



## Distribution of noble gases in Chinese tektites: Implication for neon solubility in natural glasses

Daniele L. PINTI,<sup>1\*</sup> Takuya MATSUMOTO,<sup>2</sup> Jun-Ichi MATSUDA,<sup>2</sup> and Zhong FANG<sup>3</sup>

<sup>1</sup>Laboratoire de Géochronologie Multitechniques, FRE 2566 ORSAYTERRE, Université Paris SUD, Bat. 504, 91405 Orsay Cedex, France

<sup>2</sup>Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560–0043, Japan

<sup>3</sup>Department of Earth Sciences, Nanjing University, 22 Hankou Road, Nanjing, 210093, China

\*Corresponding author. E-mail: [pinti@geol.u-psud.fr](mailto:pinti@geol.u-psud.fr)

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**Abstract**—Five indochinites from Hainan Island and the Leizhou Peninsula, China were analyzed for noble gas abundances and isotopic ratios. These splash-form tektites show vesiculation ranging from 0.4 vol% to 8 vol%, as determined by digital image analysis (software SXM<sup>®</sup>) on thin section photographs. To study the distribution of noble gases in vesicles and in glass, the gases were extracted by heating and by crushing, respectively, on 2 aliquots of the same sample. The results show that 5 to 53% of the total measured <sup>20</sup>Ne resides in vesicles. The calculated concentration of neon dissolved in the glass is higher ( $0.7\text{--}1 \times 10^{-7}$  cm<sup>3</sup>STP/g) than that expected from solubility equilibrium ( $1 \times 10^{-8}$  cm<sup>3</sup>STP/g), assuming solubility data from MORB glasses. The neon concentration of splash-form tektites, those analyzed in this work and those from other strewn-fields worldwide, is correlated with the SiO<sub>2</sub> content of glass and with the nonbridging oxygen per tetrahedral cation in the melt (hereafter NBO/T ratio), the latter being an index of the free-volume in the silica network where neon could be dissolved. These correlations suggest that the glass structure of tektite has a larger free-volume available for dissolving noble gases than MORB glasses.

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### INTRODUCTION

Tektites are silica glasses produced by cooling of impact melts ejected into Earth's atmosphere. They occur in 4 strewn fields: the North American, the Central European, the Ivory Coast, and the Australasian (Fig. 1). Tektites are subdivided traditionally into 3 groups: a) normal or splash-form tektites; b) aerodynamically shaped tektites; and c) Muong Nong-type tektites. The first 2 groups differ only in appearance, but they are both chemically and structurally homogeneous silica glasses. Muong Nong-type tektites have a chunky, blocky appearance, and they show a layered structure with abundant vesicles (e.g., Koeberl 1994).

The geochemistry of tektites provides valuable information about their formation, as documented by noble gas studies (Hennecke et al. 1975; Matsubara and Matsuda 1991; Matsuda et al. 1993, 1996; Murty 1997; Palma et al. 1997). Noble gases in tektites are clearly of atmospheric origin (Matsubara and Matsuda 1991), except for some excess of radiogenic <sup>40</sup>Ar\*. The heavy noble gas isotopes <sup>36</sup>Ar, <sup>84</sup>Kr, and <sup>130</sup>, <sup>132</sup>Xe are depleted compared to light noble gas isotopes, <sup>4</sup>He and <sup>20</sup>Ne, and with respect to the atmosphere. Matsuda et al. (1993) suggested that the low concentration of heavy noble

gases Ar, Kr, and Xe indicates that tektites solidified in an atmosphere with an ambient pressure of much less than 1 bar. Heavy noble gas concentration, thus, may be an indicator of the height to which tektites were carried by the impact before they solidified. The altitude has been estimated to be between 10 km and 40 km (Matsuda et al. 1993; Mizote et al. 2003).

The enrichment in light noble gases, particularly neon, relative to argon in the atmosphere has been interpreted to be the result of diffusion after solidification of the tektites (Matsubara and Matsuda 1991). The saturation level for the diffusion of neon from the atmosphere into the tektite glass should be equivalent to the equilibrium solubility (Matsubara and Matsuda 1991). However, the <sup>20</sup>Ne amount measured in tektites is almost one order of magnitude higher than that expected for solubility in silica glasses ( $10^{-8}$  cm<sup>3</sup>STP/g; Matsubara and Matsuda 1991). To accommodate the neon excess, Matsubara and Matsuda (1991) suggested that part of neon resides in vesicles rather than in the glass. To test this hypothesis Mizote et al. (2003) measured noble gases in vesicles and in glass of Muong Nong-type tektites. They showed that the neon concentration varies by approximately an order of magnitude (from 1.8 to  $13.8 \times 10^{-7}$  cm<sup>3</sup>STP/g) and that the neon, along with all other noble gases, resides

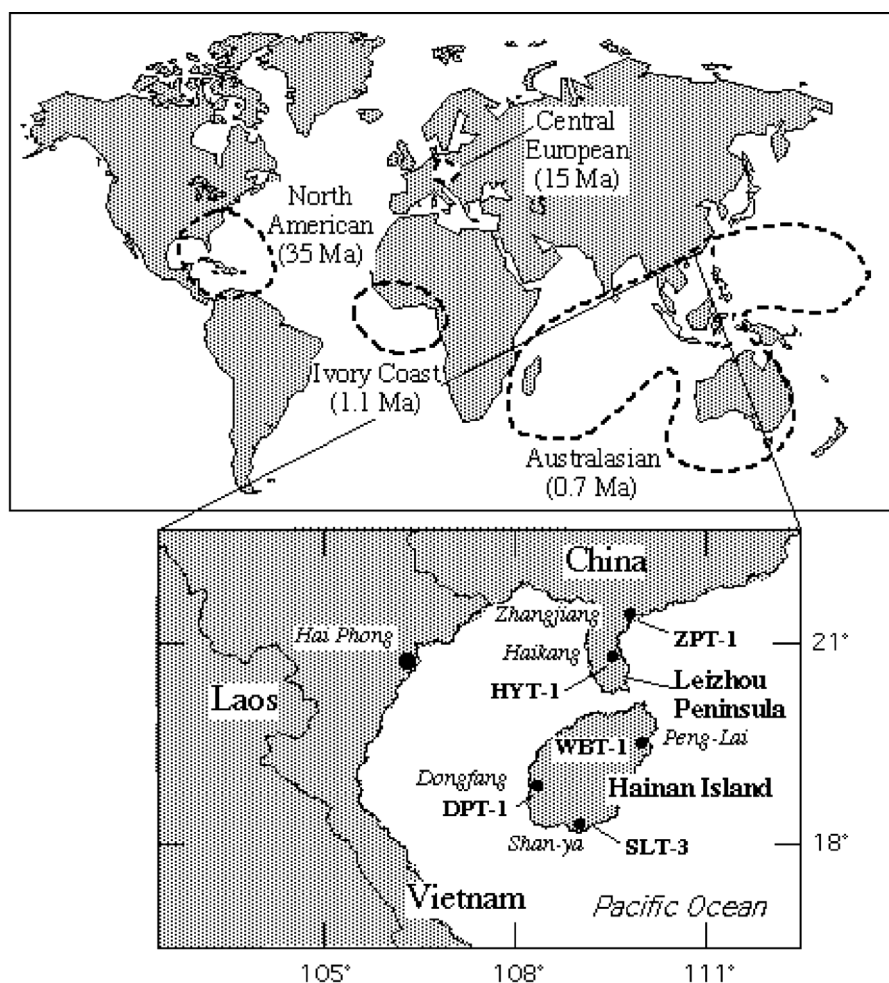


Fig. 1. Tektite strewn fields on the earth with stratigraphic ages and location of Chinese tektites from the Leizhou Peninsula and Hainan Island, China.

predominantly in the vesicles (from 70% to 85% of the total measured amount).

The distribution of noble gases between vesicles and glass likely archive significant information on the formation of tektites. In this work, new noble gas data from splash-form tektites from Hainan Island and the Leizhou Peninsula, China are presented (Fig. 1). To decipher the distribution between glass and vesicles, noble gases were extracted by heating and by crushing, respectively. The results for neon differ from those reported by Mizote et al. (2003) for Muong Nong tektites; 50 to 94% of the total measured neon resides in the glass. Here, the implications concerning Ne solubility in tektite glasses are discussed.

#### SAMPLE DESCRIPTION AND EXPERIMENTAL PROCEDURES

Five indochinites from the Leizhou Peninsula and Hainan Island, Southern China were selected for this study (Fig. 1; Table 1). The samples from the Leizhou Peninsula

are: HYT-1, a black dumbbell-shaped tektite from Haikang; and ZPT-1, a black drop-shaped tektite from Zhangjiang. The samples from Hainan Island are: DPT-1, SLT-3, and WBT-1, 3 black bark-shaped tektites from Dongfang, Shan-ya, and Peng-Lai, respectively (Fig. 1).

DPT-1 and SLT-3 contain many vesicles with sizes ranging from 100 to 200  $\mu\text{m}$ , while HYT-1, WBT-1 and ZPT-1 have fewer vesicles, which are also of smaller size, between 10 and 30  $\mu\text{m}$  (Fig. 2). A semi-quantitative estimate of vesiculation of each sample was obtained using the following procedure. Detailed digital images of thin sections of 20 mm-size grains selected from the 5 indochinites were obtained with a Leica® WILD M420 microscope. The digital images were analyzed using the public domain SXM® Image software. The measured volumes of the vesicles of samples DPT-1 and SLT-3 are heterogeneous and range from 3.3 vol% to 11.8 vol% (average  $8.0 \pm 4.3$  vol%) and from 3.1 vol% to 13.8 vol% (average  $7.4 \pm 4.6$  vol%), respectively. The volumes of the vesicles in the glassy samples HYT-1, WBT-1 and ZPT-1 are more homogeneous and range from 0.9 vol% to

Table 1a. Noble gas amount of Chinese tektites for heating and crushing experiments.<sup>a</sup>

Sample	Weight (g)	Weight <sup>b</sup> 150 $\mu\text{m}$ (g)	Temperature/ Strokes <sup>c</sup>	Vesicularity		$^4\text{He} \times 10^{-8}$ $\text{cm}^3\text{STP/g}$	$^{20}\text{Ne} \times 10^{-7}$ $\text{cm}^3\text{STP/g}$	$^{36}\text{Ar} \times 10^{-10}$ $\text{cm}^3\text{STP/g}$	$^{84}\text{Kr} \times 10^{-12}$ $\text{cm}^3\text{STP/g}$	$^{132}\text{Xe} \times 10^{-12}$ $\text{cm}^3\text{STP/g}$
				vol%	min-max					
Cold blank	-	-				$\leq 0.00004$	$0.03-0.04$	-	-	-
Cold blank-nc	-	-				$0.00003$	$0.13$	$1.10$	$0.09$	
Hot blank	-	-				$\leq 0.0007$	$0.11-0.41$	$0.31-0.91$	$0.07$	
Heating										
Hainan Island										
DPT-1	1.182	-	1800°C	3.3-11.8		$1.05 \pm 0.03$	$9.09 \pm 0.18$	$19.00 \pm 0.68$	$1.59 \pm 0.21$	
SLT-3	1.146	-	1800°C	3.1-13.8		$1.10 \pm 0.03$	$8.20 \pm 0.16$	$16.71 \pm 0.60$	$1.18 \pm 0.16$	
WBT-1	1.011	-	1800°C	1.1-1.2		$0.94 \pm 0.02$	$2.12 \pm 0.04$	$2.92 \pm 0.12$	$1.05 \pm 0.14$	
Leizhou Peninsula										
HTY-1	1.186	-	1800°C	0.9-1.6		$0.76 \pm 0.02$	$1.89 \pm 0.04$	$2.89 \pm 0.12$	$1.08 \pm 0.14$	
ZPT-1	1.184	-	1800°C	0.2-0.5		$0.90 \pm 0.02$	$3.61 \pm 0.07$	$7.96 \pm 0.29$	$1.52 \pm 0.20$	
Crushing										
Hainan Island										
DPT-1	0.148	0.112	x300			$0.56 \pm 0.01$	$4.52 \pm 0.07$	-	-	
SLT-3	0.117	0.085	x300			$0.25 \pm 0.004$	$4.14 \pm 0.07$	-	-	
WBT-1	0.106	0.082	x300			$0.05 \pm 0.001$	$0.60 \pm 0.01$	-	-	
WBT-1-nc <sup>d</sup>	0.134	0.089	x1000			$0.06 \pm 0.01$	$1.57^d \pm 0.15$	$<12.90 \pm 0.13$	$<1.44 \pm 0.10$	
Leizhou Peninsula										
HTY-1	0.140	0.098	x100			$0.07 \pm 0.001$	$0.41 \pm 0.01$	-	-	
ZPT-1	0.135	n.d.	x300			$0.03 \pm 0.001$	$0.37 \pm 0.01$	-	-	
ZPT-1-nc <sup>d</sup>	0.092	0.084	x1000			$0.06 \pm 0.01$	$<1.05 \pm 0.10$	$<8.68 \pm 0.09$	$<0.81 \pm 0.08$	

<sup>a</sup>Blank concentrations are expressed as  $\text{cm}^3\text{STP}$ .<sup>b</sup>Weight of grains crushed to a size smaller than 150  $\mu\text{m}$ .<sup>c</sup>For the heating extractions, temperatures at which the samples were melted to degas. For crushing extractions, the applied number of crushing strokes.<sup>d</sup>Concentrations are given as an upper limit because they are not corrected for procedural blank (except Ne).

Table 1b. Isotopic ratios of Chinese tektites for heating and crushing experiments.

Sample	F( <sup>4</sup> He)	F( <sup>20</sup> Ne)	F( <sup>84</sup> Kr)	F( <sup>132</sup> Xe)	<sup>20</sup> Ne/ <sup>22</sup> Ne	<sup>21</sup> Ne/ <sup>22</sup> Ne	<sup>38</sup> Ar/ <sup>36</sup> Ar	<sup>40</sup> Ar/ <sup>36</sup> Ar
Heating								
Hainan Island								
DPT-1	11 ± 1	220 ± 7	1.01 ± 0.04	2.35 ± 0.32	9.71 ± 0.06	0.0289 ± 0.0002	0.1886 ± 0.0004	378.1 ± 1.0
SLT-3	9 ± 1	255 ± 8	0.98 ± 0.04	1.93 ± 0.26	9.80 ± 0.06	0.0291 ± 0.0002	0.1880 ± 0.000	367.8 ± 1.0
WBT-1	10 ± 1	843 ± 27	0.67 ± 0.03	6.64 ± 0.90	9.73 ± 0.06	0.0289 ± 0.0002	0.1877 ± 0.0004	575.5 ± 1.6
Leizhou Peninsula								
HTY-1	6 ± 1	771 ± 25	0.74 ± 0.03	7.65 ± 1.03	9.81 ± 0.06	0.0293 ± 0.0002	0.1896 ± 0.0009	576.6 ± 2.0
ZPT-1	3 ± 0	479 ± 15	1.07 ± 0.04	5.65 ± 0.77	9.75 ± 0.05	0.0288 ± 0.0002	0.1868 ± 0.0005	449.7 ± 1.2
Crushing								
Hainan Island								
DPT-1	29 ± 1	237 ± 5	–	–	9.80 ± 0.05	0.0293 ± 0.0003	0.1890 ± 0.0016	310.2 ± 1.4
SLT-3	–	114 ± 3	–	–	9.79 ± 0.06	0.0294 ± 0.0005	0.1886 ± 0.0022	307.6 ± 1.5
WBT-1	–	151 ± 4	–	–	9.80 ± 0.08	0.0289 ± 0.0005	0.1972 ± 0.0063	299.7 ± 4.6
WBT-1-nc*	–	–	–	–	9.70 ± 0.11	0.0291 ± 0.0004	0.1980 ± 0.0010	296.0 ± 0.6
Leizhou Peninsula								
HTY-1	–	303 ± 9	–	–	9.94 ± 0.07	0.0289 ± 0.0005	0.2025 ± 0.0079	294.4 ± 5.7
ZPT-1	–	157 ± 4	–	–	–	–	0.1934 ± 0.0044	306.9 ± 3.1
ZPT-1-nc*	–	–	–	–	9.76 ± 0.12	0.0291 ± 0.0005	–	–
Air	1	1	1.00	1.00	9.80	0.0290	0.1880	295.5

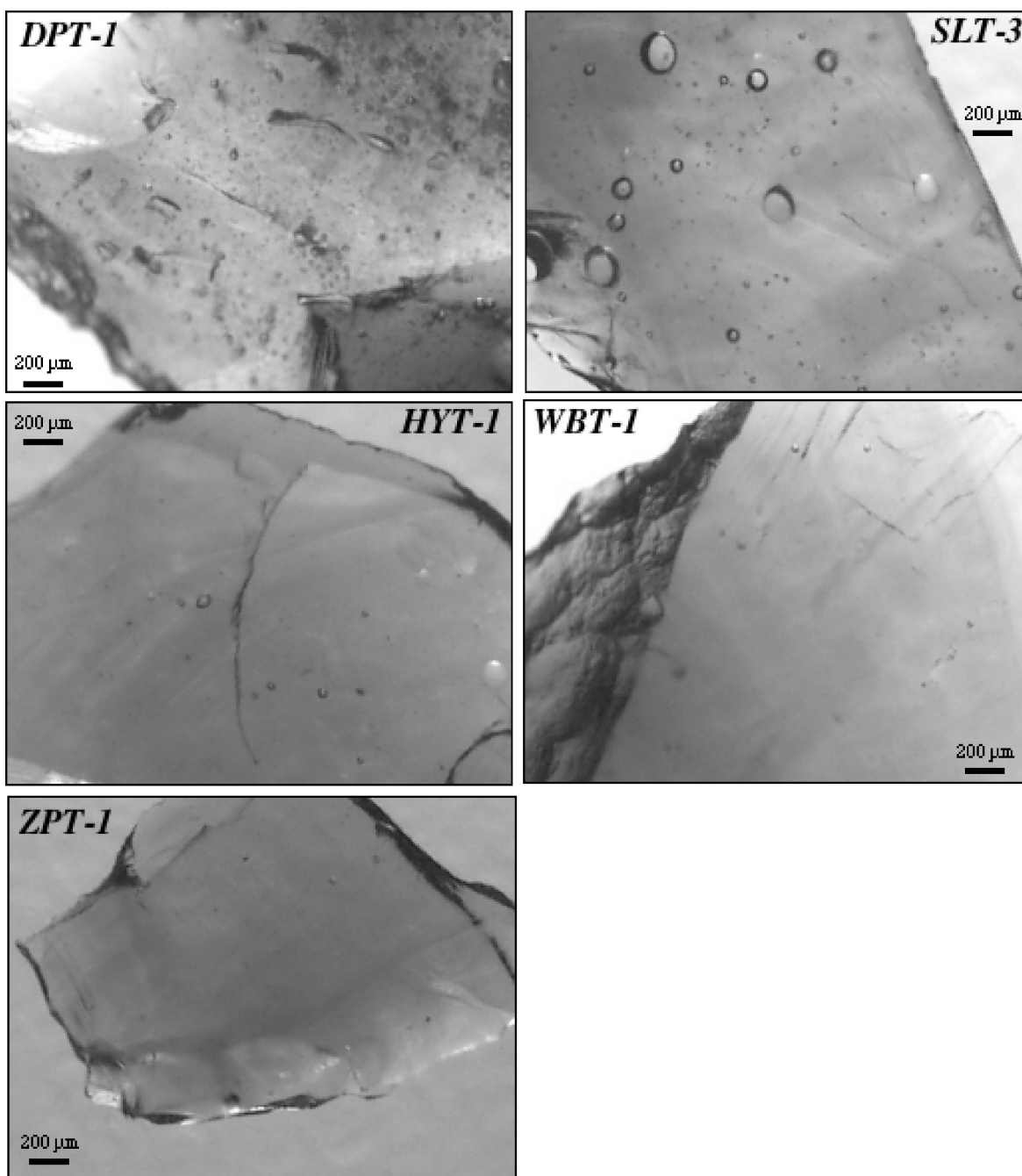


Fig. 2. Microphotographs (60× enlargements) of polished grains of the studied Chinese tektites.

1.6 vol% (average  $1.2 \pm 0.3$  vol%), from 1.1 vol% to 1.2 vol% (average  $1.2 \pm 0.1$  vol%), and from 0.2 vol% to 0.5 vol% (average  $0.4 \pm 0.1$  vol%), respectively.

Two sample aliquots from each sample were prepared for this study. For the first one, fresh pieces of about 1 g were picked up for heating experiments (Table 1). They were washed with ethanol and acetone in an ultrasonic bath for 30 min each and put into a Mo-Ta crucible. The latter is fitted in a stainless steel purification line connected to a noble gas mass spectrometer VG 5400 (Micromass Instruments®). The

samples were baked at  $\sim 100^\circ\text{C}$  overnight to remove any superficial contaminants. The gases were extracted at  $1800^\circ\text{C}$  and purified using Ti-Zr getters. Noble gas elemental and isotopic compositions were measured using a VG5400, which was calibrated using air pipettes (Table 1). Details of the noble gas measurements are described elsewhere (Pinti et al. 1999). The procedural blanks are reported in Table 1.

A second aliquot of samples was selected for crushing experiments to quantify the amount of gas contained in the vesicles. Pieces of 0.1–0.15 g were picked up, washed in an

ultrasonic bath with ethanol and acetone, and placed in an air-operated, piston-driven crusher (Pinti et al. 1999). The gases were extracted by crushing in vacuum ( $\times 100$ – $300$  strokes); the purification and analysis was identical in procedure as for the heated samples. The crushing experiments have been repeated for 2 of the samples, WBT-1 and ZPT-1, using a recently developed stainless steel crusher with 6 holders (Matsumoto et al. 2001). All removable parts are washed in an ultrasonic bath with ethanol and acetone and then loaded into the stainless-steel sample containers of the crushing device. To determine procedural blank levels, one of the containers was left empty. The procedural blanks are reported in Table 1. Details of the analytical procedure are given elsewhere (Matsumoto et al. 2001).

In both crushing experiments, the recovered samples were sieved. The grains less than  $150\ \mu\text{m}$  in size were assumed to be the hosts of the vesicles from which the noble gases were released. The noble gas concentrations were calculated using the weights of the  $<150\ \mu\text{m}$ -size fractions and are given in Table 1, except for ZPT-1 for which the  $<150\ \mu\text{m}$ -size fraction weight could not be determined. Because the glassy samples contains vesicles smaller than  $150\ \mu\text{m}$  (Fig. 2), the concentration of noble gases measured in the crushed fraction should be regarded as a lower limit for gases trapped in vesicles.

## RESULTS

### Heating Experiments

The elemental abundances of He, Ar, and Kr are higher in the vesicle-rich samples DPT-1 and SLT-3 than those of the vesicle-poor samples HYT-1, WBT-1, and ZPT-1; Ne and Xe have a nearly constant concentration in all samples (Table 1). The noble gas fractionation factor,  $F(m)$ , defined as  $F(m) = (mX/^{36}\text{Ar})_{\text{sample}} / (mX/^{36}\text{Ar})_{\text{air}}$ , is given in Table 1. This factor compares the elemental abundance pattern of noble gases in tektites to those of air. He, Ne, and Xe show abundances higher than those of  $^{36}\text{Ar}$  and air. The xenon excesses can be explained by an adsorbed component on the surface, as is usually observed in most silicate glasses (Palma et al. 1997).

The isotopic ratios of He have not been determined because of the low  $^3\text{He}$  concentration. Those of Ne ( $^{20}\text{Ne}/^{22}\text{Ne}$  and  $^{21}\text{Ne}/^{22}\text{Ne}$ ) and the argon isotopic ratio  $^{38}\text{Ar}/^{36}\text{Ar}$  are consistent with atmospheric compositions within experimental uncertainties. The argon isotopic ratio  $^{40}\text{Ar}/^{36}\text{Ar}$  is higher than the atmospheric ratio of 295.5, due to the occurrence of radiogenic  $^{40}\text{Ar}^*$ .

### Crushing Experiments

The contents of He, Kr, and Xe were not determined (except He for DPT-1) during the first crushing experiments since the concentrations were indistinguishable from the

blank (Table 1). Kr and Xe have been measured in the samples WBT-1-nc and ZPT-1-nc (“nc” = new crusher; Table 1), but they are also consistent with the procedural blanks and are reported as an upper limit.

The total abundances of He, Ne, and Ar are higher for the vesicle-rich samples, while they are lower in the glassy samples. The neon isotopic ratios are identical to those in the atmosphere within stated uncertainties. The  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios vary from values close to the atmospheric ratio of 295.5 ( $294.4 \pm 5.7$  for HYT-1) up to  $310.2 \pm 1.4$ , measured in DPT-1, suggesting that some of the radiogenic  $^{40}\text{Ar}^*$  is also released by crushing from the glass matrix, as is often observed in crushing experiments of silicate minerals (Matsumoto et al. 2002).

### Ne and Ar Distribution Between Glass and Vesicles

The distribution of  $^{20}\text{Ne}$  and  $^{36}\text{Ar}$  between the glass and the vesicles is represented graphically in Fig. 3 and computed from noble gas amounts measured from heating and crushing experiments, respectively (Table 1). Note that these experiments have been carried out on different aliquots of the same sample, so we made the assumption that vesiculation is uniform in our samples. This assumption is certainly valid for the homogeneous, glassy samples HYT-1, WBT-1, and ZPT-1 (average vesicle vol% =  $1.2 \pm 0.3$ ,  $1.2 \pm 0.1$ , and  $0.4 \pm 0.1$ , respectively), while for the heterogeneous vesicle-rich samples DPT-1 and SLT-3 (average vesicle vol% =  $8.0 \pm 4.3$  and  $7.4 \pm 4.6$  vol%), the values from Fig. 3 should be taken as indicative.

We do not report He, Kr, and Xe results because of the lack of reliable data. The neon concentration distribution in vesicles and glass is directly related to the vol% of vesicles in the samples. An average  $53.4 \pm 1.6\%$  and  $22.6 \pm 0.7\%$  of the bulk  $^{20}\text{Ne}$  amount resides inside vesicles in samples DPT-1 (average vesicle vol% =  $8.0 \pm 4.3$ ) and SLT-3 (average vesicle vol% =  $7.4 \pm 4.6$ ). Samples HYT-1, WBT-1, and ZPT-1 (average vesicle vol% are  $1.2 \pm 0.3$ ,  $1.2 \pm 0.1$ , and  $0.4 \pm 0.1$ , respectively) have most of the  $^{20}\text{Ne}$  residing in the glass, the vesicles containing from  $5.0 \pm 0.2\%$  up to  $8.6 \pm 0.3\%$  of the total measured  $^{20}\text{Ne}$  amount. Sample ZPT-1 had the lowest fraction,  $3.3 \pm 0.1\%$  of  $^{20}\text{Ne}$  total amount residing in the vesicles, and is considered to be a lower limit because it is calculated using the total sample weight (Fig. 3).  $^{36}\text{Ar}$  is more concentrated in the vesicles than in the glass relative to  $^{20}\text{Ne}$ . The  $^{36}\text{Ar}$  amount in vesicles varies from  $21.7 \pm 0.7\%$  up to  $50.5 \pm 1.3\%$  and is also related to the amount of vesicles. Sample WBT-1-nc (and ZPT-1-nc) had the largest fraction,  $74.1 \pm 7.4\%$  in the vesicles, an amount that is regarded as an upper limit because  $^{36}\text{Ar}$  is not blank-corrected.

## DISCUSSION AND CONCLUSIONS

The distribution of  $^{20}\text{Ne}$  and  $^{36}\text{Ar}$  in splash-form tektites differs from that found in Muong Nong tektites by Mizote et

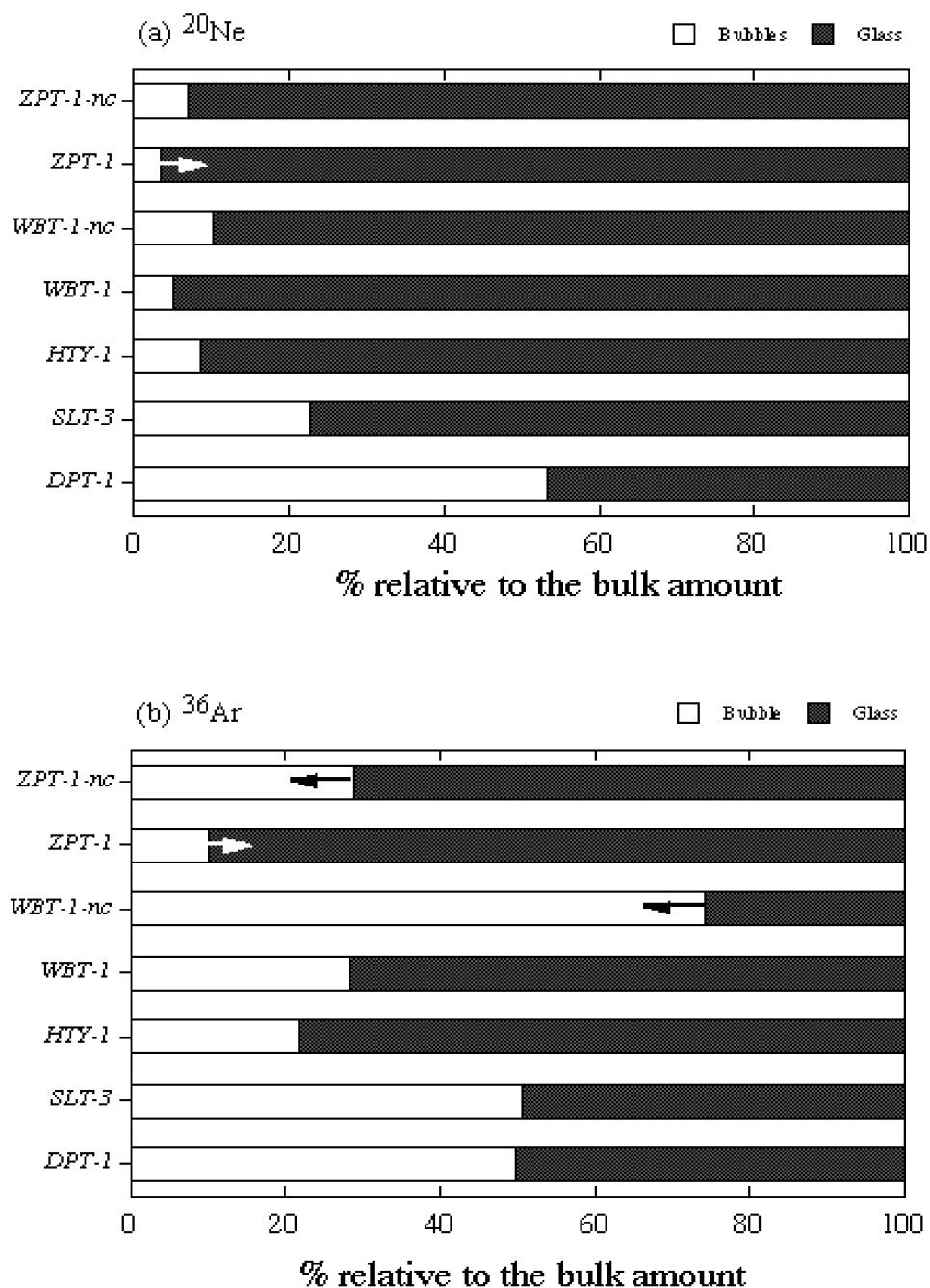


Fig. 3. Distribution of (a)  $^{20}\text{Ne}$  and (b)  $^{36}\text{Ar}$  between vesicles and glass in Chinese splash-form tektites. The left and right arrows indicate upper limits from the crushing and heating methods, respectively.

al. (2003).  $^{20}\text{Ne}$  and  $^{36}\text{Ar}$  are predominantly preserved in vesicles of Muong Nong tektites (70 to 85% of the total amount; Mizote et al. 2003), while they seem mostly preserved in the glass for splash-form tektites (this study). We cannot exclude, however, that neon could have been preserved in very small vesicles that are not broken during the crushing experiments (Matsubara and Matsuda 1995). If we assume that the partial pressure of  $^{20}\text{Ne}$  in vesicles is the same as that in the atmosphere at room temperature, the

volume of vesicles required for accommodating the neon excesses should be about 1.2–1.4 vol%. Except for ZPT-1 (0.4 vol%), all the other samples have vesicle volumes in this range or higher. This implies that the samples DPT-1 and SLT-3, which are characterized by a high degree of vesiculation, could contain Ne at a partial pressure lower than atmospheric, as observed previously in bubble-rich tektites (Matsuda et al. 1996).

The Chinese tektites show  $^{20}\text{Ne}$  concentrations within

the range measured in splash-form tektites ( $1.0 \pm 0.3 \times 10^{-7}$   $\text{cm}^3\text{STP/g}$ ; average value calculated from 28 tektites from the 4 known strewn fields; Fig. 4). In Muong Nong tektites, the amount of  $^{20}\text{Ne}$  is generally larger than that in splash-form tektites (Fig. 4) and is highly variable (from  $1.8$  to  $13.8 \times 10^{-7}$   $\text{cm}^3\text{STP/g}$ ; Mizote et al. 2003). This is likely due to the occurrence of larger and heterogeneous populations of vesicles (Müller and Gentner 1968; Koeberl 1994) accommodating the  $^{20}\text{Ne}$  excesses. The amount of argon in glass is less than that of neon because argon diffuses slowly, presumably after tektite solidification. Most argon is likely introduced before the tektite solidification and mainly in vesicles, as already suggested by Matsuda et al. (1993).

Neon can diffuse rapidly into tektite glass reaching the saturation level, which can be compared to the concentration attained by solubility (Matsubara and Matsuda 1995). The suggestion that Ne concentrations in tektites may represent a solubility saturation level has been previously discarded on the basis of solubility calculations (Matsubara and Matsuda 1991). The total amount of  $^{20}\text{Ne}$  that can be dissolved in silicate glass at equilibrium with atmospheric pressure and at a melting temperature of  $1350^\circ\text{C}$  cannot exceed  $0.13 \times 10^{-7}$   $\text{cm}^3\text{STP/g}$  (Matsubara and Matsuda 1991). This value was

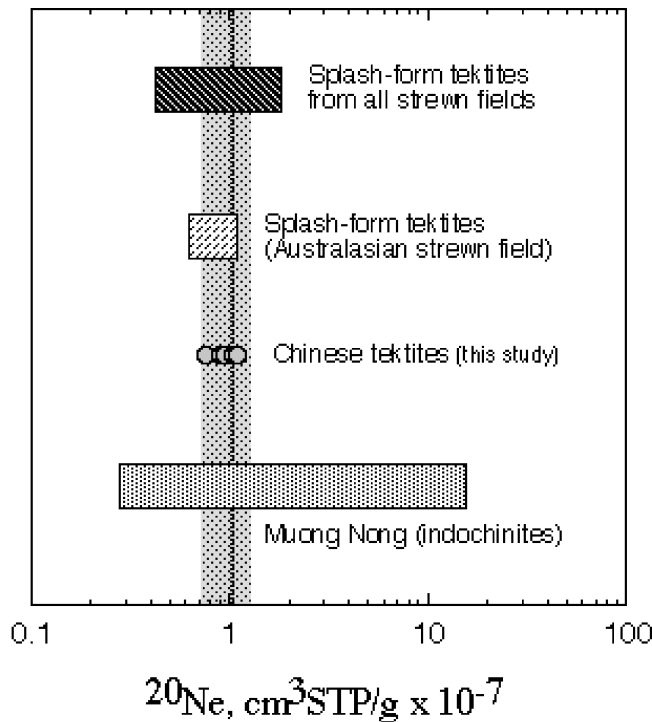


Fig. 4. Range of  $^{20}\text{Ne}$  concentration in splash-form tektites (Hennecke et al. 1975; Matsubara and Matsuda 1991; Matsuda et al. 1993, 1996; Palma et al. 1997), Muong Nong tektites (Murty 1997; Mizote et al. 2003), and Chinese tektites (this study). The dashed line and dotted area represent the average  $^{20}\text{Ne}$  concentration in splash-form tektites and its standard deviation, respectively. Note that the x-axis is in log scale.

determined from Ne solubility data of MORB glasses (Lux 1987).

However, the chemical composition of MORB glasses and of tektites is different, and this parameter has a strong influence on the permeation, diffusion, and solubility of noble gases (e.g., Norton 1951, 1956; Shibata et al. 1996, 1998). Noble gases diffuse in the glass through the free-volume of glass, which is produced by the  $\text{SiO}_2$ -ring network; the permeation (“permeation” is the over-all steady-state flow process of gas through a glass and includes the internal process of diffusion; Norton 1951) is dependent of the amount on the glass-forming oxides such as  $\text{SiO}_2$  (Norton 1956). The solubility of the gas, i.e., the total amount of gas dissolved in the glass through permeation, is also dependent on the free-volume available in the glass structure (Doremus 1994). Thus, the highest noble gas solubility is reached in  $\text{SiO}_2$ -rich glasses (Carroll and Stolper 1993).

MORB glasses are relatively silica-poor glasses, with  $\text{SiO}_2$  contents from 45 to 50 wt%. In the terms of petrology, tektites can be considered as rhyolitic melts, with  $\text{SiO}_2$  contents from 70 to 83 wt% (Heide et al. 2001). If we plot the average  $^{20}\text{Ne}$  concentration for each strewn field (data from Hennecke et al. 1975; Matsubara and Matsuda 1991; Matsuda et al. 1993, 1996; Palma et al. 1997; this study) against the  $\text{SiO}_2$  content (data from Koeberl 1990; Glass 1990; Dressler and Reimold 2001), a striking correlation is observed (Fig. 5). This correlation can be interpreted as the relation between the  $^{20}\text{Ne}$  permeation and the silica content

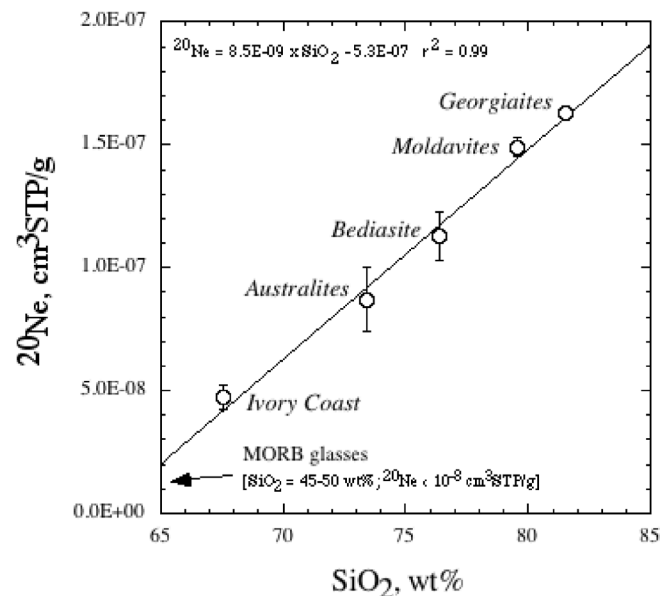


Fig. 5. Average  $^{20}\text{Ne}$  concentration in splash-form tektites calculated for each strewn field plotted against the average  $\text{SiO}_2$  content. See the text for data sources. The arrow indicates the  $^{20}\text{Ne}$  concentrations and  $\text{SiO}_2$  contents characteristics of MORB glasses (internal compilation of literature data).

of tektite. The higher the  $\text{SiO}_2$  content, the higher the total amount of  $^{20}\text{Ne}$  dissolved into the tektite glass. If we assume that 80–90% of the measured  $^{20}\text{Ne}$  is contained in glass, as observed in the samples HYT-1, WBT-1 and ZPT-1, the  $^{20}\text{Ne}$  concentration in tektite glass worldwide would range from 0.38 to  $1.4 \times 10^{-7} \text{ cm}^3\text{STP/g}$ . If we use solubility data for fused silica and quartz (Frank et al. 1961; Perkins and Begeal 1971; Shackelford and Studt 1972), which better represent the chemical composition of tektites (Jakes et al. 1991), the total amount of  $^{20}\text{Ne}$  that can be dissolved into glass ranges from 0.28 to  $0.63 \times 10^{-7} \text{ cm}^3\text{STP/g}$ , a figure that is closer to the measured amount (Table 1) and is higher than that calculated using MORB solubility data.

However, the  $\text{SiO}_2$  content is not the only parameter controlling the permeation and solubility of noble gases in glasses. The occurrence of large cations, such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$ , which are called “network-modifiers,” can modify the  $\text{SiO}_2$  network, reducing the free-volume available to dissolve the gas. Conversely, smaller and highly charged cations, such as  $\text{Si}^{4+}$ ,  $\text{Ti}^{4+}$ ,  $\text{Al}^{3+}$ , and  $\text{Fe}^{3+}$ , are “network-forming” cations, which enlarge the silicate structure allowing more gas to be dissolved. An index of the silicate network is the NBO/T ratio, which is the average number of nonbridging oxygen per tetrahedral coordinated cation in melt. The NBO/T ratio is calculated as follows:

$$\text{NBO/T} = \frac{2M \cdot \{(\text{CaO}, \text{MgO}, \text{FeO}) + M \cdot (\text{Na}_2\text{O}, \text{K}_2\text{O}) - M(\text{Al}_2\text{O}_3, \text{Fe}_2\text{O}_3)\}}{M(\text{SiO}_2, \text{TiO}_2, \text{Al}_2\text{O}_3, \text{Fe}_2\text{O}_3)} \quad (1)$$

where  $M$  is the mol% of each chemical compound in the glass. A high NBO/T ratio means a higher concentration of “network-modifying” cations, which in turn lowers the noble gas permeation (Norton 1951, 1956) and solubility (Shibata et al. 1998). For MORB and synthetic silica glasses, the NBO/T ratio ranges from 0.4 to 1.8 (calculated from the data of Jambon et al. [1986], Lux [1987], Broadhurst et al. [1992], and Shibata et al. [1998]). Theoretical calculations of Jakes et al. (1991) based on Raman spectra of tektite glasses give NBO/T ratios = 0.09. We calculated the NBO/T ratio in tektites for each strewn field using the main oxide composition of glasses from Glass (1990), Koeberl (1990), and Dressler and Reimold (2001). The obtained NBO/T ratios range from 0.03 for georgiaites (North American strewn field) to 0.3 for Ivory Coast. These values are lower than those measured in MORB glasses, suggesting that the silica network in tektites is much less modified and, thus, more favorable to the permeation and solution of larger amounts of noble gases. The calculated NBO/T ratios in tektites are plotted against the  $^{20}\text{Ne}$  concentration (Fig. 6), showing an inverse correlation supporting the relationship between the chemical composition of structure of the glass and the amount of dissolved neon.

The same should be true for the heavier noble gases, but we did not observe this to be the case. This can be explained by the occurrence of heavier noble gases, mostly in vesicles,

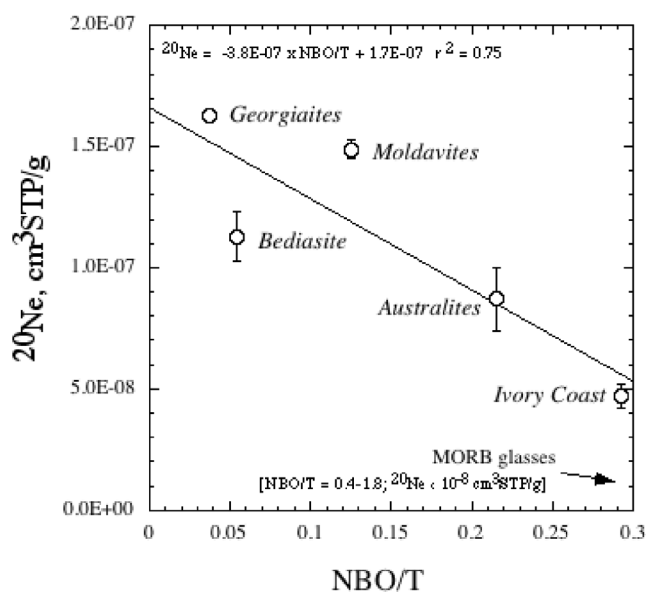


Fig. 6. Average  $^{20}\text{Ne}$  concentration in splash-form tektites calculated for each strewn field plotted against the NBO/T ratio (nonbridging oxygen per tetrahedral cation in the melt). See the text for data sources. The arrow indicates the  $^{20}\text{Ne}$  concentrations and the NBO/T ratios characteristics of MORB glasses (internal compilation of literature data).

as observed in Chinese tektites for Ar (Fig. 3). Ar, Kr, and Xe have very low permeation and diffusion velocities through silica glasses, and thus, they never reach their respective solubility saturation levels. Indeed, the low amount of heavy noble gases observed in tektites is likely due to the solubility equilibrium at high altitude before solidification. Permeation at room temperature does not drastically modify the initial amount.

In conclusions, tektites could be an interesting natural analogue to study the relation between the  $\text{SiO}_2$  structure and the solubility of light noble gases in  $\text{SiO}_2$ -rich glasses.

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