

Reports

Origin of tektites: Constraints from heavy noble gas concentrations

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Abstract—Heavy noble gas concentrations in tektites (splash-form type) are considerably lower than those in impact glasses. This can not be explained only by high formation temperatures for tektites, as might be expected from low concentrations of water and most volatile elements in tektites, and indicates that tektites solidified in an atmosphere with an ambient pressure of much less than 1 atm. The heavy noble gas concentrations may be an indicator of the height to which tektites were carried by the impact before they solidified.

INTRODUCTION

Tektites are natural silica-rich glasses and, at first glance, resemble obsidian. They are small pieces up to a few cm in size. The color ranges from green or brown to black. Tektites are generally symmetric in shape, homogeneous in chemistry, and have very low water contents. Impact glasses are often irregular in shape, less homogeneous, and have higher water contents. Tektites occur on Earth in four geographically restricted areas, the so-called strewn fields; distribution in strewn fields is part of the definition of tektites. Numerous geochemical and isotopic studies have confirmed the terrestrial impact origin (Taylor, 1973; King, 1977; Glass, 1990; Koeberl, 1986; 1990). Normal impact glasses are known to occur at impact craters on Earth, and are considered to have originated during a meteorite impact. Thus, while both tektites and impact glasses have been produced by impact melting of terrestrial surface rocks, there are differences between tektites and impact glasses; e.g., impact glasses are found directly at a crater, while tektites occur in a strewn field away from the source crater.

Noble gases are generally chemically inert and volatile, and their geochemical behavior depends only on physical conditions such as temperature and pressure. Studies of noble gases in tektites and impact glasses provide valuable information about the condition of their formation. Matsuda *et al.* (1989) measured noble gas contents in Darwin impact glasses and found elemental abundance patterns with Ne enrichments relative to air. Neon enrichments are common in silica-rich glasses such as tektites (Hennecke *et al.*, 1975; Matsubara and Matsuda, 1991), impact glasses (Matsuda *et al.*, 1989; Matsubara *et al.*, 1991) and obsidians (Matsuda *et al.*, 1989; Miura and Nagao, 1991) and are attributed to the high diffusion of Ne in these glasses after solidification (Matsuda *et al.*, 1989). Neon concentrations are about 10^{-7} cm³STP/g in both impact glasses and tektites (Matsubara *et al.*, 1991). Thus, Ne (and also He) does not provide any information on the origin of these glasses. On the other hand, the heavy noble gas concentrations are quite different between tektites and impact glasses: Heavy noble gases (Ar, Kr, and Xe) are highly depleted in tektites compared to impact glasses and can be used as tracers to study the origin of these glasses. In this paper, we report new noble gas data on tektites and discuss constraints on the origin of tektites from heavy noble gas abundances.

EXPERIMENTAL AND RESULTS

Noble gas concentrations were determined by mass spectrometry in nine tektites from the Czechoslovakian (Central European) and the

TABLE 1. Noble gas concentrations* in tektites.

Sample Name	Sample Weight (g)	4He	20Ne	36Ar	84Kr	132Xe
		(x10 ⁻⁸ cm ³ STP/g)	(x10 ⁻⁸ cm ³ STP/g)	(x10 ⁻¹⁰ cm ³ STP/g)		
THAI-1 (Thailandite)	0.574	1.02 (1.33)	10.2 (10.4)	0.177 (0.720)	0.00213 (0.0220)	...** (0.00645)
THAI-2 (Thailandite)	0.709	0.610 (0.857)	8.32 (8.35)	0.644 (1.08)	0.000287 (0.0164)	0.000372 (0.00578)
T8202 (Indochinite)	0.783	0.936 (1.17)	10.6 (10.7)	0.729 (1.21)	0.0110 (0.0191)	0.00655 (0.0101)
TE6 (Australite)	0.985	0.410 (0.581)	7.46 (7.46)	1.45 (2.31)	0.125 (0.181)	0.0298 (0.0430)
TE7 (Australite)	1.07	18.8 (19.0)	9.09 (9.10)	2.07 (2.43)	0.139 (0.145)	0.0147 (0.0173)
TE8 (Moldavite)	1.44	2.38 (2.51)	14.6 (14.6)	1.00 (1.26)	0.0163 (0.0233)	0.00825 (0.0111)
TE9 (Australite)	1.30	1.57 (1.72)	7.87 (7.89)	2.00 (2.26)	0.0438 (0.0481)	0.00311 (0.00591)
TE10 (Australite)	1.32	1.17 (1.32)	7.33 (7.35)	1.84 (2.09)	0.0427 (0.0468)	0.00957 (0.0123)
TE11 (Indochinite)	1.40	0.965 (1.10)	7.43 (7.44)	1.18 (1.44)	0.0149 (0.0222)	0.00541 (0.00831)

* The data without blank correction are given in parentheses.

**Measured value was lower than that of hot blank.

Australasian strewn fields. Samples TE6 to TE11 are commercial ones, for which only noble gas measurements were made. We used chipped samples for the analyses. Gas extraction was carried out at 1600 °C for 20 minutes. Details on analytical procedure of the noble gas determinations were reported previously (Matsuda and Matsubara 1989; Matsuda *et al.*, 1989). Results are listed in Table 1. The reproducibility in the noble gas analysis was better than 10% when we measured the pipetted amounts of noble gases as a standard. We listed the data after blank correction and the measured data as upper limits without blank correction in parentheses. The blank corrections were negligible for all Ne concentration. Most of the measured values for ⁸⁴Kr and ¹³²Xe in THAI-1 and THAI-2 and ³⁶Ar in THAI-1 were from hot blanks. For other data, blank correction was less than 50%. For data with blank correction of nearly 50%, the real value have errors of up to a factor 2, or smaller than the corrected value when taking the blank correction into account.

DISCUSSION

Elemental Abundance Patterns and Concentrations

In the noble gas abundance patterns of the tektites, we plot the fractionation factor F(m) defined by:

$$F(m) = ({}^m\text{X}/{}^{36}\text{Ar})_{\text{sample}} / ({}^m\text{X}/{}^{36}\text{Ar})_{\text{air}}$$

where ${}^m\text{X}$ represents a noble gas isotope of mass "m" (Fig. 1). The abundance patterns are similar to those reported by Matsubara and Matsuda (1991), showing anomalous Ne enrichments. It is likely that the high relative Ne abundance is essentially an equilibrium effect after solidification, facilitated by the relatively high diffusion coefficient of Ne. The ${}^{20}\text{Ne}$ concentrations in this study are $(7.3\text{--}15) \times 10^{-8} \text{cm}^3 \text{STP/g}$ and are in agreement with those reported by Matsubara and Matsuda (1991). The Ne concentrations are similar for all tektites with different ages and are in agreement with the diffusion coefficients measured by Reynolds (1960).

While Matsubara and Matsuda (1991) gave only upper limits (more than 50% blank correction) for most heavy noble gas abundances, we accurately determined them by using larger samples. Although Xe is slightly enriched (Fig. 1), $F(84)$ in five of the seven samples is near unity, indicating that the Kr/Ar ratios are atmospheric.

Figure 2 is a compilation of the heavy noble gas data obtained so far for tektites (splash-form type) and impact glasses. For all the data points, we listed the data after blank correction in case blank corrections are less than 50% and those as upper limits without blank correction when the blank correction is more than 50%. Some of data with large blank corrections have errors of up to a factor 2, or lower than the presented values even when the blank variation is 100%. The noble gas concentration in impact glasses is high, and blank corrections were less than 20% in many samples (Matsuda *et al.*, 1989; Matsubara *et al.*, 1991). Therefore, the errors of data points are utmost about 20% for impact glasses. From this plot, it is clear that heavy noble gas concentrations in impact glasses are distinct from, and higher than, those in tektites.

We released the noble gases by heating the samples for 20 min at 1600 °C. The stepwise heating experiment of Ar in tektite samples by Zähringer (1963) showed that 70% of the gas released below 1500 °C. The variation of the axis in Fig. 2 ranges over five orders of magnitude. The experimental condition for tektites and impact glasses are the same in our experiments.

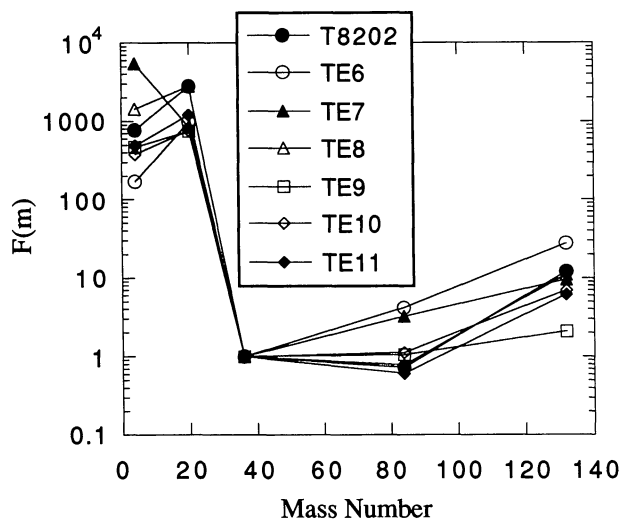


FIG. 1. The elemental abundance patterns of noble gases in tektites displayed by the fractionation factor $F(m)$. We did not plot THAI-1 and THAI-2 because they have large error in Kr and Xe concentrations.

Therefore, the comparison is meaningful. The ${}^{36}\text{Ar}$ contents of Libyan Desert and Aouelloul glass in Zähringer (1963) are lower than those in Matsubara *et al.* (1991) by a factor of 2 to 6; however in Darwin glass, the former is higher than that in Matsuda *et al.* (1989) by a factor of 2. We suppose the sample heterogeneity in noble gas content is very large, especially in impact glasses. For example, the ${}^{36}\text{Ar}$ contents in Aouelloul impact glasses and those in Zhamanshin impact glasses showed variation over a factor of 2 and 10, respectively, among the samples even in Matsubara *et al.* (1991). However, these variations are not large compared to the whole variation shown in Fig. 2.

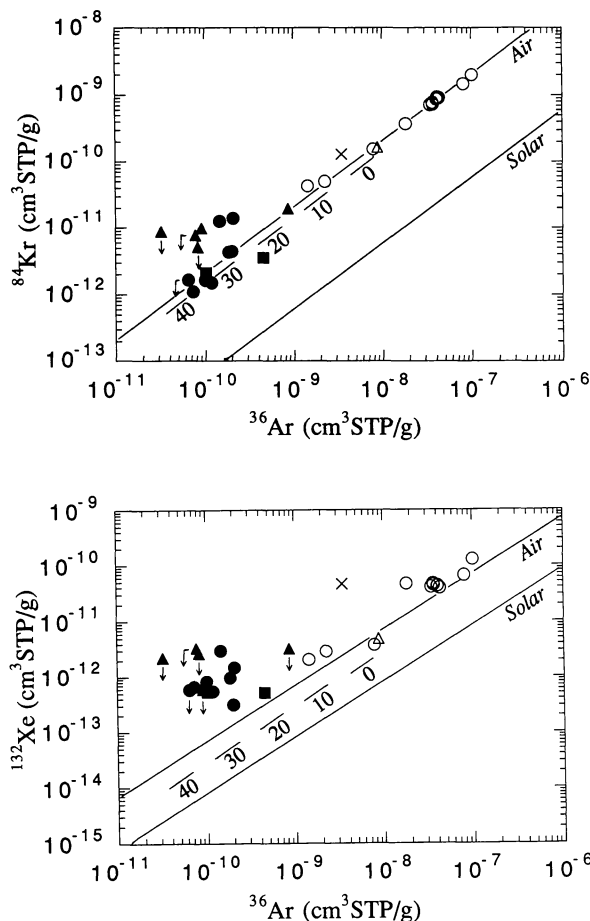


FIG. 2. ${}^{84}\text{Kr}$ (a, upper) and ${}^{132}\text{Xe}$ (b, lower) contents are plotted against ${}^{36}\text{Ar}$ content in tektites and impact glasses. Impact glasses (open symbol) are Darwin glasses (Δ : Matsuda *et al.*, 1989), and Aouelloul, Zhamanshin, Libyan Desert glasses (\circ : Matsubara *et al.*, 1991). Tektites (closed symbol) are normal splash-form ones from three strewn fields (the Czechoslovakian, the Australasian, and the North American) (\blacksquare : Hennecke *et al.*, 1975; \blacktriangle : Matsubara and Matsuda, 1991; \bullet : this work). The data without arrows are after blank correction which was less than 50%, and those with arrow show the data without blank correction (upper limits). The data of tektites may be larger by up to a factor of 2 depending on blank correction. The Zli sandstone is shown by "x" (Matsubara *et al.*, 1991). "Air" and "Solar" shows the lines corresponding to the ratio of noble gases in terrestrial atmosphere and in solar wind on lunar fines (Eberhardt *et al.*, 1972), respectively. The bar with "0" shows the solubility data of noble gases at the Earth's surface under one atmospheric pressure.

According to Zähringer (1963), the ^{36}Ar contents in 13 tektite samples from Ivory Coast and Philippines are less than $3 \times 10^{-9}\text{cm}^3/\text{g}$ except one sample of which ^{36}Ar content was as high as $2 \times 10^{-8}\text{cm}^3/\text{g}$. One sample from Hai Nan and one sample from Java also gave high ^{36}Ar contents like $1.5 \times 10^{-8}\text{cm}^3/\text{g}$. These high ^{36}Ar contents are located in the lower range of the impact glasses in Fig. 2. It is likely that the boundary between tektites and impact glasses is continuous.

Heavy Noble Gases in Impact Glasses

The data points of impact glasses plot directly on the air ratio line (Fig. 2), suggesting that the noble gases were trapped without elemental fractionation. Noble gases in air enclosed in pores in the host rocks were implanted during the impact shock without elemental fractionation, which was confirmed by laboratory shock-experiments (Bogard *et al.*, 1986). In Fig. 2, we also show the solubility data for silica-rich glasses equilibrated with air at a pressure of 1 atm.

The solubility of noble gases depends on the chemical composition of the glasses. Lux (1987) gave solubility data of noble gases at 1350 °C as a function of density in silicate liquids. Jambon *et al.* (1986) also gave solubility data in a tholeiitic basalt melt in the temperature range 1250–1600 °C, which are in the same range as Lux's solubility data. We calculated the solubility of noble gases based on Lux's equations (1350 °C) for the density range of 2.28–2.52 g/cm^3 (Cassidy *et al.*, 1969). In Fig. 2, the noble gas concentrations in impact glasses are higher than the values calculated from equilibrium solubility and than those in source rock, suggesting that the noble gases in impact glasses reside in the gas phase in vesicles.

Heavy Noble Gases in Tektites

As can be seen in Fig. 2, the heavy noble gas abundances in tektites are lower than those calculated from equilibrium solubility with air at a pressure of 1 atm. Tektites are known to have low water (Gilchrist *et al.*, 1969; Koeberl and Beran, 1988) and volatile element contents (Matthies and Koeberl, 1991), which is generally believed to be due to high temperatures during the formation of tektites. However, high formation temperatures are not compatible with low noble gas contents. Different from the solubility of water in silicate melts, solubilities of noble gases increase with increasing temperature in silicate melts (Jambon *et al.*, 1986). Noble gases are gaseous at room temperature, which is different from other volatiles such as halogens, In, Bi, *etc.* which are solids in the target rock, and do not occur in the atmosphere. The noble gas content of tektites would be expected to increase with increasing temperature only if the noble gas content in the starting solid material was less than the equilibrium solubility under the atmosphere.

Therefore, the low concentrations of heavy noble gases in tektites are better explained if tektites were formed under low partial pressure as is believed to be the case. In Figs. 2a, b we plotted the ratio of the solar noble gases observed on the lunar surface (Eberhardt *et al.*, 1972). The data points for tektites lie on or near the terrestrial line, not the solar line (Fig. 2a, b). Some data points plot above the terrestrial line (Fig. 2b), which might be due to adsorption of heavy noble gases (especially Xe) on the glass surface. Because of the small amount of Xe in

these samples, adsorption may produce a large effect although we preheated the sample at 150 °C for several hours in the sample line of the mass spectrometer. This could be the cause of the high Xe/Ar ratios, while the Kr/Ar ratios a nearly atmospheric (Fig. 1).

Our results confirm that tektites are of terrestrial origin, as proposed before by numerous other authors (see, *e.g.*, Taylor, 1973; Koeberl, 1986) and were exposed to a low-pressure atmosphere by being carried up to high altitudes by the meteorite impact (O'Keefe and Ahrens, 1982). In Fig. 2, short bars with numerical values show the calculated solubility of noble gases in silicate glasses at high altitudes using Lux's (1987) equation (1350 °C, 2.28–2.52 g/cm^3 in density). The calculations were done under the assumptions that the total pressure of air decreases exponentially with the scale height of 8.4 km. The numerical values represent the altitude (km). The tektite data may be explained by equilibration of the molten glass with the atmosphere at an altitude of 20–40 km (0.01–0.1 atm).

The model is based on the assumption that tektites were under equilibrium with an ambient atmosphere at the time of solidification. One may argue that tektites were aloft for a time inadequate for to equilibrate with the ambient atmosphere. However, terrestrial sedimentary rocks (tektite source rocks) have higher noble gas contents than tektites. For example, noble gas concentrations in Zli sandstone, the source rock of the Auouellou impact glass, are higher than those in tektites. Therefore, tektites should have degassed extensively during melting early in their formation history. Noble gases can not degas from the melt below the concentration dictated by equilibrium solubility. For the noble gases, the concentrations in source rocks are similar to those estimated from the equilibrium at one atm and ambient temperatures. Thus if source rocks were melted under non-equilibrium condition at one atm, they maintain their high noble gas contents. Another possibility is that noble gases were residing in the pores of the source rock and that they were simply driven out of the pores and never had time to enter the melt, resulting in low noble gas contents in the tektites. However, laboratory shock experiments show that the implantation efficiencies of noble gases are greater than 50% at 20 and 35 GPa, where modest amounts of sample melting begins at grain boundaries (Bogard *et al.*, 1986). It therefore seems unlikely that noble gases in the pores were simply driven out from the sample during the shock event, as far as the source rock had melted. Bogard *et al.* (1986) stated that they could not offer no explanation for the apparent absence of shock-implanted noble gases in terrestrial samples although EETA79001 glass showed appreciable amounts of Ar implanted by shock on Mars. Thus, tektites were probably exposed to a low ambient pressure to degas the noble gases, even in a non-equilibrium situation. The equilibrium temperature of 1350 °C used here is lower than the formation temperature of tektites estimated from oxygen fugacity measurements (Brett and Sato, 1984). Hence, the 20–40 km obtained above is the lower limit for the altitude.

Zähringer and Gentner (1963) and Zähringer (1963) reported low total pressures ($<2.5 \times 10^{-3}$ atm) in bubbles of Phillipinites by cracking the samples in the ultra-high vacuum. At temperature of tektites formation the bubble pressure would be about 10 times higher (Zähringer, 1963). Müller and Gentner (1968) reported higher pressures (0.02–1 atm) for

indochinites and moldavites, although more than half of the bubbles in indochinites were gas-free. The pressure of about 1 atm in a moldavite bubble found by Müller and Gentner (1968) may be the result of leaking. The low observed pressures in bubbles is compatible with the formation of tektites under low ambient pressure. However, the altitude estimated in our study would be even higher if the heavy noble gases reside mainly in the bubbles in tektites, although it depends on spatial density of the bubbles.

The formation of tektites under low ambient pressure applies probably only for normal (splash-form) tektites. For Muong Nong type tektites, higher bubble pressures in the range of 0.2 to 0.3 atm (Jessberger and Gentner, 1972) and up to 0.7 atm (Müller and Gentner, 1968) have been reported. Therefore, it seems likely that the gas in the bubbles of Muong Nong type tektites may have been incorporated closer to the terrestrial surface than for the normal tektites (Zähringer, 1963).

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