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## U–Pb isotopic study of relict zircon inclusions recovered from Muong Nong-type tektites

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**Abstract**—Isotopic compositions of U and Pb were determined for relict zircon inclusions recovered from Muong Nong-type tektites from the Australasian and North American strewn fields. These inclusions are generally opaque white with granular textures, probably representing mechanical disaggregation and/or local melting and recrystallization. All zircons have strongly discordant U–Pb isotopic ratios and the isotopic ratios of most of the zircons are dominated by common Pb. This is interpreted as being the result of complete resetting of the isotopic system during the impact event and exchange with Pb from the target sediments. Ages that may represent the target rocks were only retained by one sample, representing a zircon that was extracted from a Muong Nong-type georgiaite. A value of 0.6 Ga was obtained, which is similar to the Nd and Sr model ages obtained for the North American tektites. Our results indicate that the U–Pb isotopic system in almost all zircons from tektites has been totally reset during the impact event; this is in contrast to zircons extracted from impact melt rocks at some impact structures and/or distal ejecta, some of which are only partly reset. Copyright © 2001 Elsevier Science Ltd

## 1. INTRODUCTION

Tektites are naturally occurring glass objects of impact origin found scattered over regions of the Earth's surface called strewn fields (Glass, 1990; Koeberl, 1994). Four tektite strewn fields are known: (1) Australasian, (2) Ivory Coast, (3) Central European, and (4) North American. The tektites from these strewn fields have formation ages of 0.77, 1.1, 15, and 35 Ma, respectively (see Koeberl, 1994, for a review). It has been proposed that the Ivory Coast, Central European, and North American tektites were derived from the Bosumtwi, Ries, and Chesapeake Bay impact craters, respectively (e.g., Glass, 1990; Koeberl et al., 1996). The source crater for the Australasian strewn field has not yet been found; however, based on a variety of evidence, several authors have suggested that it must be somewhere in Indochina (Stauffer, 1978; Ford, 1988; Schnetzler, 1992; Blum et al., 1992; Glass and Pizzuto, 1994).

Most tektites occur as splash forms (spheres, teardrops, dumbbells, etc.). Some of the splash-form tektites show evidence of atmospheric ablation. Another group has a blocky, layered appearance. The layered tektites are called Muong Nong-type (MN) tektites after the area in Laos where they were first found. Some MN tektites are fairly large, weighing as much as 24 kg (Koeberl, 1992). MN tektites are mostly found in the Indochina part of the Australasian strewn field, but a few layered or MN tektites have been recovered from the Central European and North American strewn fields (e.g., Glass et al., 1990; Glass et al., 1995). The MN tektites exhibit compositional and petrographic evidence indicating that they were not as intensely heated as the splash form and ablated tektites (Koeberl, 1992) and, as a result, some MN tektites contain relict inclusions from the parent or target rock that was melted

to produce them (Glass and Barlow, 1979). Relict mineral phases that have been found include: quartz, zircon, rutile, chromite, and monazite. Shock-produced phases include: coesite, baddeleyite (formed by decomposition of zircon), and corundum (formed by the decomposition of an  $Al_2SiO_5$  phase to corundum plus  $SiO_2$  glass). The relict inclusions provide information about the target rock and the tektite formation process (Glass and Barlow, 1979).

Shaw and Wasserburg (1982) studied the Rb–Sr and Sm–Nd systematics of tektites from the various strewn fields. They showed that all tektites have negative  $\epsilon_{Nd}$  and large positive  $\epsilon_{Sr}$  values unique to old continental crust. The Nd model ages of tektites reflect the age of the source terrain of the target rocks. Shaw and Wasserburg (1982) found Precambrian ages for the source terrain for the target rocks of all the tektite strewn fields. Blum et al. (1992) studied the Rb–Sr and Sm–Nd isotopic systematics of MN and splash-form Australasian tektites and confirmed that the source material in the target rock was derived from Precambrian crust with Nd model ages ranging from 1.04 to 1.19 Ga. Bodet and Schärer (2000) found U–Pb ages clustering around 2.5, 2.3, 1.9, 1.1, and 0.8 Ga in zircons from rivers in SE Asia, which is the general source area of the Australasian tektites. The North American tektites have Nd model ages ranging between 620 and 720 Ma (Shaw and Wasserburg, 1982; Stecher et al., 1989; Glass et al., 1995).

The purpose of the present study was to determine the U–Pb systematics of relict zircon crystals recovered from MN tektites from the Australasian and North American strewn fields. This was done to find out if the zircon ages are either largely reset due to the impact event (as is known for zircons from impact melt rocks and in the distal ejecta from several impact structures; see below), or if some of them have retained pre-impact information to constrain the ages of the source terrain of the target rocks and to better characterize the source rocks.

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Table 1. Description of zircons from tektites studied by SEM and ion microprobe.

Zircon number	Size ( $\mu\text{m}$ )	Shape	Texture	Tektite*
<i>Australasia</i>				
MN-d	33 $\times$ 34	Subrounded, equant	Granular to blade-like	F16
MN-e	28 $\times$ 45	Rounded, elongate	Radial blade-like	F11.3
MN-i	38 $\times$ 45	Rounded, equant	Granular around margins, cracked	TC-1
MN-m	40 $\times$ 52	Irregular, equant	Granular	TC-1
MN-n	20 $\times$ 47	Subrounded, elongate	Granular	TC-1
MN-p	20 $\times$ 28	Rounded to subangular, elongate	Granular	F18
MN-3	34 $\times$ 50	Subrounded, slightly elongate	Mostly granular, cracked	A-65
MN-7	30 $\times$ 50	Rounded, slightly elongate	Granular	TT
<i>Georgia</i>				
Ga4	32 $\times$ 70	Rounded, elongate	Granular	MNGaTek
Ga5	20 $\times$ 27	Subangular, elongate	Granular	MNGaTek

\* F16, F11.3, and F18 are from Thailand, courtesy D. S. Futrell; TC-1 is from Thailand, courtesy Smithsonian Institution, Washington, DC; TT is from Thailand; A-65 is from Danang, Vietnam; MNGaTek is from Riddleville, Georgia, USA, courtesy R. L. Strange.

## 2. TEKTITE SAMPLES, ZIRCON RECOVERY AND DESCRIPTION

The zircons used in this study were recovered from one MN-type North American tektite from Georgia (Glass et al., 1995) and seven MN-type Australasian tektites (Table 1). The tektites were cleaned, weighed, crushed, and then sieved. The 74–149  $\mu\text{m}$  size fractions were subjected to heavy liquid separations to recover glass fragments with high specific gravity. These fragments were then observed with a binocular microscope with up to 50 times magnification and grains containing inclusions were recovered (see Glass and Barlow, 1979). The inclusions were identified using x-ray diffraction. The glass fragments containing zircons were then mounted in epoxy, ground down to expose the zircons, and polished. For characterization, the samples were studied by scanning electron microscopy (SEM), and BSE images were obtained with a Jeol JSM-6400 SEM instrument.

The zircon grains range in size from 20  $\times$  28 to 30  $\times$  1240  $\mu\text{m}$  (Table 1). Most are opaque white, but several are slightly translucent. They range from equant to elongate in shape. In cross section, they range from rounded to subangular. Scanning electron microscope photographs (BSE images) of polished sections show that they have a granular texture and some are highly disaggregated and cracked (Fig. 1a–f). In the polished sections, only part of the zircons are exposed at any time; thus, the sample size seen by the SEM or ion probe is smaller than the grain dimensions mentioned above. Each grain was studied by x-ray diffraction using Debye–Scherrer or Gandolfi cameras (Glass and Barlow, 1979). Most zircons appear in the BSE images as if they have broken down to baddeleyite plus  $\text{SiO}_2$  glass (i.e., showing a “brain-like” texture with brighter and darker areas, where the brighter areas would indicate the higher Zr content of baddeleyite), but none of them shows any lines for baddeleyite in the x-ray diffraction patterns (none have the scheelite structure of zircon, either). As the grains are all very small and embedded in a glass matrix, they do not show very good diffraction patterns, but not even the strongest baddeleyite lines are present. We estimate that it would be possible to detect  $\geq 20\%$  baddeleyite in the zircon grains. The areas that are brighter in the BSE images have slightly higher Zr contents if analyzed by energy dispersive spectrometry in the SEM, but

due to the small sizes (sub- $\mu\text{m}$ ) of the areas, no quantification is possible.

## 3. EXPERIMENTAL METHODS AND RESULTS: U–PB DATING

Measurement of the Pb isotopes by “conventional” mass spectrometry (e.g., as done for zircons from Chicxulub or Vredefort impact melt rocks and/or distal ejecta; Krogh et al., 1993; Kamo and Krogh, 1995; Kamo et al., 1996; Moser, 1997) is not possible for the zircons in tektites due to their small size and fragmented nature. Attempts to isolate the zircons by dissolving the glass using dilute hydrofluoric acid failed, with the zircon collapsing into  $\mu\text{m}$  to sub- $\mu\text{m}$ -sized powder (Glass, 2000). Thus, these samples could only be studied by ion probe, with a corresponding loss in precision.

Analyses for U, Th, and Pb concentrations and Pb isotopic compositions were performed on the high-resolution CAM-ECA IMS 1270 ion microprobe at CRPG–CNRS, Nancy. A primary beam of 12.5 kV with 10 nA  $\text{O}^{2-}$  ions was focussed to a  $\leq 40$   $\mu\text{m}$  diameter spot, and the sample sputtered under an  $\text{O}_2$  pressure of  $2 \times 10^{-6}$  torr. Ratios of Pb/Pb, Pb/U, UO/U, and ThO/UO, as well as the intensity of the  $\text{Zr}_2\text{O}$  beam as internal reference, were measured at a mass resolution of 5400 by peak jumping. Each analyzed spot was counted for 20 minutes, with 15 cycles covering the different masses. The measured ratios were normalized to those of the standard G91500 (Wiedenbeck et al., 1995), measured during the same session, by using the relationship between  $\text{Pb}^+/\text{U}^+$  and  $\text{UO}^+/\text{U}^+$  as described by Williams et al. (1984). Common Pb corrections were based on the measured  $^{204}\text{Pb}$  content, assuming a present-day crustal Pb isotopic composition (Stacey and Kramers, 1975). For most of the samples, the measured  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio is low ( $< 100$ ), with low counting rates on  $^{206}\text{Pb}$ . Due to its low abundance, the error on  $^{204}\text{Pb}$  is high (but the count rate on  $^{204}\text{Pb}$  is still about 50 to 200 times higher than the background, making it unlikely that the  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios are influenced by analytical problems). Furthermore, most of the samples have an isotopic composition close to that of common Pb (either due to overlap with glass areas, or due to exchange between the Pb in the glass and the zircons), which makes the accurate discrimination of

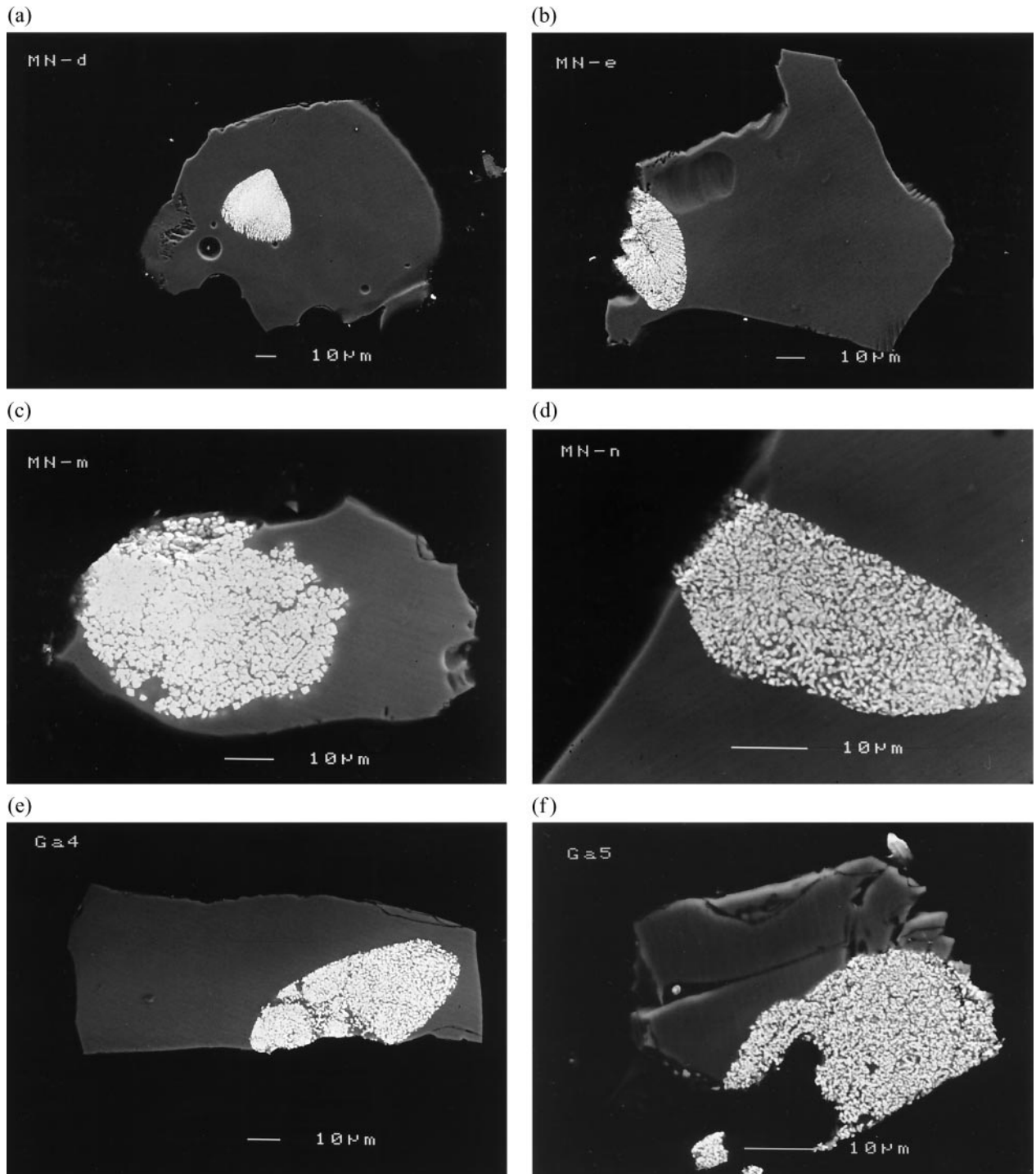


Fig. 1. Back-scattered scanning electron microscope photographs of zircon inclusions from various Muong Nong-type tektites. See Table 1 for descriptions. Exposed parts of zircons are smaller than total sizes listed in Table 1.

radiogenic Pb impossible. Only samples with high  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio may provide some age information.

No obvious relationship exists between the appearance of the zircon inclusions and the radiogenic Pb content or the U, Th, and Pb concentrations in the zircons. The Pb isotopic composition was also measured for two spots on glass near the zircon inclusions in samples MN-d and MN-n. The results for the

glass are exactly the same as for the nearby zircons: e.g.,  $^{207}\text{Pb}/^{206}\text{Pb} = 0.825 \pm 0.005$  for zircon MN-d and  $0.828 \pm 0.002$  for the glass. Due to the small size (a few  $\mu\text{m}$ ) of the exposed area of the zircon inclusions, and the similar diameter of the ion beam, most ion probe spots on zircons include a tektite glass component (cf. Fig. 1). No significant change in the  $^{207}\text{Pb}/^{206}\text{Pb}$  ratio between glass and zircon inclusions is

Table 2. Concentrations and isotopic compositions of U, Th, Pb, and ages of zircons in tektites.

	Concentrations (ppm)			Pb isotopic ratios ( $\pm 1\sigma$ )		Pb/U ratios*		Apparent ages (Ga) <sup>†</sup>		
	U	Th	<sup>206</sup> Pb	<sup>206</sup> Pb/ <sup>204</sup> Pb	<sup>207</sup> Pb/ <sup>206</sup> Pb	<sup>206</sup> Pb/ <sup>238</sup> U	<sup>207</sup> Pb/ <sup>235</sup> U	<sup>206</sup> Pb/ <sup>238</sup> U	<sup>207</sup> Pb/ <sup>235</sup> U	<sup>207</sup> Pb/ <sup>206</sup> Pb
Muong Nong-type tektites from Indochina										
Zircons										
MN-d	5.7	28.9	3.1	19.2 $\pm$ 1.8	0.825 $\pm$ 0.005	0.044	3.80			
MN-e	45.7	289.2	25.3	19.1 $\pm$ 0.5	0.834 $\pm$ 0.003	0.130	11.68			
MN-i (spot 1)	61.3	899.1	0.8	15.0 $\pm$ 2.7	0.723 $\pm$ 0.008	0.0009	0.05			
MN-i (spot 2)	69.6	693.5	1.9	16.7 $\pm$ 2.3	0.807 $\pm$ 0.006	0.0024	0.21			
MN-i (spot 3)	61.3	75.3	0.5	23.8 $\pm$ 6.6	0.579 $\pm$ 0.018	0.0004	0.02			
MN-m	20.2	119.1	0.1	20.7 $\pm$ 5.0	0.647 $\pm$ 0.014	0.0003	0.02			
MN-n (spot 1)	8.0	40.5	5.1	18.9 $\pm$ 0.3	0.837 $\pm$ 0.002	0.094	8.40			
MN-n (spot 2)	9.2	46.1	8.1	19.2 $\pm$ 0.7	0.832 $\pm$ 0.003	0.059	5.28			
MN-p	20.2	67.9	12.0	11.4 $\pm$ 0.9	0.836 $\pm$ 0.004	0.013	0.84			
MN-3	47.7	138.9	1.5	2400 $\pm$ 483	0.807 $\pm$ 0.008	0.004	0.47			
MN-7 (spot 1)	25.0	196.1	4.3	4880 $\pm$ 1784	0.851 $\pm$ 0.009	0.024	2.81			
MN-7 (spot 2)	30.4	222.9	6.2	1915 $\pm$ 209	0.771 $\pm$ 0.005	0.030	3.13			
Tektite glass										
MN-d-glass	0.5	23.8	16.6	20.0 $\pm$ 0.9	0.828 $\pm$ 0.002	0.046	4.23			
MN-n-glass	0.4	23.5	20.4	11.8 $\pm$ 0.9	0.838 $\pm$ 0.008	0.033	2.30			
Muong Nong-type tektite from Georgia										
Ga 4	15.7	131.4	21.4	21.8 $\pm$ 0.5	0.730 $\pm$ 0.003	0.028	1.79			
Ga 5 (spot 1)	30.3	33.5	258.0	1282 $\pm$ 113	0.071 $\pm$ 0.001	0.039	0.34	0.248 $\pm$ 16	0.297 $\pm$ 9	0.587 $\pm$ 32
Ga 5 (spot 2)	33.9	34.3	79.9	769.2 $\pm$ 48.2	0.079 $\pm$ 0.004	0.039	0.35	0.244 $\pm$ 13	0.304 $\pm$ 20	0.597 $\pm$ 140

\* Pb/U ratio cannot be corrected for common lead, with exception of two spots on Ga5 containing measurable amounts of radiogenic Pb.

<sup>†</sup> Statistically significant discordant ages can only be calculated for two analyses of sample Ga5 (errors refer to the last digits and are  $1\sigma$ ).

noticeable. Among the 10 zircon inclusions studied, only two analyses show significant amounts of radiogenic lead with  $^{207}\text{Pb}/^{206}\text{Pb} < 0.2$  (Table 2). These two analyses—from the North American georgiaite—give a discordant age of about  $0.6 \pm 0.1$  Ga (Fig. 2). For all other samples a correction for common Pb is not possible and, therefore, no meaningful ages can be obtained.

#### 4. DISCUSSION

A common feature of the zircon inclusions in tektites studied here is a strong discordancy of the U–Pb system or even a total absence of radiogenic Pb, indicating complete resetting at the time of the impact event, which makes it impossible to calculate meaningful precursor ages for most samples. Deutsch and Schärer (1990) and Schärer and Deutsch (1990) studied the effects of shock metamorphism at pressures of up to 59 GPa on the U–Pb system and observed no measurable fractionation of the Pb isotopes, and no significant loss of Pb, at these shock pressures. In contrast, Krogh et al. (1993) and Kamo and Krogh (1995) studied zircons recovered from the Cretaceous–Tertiary boundary event distal ejecta and from melt rocks from the Chicxulub impact structure and found that the ages of the zircons, which had an original age of about  $548 \pm 6$  Ma, were partially to completely reset at the time of the impact event at 65 Ma. These authors also observed a correlation between the degree of shock metamorphism and the degree of isotopic discordance. The degree of shock metamorphism was defined according to Bohor et al. (1993) with respect to the occurrence of planar features in zircons at low shock pressures and gran-

ular texture at high shock pressure. Kamo and Krogh (1995) noted that among their samples, entirely granular zircons are commonly completely reset to the time of the impact event. Similar resetting to the time of the impact event have been observed for zircons extracted from impact melt rocks and

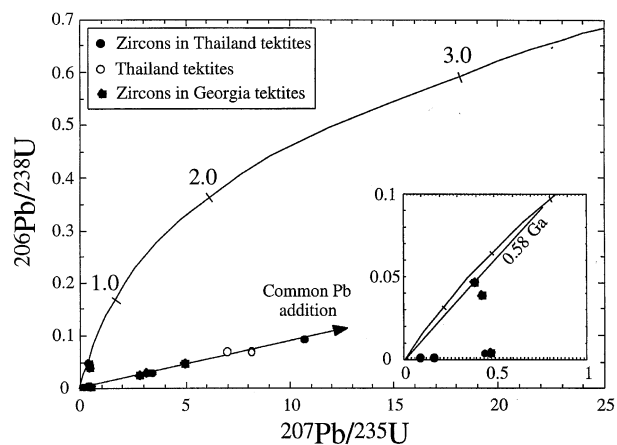


Fig. 2. Concordia diagram for zircons in tektites. Only two measurements for Ga5 zircons give discordant ages with zero age intercept (inset). The addition of common lead is calculated as the addition of pure lead with a  $^{207}/^{206}$  isotopic ratio of 0.83, yielding  $^{206}\text{Pb}/^{238}\text{U}$  vs.  $^{207}\text{Pb}/^{235}\text{U}$  of 0.0087 when the proportion of sample initial lead becomes negligible. Two analyses of tektite glass 50–100  $\mu\text{m}$  from the adjacent zircon inclusions are indicated by open circles.

breccias from the 2 Ga Vredefort impact structure (Kamo et al., 1996; Moser, 1997).

The zircon inclusions in the tektites studied here all appear granular, especially in the BSE images. This could be the result of local melting and recrystallization, and/or some sort of solid-state recrystallization. The dark area might represent zircon-rich glass. Thus, it seems plausible that the U–Pb system of most zircons was completely reset to the time of the impact, which occurred at 0.8 Ma for the Australasian tektites. As Deutsch and Schärer (1990) did not observe any obvious Pb isotope fractionation, the resetting observed here (and by Kamo and Krogh, 1995) could be the result of shock pressures higher than 59 GPa or of high temperature. Schärer and Deutsch (1990) studied zircons extracted from a polymict breccia, whereas the zircons from Chicxulub originated from a melt rock. The situation is likely to be even worse for tektites, as there is evidence that the glass formed at temperatures exceeding 1800°C (cf. Koeberl, 1994). Also, zircon textures observed in shock experiments at up to 59 GPa (Leroux et al., 1999) only showed the development of planar features, but no evidence of a granular texture. Glass (2000) noted that some zircons from a Muong Nong-type moldavite (Glass et al., 1990) and from a Muong Nong-type georgiaite have partly decomposed to baddeleyite, but show textures that are similar to those recovered from the Muong Nong-type indochinites.

Following the high-temperature and high-pressure resetting, it is possible that the zircons in the tektites have acquired the isotopic signature of common Pb by exchange with the molten glass. It is also possible that the presence of glass residing within the zircon grains (the dark areas in the BSE images) influenced the Pb isotopic signature. The isotopic composition of the glass near the zircons was found to be dominated by common Pb, identical to that of the nearby zircons. These data are in agreement with data by Tilton (1958), who found  $^{207}\text{Pb}/^{206}\text{Pb} = 0.829\text{--}0.834$  in tektites, in accordance with an origin of the Pb from recent sediments.

The U–Pb system was completely reset in all but one of the zircon grains. Zircons derived from old source rocks may have been metamict and would have easily lost Pb even at moderate temperatures and pressures. For the Muong Nong-type indochinites, Nd model ages of  $T(\text{Nd})_{\text{CHUR}} = 1.04\text{--}1.2$  Ga and  $T(\text{Nd})_{\text{DM}} = 1.49\text{--}1.62$  Ga were derived by Blum et al. (1992), who, in agreement with Shaw and Wasserburg (1982), concluded that the parent sediments were mainly derived from a Precambrian crustal segment. Bodet and Schärer (2000) studied zircons from rivers in southeast Asia (the likely target area of the Australasian tektites) and found U–Pb ages representing crustal growth events at about 2.5, 2.3, 1.9, 1.1, and 0.8 Ga. Unfortunately no zircons with such precursor ages were preserved in the Muong Nong-type indochinites. However, two spots on a zircon from the only known Muong Nong-type georgiaite (Glass et al., 1995) gave ages of about  $0.6 \pm 0.1$  Ga (Table 2; Fig. 2). This age is in agreement with Nd and Sr model ages of 0.62 to 0.67 and 0.52 to 0.56 Ga, respectively, obtained on North American tektites (Shaw and Wasserburg, 1982). These data are in accordance with the suggestion that the Chesapeake Bay impact structure is the source crater of the North American tektites (Koeberl et al., 1996).

In conclusion, zircon inclusions recovered from Australasian and North American Muong Nong-type tektites show a

strongly discordant behavior of the U–Pb isotopic system, with the Pb isotopic composition of most samples dominated by common Pb. This is interpreted as the result of complete resetting of the U–Pb isotopic system during the impact event. Only two analyses, from one zircon, yielded data that were not reset by the impact event and that could be interpreted as the age of the source rock(s) from which the host tektite was derived. This sample, from a Muong Nong-type georgiaite from the North American tektite strewn field, gave an age of 0.6 Ga, in (maybe fortuitous) accordance with Nd and Sr model ages obtained from these tektites. Our results illustrate that the U–Pb isotopic system can be totally reset during an impact event, obscuring the isotopic evidence for the isotopic age of the target rocks.

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