μm.
[c]Number of crushing strokes for the crushing extraction. For the heating extractions, the temperatures to which the sample were heated are given.

glass. As shown in Fig. 3, the present samples appear to have roughly 70 to 85% of Ne, Ar, and Kr in their vesicles. A larger amount of xenon seems to be dissolved in the glass compared to other noble gases. However, we can estimate the Xe amount in glass from the atmospheric Xe/Ar ratio and the observed Ar abundance in the glass. The abundances of xenon in glass would be about 1/9 to 1/39 of the total amount observed in the powdered samples, as shown in Fig. 1b. The correction indicates that about 80–85% of Xe resides in vesicles.

Likely, the observed noble gases from the powdered samples are also released from small vesicles (<150 μm) rather than from the glass matrix itself. In this case, the fraction of gas residing in vesicles should be higher than the values above.

Altitude of Closure and Noble Gases in Muong Nong-Type Tektites

Noble gases trapped in vesicles may record the ambient atmospheric pressure of the altitude at which the tektites solidified. First, we attempt to estimate the volumes of the vesicles that were crushed to release gases in each sample, which is necessary to estimate the internal noble gas pressures in the vesicles. Note that the volumes estimated from thin sections might not be useful because of the heterogeneous distribution of the vesicles and uncertainty relating incomplete crushing of smaller vesicles; i.e., we need to determine the volume of the vesicles that were actually crushed in the experiment. Thus, we estimated an "actual experimental vesicle volume" ("effective" vesicularity) using the neon contents as described below.

The reason that neon concentrations in the present samples are useful to determine the sample's effective vesicularity lies in the high diffusivity of neon in glass. Matsubara and Matsuda (1995) showed experimentally that neon can diffuse into 149–250 μm obsidian grains and that its concentration approached saturation at room temperature for time scales of several tens of days, which results in preferential acquisition of neon compared to heavier noble gases. Because K-Ar ages of these Muong Nong-type tektites are about 0.7 Myr, we can reasonably assume that the partial pressure of neon in the vesicles is in equilibrium with that of air. Thus, we may estimate the effective vesicularity of the samples from the following equation:

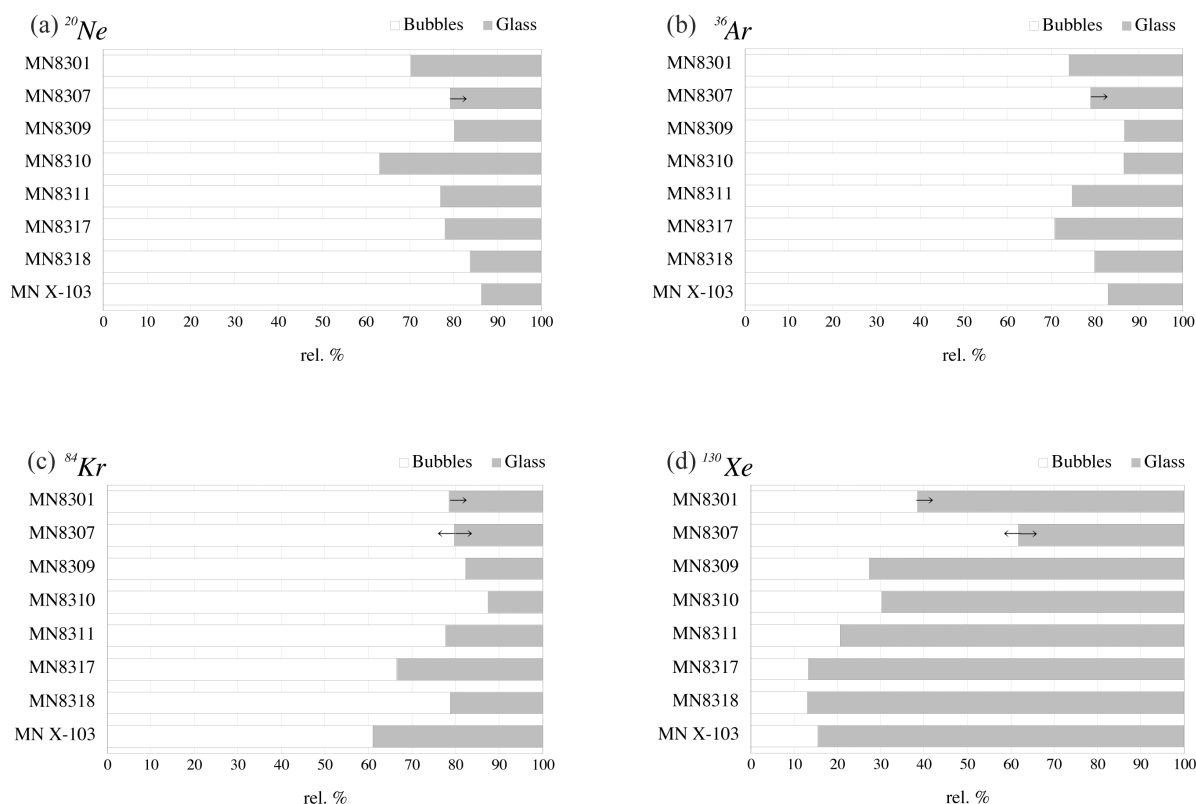$$V_{vesicle} = M \times C_{^{20}Ne} / P_{^{20}Ne(air)} \tag{2}$$

Fig. 3. Distribution of Ne (a), Ar (b), Kr (c), and Xe (d) in Muong Nong-type tektites between vesicles and glasses. The left and right arrows indicate the upper limits from the crushing and heating methods, respectively. Note that high Xe fraction in glass is due to the adsorption of Xe in atmosphere (see text).

where $V_{vesicle}$ is the volume of actually crushed vesicles, M is the weight of the crushed samples (in grams), C_{20Ne} is the amount of ^{20}Ne in 1 gram of crushed sample (in cm^3 STP/g), and $P_{20Ne(air)}$ is the partial pressure of ^{20}Ne in atmosphere (1.65×10^{-5} atm; Ozima and Podosek 1983).

We applied this method for the estimation of the vesicularity to a moldavite with a large bubble; for this sample, the accurate bubble volume was measured with an X-ray computed tomography (CT) scanner (Matsuda et al. 2000). The bubble volume estimated from the Ne concentration was 0.13 cm^3, and that obtained from the X-ray CT scanner was 0.16 cm^3.

Using the estimated bubble volume, we can calculate the partial pressures of the heavy noble gases (Ar, Kr, and Xe) in the vesicles. As discussed above, the heavier noble gases in vesicles have atmospheric elemental composition, while the Ne/Ar, Ne/Kr, and Ne/Xe ratios are significantly larger than air. We found no indication of diffusive input of these heavier noble gases into Muong Nong-type tektites, thus, we can safely conclude that these gases preserve their partial pressures during solidification in glass. Then, similar to Equation 2, we can write:

$$V_{vesicle} = M \times C_{36Ar} / P_{36Ar} \qquad (3)$$

where P_{36Ar} denotes the partial pressure of ^{36}Ar in 1 atm of the air vesicles with their effective total volumes ($V_{vesicle}$) estimated from neon above. Using the above two equations, we can calculate the P_{36Ar} simply from the Ne and Ar concentrations in the sample (Table 5). If we assume the density of the sample, the vesicularity (cm^3/cm^3) can also be calculated. The vesicularities obtained by the above method are typically about 1 vol% of the total sample (Table 5).

As listed in Table 5, the estimated partial pressures in vesicles are from 8.6×10^{-7} to 1.2×10^{-5} atm; these values are lower than the partial pressure of ^{36}Ar in 1 atm of the air (= 3.14 $\times 10^{-5}$ atm). Note that concentrations of argon in the glass (measured in powdered samples by fusion) are much lower than those of normal sedimentary rocks (Matsubara et al. 1991), which are equilibrated with air at atmospheric pressure. Thus, the tektite source rocks have lost their original noble gases during the first stages of tektite formation (Matsuda et al. 1993). Subsequent equilibration of atmospheric noble gases with the melt is unlikely, as equilibrium solubility should result in elemental fractionations favoring lighter noble gases in the melt reflecting larger values of Henry's constant for the lighter noble gases (e.g., Lux 1987). In addition, gases trapped in vesicles are unlikely to be those exsolved from solidifying melts to form vesicles, because no difference exists in the noble gas elemental ratios between glass and vesicles; (Kr/Ar)$_{melt}$

Table 3. Kr concentrations and isotopic compositions in Muong Nong-type tektites.[a]

Sample	Weight[b]	Crushing[c]	^{84}Kr (10^{-10} cm^3 STP/g)	^{78}Kr/^{84}Kr (10^{-3})	^{80}Kr/^{84}Kr (10^{-2})	^{82}Kr/^{84}Kr	^{83}Kr/^{84}Kr	^{86}Kr/^{84}Kr
Crushing								
MN 8301	0.135 g	×1000	2.4	6.11 ± 0.33	3.93 ± 0.06	0.201 ± 0.002	0.203 ± 0.001	0.306 ± 0.002
MN 8307	0.203 g	×1000	1.7	6.31 ± 0.31	3.98 ± 0.07	0.197 ± 0.005	0.204 ± 0.002	0.305 ± 0.002
	–	×2000	<0.13	–	–	–	–	–
	–	Total	<1.8	–	–	–	–	–
MN 8309	0.150 g	×1000	3.2	6.01 ± 0.28	3.95 ± 0.04	0.202 ± 0.002	0.201 ± 0.001	0.304 ± 0.002
MN 8310	0.165 g	×1000	6.4	5.98 ± 0.18	4.00 ± 0.04	0.202 ± 0.001	0.201 ± 0.001	0.307 ± 0.001
MN 8311	0.128 g	×1000	2.9	5.85 ± 0.35	3.90 ± 0.04	0.201 ± 0.001	0.201 ± 0.001	0.306 ± 0.002
MN 8317	0.151 g	×1000	1.6	6.03 ± 0.42	3.99 ± 0.05	0.203 ± 0.001	0.203 ± 0.002	0.302 ± 0.002
MN 8318	0.155 g	×900	2.4	5.99 ± 0.27	3.92 ± 0.07	0.200 ± 0.002	0.201 ± 0.001	0.309 ± 0.002
MN X-103	0.223 g	×1000	1.4	6.07 ± 0.31	3.95 ± 0.05	0.203 ± 0.002	0.203 ± 0.001	0.310 ± 0.002
Heating								
MN 8301	0.110 g	1800°C	<0.71	–	–	–	–	–
MN 8307	0.189 g	800°C	0.19	–	4.66 ± 0.06	0.171 ± 0.002	0.199 ± 0.002	0.296 ± 0.002
	–	1200°C	0.062	–	3.90 ± 0.45	0.214 ± 0.010	0.212 ± 0.009	0.310 ± 0.013
	–	1600°C	0.083	–	3.85 ± 0.25	0.212 ± 0.008	0.201 ± 0.010	0.306 ± 0.011
	–	1800°C	<0.13	–	–	–	–	–
	–	Total	<0.46	–	–	–	–	–
MN 8309	0.148 g	1800°C	0.70	–	3.98 ± 0.12	0.204 ± 0.003	0.202 ± 0.004	0.307 ± 0.005
MN 8310	0.135 g	1800°C	0.93	–	3.91 ± 0.07	0.204 ± 0.003	0.204 ± 0.001	0.308 ± 0.002
MN 8311	0.128 g	1800°C	0.83	–	3.86 ± 0.06	0.200 ± 0.002	0.198 ± 0.001	0.307 ± 0.003
MN 8317	0.121 g	1800°C	0.80	5.20 ± 0.31	3.87 ± 0.12	0.210 ± 0.002	0.204 ± 0.001	0.305 ± 0.004
MN 8318	0.144 g	1800°C	0.64	4.56 ± 0.35	4.01 ± 0.11	0.205 ± 0.002	0.202 ± 0.003	0.310 ± 0.002
MN X-103	0.181 g	1800°C	0.89	5.34 ± 0.16	3.91 ± 0.08	0.202 ± 0.002	0.202 ± 0.002	0.306 ± 0.002
Air	–	–	–	6.09	3.96	0.202	0.201	0.305

[a]Concentrations of gases and isotopic ratios are corrected for procedural blank, but when blank levels exceed 30% of the sample signals, the concentrations are simply given as upper limits without blank correction.

[b]Weight of samples. For the crushing extractions, the weight is for the grains smaller than 150 μm.

[c]Number of crushing strokes for the crushing extraction. For the heating extractions, the temperatures to which the sample were heated are given.

and (Xe/Ar)$_{melt}$ should be smaller than (Kr/Ar)$_{vesicle}$ and (Xe/Ar)$_{vesicle}$ by 30 and 70%, respectively, for a suggested vesicularity of 1%. Although an adsorption effect of atmospheric Xe in the glass samples exists, the fractions of gases in bubble to glass remain the same for all noble gases if the correction for the atmospheric Xe/Ar ratio is made for the glass samples. The gases in the vesicles constitute about 70 to 80% of the whole noble gas content of the tektites. Therefore, incorporation and/or occlusion of ambient argon at a high altitude is our explanation for the low argon pressure in the tektite vesicles. We suspect that, although the formation of vesicles in melts is facilitated by the exsolution of gases during a decrease of the ambient temperature, the gases in the vesicles were rapidly equilibrated with the atmosphere at high altitudes, resulting in systematically lower argon partial pressure in the present samples than at sea level. Note that the atmospheric pressure decreases exponentially with a scale height of 8.4 km (Matsuda et al. 1993). Thus, we calculated the altitude where the partial pressure of ^{36}Ar in the vesicles is identical to that in the ambient air using the equation:

$$P_{^{36}Ar} = P_{^{36}Ar0} \ln(-Z/H) \qquad (4)$$

where $P_{^{36}Ar0}$ is the partial pressure of ^{36}Ar at the sea level (=3.14×10^{-5} atm), Z is the altitude, and H is the scale height (=8.4 km). The range of partial pressures of ^{36}Ar estimated for the present samples is equivalent to altitudes of 8 to 30 km (Table 5).

However, the estimates of the vesicle volumes are based on the assumption that the atmosphere at sea level had an atmospheric pressure of 1 during the tektite-forming event, but the pressure of the atmosphere might have been lower than 1 atmospheric pressure, and the temperature should have been much higher than during normal ambient conditions. Thus, the estimated partial pressures of Ar should be regarded as lower limits and the estimated altitudes as maximum values.

Implications for the Formation of the Muong Nong-Type Tektites

As noted earlier, the overall characteristics of the Muong Nong-type tektites resemble those of impact glasses. This is confirmed by the heavy noble gas data shown in Fig. 4, where the Kr and Xe concentrations are plotted against the Ar concentration. The heavy noble gas data of Muong Nong-type tektite plot in the field also occupied by impact glasses. The

Table 4. Xe concentrations and isotopic compositions in Muong Nong-type tektites.[a]

Sample	Weight[b]	Crushing[c]	^{130}Xe (10^{-12} cm^3 STP/g)	^{124}Xe/^{130}Xe (10^{-2})	^{126}Xe/^{130}Xe (10^{-2})	^{128}Xe/^{130}Xe	^{129}Xe/^{130}Xe	^{131}Xe/^{130}Xe	^{132}Xe/^{130}Xe	^{134}Xe/^{130}Xe	^{136}Xe/^{130}Xe
Crushing											
MN 8301	0.135 g	×1000	1.5	2.40 ± 0.41	2.01 ± 0.29	0.409 ± 0.022	5.77 ± 0.22	4.78 ± 0.13	6.58 ± 0.16	2.35 ± 0.06	1.89 ± 0.07
MN 8307	0.203 g	×1000	0.93	–	1.98 ± 0.36	0.356 ± 0.070	6.65 ± 0.10	5.12 ± 0.13	6.38 ± 0.14	2.68 ± 0.04	2.16 ± 0.03
	–	×2000	<0.11	–	–	–	–	–	–	–	–
	–	Total	<1.0	–	–	–	–	–	–	–	–
MN 8309	0.150 g	×1000	1.7	–	–	0.395 ± 0.048	6.53 ± 0.09	5.29 ± 0.08	6.63 ± 0.07	2.58 ± 0.04	2.20 ± 0.03
MN 8310	0.165 g	×1000	3.0	2.17 ± 0.20	2.22 ± 0.17	0.477 ± 0.009	6.57 ± 0.09	5.26 ± 0.05	6.62 ± 0.08	2.55 ± 0.04	2.13 ± 0.03
MN 8311	0.128 g	×1000	1.8	–	–	0.438 ± 0.025	6.43 ± 0.06	5.16 ± 0.06	6.60 ± 0.07	2.57 ± 0.04	2.14 ± 0.03
MN 8317	0.151 g	×1000	1.0	–	–	0.364 ± 0.054	6.44 ± 0.09	5.11 ± 0.07	6.43 ± 0.06	2.55 ± 0.06	2.16 ± 0.06
MN 8318	0.155 g	×900	1.3	2.14 ± 0.35	2.14 ± 0.38	0.356 ± 0.064	6.58 ± 0.15	5.32 ± 0.13	6.68 ± 0.15	2.57 ± 0.05	2.17 ± 0.04
MN X-103	0.223 g	×1000	0.87	2.15 ± 0.45	–	0.395 ± 0.046	6.55 ± 0.07	5.30 ± 0.06	6.73 ± 0.08	2.62 ± 0.03	2.20 ± 0.04
Heating											
MN 8301	0.110 g	1800°C	<2.6	–	–	–	–	–	–	–	–
MN 8307	0.189 g	800°C	<0.17	–	–	–	–	–	–	–	–
	–	1200°C	<0.15	–	–	–	–	–	–	–	–
	–	1600°C	0.15	–	–	0.591 ± 0.104	6.95 ± 0.99	6.38 ± 0.77	9.06 ± 1.18	3.02 ± 0.32	2.47 ± 0.20
	–	1800°C	0.18	–	–	0.473 ± 0.030	6.54 ± 0.15	5.93 ± 0.50	8.02 ± 0.77	2.62 ± 0.10	2.33 ± 0.13
	–	Total	<0.66	–	–	–	–	–	–	–	–
MN 8309	0.148 g	1800°C	4.4	–	–	0.465 ± 0.009	6.41 ± 0.08	5.37 ± 0.15	7.30 ± 0.23	2.57 ± 0.06	2.16 ± 0.04
MN 8310	0.135 g	1800°C	6.8	2.19 ± 0.08	2.16 ± 0.12	0.472 ± 0.007	6.53 ± 0.09	5.21 ± 0.04	6.62 ± 0.06	2.59 ± 0.03	2.16 ± 0.02
MN 8311	0.128 g	1800°C	6.9	2.30 ± 0.05	2.06 ± 0.14	0.478 ± 0.007	6.58 ± 0.10	5.20 ± 0.05	6.59 ± 0.06	2.57 ± 0.04	2.18 ± 0.03
MN 8317	0.121 g	1800°C	6.7	2.31 ± 0.09	1.71 ± 0.20	0.476 ± 0.008	6.52 ± 0.08	5.20 ± 0.04	6.60 ± 0.05	2.58 ± 0.03	2.16 ± 0.03
MN 8318	0.144 g	1800°C	8.8	2.31 ± 0.09	1.72 ± 0.20	0.477 ± 0.006	6.58 ± 0.07	5.25 ± 0.03	6.67 ± 0.05	2.57 ± 0.03	2.17 ± 0.02
MN X-103	0.181 g	1800°C	4.8	2.46 ± 0.05	1.69 ± 0.23	0.474 ± 0.007	6.58 ± 0.06	5.25 ± 0.03	6.65 ± 0.04	2.58 ± 0.03	2.19 ± 0.02
Air	–	–	–	2.34	2.18	0.472	6.50	5.21	6.61	2.56	2.18

[a] Concentrations of gases and isotopic ratios are corrected for procedural blank, but when blank levels exceed 30% of the sample signals, the concentrations are simply given as upper limits without blank correction.

[b] Weight of samples. For the crushing extractions, the weight is for the grains smaller than 150 μm.

[c] Number of crushing strokes for the crushing extraction. For the heating extractions, the temperatures to which the sample were heated are given.
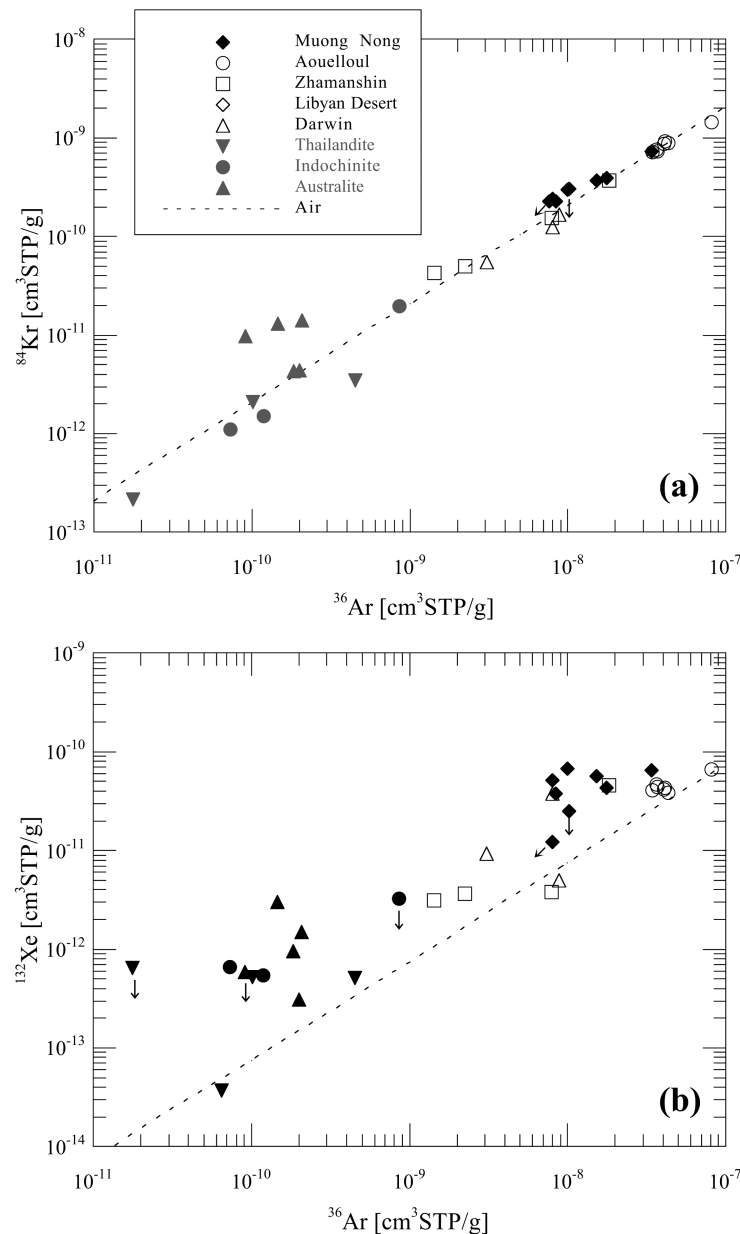
Fig. 4. Concentrations of ^{84}Kr (a) and ^{132}Xe (b) plotted against ^{36}Ar content in Muong Nong-type tektites, splash-form tektites, and impact glasses. Impact glasses (open symbols) indicate Darwin glasses (open triangles: Matsuda et al. 1989), Aouelloul (open circles), Zhamanshin (open squares), and Libyan Desert glasses (open diamonds: Matsubara et al. 1991). Normal tektites (closed symbol) are from the Australasian strewn fields: thailandites (closed triangles: Hennecke et al. 1975; Matsuda et al. 1993), indochinites from Vietnam (closed circles: Matsubara and Matsuda 1991; Matsuda et al. 1993), and australites (closed triangles: Matsubara and Matsuda 1991; Matsuda et al. 1993). These data were obtained by heating of bulk samples. In the present work, we plotted the total values for each sample as the data on Muong Nong-type tektites (closed diamonds) because we analyzed each Muong Nong-type tektite sample both by the crushing and the heating techniques. The data without arrows are after blank correction, if it was less than 30% of the value and those with arrows show data without blank correction (i.e., upper limits). A dashed line labeled as "Air" shows the ratio of noble gases in the terrestrial atmosphere.

Kr and Ar data lie on the air line, but Xe shows a slight enrichment compared to the atmospheric ratio, as is also shown in Fig. 1.

Matsuda et al. (1993) indicated that splash-form tektites incorporated their nobles gases at pressures equivalent to 20–40 km altitude, based on the assumption of simple

equilibrium solubility. As these authors did not carry out the crushing and heating experiments performed here, their values are based on the gas amounts released by total fusion. Furthermore, they used solubility data at 1350°C, much lower than the formation temperature of tektites. Thus, their altitude values represent lower limits. The altitude estimated from the

Table 5. Estimated vesicularities and closing altitudes of the samples.

Sample	$V_{vesicle}$ (10^{-4} cm^3)	Vesicularity[a] (cm^3/cm^3)	P_{36Ar} (10^{-6} atm)	Altitude (km)
MN 8301	3.6	0.60%	2.9	20
MN 8307	9.7	1.1%	1.3	27
MN 8309	7.5	1.2%	3.1	20
MN 8310	3.9	0.54%	12	7.8
MN 8311	6.2	1.1%	2.4	22
MN 8317	9.9	1.5%	0.86	30
MN 8318	10	1.5%	1.2	28
MN X-103	2.4	0.2%	6.5	13

[a]Vesicularities [cm^3/cm^3] were calculated assuming a density of 2.3 g/cm^3. Uncertainties in the determinations of Ar and Ne contents in the sample would result in uncertainties of about ±1 km in the estimated altitudes.

partial pressure of the noble gases in a large vesicle in a phillippinite was 40–50 km (Matsuda et al. 1996). The value of 8 to 30 km estimated for the Muong Nong-type tektites as the maximum altitude in this study is lower than those for splash form tektites, in agreement with the occurrence of Muong Nong-type tektites closer to the (inferred) source crater. The wide distribution of splash-form tektites, and the rather limited geographical distribution of the Muong Nong-type tektites—10^6 km^2 (Schnetzler 1992), are consistent with the estimated lower heights. Therefore, the present noble gas results are in agreement with the suggestion that Muong Nong tektites have formed at lower altitudes and closer to the source crater than splash-form tektites.

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