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^{10}Be in Australasian microtektites compared to tektites: Size and geographic controls

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ABSTRACT

High ^{10}Be contents in tektites reported in literature are taken as evidence of a source material, melted at the impact site, enriched in atmospheric ^{10}Be; i.e., a soil or sediment. In 0.8 Ma Australasian tektites, ^{10}Be content increases with distance from the putative impact location in Indochina, with geographic averages from 69 × 10^6 atoms/g (Indochina) to 136 × 10^6 atoms/g (Australia). Here we report, for the first time, ^{10}Be contents in microtektites collected from Antarctica and the South China Sea. We show that microtektites are ~30 × 10^6 atoms/g richer in ^{10}Be than tektites from the same geographic areas. Antarctic microtektites, with an average ^{10}Be content of 184 × 10^6 atoms/g after correction for *in situ* production, are the richest impact glass ever measured. The simplest explanation for such systematic size and geographic trends is that the source depth of the melt within the target surface decreases with ejection velocity. Indeed, higher initial kinetic energy implies higher launch distances and higher fragmentation of the ejecta. Antarctic microtektite source depth may tentatively be restricted to the upper tens of centimeters at the impact site. Alternative models invoking a marine or loessic sediment source, or a secondary enrichment in the microtektite (either by atmospheric scavenging, selective fractionation by volatilization, or post-depositional contamination) fail to reproduce the observed relationships.

INTRODUCTION

Tektites are a particular type of natural silicate glass produced by hypervelocity impacts and long-distance ejection (Glass and Simonson, 2013). They are recovered on continental surfaces, mostly as centimetric splash-form masses dispersed over large strewn-fields. Similar material is found as <1mm quenched droplets, mostly in oceanic sediments, known as microtektites (MTKs). They can record extremely high-pressure and high-temperature conditions (Cavosie et al., 2018) and their formation mechanism is still poorly understood. Only four tektite strewn-fields are recognized, compared to nearly 200 impact structures documented on Earth (PASSC, 2018). These strewn-fields extend over ranges varying from 10^2 to 10^4 km and at a minimal distance of 250 km from the inferred source craters. Such a wide distribution implies that they were ejected to outside Earth atmosphere at velocities of several kilometers per second.

The Australasian tektite and MTK strewn-field is the largest on Earth (Fig. 1A). It was produced at ca. 0.8 Ma by an impact hypothetically situated in Indochina. The smallest strewn-field, called Ivory Coast, is associated with the Bosumtwi crater resulting from an impact at 1.07 Ma in Ghana (e.g., Glass and Simonson, 2013).

In both these strewn-fields, tektites have been shown to originate from the near-surface layers of the impacted target (likely soil or sediment) based on their high contents of ^{10}Be cosmogenic nuclide (Ma et al., 2004; Serefiddin et al., 2007). Such high ^{10}Be concentrations cannot be reached through *in situ* production since the tektite deposition, and must therefore originate from inherited atmospheric ^{10}Be accumulated within the first meters of the continental surface melted during the impact. Alternatively, the high ^{10}Be concentrations may correspond to impact melting of a thicker Quaternary sedimentary sequence, as high atmospheric ^{10}Be content are observed in such sequences, regardless of depths, up to ~100 m (e.g., Gu et al., 1996; Simon et al., 2016). Given the short half-life of ^{10}Be (1.39 m.y.; Korschinek et al., 2010) the two other strewn-fields (central European, ca. 14.4 Ma; North American, ca. 35.5 Ma) cannot be investigated through ^{10}Be measurements.

One major result of the study of the Australasian tektites was that a consistent increase of ^{10}Be content versus distance was observed (average values range from 69 to 136 Mat/g; i.e., 10^{6}atoms/g, from Indochina to Australia, respectively; Ma et al., 2004), giving possible insight on a relationship between excavation

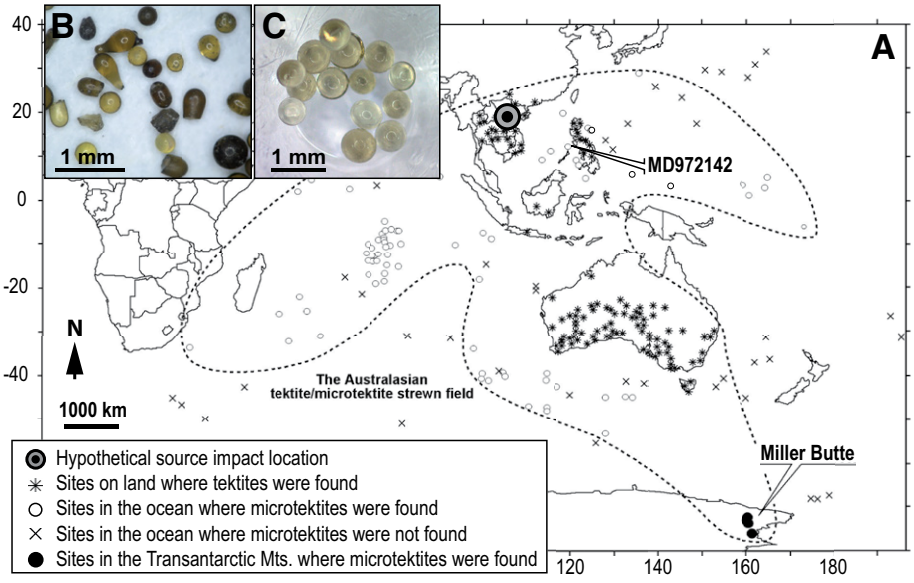

Figure 1. A: The Australasian tektite-microtektite (MTK) strewn-field (modified after Folco et al., 2016). The two MTK sample locations are shown: in the South China Sea (sediment core MD97–2142; Lee and Wei, 2000) and in the Transantarctic Mountains, Antarctica (Miller Butte). The possible source impact location in Indochina is also indicated (~17°N, 107°E; Ma et al., 2004). B,C: Stereomicrographs of the MTKs analyzed in this work from core MD97–2142 and from Miller Butte, respectively.

depth of the melted material and the ejection velocity and angle. The principal objectives of our study are to verify if this distance relationship extends further by measuring ^{10}Be contents in the Australasian MTKs recently found in Antarctica (Folco et al., 2008), and to evaluate whether MTKs and tektites have comparable ^{10}Be contents at the same distances from the impact location. Indeed, the three-orders-of-magnitude difference in volume between individual tektites and MTKs could provide new insight into their formation process and origin in the target. Therefore, we have analyzed MTKs from a piston core from the South China Sea (SCS; core MD97–2142, Lee and Wei, 2000) which is proximal to the proposed impact site (Fig. 1). This core contains one of the highest known concentrations of MTKs (see review in Prasad et al., 2007), with a significant fraction of large MTKs (Lee and Wei, 2000).

SAMPLES AND METHODS

Antarctic MTKs were extracted under a ZEISS Stemi 2000 stereomicroscope from the 400–800 µm size fraction of a loose soil sample collected on the flat summit plateau of Miller Butte, Victoria Land Transantarctic Mountains, during the 2006 Italian Programma Nazionale di Ricerche in Antartide (PNRA) expedition. The MTKs were cleaned in an ultrasonic bath and deionized water. Two batches of 11 and 14 fresh and optically homogenous MTKs were prepared to produce two samples of >3 mg for ^{10}Be measurements.

Lee and Wei (2000) identified, in core MD97–2142, a MTK peak centered on 3425 cm depth and extending over 20 cm. 1-cm-thick layers were obtained from the core half at 3418.5 cm and 3426.5 cm depths (samples 1 and 2) and treated at the Institute of Earth Sciences in Taipei. They were dispersed in water and sieved to 300 µm. MTKs were picked and shipped to Aix en Provence (France), where they were cleaned using alcohol and an ultrasonic bath. A >3 mg aliquot (with 15–20 spherules the 300–500 µm range) was prepared for each depth, by selecting optically clear, intact, yellow-colored spherules and avoiding fragmented, dark, inclusion-bearing MTKs.

^{10}Be measurements are described in GSA Data Repository[1]. To test our preparation protocol and check our ability to reproduce the findings of Ma et al. (2004), we measured a 114 mg aliquot of a large splash-form tektite from Vietnam (retail acquisition in Hanoi by Rochette). A sample of the host soil (<100 µm fraction) from Miller Butte was also analyzed.

The Antarctic MTKs have been exposed to cosmic rays on top of Miller Butte since their emplacement. Therefore, to determine their original ^{10}Be content, the calculated ^{10}Be produced *in situ* over the last 0.8 m.y. has to be subtracted from the measured ^{10}Be concentrations. Using a local spallation production rate of 43.52 at/g/yr (scaled following the Stone polynomial [Stone, 2000], from a sea-level and high-latitude [SLHL] production rate of 4.02 at/g/yr [Borchers et al., 2016] and an Antarctic pressure of 702 mbar), the *in situ* production is estimated to be 29 Mat/g at most. However, accounting for the fact that these MTKs were found below ~15 cm of granitic debris (density = 1.8 g/cm^3) and have been snow-covered for a significant proportion of time (a 10 cm water equivalent layer is likely a minimum), the *in situ* production is more realistically ~23 Mat/g. The SCS MTKs have been shielded from cosmic rays since their emplacement and, therefore, no correction is needed. Ma et al. (2004) discussed the *in situ* production of ^{10}Be in Australasian tektites but concluded it must be <<10 Mat/g. This is due to the combination of a near-zero altitude and low latitude compared to Antarctica. Moreover, those tektites have been buried in soil and sediments for most of their residence time. Consequently, no correction has been applied to the data of Ma et al. (2004).

RESULTS

Results from our four MTK samples, the test tektite from Vietnam, Miller Butte soil, and average tektite data from Ma et al. (2004) have been ordered according to distance from the Indochina impact site (Fig. 2; Table 1). The control sample from Vietnam, yielded ^{10}Be contents of 79.3 ± 2.5 Mat/g, the same as the average splash-form value for Indochina (76 ± 14), within error, ensuring that our preparation procedure reproduced Ma et al.'s (2004) results.

Analytical uncertainties of ^{10}Be contents from MTKs were estimated at ~10 Mat/g. The difference between the two measurements from Antarctica and from SCS is 18 and 7 Mat/g, respectively, which is <2× the analytical error. This shows that the sampling and pooling procedure produced a reliable average value for the whole MTK collection. The weighted mean for the Antarctic MTKs, after the data were corrected for *in situ* ^{10}Be production is 184 ± 8 Mat/g, 32% and 35% higher than the values for the SCS MTKs and Australian tektites, respectively (see Table 1; Fig. 2).

DISCUSSION

^{10}Be in MTKs has been reported previously in abstract form by Koeberl et al. (2015). They reported a composite 0.62 mg sample yielded 260 ± 60 Mat/g, which is not significantly different from our Antarctic uncorrected values, while 13 individual MTKs yielded values from 90 to 1230 Mat/g. As no information is available on the size and provenance sites of the MTKs studied by Koeberl et al., as well as on their analytical conditions and errors, we will not comment further on these values.

The fact that SCS MTKs are significantly enriched in ^{10}Be compared to the Philippine and Indonesian tektites of Ma et al. (2004) (by 15 and 22%, respectively), although these two sites are farther from the impact site, indicates that MTKs recovered from approximately the same locality derive from a precursor material enriched in ^{10}Be compared to the tektite source (see the trends in Figure 2). Therefore, comparing Australian tektites with Antarctic MTKs implies that one part of this increase in ^{10}Be may be linked to the increased launch distance, and the remainder to the contrast between tektites and MTKs. Although Figure 2 suggests these two parts are similar, we do not give too much significance to these simplistic interpolations. To better constrain this proportion, one should

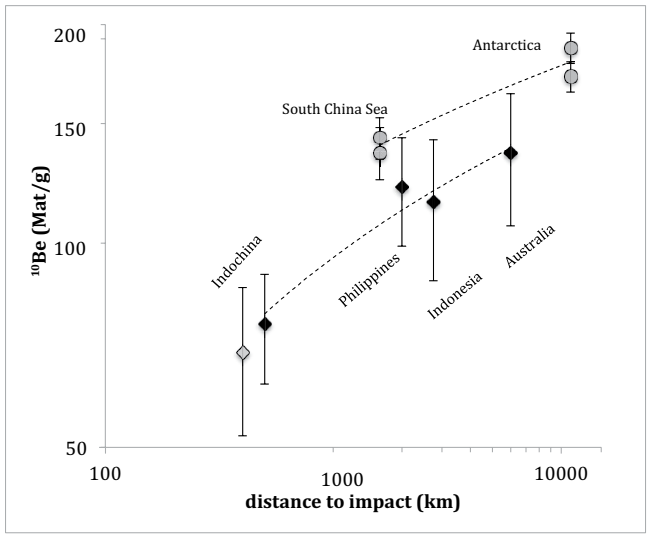

Figure 2. ^{10}Be (Mat/g) contents in tektites (diamonds: gray for layered, black for splash-forms; after Ma et al., 2004) and microtektites (circles, this work) versus average distance from the assumed impact site (see Table 1). Error bars are one standard deviation. The average distance was arbitrarily set for Indochina layered and splash forms at 400 and 500 km, respectively. Note that the dashed lines give a visual reference but have no physical or statistical meaning.

[1]GSA Data Repository item 2018291, details on measurements, discussion, and Figures DR1–DR5 and Table DR1, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

TABLE 1. ^{10}BE RESULTS FROM THIS STUDY

Tektite	^{10}Be (Mat/g; 10^6 x atoms/g)	s.d.	n	D (10^3 km)
Indochina L*	69	17	29	<0.8
Indochina SF*	76	14	12	<0.8
Philippines*	121	22	19	1.6–2.5
Indonesia*	115	27	6	2.5–3
Australia*	136	30	20	5–7
Vietnam SF	79.3	2.5	1	<0.8
Microtektite	**^{10}Be (Mat/g)**	**error**	**mass (mg)**	**D (10^3 km)**
SCS 1	136	12	3.8	1.6
SCS 2	143	10	3.9	1.6
Antarctic 1	199	11	3.6	11
Antarctic 2	217	12	3.4	11
Antarctic 1	176	11	3.6	11
Antarctic 2	194	12	3.4	11
Miller Butte soil	21115	330	525	11

Note: s.d.—standard deviation; D—estimated distance to source (based on Glass and Pizzuto, 1994). L—layered; SF—splash form. Site coordinates: ~72°42′S, 160°14′E, 2600 m a.s.l. for Antarctica; 12°41′N, 119°28′E, 1557 m b.s.l. for the South China Sea (SCS). Underlined samples are corrected from *in situ* production.

*Geographical averages are from Ma et al (2004).

measure Australian MTKs. However, the low concentration (100× less than in the SCS) and small size of the MTKs in sedimentary cores collected near Australia make it virtually impossible to obtain suitable samples (Glass and Pizzuto, 1994).

Here we first discuss how our results can be interpreted in terms of present theories on tektite production processes, by impact or giant airburst (Stöffler et al., 2002; Wasson, 2003). In particular, what can our results tell us about the target? We also explore post-impact processes that may modify ^{10}Be concentration. Finally, the type of target surface (thick recent sediment versus thin soil layer) is discussed.

Relationships Among ^{10}Be Concentration, Tektite Size, Target Source Depth, and Ejection Distance

A simple interpretation of our results, and their comparison with previous tektite results, assumes (1) a target whose atmospheric ^{10}Be content decreases with depth, as is typical for *in situ* continental soils, developed on old bedrock, and (2) a mechanism that connects source depth with launch distance and melt droplet size. From 22 worldwide soil profiles, Graly et al. (2010) determined an average ^{10}Be concentration in the A and B soil horizons of ~450 Mat/g, well above our Antarctic MTK value corrected for decay over 0.8 m.y. (~275 Mat/g). This concentration decreases to zero on a 1–10 m depth range. MTKs would come from shallower depths than tektites for a given launch distance, and sampling depth will also decrease according to increasing launch distance. A phenomenological model where sampling depth is connected to the initial kinetic energy imparted to the ejected material (higher energy toward the surface) would satisfy the distance trend. Modeling of impact melt production and ejection supports this relationship (Stöffler et al., 2002; Artemieva, 2008). Concerning MTKs, one can assume that they received higher initial kinetic energy than tektites, but were subsequently slowed down in the atmosphere (to reach the same launch distance as tektites), or that they were simply produced before tektite at the very first contact between the continental surface and the impactor. In the latter case, sequential melting would generate tektites from deeper in the soil than MTKs. Note that the relationship between melt source depth and launch distance may be valid either in the standard impact crater model (Stöffler et al., 2002), or the alternative airburst model of Wasson (2003).

Alternative Interpretations: Host Contamination, Atmospheric Scavenging, or Volatilization

Our interpretative model for the contrast between MTKs and tektites may be challenged by three alternative ways that objects that have a higher surface/volume ratios or have experienced higher temperatures obtain higher ^{10}Be content. The first mechanism could be linked to variable post-impact volatilization, as evidenced by the decrease of volatiles (Na and K) versus distance in MTKs (Folco et al., 2010). Indeed, the loss of volatiles may result in enrichment in refractories, like Be. However, elemental analyses of typical refractories (Ti, Al, Ca) performed on SCS and Antarctic MTKs (see the Data Repository) as well as on tektite from Indochina, disproves significant Be enrichment due to this effect.

The second mechanism suggests that, during their atmospheric flight, MTKs (in a molten or hot stage) scavenge the ^{10}Be produced in the atmosphere. The total ^{10}Be production per unit area in an atmospheric column is estimated to be 0.03 atom s^{-1} cm^{-2} (Kovaltsov and Usoskin, 2010). Using an atmospheric residence time of 3 yr (Baroni et al., 2011) and the geometric cross section of a 500 µm MTK, the corresponding scavenging potential is 5700 atoms. With a glass density of 2.5, this translates into 20 Mat/g; i.e., the approximate difference observed between tektites and MTKs. However, this scavenging mechanism is likely to be efficient only in a narrow range of atmospheric entry velocities, and would be counteracted by surface ablation during flight.

The third possibility is that surface contamination from the embedding soil or sediment would add ^{10}Be to MTKs. Indeed, Serrefidin et al. (2007) have inferred that the first 500 µm of the surface of moldavite tektites is enriched in ^{10}Be (by 10 Mat/g), possibly from the surrounding sediment or percolating water. Extrapolating these results would imply that ^{10}Be exchange may have occurred down to the center of the studied MTKs. In core MD97–2143, situated 400 km east of SCS core MD97–2142, an average of 837 Mat/g ^{10}Be was obtained by Simon et al. (2018) for the period 790–830 ka. In our shallower core, the ^{10}Be content is likely lower, but by a factor less than 2. Therefore, it would be possible to attribute the higher ^{10}Be in SCS MTK compared to tektites to sediment contamination. The same mechanism can be invoked for the Antarctic MTKs, as their host sediment is extremely enriched in ^{10}Be (Table 1; this exceptionally high value is discussed in detail in the Data Repository). However, significant low-temperature diffusion of Be in silicates has never been documented and is not considered to be a potential source of contamination.

Considering the three mechanisms invoked here, smaller MTKs (i.e., those with higher specific surfaces), should yield higher ^{10}Be contents. MTKs in Antarctic sample #2 are smaller than in sample #1 (originating from 400–600 µm and 600–800 µm sieved fractions, respectively). However, we found that their ^{10}Be contents are not significantly different.

Rejecting a Purely Marine or Loessic Sedimentary Target

The model based on the assumption of a target in which atmospheric ^{10}Be content decreases with depth fails if the target is a thick enough sedimentary sequence, either loessic or marine, without involvement of underlying bedrock. In such sequences, ^{10}Be content does not necessarily decrease with depth, but may be constant or variable with sedimentation rate, sediment composition, and origin (see examples in Data Repository). In this case, we would not expect a consistent variation of ^{10}Be contents with launch distance or size, unless an unlikely configuration in terms of the ^{10}Be depth gradient was present, by chance over the entire melted surface. Also, the presence of relatively large, residual detrital grains of quartz and zircon in tektites and MTKs (e.g., Glass and Fries, 2008) and the significant chemical heterogeneity observed, argue

against a homogeneous, very fine-grained target material, such as loess or marine sediments. Conversely, a residual continental soil has the required grain size and chemical heterogeneity to account for all the observations of this study. Our model fits with one derived from Sr and Nd isotopic systems (Blum et al., 1992), with a bedrock of Jurassic continental deposits. The large spread in $^{87}Sr/^{86}Sr$ ratios also hints at a variable weathered/fresh bedrock mixture.

Therefore, we conclude that the most likely interpretation of the observed values and geographic trends of ^{10}Be content in MTKs is a common mechanism involving a target whose ^{10}Be content decreases with depth (as observed in continental emerged surfaces), and an inverse relationship between melt source depth and ejection velocity. Antarctic MTKs thus have the shallowest impact site source, which may tentatively be restricted to the first tens of centimeters.

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