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Abstract—By using accelerator mass spectrometry we have measured the ¹⁰Be concentrations of 86 Australasian tektites. Corrected to the time of tektite production ~0.8 My ago, the ¹⁰Be concentrations (10⁶ atom/g) range from 59 for a layered tektite from Huai Sai, Thailand, to 280 for an australite from New South Wales, Australia. The average value is 143 ± 50. When tektites are sorted by country, their average measured ¹⁰Be concentrations increase slowly with increasing distance from Southeast Asia, the probable location of the tektite producing event, from 59 ± 9 for 6 layered tektites from Laos to 136 ± 20 for 20 splash-form tektites from Australia. The lowest ¹⁰Be concentrations for tektites fall on or within a contour centered off the shore of Vietnam, south of the Gulf of Tonkin (107°E; 17°N), but also encompassing two other locations in the area of northeastern Thailand previously proposed for the site of a single tektite-producing impact. The ¹⁰Be concentrations of layered tektites show only a weak anticorrelation (R ~ -0.3) with the numbers of relict crystalline inclusions.

Loosely consolidated, fine-grained terrestrial sediments or recently consolidated sedimentary rocks are the most likely precursor materials. Dilution of sediments with other kinds of rock raises problems in mixing and is not supported by petrographic data. Sedimentary columns that have the right range of ¹⁰Be concentrations occur off the coasts of places where sedimentation rates are high relative to those in the deep sea. A single impact into such a region, 15 to 300 m thick, could have propelled near-surface, high-¹⁰Be material farthest—to Australia—while keeping the deeper-lying, low-¹⁰Be layers closer to home. We do not rule out, however, other proposed mechanisms for tektite formation. Copyright © 2004 Elsevier Ltd

1. INTRODUCTION

The Australasian tektites probably originated somewhere in Southeast Asia. Schnetzler (1992) discussed several of the proposed sites of origin in that region (Table 1). In a search for new clues to the location(s) and characteristics of the tektite-forming event(s), we analyzed a number of Australasian tektites for ¹⁰Be (T_{1/2} = 1.5 My; NuDat, 2004).

Pal et al. (1982) showed that the Australasian tektites contain ¹⁰Be and concluded that the ¹⁰Be formed neither in space nor on the Moon, but on the Earth when cosmic rays interacted with atoms in the atmosphere. For the most part, precipitation quickly washed the ¹⁰Be down from the sky. Once at the surface, the ¹⁰Be atoms clung to virtually any nearby silicate grains. At some time before all the ¹⁰Be could decay—within a few million years—some of those grains and their cargo of ¹⁰Be became part of tektites. Tera et al. (1983a, b, and c) and Klein and Middleton (1984) extended the work of Pal et al. (1982). They observed that the ¹⁰Be concentrations of Aus-

tralasian tektites tend to increase with increasing distance from Southeast Asia (see also Raisbeck et al., 1988). For several reasons we thought that this trend deserved more detailed study. First, most of the tektites analyzed for ¹⁰Be were splash form; relatively few were layered (Muong-Nong-type). The layered tektites, which come mainly from Laos, Vietnam, and Thailand, probably remained closest to and may, therefore, provide especially useful information about the source region (Koeberl, 1992; Koeberl, 1994; Dass and Glass, 1999). Second, except for Pal et al. (1982), none of the references cited above included results for individual tektites. We wanted to make these data available. Presented here are new analyses of ¹⁰Be in 43 Australasian tektites, 27 of them layered. Aggrey et al. (1998) and Ma et al. (2001) published preliminary accounts of this work. In addition, we present the results of numerous individual analyses of Australasian tektites made by Tera et al. (1983a, b, and c) and by Klein and Middleton (1984).

2. EXPERIMENTAL METHODS**2.1. Samples**

The samples newly analyzed for this work (group 1) came from three sources: (1) the collection of John Wasson. Many of these samples were previously analyzed for trace elements. Details concerning the provenance of a few tektites not previously described in the literature appear in Appendix 1; (2) the collection of Billy Glass. Dass and Glass (1999) had searched these samples for relict mineral inclusions; and (3) the collection of the US National Museum, courtesy of Glenn MacPherson. Fouad Tera and colleagues obtained their samples (group 2) from the US National Museum courtesy of Brian Mason and from the collection of Billy Glass, who in turn obtained some of them from

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Table 1. Suggested locations of a cratering event, which may have produced Australasian tektites.

Location	Coordinates	Reference
South China Sea, due east of Bangkok and about 200 km off the coast of Vietnam Northeastern Cambodia	109°E 14°N 106°34'E 13°55'N	Schnetzler et al. (1988) Hartung and Rivolo (1979)
Beneath alluvial deposits in the Lower Mekong Valley, Vietnam Lake Tonle Sap, west-central Cambodia	106°E 10°N 104°E 13°N	Stauffer (1978) Hartung and Koeberl (1994)
Laos/Thailand border in a region centered on the town of Mukdahan Buntharik, Thailand; either the Khorat Plateau or the adjacent Mekong River valley. Central Cambodia	105°E 16°N 105°25'E 14°46'N 106°E 12°N	Schnetzler (1992) Schmidt et al. (1993) Glass and Pizzuto (1994) Lee and Wei (2000)
Off the Vietnam coast, near the mouth of the Mekong River in the South China Sea	107°E 9°N	Chaussidon and Koeberl (1995)
Southeast corner of northeast Thailand Song Hong Basin	105°E 15°N 107°E 17°N	Glass (2003) This work

Virgil Barnes. One sample provided by John Wasson (TS-6) was a section ~1 mm thick that had been sawed from a large, 15-cm thick tektite. Layering was apparent. We analyzed separately lighter and darker layered material from the slab.

2.2. Chemical Separation of ^{10}Be

An initial leach with HF removed possible surface contamination carried by adhering soils or introduced by adsorption. In processing, we ground each sample with a mortar and pestle; weighed a portion of it (100–500 mg usually); added 2 to 3 mg of Be dissolved in a known mass of solution containing ~1.5 mg Be/(g solution); and dissolved the material in concentrated HF. Vogt et al. (1991) described the chemical procedures used to separate beryllium as the oxide from dissolved samples.

2.3. Accelerator Mass Spectrometry

By using accelerator mass spectrometry, we determined the $^{10}\text{Be}/^9\text{Be}$ ratios of the beryllium oxide separated from the samples (Table 2). From these ratios and the amounts of carrier added, we calculated the ^{10}Be concentrations of the samples. The isotopic analyses of group 1 samples were made at Purdue Rare Isotope Measurement Laboratory (PRIME Lab) of Purdue University. The $^{10}\text{Be}/^9\text{Be}$ blank for the chemical procedure was less than 7×10^{-15} (atom/atom). As a check on accuracy in each accelerator run, we included aliquots of a homogenized powder made from the Dhurmsala LL6 chondrite and kindly supplied by R. Michel. The external reproducibility (different preparations of the same tektite) of the measurements is ± 5 to 15% (Fig. 1). The internal reproducibility (average relative standard deviation of a single measurement based on the counting statistics of samples, standards, and blanks) is typically smaller, 4 to 8%. The difference suggests that ^{10}Be concentrations may vary within the samples. The size of such variations remains an open question. Our analyses of samples separated by 1 cm or so (light and dark layers of slab TS-6) gave $^{10}\text{Be} = 74 \pm 4 \times 10^6$ atom/g (light) and $77 \pm 3 \times 10^6$ atom/g (dark), respectively. These results do not differ significantly, but we cannot generalize from them. Based on the observed variations of major elements within single samples of Muong Nong tektites—up to 17% for FeO, 25% for CaO, and 8% for K_2O (Schnetzler, 1992), and the variability of meteoric ^{10}Be concentrations in natural settings (see below)—we would expect comparable variations in ^{10}Be concentration.

The ^{10}Be measurements of the group 2 samples were made at the University of Pennsylvania using procedures described by Klein et al. (1982) and Middleton et al. (1983).

3. RESULTS

3.1. Average and Range of ^{10}Be Concentrations of Australasian Tektites

The average measured ^{10}Be concentration of the Australasian tektites listed in Table 2 is $100 \pm 36 \times 10^6$ atom/g; the

range is from a minimum of $41 \pm 2 \times 10^6$ atom/g for a layered tektite from Huai Sai, Thailand, to a maximum of $196 \pm 16 \times 10^6$ atom/g for an australite from New South Wales, Australia. The uncertainty $\pm 36 \times 10^6$ atom/g quoted above is one sample standard deviation. Corrected to the time of fall, ~0.8 My B.P. (0.77 My B.P.: Izett and Obradovich, 1992; 0.79 My B.P.: Baksi et al., 1992; Schneider et al., 1992; 0.786 ± 0.012 My B.P.: Kunz et al., 1995), the ^{10}Be concentrations (10^6 atom $^{10}\text{Be}/\text{g}$) are between 59 and 280 with an average of 143 ± 50 . Some statistical properties of the data set of Table 2 (86 tektites in all; data *not* corrected to the time of fall) appear in Table 3. Figure 2 shows the distributions of ^{10}Be by country.

Interlaboratory comparisons of various kinds of samples analyzed at the University of Pennsylvania and PRIME have revealed, at most, marginal biases (<10%). In particular, the average ^{10}Be concentrations (10^6 atom/g) for australites are best and most easily compared. The distances that these objects traveled from the source region are so large that differences in collection location within Australia probably only correlate weakly with ^{10}Be concentration. For australites, we obtain an average of 122 ± 33 (N = 4) for samples analyzed at PRIME Lab and 140 ± 30 (N = 15) for samples analyzed by Tera et al. (1983a, b, and c). The agreement is satisfactory. In contrast, for thailandites, we have 60 ± 17 (N = 7; this work) and 76 ± 15 (N = 9; Tera et al., 1983a–c). Here, agreement is less convincing. Two factors, however, make this second comparison questionable. First, we do not know the collection locations for many of the samples and therefore cannot control for that influence (which should be less important for the australites). Second, in this work we analyzed only layered thailandites, whereas Tera et al. (1983a, b, and c) analyzed splash-form tektites. The two groups need not have the same ^{10}Be concentrations.

3.2. Geographical Distribution of ^{10}Be in Tektites

Tektites collected on the Southeast Asian mainland and nearby Hainan Island, China, have an average ^{10}Be concentration of $71 \pm 16 \times 10^6$ atom/g (N = 41), compared to $127 \pm 27 \times 10^6$ atom/g (N = 45) for tektites found in Indonesia, the Philippines, and Australia. The uncertainties are standard deviations. The differing averages confirm the observations of Tera et al. (1983a, b, and c) and suggest a broad systematic relation between ^{10}Be concentration and find location.

Table 2. ¹⁰Be concentrations (10⁶ atom/g) of Australasian tektites.

Location	ID	Source	Lat.	Long. (E)	¹⁰ Be	Ref.
Laos						
Muong Nong ^L	C-2	BG	16.42	106.5	74 ± 7	1
Site 2 ^L	iT157	JTW	16.37	106.46	63 ± 5	1
Site 3 ^L	iT158	JTW	16.37	106.46	58 ± 6	1
Muong Nong ^L	T088 ^a	JTW	16.38	106.52	62 ± 19	1
Muong Nong ^L	MN3-Site 3	BG	16.37	106.46	49 ± 2	1
Muong Phin ^L	MP-26	BG	16.53	106.02	50 ± 2	1
Vietnam						
Vinh ^L	iT099 ^a	JTW	18.42	105.41	55 ± 3	1
Vinh ^L	A-82	BG	19.1	105	59 ± 20	1
Danang ^L	A-65	BG	15.8	108.3	60 ± 3	1
Khe-Sahn ^L	iT160	JTW	16.62	106.83	66 ± 2	1
Nam Dan ^L	TK-26	BG	18.7	105.5	69 ± 3	1
Nam Dan ^L	TK-27	BG	18.7	105.5	71 ± 3	1
Dalat ^L	VC-9	BG	11.9	108.4	73 ± 2	1
Tam Ky ^L	iT161	JTW	15.53	108.50	74 ± 4	1
Saigon ^L	TK-1	BG	10.76	106.6	75 ± 3	1
Dalat ^L	VC-10	BG	11.9	108.4	76 ± 3	1
Da Thieu ^L	iT92b	JTW			76 ± 3	1
— ^L	2581	SI			89 ± 7	2
Da Thieu ^L	VC-1	BG	11.97	108.45	103 ± 3	1
Thailand						
Huai-Sai ^L	iT154 ^a			41 ± 2	1	
Nakhon Phanom ^L	TT-30-6	BG	17.4	104.8	42 ± 2	1
Kan Laung Dong ^L	TT-43	BG	16.8	104.55	52 ± 2	1
Non-Hung ^L	iT153 ^a	JTW			52 ± 2	1
— ^L	TS-6 Slab	JTW			76 ± 2	1
—	U2349	SI			74 ± 12	3
—	2172	SI			75 ± 6	2
Ubonratchathani ^L	TU-3	BG	15.2	104.9	76 ± 2	1
Phang Daeng ^L	TT-41	BG	16.8	104.4	79 ± 3	1
—	U2172	SI			79 ± 12	3
—	U5424	SI			97 ± 19	3
—	TS-75	SI			88 ± 7	2
—	TS-99	SI			101 ± 8	2
—	TS-108	SI			87 ± 7	2
—	TS-138	SI			57 ± 5	2
—	TS-187	SI			69 ± 6	2
—	TS-192	SI			71 ± 6	2
—	TS-201	SI			84 ± 7	2
—	TS-209	SI			55 ± 4	2
China						
Lingshui ^L	iT077 ^a	JTW			58 ± 3	1
Guangdong ^L	CG-1	BG			96 ± 7	1
Hainan ^L	CNC-1	BG			101 ± 3	1
Indonesia						
Javanite	Java300#29				97 ± 7	1
Sangiran, Java	Java2	SI			99 ± 4	1
Javanite	Java300#16				103 ± 10	1
Billiton	77500	SI			105 ± 8	2
Belitung	uT031b	JTW	-2.91	108.46	116 ± 6	1
Sangiran, Java	Java1	SI	-7.33	110.50	169 ± 17	1
Philippines						
Busuanga	2042	SI			90 ± 7	2
Cabarruyan	1824	SI			103 ± 8	2
Camarin	1886	SI			111 ± 9	2
Coco Grove	2598	SI			142 ± 11	2
Coco Grove	PC18	SI			128 ± 7	1
Isabela	Pi-75	SI	17.00	122.00	122 ± 7	1
Luzon	U1916	SI			128 ± 15	3
Ortigas site	Po	SI	14.35	121.03	112 ± 4	1
Paracale	iT104	JTW	14.25	122.77	115 ± 6	1
Pasig	5422	SI			125 ± 10	2
Pugad Babuy	Pp-176	SI			109 ± 4	1
Pugad Babuy	1957	SI			138 ± 11	2
Santa Mesa	PSM-26	SI	14.38	121.00	96 ± 5	1
Santa Mesa	U1953	SI			92 ± 21	3
Santa Mesa	1945	SI			143 ± 11	2
Santa Mesa	1967	SI			105 ± 8	2

Table 2. (Continued)

Location	ID	Source	Lat.	Long. (E)	^{10}Be	Ref.
Santiago	1906	SI			154 ± 12	2
Santiago	2043	SI			111 ± 20	2
Wak-Wak	1932	SI			174 ± 14	2
Australia						
Divided Bluffs		SI			79 ± 4	1
Lake Margaretta		SI	-25.26	125.41	156 ± 6	1
Serpentine Lake		SI	-28.50	128.35	135 ± 4	1
Charlotte	2537	SI			147 ± 26	2
Durrie	5799	SI			155 ± 12	2
Earaheedy	5796	SI			180 ± 26	2
Frome Downs	2533	SI			89 ± 7	2
Granite Peak	3400	SI			145 ± 12	2
Hughes	2546	SI			159 ± 13	2
Lake Wilson		SI	-26.20	129.20	117 ± 4	1
Lake Wilson	2534	SI			139 ± 20	2
Lake Yindarllooda	5733	SI			155 ± 12	2
Macumba	2535	SI			121 ± 10	2
Mannahill	4831	SI			98 ± 8	2
Mulka	4845	SI			131 ± 10	2
NSW	88454	SI			160 ± 13	2
Oakvale	3432	SI			119 ± 10	2
Pindera, NSW	2242	SI			196 ± 16	2
Pine Dam	5802	SI			104 ± 8	2
Kalgoorlie	SAM433	VB			135 ± 32	3

Notes and units. Source: JTW = John Wasson; BG = Billy Glass; SI = Smithsonian Institution, Brian Mason and Glenn MacPherson; VB = Virgil Barnes. Positive (unsigned) latitudes are in degrees north; negative latitude denotes degrees south; longitudes are in degrees. Ref.: 1 = this work; 2 = Tera et al. (1983a-c); 3 = Pal et al. (1982). ^L = layered or Muong-Nong type tektite. Alternate sample names: a) iT088 = LLAMUNO1; iT099 = LVIVINH2; iT154 = LTHUSA1; iT153 = LTHNOHU1; iT077 = LHALISHI.

When grouped by country, average ^{10}Be concentrations of Australasian tektites tend to increase in the order Laos < Thailand < Vietnam < China < Indonesia < Philippines < Australia (Table 3). The differences between adjacent pairs on the list (e.g., Vietnam and Thailand) are not significant, however, and different countries of origin for tektites may not mean different distances from the source location. We examine this issue at higher geographical resolution below.

4. DISCUSSION

4.1. Models for Tektite Formation

Most workers agree that the arrival of an extraterrestrial object or objects produced the Australasian tektites. Opinion divides, and has for some time, on the questions of how many objects struck the Earth or exploded above it, how deep any craters were, the nature of the target, and the mechanism of material transport (see O'Keefe, 1976; Wasson, 1991; Koeberl, 1994; Wasson, 2003). Our ^{10}Be measurements do not resolve the disputes, but constrain the nature and vertical extent of the target. We will see below that the constraints are strongest in the context of a one-crater model.

4.2. ^{10}Be Production Rate In the Atmosphere and Deposition Rates at the Earth's Surface

Virtually all the ^{10}Be in tektites is made in the Earth's atmosphere, most of it in the stratosphere. Some recent estimates of the average global production rate of ^{10}Be ($P_{10}(\text{global})$ in $\text{atom } ^{10}\text{Be cm}^{-2}\text{-s}^{-1}$) are 0.030 (Nagai et al., 2000), 0.018 (Masarik and Beer, 1999), and higher if somewhat doubtful values, ~ 0.038 , from experimental measure-

ments (see Monaghan et al., 1986; Brown et al., 1989). We will adopt the value of 0.030. The local production and deposition rates of ^{10}Be may differ and both rates vary appreciably with latitude, but not much with longitude. The rates of downward transport of ^{10}Be from the stratosphere to the troposphere and from there to the Earth's surface also depend on latitude (Lal and Peters, 1967). At 16° to 17° north latitude, where the tektites likely formed, local *production* rates are $\sim 50\%$ of the global average (Masarik and Beer, 1999; Nagai et al., 2000); local *deposition* rates are $\sim 66\%$ of the global average (Fig. 22, Lal and Peters, 1967). Local deposition rates commonly differ from production rates because of a strong latitudinal dependence on the transfer rates of ^{10}Be from the stratosphere to the troposphere. Deposition and production rates differ most at the highest latitudes.

4.3. Source Materials: Rocks?

4.3.1. Extraterrestrial rocks

Most silicate-dominated extraterrestrial samples—lunar samples, meteorites, and micrometeorites—contain $5000 - 25000 \times 10^6 \text{ atom } ^{10}\text{Be/g}$. These extraterrestrial materials also contain other radioactive nuclides produced by cosmic rays, ^{26}Al for example, that are not found in tektites in appreciable concentrations. In agreement with many authors (Pal et al., 1982; Klein and Middleton, 1984; Blum et al., 1992), we therefore exclude meteoritic and lunar material as sources for the ^{10}Be in the Australasian tektites, and, by a short extension, for virtually all the other atoms in the tektites.

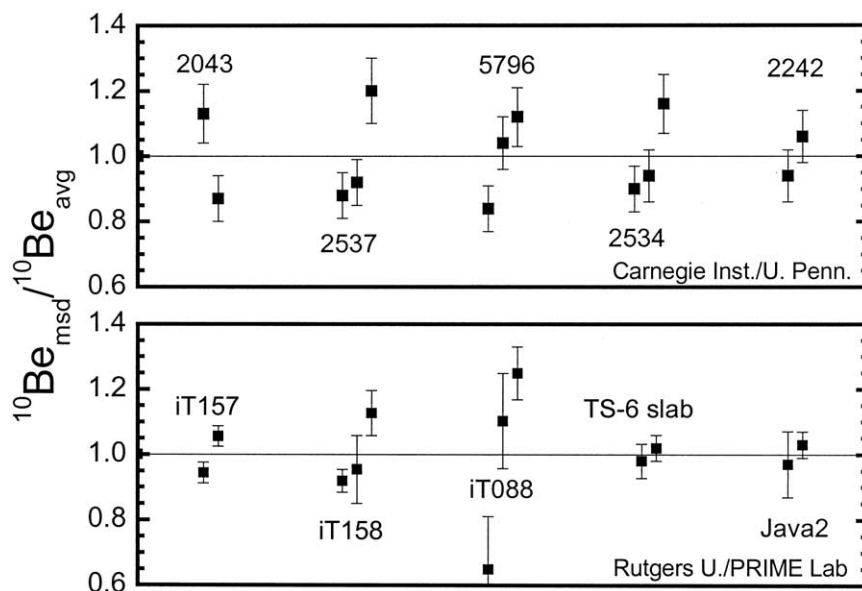


Fig. 1. Typical relative uncertainties of ¹⁰Be concentrations measured at the University of Pennsylvania and at PRIME Lab are similar. Results in the top panel are for five samples analyzed by Tera et al. (1983a, b, and c), all splash form tektites. Results in the bottom panel are for five different samples analyzed in this work, all layered tektites, except for Java2. Sample names (see Table 2) are given directly above or below each group of data points, which are plotted along the (arbitrary) x-axis. The y-axis shows the ratio of the measured (msd) ¹⁰Be concentration to the average calculated for that sample. The spread for each group of data points is about the same, 10 to 15%. Some portion of the variability within each group may owe to heterogeneity within the samples. We estimate the measurement uncertainty of a single tektite analysis to be ±5 to 15%.

4.3.2. Terrestrial rocks

For several reasons, rocks at the Earth’s surface generally contain much lower concentrations of ¹⁰Be than do Australasian tektites. First, most rocks are too old to retain much ¹⁰Be, even if they had it initially. An initial concentration of 1000 × 10⁶ atom ¹⁰Be/g decreases to ~10 × 10⁶ atom/g (one-fourth the minimum value observed in Australasian tektites) after 10 My of radioactive decay. Second, the low permeability of rock impedes infiltration by fresh ¹⁰Be carried by meteoric water, although some may seep in along fractures. Third, small soil grains readily capture ¹⁰Be in precipitation and immobilize it. Any soil covering a rock would tend to bar the way for fresh input of ¹⁰Be to the matter below. Finally, *in situ* production of ¹⁰Be in rock, primarily from cosmic rays interacting with oxygen, is low even at the very surface and decreases rapidly with depth. ¹⁰Be concentrations from this mode of production do not exceed ~10 × 10⁶ atom/g (e.g., Brown et al., 1992a; Stone, 2000). Thus to the extent that either igneous or metamorphic rocks were components of the precursors of the Aus-

tralasian tektites, we expect them to dilute any meteoric ¹⁰Be initially present. Sedimentary rocks cemented together within the last 10 My, in contrast, may contain appreciable concentrations of ¹⁰Be (Graham et al., 1998).

We conclude that the *presence* of ¹⁰Be in Australasian tektites indicates that the source material did not consist of older igneous or sedimentary rocks, but of unconsolidated materials or young sedimentary rocks. We return below to the possibility of mixing bed rock with unconsolidated surficial materials. Fluids, circulating through loosely packed grains, could have introduced meteoric ¹⁰Be. The elemental and isotopic composition of Australasian tektites and the types, sizes, and shapes of mineral inclusions found in layered tektites point to the same conclusion, an origin in particles the size of fine sand or coarse silt (Glass, 1982; Wasson and Heins, 1993; Koeberl, 1994; Chaussidon and Koeberl, 1995). Next we review the typical distributions of ¹⁰Be observed in different types of deposits and consider their similarities with the distribution of ¹⁰Be in tektites.

Table 3. ¹⁰Be concentrations in 10⁶ atom/g of tektites grouped by type and location of recovery. Values in parentheses are the numbers of samples analyzed in each group.

	Layered	Splash	All
Laos	59 ± 9 (6)	—	59 ± 9 (6)
Thailand	64 ± 20 (8)	76 ± 14 (11)	71 ± 17 (19)
Vietnam	73 ± 10 (12)	76 ± 3 (1)	73 ± 13 (13)
China	85 ± 24 (3)	—	85 ± 24 (3)
Indonesia	—	115 ± 27 (6)	115 ± 27 (6)
Philippines	—	121 ± 22 (19)	121 ± 22 (19)
Australia	—	136 ± 30 (20)	136 ± 30 (20)
All	69 ± 17 (29)	116 ± 32 (57)	100 ± 36 (86)

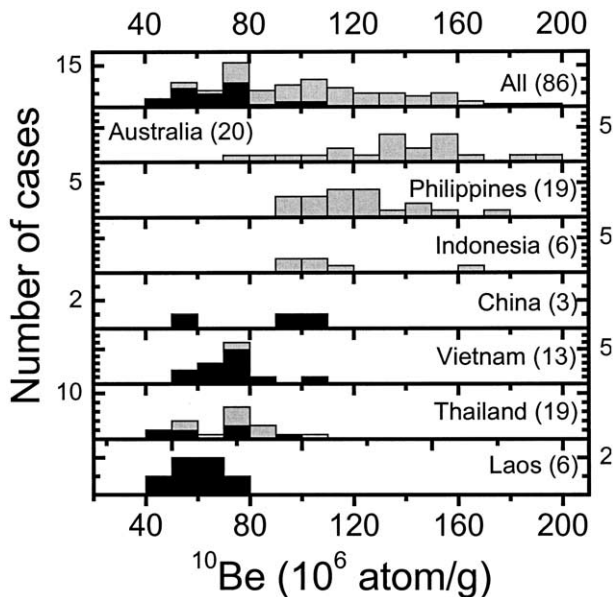


Fig. 2. Frequency distribution of ^{10}Be concentrations measured for tektites from different locations. Concentrations for tektites collected within a country vary by a factor of two or so and increase with increasing distance from Southeast Asia. Layered or Muong Nong tektites are shown in black and splash form tektites in gray. It should be understood that the reported country of origin for a tektite is not always reliable.

4.4. Source Material: Locally Derived Soils?

Locally derived soils contain appreciable concentrations of ^{10}Be (Brown et al., 1988). By locally derived soil, we mean a mixture formed by the decomposition of *local* bedrock and the addition of organic matter. We distinguish here between soil and loess that blew in from elsewhere, because loess is more likely to contain ^{10}Be “inherited” from rainout at other locations. Loess is considered separately below.

When ^{10}Be atoms in rain or snow encounter fresh silicate particles in soil, the silicates adsorb the ^{10}Be . The partition coefficient governing the distribution between aqueous phase and particulate phase is $\sim 10^5$ (in favor of the particles). Over time, the ^{10}Be either may remain in place, or be carried off by erosion, or redissolve briefly and penetrate deeper into the soil column. Loss by transport in solution, in either surface or groundwater of moderate pH, is usually small owing to the large partition coefficient. In an undisturbed soil column, the ^{10}Be distribution will penetrate to the bedrock, possibly 10 m or more below the surface, within a few half-lives. Typically, soil columns retain only $\sim 30\%$ of total estimated ^{10}Be input (Brown et al., 1988), losing the rest to a combination of decay and erosion.

It is useful to have a semiquantitative expression for estimating expected ^{10}Be concentrations in soils and sediments. For locally derived soils, we envision a continental surface initially free of sediments where ^{10}Be -free rock decomposes at a rate of S cm/yr. For non-locally derived sediments, we envision a region in which grains containing negligible ^{10}Be are deposited at a rate of S cm/yr. If the density of the grains is ρ , then the column grows at a rate $S\rho$ g/(cm² y). For times short compared to the half-life of ^{10}Be , the concentration of meteoric

Table 4. Model ^{10}Be concentrations for an idealized sedimentary column at 10° – 20° N assuming a local deposition rate for ^{10}Be of 0.018 atom cm⁻² s⁻¹. In real columns ^{10}Be concentrations may be reduced by erosion or increased by scavenging or inheritance.

Setting	S (cm/ky)	^{10}Be (10^6 atom/g)
Delta/estuary	500–50	0.4–4
Continental margin	50–10	4–21
Tektites*		60–280
Deep ocean	1–0.1	210–2100

* Corrected to time of fall.

^{10}Be in the grains will be $P_{10}/(S\rho)$, assuming that the deposition and production rates are constant and equal, no vertical transport, and no erosion. We calculate P_{10} at 16°N , from the relation $P_{10}(16^\circ\text{N}) = P_{10}(\text{global}) \times \{P_{10}(16^\circ\text{N})/P_{10}(\text{global})\}$. The ratio in curly brackets can be estimated without the effect of atmospheric transport to be 0.54 from Figure 4 of Nagai et al. (2000), or to be 0.47 from Table 3 of Masarik and Beer (1999). Alternatively, it can be estimated to be 0.66 with allowance for the effect of atmospheric transport from Figure 22 of Lal and Peters (1967). For the present purposes, the differences are not significant. Table 4 shows the surface concentrations of ^{10}Be expected for various values of S assuming a particle density of 2.65 g/cm³, and with $P_{10}(16^\circ\text{N}) = 0.030 \times 0.60 = 0.018$ atom cm⁻² s⁻¹.

In Table 5 we compare the ^{10}Be concentrations of soils and other sediments with those of Australasian tektites. We have not adjusted published data to try to compensate for variations in ^{10}Be production or deposition with latitude. As an indicator of how big such adjustments might be, however, we include in the column labeled P_{rel} the relative deposition rate for the average latitude of each sample (Lal and Peters, 1967). We also have not tried to compensate for variations in grain size, chemical composition or mineral composition, mainly because the data needed are not available.

The ^{10}Be concentrations of soils span the range observed in tektites, so in this sense soils are suitable targets for making tektites. This result is consistent with chemical studies showing that tektites have elemental compositions similar to those of soils or shales (Koeberl, 1986; Wasson, 1991). As the total vertical depth of soil columns rarely exceeds 20 m, and (although it varies widely) is typically much less (1 to 2 m in temperate zones (Brady, 1984), continental target materials were likely confined to a thin region at the surface.

4.5. Source Material: Non-Local Sediments?

Sedimentary deposits also form when erosion strips particles from one place and water or wind transports them to another. On land, such material may be weathered to form what we would call a *non-locally derived* soil. As in locally derived soils, the concentrations of ^{10}Be in these deposits tend to decrease with increasing depth. Relative to soils derived solely from local materials, however, ^{10}Be atoms in non-local sediments may be found to greater depths, 100s of meters, and in higher concentrations, up to $\sim 5 \times 10^9$ atom/g (Bourles et al., 1989). The higher concentrations can build up where sedimentation rates are low (Table 4) and the particles collect (scavenge) additional ^{10}Be in their original locations, en route, or upon resuspension. In the ideal case, when ^{10}Be

Table 5. Minimum (Min) and maximum (Max) ¹⁰Be concentrations (10⁶ atom/g) of tektites, soils, and sediments collected at various latitudes (Lat). P_{rel} is the relative deposition rate (or efficiency of deposition) at the relevant latitude for a hypothetical cosmogenic nuclide produced in the atmosphere at a rate of 1 atom per unit area and per unit time (Lal and Peters, 1967). P_{rel} may exceed 1 because of the way ¹⁰Be is transported through the atmosphere.

Soil/sediment	Location	¹⁰ Be		Δz*	Lat	P _{rel}	Ref.
		Min	Max				
Soil	Fairfax County, Va	3	1500	15	30–44 N	1.63	a
Riverine	Taiwan	3	35	—	22–25 N	0.86	b
Riverine	Amazon	10	240	—	1–10 N	0.43	c
Bauxite	Taiwan	12	306	15	25 N	0.92	b
Mixed	Taiwan coast	15	266	—	22–25 N	0.86	b
Loess/Paleosol	Shaanxi Province, China	20	650	60	34–40 N	1.63	d
Soil	Amazon	32	40	1	1–10 N	0.43	c
Terrigenous marine shelf	Castlecliff, New Zealand	40	590	30	37–42 S	1.66	e
Tektites [†]		60	280		16 N	0.66	f
Marine	Norwegian Sea	100	2000	8	70–86 N	0.25	g
Marine	Orca Basin, Gulf of Mexico	150	380	9	27 N	1.01	h
Marine [‡]	Java	200	1400	300	7 S	0.46	i
Marine	Caribbean Sea	200	1400	80	11.5 N	0.56	j
Lacustrine	Lake Baikal, Russia	500	1500	6	53 N	1.36	k
Marine	California coast	550	1500	—	33 N	1.52	l
Hemipelagic	Congo Fan/Angola Basin	600	5400	<1	3–10 S	0.45	m
Terrigenous	Congo Fan/Angola Basin	1000	4000	12	6.6 S	0.45	n
Marine	Mexico, Guayamas Basin	2700	3800	—	21 N	0.78	o

* Δz is the height (m) of the column sampled. The minimum and maximum ¹⁰Be concentrations observed do not necessarily occur at the bottom and top, respectively, of the column.

[†] Corrected to time of fall or deposition ≈0.8 My B.P.

[‡] Corrected for 3.4 My (the youngest age of any sample) (see ref 1). a = Brown et al. (1988); b = You et al. (1988); c = Brown et al. (1992b); d = Shen et al. (1992) and Gu et al. (1996); e = Graham et al. (1998); these authors corrected all ¹⁰Be concentrations to the present, thus erasing any age dependence in the results. The range of ages, however, 300 ky was small relative to the half life of ¹⁰Be, 1.5 My. f = This work; g = Eisenhauer et al. (1994); h = Somavajulu et al. (1991); i = de Boer et al. (1987); j = Aldahan and Possnert (2000); k = Horiuchi et al. (2001); l = Brown et al. (1985); m = Jansen et al. (1987); n = Rutsch et al. (1995); o = Valette-Silver et al. (1987).

deposition and particle sedimentation occur at constant rates, ¹⁰Be concentrations decrease exponentially with depth as a result of radioactive decay. In reality, few ¹⁰Be depth profiles match this description. Production rates of ¹⁰Be vary with geomagnetic field strength; climatic change may alter ¹⁰Be deposition rates; climatic changes may influence the absolute and relative rates at which multiple sources of particles are eroded and eventually deposited; and coastal sediments in particular are subject to “re-distribution caused by bottom currents and to scavenging” (Frank et al., 1997; Frank, 2000), and to slumping. For all these reasons, the use of a half-thickness to characterize the decrease of ¹⁰Be concentrations can be unreliable over depths of less than a few hundred meters.

Figure 3 illustrates the irregularities observed in three ¹⁰Be depth profiles. Gu et al. (1996) (top panel) analyzed samples from five locations of the main Loess Plateau in China. Figure 3 shows data from two of the five sites: Weinan (34.3°N, 109.3°E) selected for its overall length of coverage, 123 m; and Zhaitang (39.6°N, 116.0°E), selected because it covers only a short range of depth with several samples. Descriptions of how the samples were taken are not readily available (see Gu et al., 1996). Both sample suites include loess and paleosols (weathered loess). Paleosols have higher concentrations of ¹⁰Be presumably because they were exposed to more rain, which added to the ¹⁰Be that was present at the time of deposition. Shen et al. (1992) analyzed different samples of Chinese loess collected over a depth range of ~50 m in a natural outcrop (35°45'N, 109°25'E). Those authors describe the section as composed of alternating layers of loess and paleosol laid down over 800 ky, long enough for ~30% of the ¹⁰Be in the

oldest material to have decayed. The central panel of our Figure 3 is based on Figure 4 of their work, with their ages converted to sample depths via the approximate relation Depth (m) = Age (ky)/14.6. Again, higher ¹⁰Be concentrations in paleosols are apparent, and within layers, two-to-three fold variations of ¹⁰Be concentrations are common over depth ranges of less than 10 m. The bottom panel of Figure 3 shows results from De Boer et al. (1987), who analyzed ¹⁰Be in “Late Miocene to Early Pliocene (6–3 Ma BP) pelagic carbonates exposed along the Solo River, north of the city of Ngawi, East Java (Indonesia)” (7°S, 111°E). Samples are described as marly pelagic fine-grained mixed carbonate/clayey sediments and as coming from heights ranging from 0 to 320 m. Those authors remarked that, “On a smaller scale the ¹⁰Be data show strong deviations, up to a factor of 1.7 between adjacent samples.”

Most of the sediments listed in Table 5 have ranges of ¹⁰Be concentrations that include but extend to considerably higher and lower values than those of tektites. Taken in large enough volumes, the sediments with the highest ¹⁰Be concentrations could easily have supplied the ¹⁰Be to Australasian tektites in the total amounts required. To arrive at the right concentrations, however, the ¹⁰Be-rich sediments would have to have been either 1) diluted with material containing less ¹⁰Be; or 2) allowed to age. For example, a cube 0.8 km on a side made from surface sediments in the Congo Fan or the Guayamas Basin would provide enough ¹⁰Be. To arrive at the measured average concentration of ¹⁰Be, the sediments would have to be diluted 20 fold with material contain-

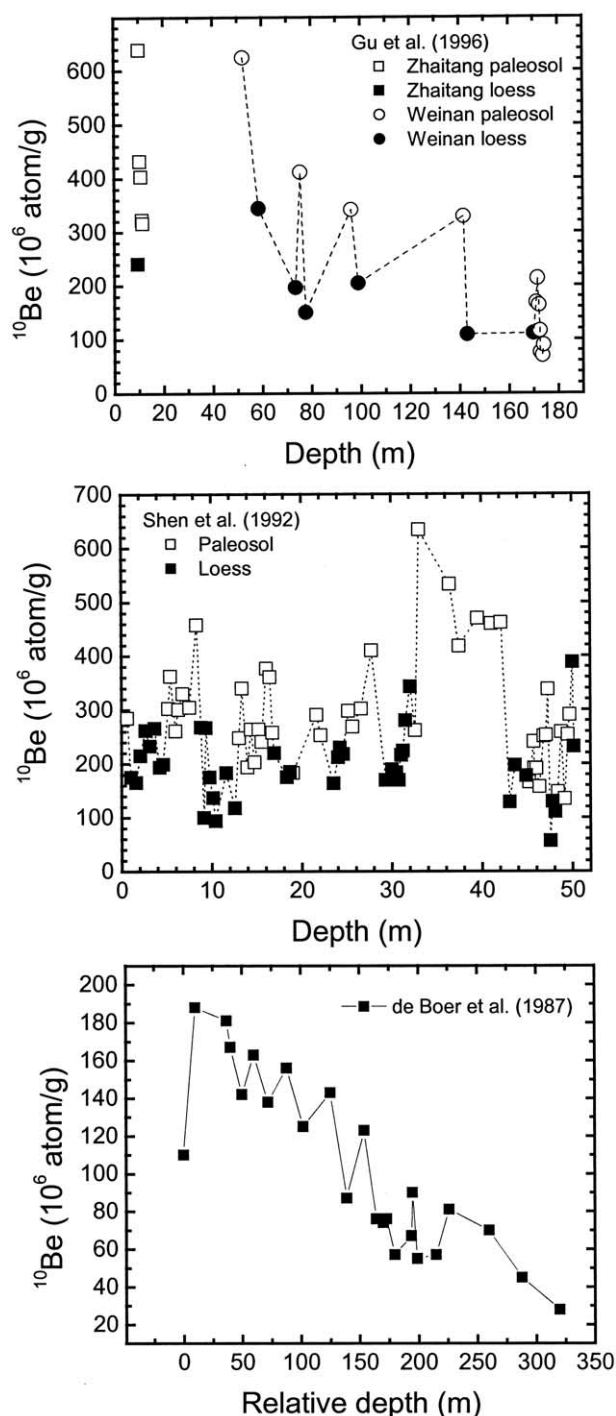


Fig. 3. ^{10}Be depth profiles in Chinese loess/paleosol sequences (Shen et al., 1992; Gu et al., 1996) and in sediments from Indonesia (de Boer et al., 1987). Although the ^{10}Be concentrations generally decrease with depth, the depth profiles are irregular over short (<100 m) distances. The age ranges spanned by the sediments are as follows: Weinan: 0–2.5 My B.P.; Zhaitang: <0.1 My B.P. (Gu et al., 1996); Luochuan: 0–0.8 My B.P. (Shen et al., 1992); East Java (de Boer et al., 1987): ~5.5–3.4 My B.P., corrected for 3.4 My of decay.

ing no ^{10}Be or allowed to decay for 6.5 My. We examine related possibilities below.

Some of the sediments listed in Table 5 have ^{10}Be concentrations (10^6 atom/g) directly comparable to those of the tektites. In

particular, You et al. (1988) and Brown et al. (1992b) discussed riverine sediments and soils with concentrations of 3 to 240 (2 to 170 after correction to 16°N latitude). You et al. (1988) and Somayajulu et al. (1991) reported concentrations in sediments collected offshore, but close to the mouths of rivers, of 150 to 380 (100 to 250 after correction to 16°N latitude). Shen et al. (1992) and Gu et al. (1996) showed that in Chinese loess ^{10}Be concentrations are similar to those of Australasian tektites.

4.6. Source Material—Loess or Loess-Like Soils?

Much of the soil in SE Asia has been described as loess-like and appears to be of aeolian origin (Boonsener, 1991), although marine and lacustrine origins have also been proposed (see Sanderson et al., 2001 and references therein). Wasson and Heins (1993) pointed out that loess from the Chinese plateau gives a reasonable match to the Australasian tektites with respect to ^{10}Be concentration. In a more detailed calculation, Wasson (2003) adjusted the measured ^{10}Be contents of Australasian tektites for decay and for local ^{10}Be deposition. The result is an average concentration of ^{10}Be in Australasian tektites that is comparable to that observed in some Chinese loess, ~200 $\times 10^6$ atom/g (e.g., Shen et al., 1992). Various criticisms have been leveled against loess as a tektite source material. By and large, recent evidence does not support these criticisms.

- Criticism: The nearest known large source of loess lies on the Chinese Plateau, far away from the likely location of the impact (Blum et al., 1992). Response: As noted, aeolian material appears to cover large parts of Indochina (Sanderson et al., 2001). In any case, it is possible that loess deposits that formed in Indochina during periods of glaciation could have washed into the sea in the time that has passed since the Australasian tektites formed.
- Criticism: Most loess deposits are more uniform with respect to major element composition than are the Australasian tektites (Taylor et al., 1983; Blum et al., 1992). Response: Given the mixing of fine grains that must occur during the transport of loess by wind, it seems reasonable that tektites made from loess would have a highly uniform composition. The argument requires, however, that the source material for the loess remain constant over time. It also requires either that weathering has a negligible effect on loess composition or that the tektite formation process selects against weathered loess. While the compositional homogeneity of loess noted by Taylor et al. (1983) is striking ($72.5 < \text{SiO}_2$ (wt %) < 74.0 for loess from Peninsula Banks, New Zealand, for example), it is based on a maximum of five sample analyses from any one location. Gallet et al. (1996) showed that SiO_2 concentrations of weathered paleosols from Luochuan, China, vary from 55 to 67%.
- Criticism: Likely weathering of loess would have produced $^{87}\text{Rb}/^{86}\text{Sr}$ ratios that vary by more than do the $^{87}\text{Rb}/^{86}\text{Sr}$ ratios observed in tektites (Blum et al., 1992). Response: Blum et al. (1992) compiled $^{87}\text{Rb}/^{86}\text{Sr}$ ratios for Australasian tektites. Their Figure 3 shows $^{87}\text{Rb}/^{86}\text{Sr}$ ratios ranging from 0.5 to 4.0. Chen et al. (1997) reported elemental Rb/Sr ratios (mass/mass) in loess

from the Chinese Plateau with values from 0.4 to 0.9, which correspond to isotopic $^{87}\text{Rb}/^{86}\text{Sr}$ ratios in the middle of the range, from 1.1 to 2.5. The Rb/Sr ratios in the loess typically vary by 50 to 100% over vertical distances of 1 m. Presumably these results include both unweathered and weathered material and thus give no sign of varying more than the corresponding ratios in tektites. More convincingly, perhaps, Gallet et al. (1996) reported separately the Rb/Sr ratios for loess and paleosols (weathered loess) from the Luochuan, China sequence. Their data give $1.28 < ^{87}\text{Rb}/^{86}\text{Sr} < 1.54$ for loess (average 1.4 ± 0.1) and $1.3 < ^{87}\text{Rb}/^{86}\text{Sr} < 2.1$ (average 1.7 ± 0.3) for paleosol. Gallet et al. (1998) presented Rb and Sr analyses for loess from Argentina ($0.5 < ^{87}\text{Rb}/^{86}\text{Sr} < 0.9$; average = 0.7 ± 0.1) and from France ($0.7 < ^{87}\text{Rb}/^{86}\text{Sr} < 2.7$; average = 1.3 ± 0.7 excluding marine sands). In summary, we find no firm evidence that $^{87}\text{Rb}/^{86}\text{Sr}$ ratios in loess from any single location either vary more than $^{87}\text{Rb}/^{86}\text{Sr}$ ratios in Australasian tektites, or define ranges that exceed the range defined by the Australasian tektites.

- Criticism: Rare earth element (REE) abundances of Australasian tektites match those of “average continental crust” better than they match those of loess (Koeberl, 1992). Response: Both the natural scatter in the data and the possibility of elemental fractionation during tektite formation blur these comparisons. Taylor et al. (1983) write that the REE abundances of loess are indistinguishable from the “upper crustal average,” which we take to be equivalent to “average continental crust.” Wasson (1991) showed that the REE patterns in North China loess closely parallel those of Australasian tektites

In sum, none of the objections raised to date rules out loess as a possible precursor for the Australasian tektites.

4.7. Processes That Would Lower the ^{10}Be Concentrations of Source Materials

As noted above, locally derived soils, sediment brought in from elsewhere, or loess columns up to 100 m thick have ranges of ^{10}Be concentrations that include but may extend to higher (and lower) values than are observed in Australasian tektites. To make tektites from material with high ^{10}Be concentrations, one must dilute it or let it age long enough for the ^{10}Be to decay.

4.7.1. Dilution (during impact)

To make a layered tektite from one part of a sediment containing $200\text{--}2000 \times 10^6$ atom $^{10}\text{Be}/\text{g}$, one would have to add 1 to 19 parts of material with no ^{10}Be . What could the diluting agent have been? If it were chunks of bed rock, then the problem of achieving uniform proportions and good mixing (as implied by the relatively constant ^{10}Be concentrations observed in tektites) seems to us formidable. Further, we know of no intermediate objects such as tektite glass mixed with relict chunks of putative bedrock. The diluent could also have been lower-lying material in the column. Here again, mixing seems to us problematic.

4.7.2. Age

Could tektites have sampled older parts of a sedimentary column in which high initial ^{10}Be concentrations had decayed to lower levels? Concentrations of ^{10}Be of $100\text{--}300 \times 10^6$ atom/g occur widely in marine sedimentary deposits at depths less than 60 m (Table 5). Thus, for sedimentation rates typical of continental margins, say 20 cm/ky, we would expect layered tektite-like concentrations of $50\text{--}150 \times 10^6$ atom $^{10}\text{Be}/\text{g}$ at depths of ~ 200 m or less. In any of these settings, either rapid erosion, or a tectonic event could have brought older material closer to the surface.

In sum, if the goal is to match the observed concentrations of ^{10}Be in Australasian tektites, then unconsolidated sediments, perhaps recycled (see Blum et al., 1992), or very young sedimentary rocks, are good candidates for source material. We favor a deposit of sediments as the source material, located off the shore of Indochina or in a formerly submerged shallow basin. Chaussidon and Koeberl (1995) reached a similar conclusion based partly on measurements of ^{11}B , B, and Li concentrations. To our knowledge, no one has measured ^{10}Be profiles of sedimentary deposits in relevant areas of SE Asia and the adjacent continental shelf.

4.8. Variability of ^{10}Be Concentrations in Tektites

4.8.1. Why do ^{10}Be concentrations in tektites vary systematically with collection location?

The correlation between the ^{10}Be concentrations of Australasian tektites and their collection locations almost certainly reflects some systematic variation of ^{10}Be concentrations in the source region. We consider first a one-crater hypothesis. In the target region, ^{10}Be concentrations must eventually decrease with increasing depth below the terrestrial surface (Table 5). Such decreases are widely observed and reflect the greater age of deeper-lying material and the barriers to downward percolation of fresh ^{10}Be presented by the overburden. Koeberl (1986) and Blum et al. (1992) have suggested that australites formed from a shallow layer thrown far from the impact site and the layered tektites from a deeper layer that stayed closer to home. Sequences of this kind are expected in smaller conventional ejecta blankets, at least (Shoemaker, 1962), and an extrapolation to tektites seems plausible.

Appealing as the “inverted stratigraphy” model may be, the ^{10}Be data by themselves do not require it, for as illustrated in Figure 3, radioactive decay is by no means the only possible cause for ^{10}Be concentrations to vary in sedimentary columns. To explain the observations in tektites, we could just as well hypothesize a more or less continuous local increase in ^{10}Be concentration with depth, although this hypothesis requires a very shallow source region. Alternatively, the tektite measurements could reflect a systematic horizontal (or radial) trend in ^{10}Be concentrations in the source region. In this picture we might find lower ^{10}Be concentrations further from the site of impact, perhaps as a result of greater erosion there that would have exposed older material. Neither of these pictures has much support from impact modeling, but that modeling is not yet very detailed.

The foregoing discussion assumes a one-crater hypothesis. Multiple impactors could have sampled sedimentary terrain at differing depths or with different ages. Koeberl (1994), Schnet-

zler (1992), and Wasson (1991, 2003) have reviewed arguments for and against the multi-impactor hypothesis. Wasson (2003) discusses a combined aerial-burst, impact-plume hypothesis.

4.9. Implications for a Crater-Forming Impact Model

4.9.1. Mass of Australasian tektites

The total mass of the Australasian tektite field is poorly known. Koeberl (1994) estimated a mass of 2×10^{15} g for the Australasian tektites. Schmidt et al. (1993) estimated a still higher value of 32×10^{15} g. With these estimates and a density of 2.65 g/cm^3 , we obtain tektite volumes from $\sim 0.75 \text{ km}^3$ to 12 km^3 . In the absence of analyses for microtektites we assume that microtektites and tektites have similar ^{10}Be concentrations. In principle then, a cube of melted sediments 900 m to 2300 m on a side with an average ^{10}Be concentration of $\sim 145 \text{ atom } ^{10}\text{Be/g}$ could have yielded the Australasian tektites.

4.9.2. Vertical extent of the source region

We now try to inject more realism into this picture of the source region based on the ^{10}Be results. As noted above, the target material must have lain close to the surface within a few million years of the time of impact, for otherwise it could not have acquired sufficient meteoric ^{10}Be .

For the sake of argument, we will assume that the variability of ^{10}Be in tektites reflects the vertical distribution of ^{10}Be in the target region. We then ask, over what vertical distance in a terrigenous or marine column we might expect to see the range of ^{10}Be concentrations observed in tektites. The twofold difference between the average ^{10}Be concentrations of australites, $\sim 200 \times 10^6 \text{ atom/g}$, and indochinites, $\sim 100 \times 10^6 \text{ atom/g}$ at the time of fall, provides a conservative estimate of that range. We consider a difference of averages rather than of extremes to allow for the local, centimeter-to-meter scale variability of ^{10}Be that probably characterized the preimpact target. This approach may underestimate the true, preimpact differences at the site, for impact-induced turbulence could have reduced even larger depth-dependent differences in ^{10}Be concentration. To proceed further, we look to the terrestrial record for guidance.

In thick terrestrial sedimentary columns (including loess), ^{10}Be concentrations typically decrease by more than a factor of 10 for vertical distances greater than 300 m (e.g., Fig. 3 and references to Table 5). These overall decreases result mainly from radioactive decay. Thus we conclude that tektite formation took place in a region less than 300 m thick. A thickness of <300 m implies sedimentation rates less than 20 cm/ky to explain (as a result of radioactive decay) the difference between the ^{10}Be concentrations of australites and of indochinites.

Table 4 shows ^{10}Be concentrations in various sediments calculated based on the assumptions of constant material sedimentation rates, no sources of ^{10}Be other than direct, local deposition, and a constant deposition rate of ^{10}Be of $0.018 \text{ atom cm}^{-2} \text{ s}^{-1}$. Comparison of the ^{10}Be concentrations of Table 4 with those measured for Australasian tektites suggests a hypothetical source region with a sedimentation rate of $\sim 1 \text{ cm/ky}$. Here 15 m would separate proto-australites from proto-indochinites. A sedimentation rate so small, however, is more typical of deep-sea environments where tektites did not form. With a sedimentation rate appropriate for continental shelves,

say $10\text{--}20 \text{ cm/ky}$, ^{10}Be concentrations would decrease the required factor of two from the top to the bottom of a layer 150 to 300 m thick. The maximum ^{10}Be concentrations attained in a closed system at sedimentation rates of $10\text{--}20 \text{ cm/ky}$ (Table 4) are only $24\text{--}12 \times 10^6 \text{ atom/g}$, however, much less than measured in tektites. We therefore infer that the grains that formed tektites did not accumulate ^{10}Be from local deposition alone, but inherited a portion of it from another location.

In sum, assuming that during crater formation neither the precursor grains nor the material melted mixed efficiently on a scale of tens of meters (N.A. Artemieva and E. Pierazzo, personal communication, 2002), we conclude that the vertical extent or thickness (as opposed to the absolute depth) of the hypothetical region that participated in tektite formation was likely between 15 and 300 m. In this conclusion we agree with Koeberl (1994). The total thickness of the deposit and excavated depth could, of course, have been larger, but the deposit may not have contributed over its whole length to tektite formation. Stöffler et al. (2002) have modeled moldavite formation as an event in which an impactor melted a continental surface layer of sand some 50 m thick.

4.9.3. Possible dimensions of the tektite-forming region

If we assume that tektite formation took place in a cylinder 50 m thick, then for total masses of 2×10^{15} g to 32×10^{15} g, the surface areas, 15 km^2 to 240 km^2 , would have been those of circles with diameters of 4.4 km to 18 km. In modeling the formation of the Ries crater, Stöffler et al. (2002) found optimal melt production for an oblique impact. In their picture, a sheet of melt erupts from the leading surface of the impactor-target interface, fans out in the downrange direction, and falls in a sector confined within an arc of $\sim 60^\circ$.

4.10. Location of the Source Crater

To search for clues to the location of a source crater, we consider the subset of Southeast Asian layered tektites for which we have information about the latitudes and longitudes of recovery. In Figure 4 we have divided those tektites into three groups according to ^{10}Be concentration (10^6 atom/g): $^{10}\text{Be} \leq 60$ ($N = 11$, smallest stars); $60 < ^{10}\text{Be} \leq 80$ ($N = 13$, stars of intermediate size); $80 < ^{10}\text{Be}$ ($N = 3$, largest stars). Lacking specific information about the locations of the Hainan and the Guangdong tektites, we assigned coordinates based on the place names. The discussion below is not sensitive to these details. For our set of samples, the locations of the tektites with the smaller ^{10}Be concentrations form a more compact geographical group. The maximum distance between any two SE Asian samples with smaller ^{10}Be concentrations (Lingshui and Huai Sai) is 422 km. The locations of the tektites with the larger ^{10}Be concentrations are more dispersed. The maximum distance between any two of these samples (Guandong and Saigon) is 1156 km.

Figure 4 shows a smooth closed curve constructed to optimize the separation between tektites with ^{10}Be concentrations less than and greater than $60 \times 10^6 \text{ atom/g}$, respectively. It also shows the minimum loop required to enclose all the samples with ^{10}Be concentrations less than $60 \times 10^6 \text{ atom/g}$. Similar conclusions apply to either curve. As might have been expected, the sorting of ^{10}Be concentrations is not perfect. Of the

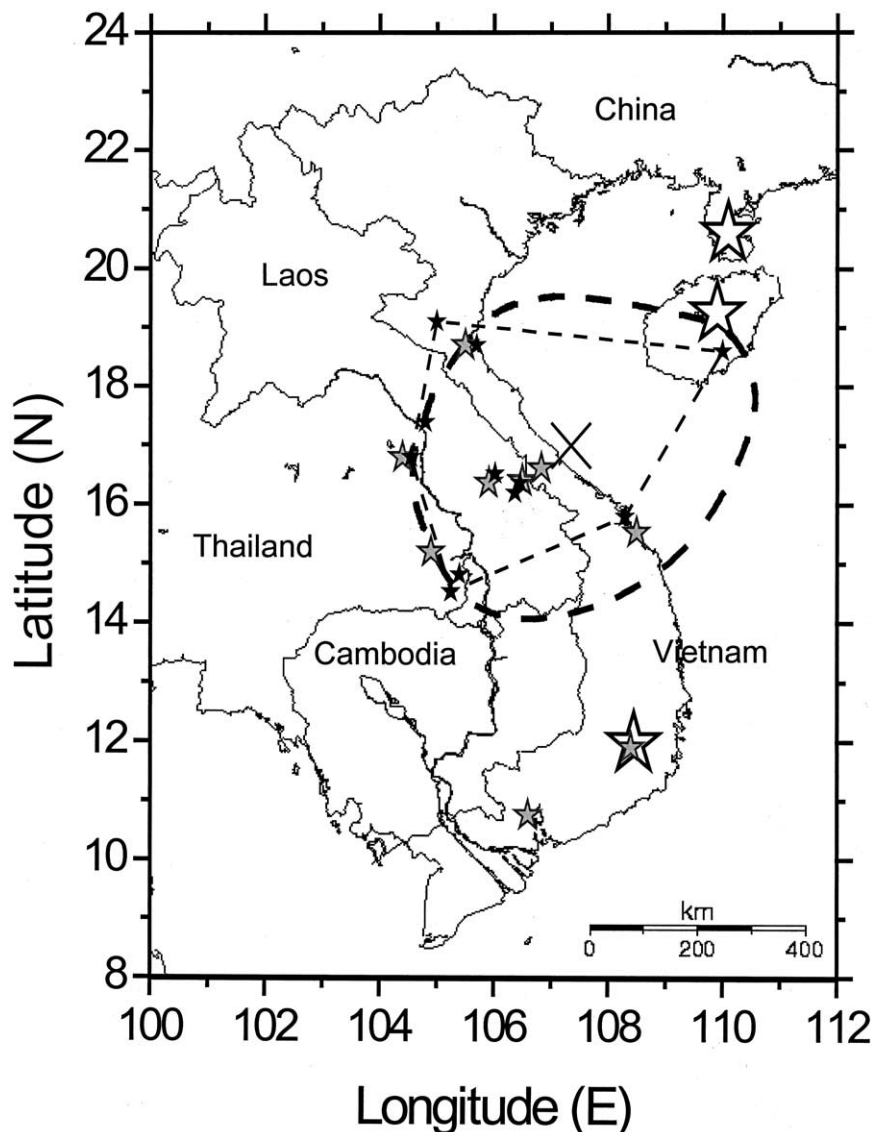


Fig. 4. An approximate smooth curve (heavy dashed line) separates tektites with lower and higher ^{10}Be concentrations and centers on a region in the southern portion of the Gulf of Tonkin. A second, lighter dashed line encloses all the tektites with ^{10}Be concentrations less than 60×10^6 atom/g. The formation of Australasian tektites probably occurred within or close to the regions bounded by these curves. The large "x" is the approximate center of the smooth curve. Symbol size denotes ^{10}Be concentration (10^6 atom/g): small black stars, <60 ; medium-sized gray stars, 60 to <80 ; large open stars, ≥ 80 .

11 samples with the lowest ^{10}Be concentrations, 7 lie within the smooth curve (where one would want them), 3 on it, and 1 outside it. For the intermediate group, 5 lie within the contour (where one would not want them), 3 on it, and 5 outside it. The high group has only three samples of which one lies close to the contour while the other two lie well outside of it.

The distribution in Figure 4 suggests a possible location of the source crater somewhere close to the east coast of Vietnam, at the western edge of the Song Hong Basin ($\sim 17^\circ\text{N}$, $\sim 107^\circ\text{E}$). For the Kontum region a little further south (15°N , 107.5°E), Carter et al. (2000) estimated denudation rates of 4 cm/ky in the early Neogene and quote thicknesses for offshore sediments ranging from 300 m to 2500 m. These values seem to be the right order of magnitude for tektite forming materials. Arguing against this proposition are the observations that the Song Hong

Basin probably formed by rifting and to date has furnished no evidence of impact events (Nielsen et al., 1999).

Although the Song Hong Basin is appealing on geometric grounds, our ^{10}Be data are also consistent with an origin along a 600-km strip running from northeast to southwest across the Gulf of Tonkin, through Vietnam, to Laos, and on to the northeast corner of Thailand. The accidents of sampling may have influenced our choice of location. In particular the location of the Lingshui tektite moves the center of our curve to the east and the absence of Cambodian layered tektites from our set of samples may bias its position to the north. Relative to other proposed locations, ours lies ~ 290 km and 360 km northeast of the spots suggested by Schnetzler (1992) and by Hartung and Rivolo (1979), respectively. Assuming that our sampling of tektites has no gross geographical bias, we conclude that the

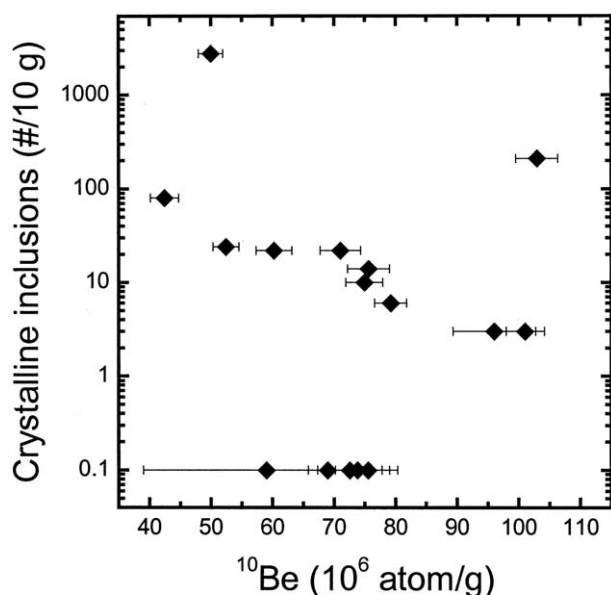


Fig. 5. The concentration of crystalline inclusions (in number/g) in Muong Nong-type (layered) tektites (Dass and Glass, 1999) does not depend uniquely on ^{10}Be concentration but generally decreases as ^{10}Be concentration increases. Higher concentrations of relict crystalline inclusions in layered tektites occur in material that originated closest to the source region.

distribution of ^{10}Be concentrations is inconsistent with a source location as far south as the Mekong Delta (Stauffer, 1978) and probably one to the Southeast at Lake Tonle Sap (Hartung and Koeberl, 1994).

Figure 5 shows the abundances of relict mineral inclusions in several of the tektites (Dass and Glass, 1999) analyzed here plotted semilogarithmically against ^{10}Be concentration. There is no statistically significant correlation, but a hint that relict zircon abundances increase as ^{10}Be concentrations decrease. Such a trend might arise if tektites with higher abundances of relict zircon grains formed from deeper-lying material that reached lower temperatures and had lower concentrations of ^{10}Be .

5. CONCLUSIONS

At present, Australasian tektites contain on average $\sim 100 \times 10^6$ atom $^{10}\text{Be}/\text{g}$. When corrected to the time of fall ~ 0.8 My ago, the ^{10}Be concentrations are so large that the ^{10}Be atoms can have entered the precursor phases only by adsorption on small grains near the surface of the Earth within the last 10 My.

The ^{10}Be concentrations of tektites increase slowly with increasing distance from Indochina: Southeast Asian tektites have the lowest values and australites the highest. In the simplest explanation for why ^{10}Be concentrations increase with increasing distance from Southeast Asia, a single impact strikes a target of relatively fine-grained, sedimentary material that is stratified in ^{10}Be by age. The near-surface materials travel the greatest distances. Based on published analyses of ^{10}Be in various terrestrial sedimentary columns, we conclude that the vertical extent of the tektite-forming region was probably between 15 m and 300 m. In these particulars, we agree with

Blum et al. (1992), except that we see no need or reason to mix solid rock into the tektite batter.

The geographic distribution of ^{10}Be concentrations in Australasian tektites is consistent with a target region in northeastern Thailand (for references, see Table 1) and also with one off the coast of eastern Vietnam in the vicinity of the Song Hong Basin. It remains to be seen whether geologic evidence supports the latter suggestion.

The complexity of the terrestrial record of ^{10}Be in sediments allows other explanations for our observations. For example, we do not rule out loess as a possible precursor either on land or as a significant component in offshore sediments.

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APPENDIX

Sample iT077 (LHALISH1) is a layered tektite given to John Wasson by Ouyang Ziyuan, the director of the Institute of Geochemistry of the Academia Sinica. It is from Lingshui, Hainan Island.

Sample iT088 (LLAMUNO1) is from the Muséum National d'Histoire Naturelle, Paris, France, catalog No. 2214. It is undoubtedly genuinely from the environs of Muong Nong, Laos.

Sample iT153 (LTHNOHU1) was recovered in 1991 by a field team led by John Wasson. It was obtained from a schoolchild who (along with numerous others) had found it while helping to dig a pond on the grounds of the school at the W edge of Non Hung village. Wasson estimates the coordinates of the find as N14.81, E105.40.

Sample iT 099 (LVIVINH2). This layered tektite from near Vinh was given to John Wasson by Le Duc An of the Vietnam Geological Survey.

The Paracale, Luzon, sample is from the Max-Planck-Institute, Mainz. It is described and figured in Koenigswald (1963). Its original mass was 648 g. Geographic coordinates are from The Times Atlas. Many of these large splash form tektites were obtained during dredging of aluminum ore from the sea floor.

The Belitung (or billitonite) specimen is from a mining geologist in Belitung. It was also found during mining operations. The center of Belitung north of Java is at 2.91 S, 108.46 E. It is a small island, so the location is probably good to within 33 km. (or 0.3°).