Geology

10Be geographic and size gradients in the Australasian tektite and microtektite strewn field

--Manuscript Draft--

Manuscript Number:	
Full Title:	10Be geographic and size gradients in the Australasian tektite and microtektite strewn field
Short Title:	10Be in australasian strewn field
Article Type:	Article
Keywords:	australasian, tektite, microtektite, Beryllium 10
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Manuscript Region of Origin:	ANTARCTICA
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^{10}Be geographic and size gradients in the Australasian tektite and microtektite strewn field

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ABSTRACT

Large ^{10}Be content in tektites has been shown to be evidence of a source material enriched in atmospheric ^{10}Be, i.e. a soil or sediment. In Australasian tektites ^{10}Be content increases with distance from the putative source crater in Indochina, with geographic averages from 69 to 136x10^6 at/g. Here we show that the same trend exists in microtektites by measuring samples from Antarctica and South China Sea. Moreover, microtektites are ~30x10^6 at/g richer than tektites from the same geographic area. Antarctic microtektites, with an average ^{10}Be content of 184x10^6 at/g after correction for in situ-production, are the richest impact melt ever measured. The simpler hypothesis for such systematic size and geographic gradient is that the source depth of the melted material in the target soil surface decreases with ejection velocity. A higher initial kinetic energy indeed means a higher launch distance and a higher fragmentation. Alternative models invoking a marine or loessic sediment source or a secondary enrichment in the microtektite (either by atmospheric scavenging or host contamination) fail to reproduce the observed relationships.

INTRODUCTION

Tektites are a particular type of natural silicate glass produced by hypervelocity impact and long distance ejection (Glass and Simonson, 2013). They are recovered on continental surfaces mostly as centimetric splash-forms masses dispersed over large strewn-fields. The same material is found as <1mm droplets, mostly in oceanic sediments, and called microtektites. They have recorded extreme high pressure and 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 impacts structures documented on Earth. These strewn-fields extend over ranges varying from 10^2 to 10^4 km and at a minimal distance of 250 km from the source crater. This implies that they were ejected outside the atmosphere at several km/s velocities.

The Australasian tektite and microtektite strewn-field is the largest (Folco et al., 2016). It was produced 0.79 Ma ago by an impact hypothetically situated in Indochina and its extension is presented in Fig.1a. The smallest strewn field, called Ivory Coast, was produced by the Bosumtwi crater in Ghana 1.07 Ma ago (Glass and Simonson, 2013).

In both 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 content of cosmogenic nuclides ^{10}Be (Ma et al., 2004; Sereffidin et al., 2007). This high content cannot be reached through in situ-production since tektite fall and must thus originates from inherited atmospheric ^{10}Be accumulated at the continental surface melted by the impact. Alternatively, the high concentration may correspond to impact melting of a thicker Quaternary sedimentary sequence, as high atmospheric ^{10}Be content are observed in such sequence regardless of depth (e.g. Gu et al., 1996; Simon et al., 2016). The two other strewn fields are much older than the

half-life of ^{10}Be (1.39 Ma), thus they cannot be investigated for that purpose (Korschinek et al., 2010).

One major result of the study of the Australasian tektites was that a consistent increase of ^{10}Be content versus distance (69 to 136x10^6at/g (Mat/g) from Indochina to Australia averages) was observed, giving possible insight on a relationship between excavation depth of the melted material and the ejection velocity and angle. The first purpose of our study was to verify if this distance relationship extend further by measuring ^{10}Be content in the Australasian microtektites recently found in Antarctica (Folco et al., 2008). However, it remains to evaluate if microtektites have the same ^{10}Be content than tektite from the same distance to source. Therefore we include in the present study microtektites from a proximal site. A good candidate for that appeared to be the MD97-2142 South China Sea core (Fig.1) as it has already been demonstrated to be one of the richest core in microtektites (see review in Prasad et al., 2007) with a significant number of large ones (Lee and Wei, 2000).

SAMPLE AND METHODS

Antarctic microtektites were extracted under a ZEISS Stemi 2000 stereomicroscope from the 4-00-800 µm size fraction of loose soil sample collected on the flat summit plateau of Miller Butte, Victoria Land Transantarctic Mountains (~72°42'S, 160°14'E; 2600 m a.s.l.) during the 2006 PNRA expedition. They were cleaned in ultrasonic bath and deionized water. Two batches of about 11 and 14 fresh and homogenous microtektites were prepared to produce two samples >3 mg for ^{10}Be measurements.

Lee and Wei (2000) identified in core MD97-2142 a microtektite peak at 3425 cm depth extending over 20 cm. One-cm thick layers were obtained from the archive half at 3418.5 and 3426.5 cm depth and treated at the Institute of Earth Sciences in Taipei. They were dispersed in water and sieved at 300 µm. Microtektites were picked and shipped to

CEREGE, where a further cleaning was applied using alcohol and ultrasonic bath. A > 3 mg aliquot (with 15-20 spherules of size in the 300-500 µm range) was prepared for each depth, by selecting the clear intact yellow colored spherule, avoiding fragmented, dark and inclusion bearing microtektites.

To test our preparation protocol and check our ability to reproduce Ma et al. (2004) results we also measured a 114 mg aliquot of a large splash form tektite from Vietnam (acquired in Hanoi by P.R.). A sample of the host soil (<100 µm fraction) from Miller Butte was also analyzed.

A carefully weighted amount of microtektite, spiked with ~0.1mg a (3025±9)-ppm in-house ^{9}Be carrier (Merchel et al., 2008) was totally dissolved in few ml of 48% HF then fumed in PTFE beaker to dryness. The precipitated was recovered with nitric acid and the Be was purified by solvent extractions and alkaline precipitations. After being oxidized at 800°C for one hour, the BeO was mixed with niobium powder and analyses by accelerator mass spectrometry (AMS) at the French AMS national facility ASTER housed at CEREGE, Aix en Provence, France. All measurements were standardized against the in-house STD11 standard (Braucher et al., 2015).

The collected Antarctic microtektites have resided exposed to cosmic rays on top of Miller Butte since their fall. Therefore, to determine their original ^{10}Be content, the in situ produced ^{10}Be accumulated over the last 0.8 Ma has to be subtracted to the measured ^{10}Be concentrations. Using a local production spallation production rate of 43.52 at/g/a (scaled following Stone polynomial (Stone, 2000), from a SLHL production rate of 4.02 at/g/a (Borchers et al., 2016) and an Antarctic pressure of 702 mbar), the in situ content is estimated to be at most 29 Mat/g. However, accounting from the fact that microtectites were found below about 15 cm of granitic debris (1.8 g/cm^3) and a snow cover variable with time (a 10 cm water equivalent layer is likely a minimum), the in situ-production should be reduced to

100 23 Mat/g. The China Sea microtektites have been shielded from cosmic ray since their fall,
101 thus no correction is need. Ma et al. (2004) discussed the in-situ production in tektites but
102 concluded it must be <<10 Mat/g. This is due to the combination of a near zero altitude and
103 low latitude compared to Antarctica. Moreover, the tektites have been buried in soil and
104 sediments for most of their residence time since their fall. We will thus not apply any
105 correction to Ma et al. (2004) data to compare with the microtektite results.
106
107 **RESULTS**
108 Table 1 lists our results on the four microtektite samples as well as the test tektite from
109 Vietnam and Miller Butte soil, and average tektite data from Ma et al. (2004) ordered
110 according to distance from Indochina. Test tektite sample yields 79.3±2.5 Mat/g, within the
111 average splash form value for Indochina (76±14), ensuring that our preparation procedure
112 reproduce Ma et al. (2004) results.
113 Analytical uncertainties on our microtektite measurements were around 10 Mat/g. The
114 difference between the two measurements from Antarctica and South China Sea amounts to
115 18 and 7 Mat/g, i.e. less than two times the analytical error. This shows that the sampling and
116 pooling procedure ensures the determination of a reliable average value for the whole
117 microtektite collection. The weighted mean for the Antarctic microtektites after in situ-
118 production correction (184±8 Mat/g) is 32 and 35% higher than the South China Sea
119 microtektites and Australian tektites, respectively (see Table 1 and Fig.2).
120 ^{10}Be measurements in microtektites have been reported previously in abstract form by
121 Koeberl et al. (2015). A composite 0.62 mg sample was reported to yield 260±60 Mat/g, not
122 significantly different from our Antarctic uncorrected values, while 13 individual
123 microtektites yield values from 90 to 1,230 Mat/g. As no information is available on the size

and provenance sites of the microtektites, as well as on analytical conditions and errors, we will refrain to comment further these values.

DISCUSSION

A depth in aerial target surface versus distance and size relationship

The fact that SCS microtektites are significantly enriched in ^{10}Be compared to the Phillipines tektites (by 15%) indicates that microtektites recovered from approximately the same locality derive from a precursor material enriched in ^{10}Be compared to the tektite source. Therefore when comparing Australian tektites with Antarctic microtektites, one part of the increase may be linked to the increased launch distance and one part to the contrast between tektites and microtektites. Although Fig.2 appears to suggest these parts are of the same order, we should refrain to give too much significance to simplistic interpolations. To better constrain this point one would have to measure Australian microtektites. However, the low concentration (100 times less than SCS) and small microtektite size for the sedimentary cores around Australia make this task hardly achievable (Glass and Pizzuto, 1994).

A simple interpretation of our results and comparison with tektite results can be put forward assuming a target surface whose atmospheric ^{10}Be decreases content with depth, as is typical for in situ continental soils, formed on old bedrock. From 22 worldwide distributed soil profiles, Graly et al. (2010) determined an averaged ^{10}Be concentration in the A and B soil horizons of ~450 Mat/g, well above our Antarctic microtektite value corrected for decay over 0.8 Ma (~ 275 Mat/g). With that assumption, microtektites would come from shallower surface 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

149 the surface) would satisfy this distance scheme. Concerning microtektites, one may assumed
150 that they received higher initial kinetic energy than tektites, but were subsequently slowed
151 down in the atmosphere (to reach the same launch distance than tektite), or that they were
152 simply produced before tektite at the very first contact between continental surface and the
153 impactor. In that case, sequential melting would sample tektites deeper in the soil than
154 microtektites.
155
156 **Discarding a purely marine or loessic sedimentary target**
157 The whole above scheme falls apart if one assumes that the target is a thick enough
158 sedimentary sequence, either loessic or marine. In such sequences, ^{10}Be content does not
159 necessarily decrease with depth but may be constant or variable with sedimentation rate,
160 sediment composition and origin. In this case, we would not expect a consistent variation of
161 ^{10}Be content with launch distance or size. Also, the presence of relatively large residual
162 detrital grains of quartz and zircon in tektites and microtektites (e.g. Glass and Fries, 2008)
163 and the significant chemical heterogeneity observed argue against a homogeneous very fine
164 grained target material, as loess or distal marine sediment. On the other hand, a residual
165 continental soil has the required grain size and chemical heterogeneity to account for all the
166 observations.
167
168 **Alternative interpretations by host contamination or atmospheric scavenging**
169 Our interpretative model for the microtektite/tektite contrast may be challenged by two
170 alternative ways to obtain higher ^{10}Be content for object that have a higher surface/volume
171 ratio. The first is that we would partly measure in our microtektites a surface contamination
172 from the embedding soil or sediment. Indeed, Serrefidin et al. (2007) have shown that the first
173 500 µm of the surface of moldavites tektites is enriched in ^{10}Be (by 10 Mat/g) from the

surrounding sediment or percolating water. If we can extrapolate these results, it would mean that ^{10}Be exchange may have occurred down to the center of the studied microtektites. In core MD97-2143, situated 400 km E of our core MD97-2142, an average of 837 Mat/g was obtained (Q. Simon, personal communication) 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 could possible to account for the larger ^{10}Be in SCS microtektite compared to tektite by a sediment contamination. The same mechanism can be invoked for the Antarctic microtektites as their host sediment is extremely enriched (Table 1). However, non-negligible low temperature diffusion of Be in silicates has never been documented and reported.

The other hypothesis is that during their atmospheric flight, microtektites, in molten or hot stage, scavenge the ^{10}Be content of the atmosphere. The total ^{10}Be production per surface in an atmospheric column in estimated to be 0.03 atom $s^{-1}.cm^{-2}$ (Kovalstov and Usoskin, 2010). Using an atmospheric residence time of 3 yrs (Baroni et al., 2011) and the section of a 500 µm microtektite, the corresponding scavenging potential is 5,700 atoms. With a glass density of 2.5, this translates into 20 Mat/g, i.e. about the difference observed between tektite and microtektite. However, this scavenging mechanism is likely to be efficient only in a narrow range of atmospheric entry velocity and will be counteracted by surface ablation during flight.

In both mechanisms invoked, lower sized microtektites, i.e. with higher specific surface, should yield higher ^{10}Be contents. Microtektites in sample #2 are smaller than in sample #1 (originating from 400-600 µm and 600-800 µm sieved fractions, respectively). However, their ^{10}Be content is not significantly different.

Therefore, we conclude that the most likely interpretation of the observed size and geographic gradients is a common mechanism with a decreasing content with depth in the

target (as observed in continental emerged surfaces) and an inverse relationship between melt source depth and ejection velocity.

ACKOWLEDGEMENTS

Work (partially) supported by PNRA (id. PNRA16_0029). Taiwan Ocean Research Institute provided sediments of marine core MD97-2142 for the study. The ^{10}Be concentration measurements were performed at the ASTER AMS national facility (CEREGE, Aix en Provence) which is supported by the INSU/CNRS, the ANR through the "Projets thématiques d'excellence" program for the "Equipements d'excellence" ASTER-CEREGE action and IRD.

REFERENCES CITED

Baroni, M., Bard, E., Petit, J.R. , Magand, O., and Bourlès, D., 2011,Volcanic and solar activity and atmospheric circulation influences on cosmogenic ^{10}Be fallout at Vostok and Concordia (Antarctica) over the last 60 years: Geochimica et Cosmochimica Acta, v. 75, p. 7132-7145.

Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K., Phillips, F., Schaefer, J., and Stone, J., 2016, Geological calibration of spallation production rates in the CRONUS-Earth project: Quaternary Geochronology, v. 31, p.188–198, https://doi.org/10.1016/j.quageo.2015.01.009.

Braucher, R., Guillou, V., Bourlès, D.L., Arnold, M., Aumaître, G., Keddadouche, K., and Nottoli, E., 2015, Preparation of ASTER in-house ^{10}Be/^{9}Be standard solutions: Nuclear Instruments and Methods in Physics Research B, v. 361 , p. 335-340.

Cavosie, A.J., Timms, N.E., Erickson ,T.M., and Koeberl, C., 2018, New clues from Earth's most elusive impact crater: Evidence of reidite in Australasian tektites from Thailand: Geology https://doi-org.insu.bib.cnrs.fr/10.1130/G39711.1.

Folco, L., Rochette, P., Perchiazzi, N., D'Orazio, M., Laurenzi, M. A., and Tiepolo, M., 2008, Microtektites from Victoria Land Transantarctic Mountains: Geology, v. 36, p. 291-294.

Folco, L., D'Orazio, M., Gemelli M., and Rochette P., 2016, Stretching out the Australasian microtektite strewn field in Victoria Land Transantarctic Mountains: Polar Science, v. 10, p. 147-159.

Glass, B. P., and Pizzuto, J. E., 1994, Geographic variation in Australasian microtektite concentrations: Implications concerning the location and size of the source crater: Journal of Geophysical Research, v. 99, p.19,075–19,081.

Glass, B. P., and Fries, M., 2008, Micro-Raman spectroscopic study of fine-grained, shock-metamorphosed rock fragments from the Australasian microtektite layer: Meteoritics & Planetary Science, v. 43, p.1487-1496.

Glass, B.P., and Simonson, B.M., 2013, Distal Impact Ejecta Layers: A Record of Large Impacts in Sedimentary Deposits. Springer, Heidelberg, 716p.

Graly, J.A., Bierman, P.R., Reusser, L.J., and Pavich, M.J., 2010, Meteoric ^{10}Be in soil profiles – A global meta-analysis: Geochimica et Cosmochimica Acta, v. 74, p. 6814–6829

Gu, Z.Y., Lal, D., Liu, T.S., Southon, J., Caffee, M.W., Guo, Z.T., Chen, M.Y., 1996, Five million year Be-10 record in Chinese loess and red-clay: Climate and weathering relationships: Earth and Planetary Science Letters, v. 144, p. 273-287.

Koeberl, C., Nishiizumi, K., Caffee, M.W., and Glass, B.P., 2015, Beryllium-10 in individual australasian microtektites and origin of tektites: Meteoritical Society abstract #5187.

Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G., Wallner, A., Dillmann, I., Dollinger, G., von Gostomski, L.C., Kossert, K., Maiti, M., Poutivtsev, M., and Remmert, A., 2010, A new value for the half-life of ^{10}Be by Heavy-Ion

Elastic Recoil Detection and liquid scintillation counting: Nucl. Instrum. Methods Phys., Res. Section B-Beam Interactions with Materials and Atoms, v. 268, p. 187-191.

Kovaltsov, G.A, and Usoskin, I.G., 2010, A new 3D numerical model of cosmogenic nuclide ^{10}Be production in the atmosphere: Earth and Planetary Science Letters , v.291, p. 182–188

Lee, M.-Y., and Wei, K.-Y., 2000, Australasian microtektites in the South China Sea and the West Philippine Sea: implications for age, size, and location of the impact crater: Meteoritics & Planetary Science, v. 35, p. 1151–1155.

Ma, P., Aggrey, K., Tonzola, C., Schnabel, C., De Nicola, P., Herzog, G.T., Wasson, J.T., Glass, B.P., Brown, L., Tera, F., Middleton, R., and Klein, J., 2004, Beryllium-10 in Australasian tektites: constraints on the location of the source crater: Geochimica et Cosmochimica Acta, v. 68, p. 3883-3896.

Merchel, S., Arnold, M., Aumaître, G., Benedetti, L., Bourlès, D.L., Braucher, R., Alfimov, V., Freeman, S.P.H.T., Steier, P., and Wallner, A., 2008, Towards more precise^{10}Be and ^{36}Cl data from measurements at the 10–14 level: influence of sample preparation: Nucl. Instr. Meth. B, v. 266, p. 4921–4926.

Prasad, M.S., Mahale, V.P., and Kodagali, V.N., 2007, New sites of Australasian microtektites in the central Indian Ocean: Implications for the location and size of source crater: Journal of Geophysical Research. v.112, E06007, https:// doi .org /10 .1029 /2006JE002857.

Serefiddin, F., Herzog, G.F., and Koeberl, C., 2007, Beryllium-10 concentrations of tektites from the Ivory Coast and from Central Europe: Evidence for near-surface residence of precursor materials: Geochimica et Cosmochimica Acta, v. 71, p. 1574-1582.

Simon, Q., Thouveny, N., Bourlès, D.L., Valet, J.P., Bassinot, F., Ménabréaz, L., Guillou, V., Choy, S. and Beaufort, L., 2016, Authigenic 10Be/9Be ratio signatures of the

cosmogenic nuclide production linked to geomagnetic dipole moment variation since the Brunhes/Matuyama boundary: Journal of Geophysical Research: Solid Earth, v. 121(11) DOI10.1002/2016JB013335.

Stone, J.O., 2000, Air pressure and cosmogenic isotope production: Journal of Geophysical Research, v. 105, p. 23753–23759, https://doi.org/10.1029/2000JB900181.

Figure captions

Figure 1: a) The Australasian tektite-microtektite strewn field modified after Glass and Koeberl (2006) and Folco et al. (2016). The two locations in South China Sea (MD97-2142) and in the Transantarctic Mountains (Miller Butte) where the microtektites analyzed in this work were found are shown. The possible source impact location in Indochina is also indicated (~17°N, 107°E; Ma et al., 2004); b) and c) Stereomicrographs of the microtektite analysed in this work from MD97-212 and Miller Butte, respectively. Field of view is 2.5 mm.

Fig.2: ^{10}Be (Mat/g) contents in tektites (diamond, gray for Muong Nong, after Ma et al., 2004) and microtektites (circles, this work) versus relative distance from assumed impact site. Note that the dashed lines give a visual help but have no physical or statistical meaning.

Figure 1

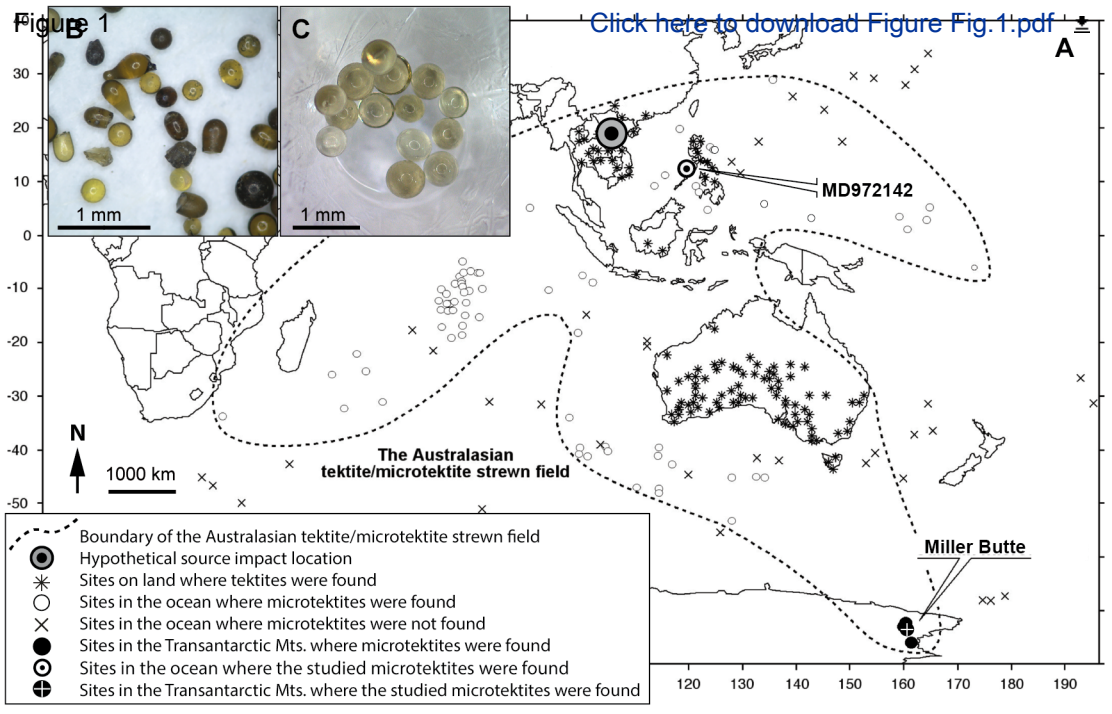

Figure 2

Click here to download Figure Fig.2.pdf

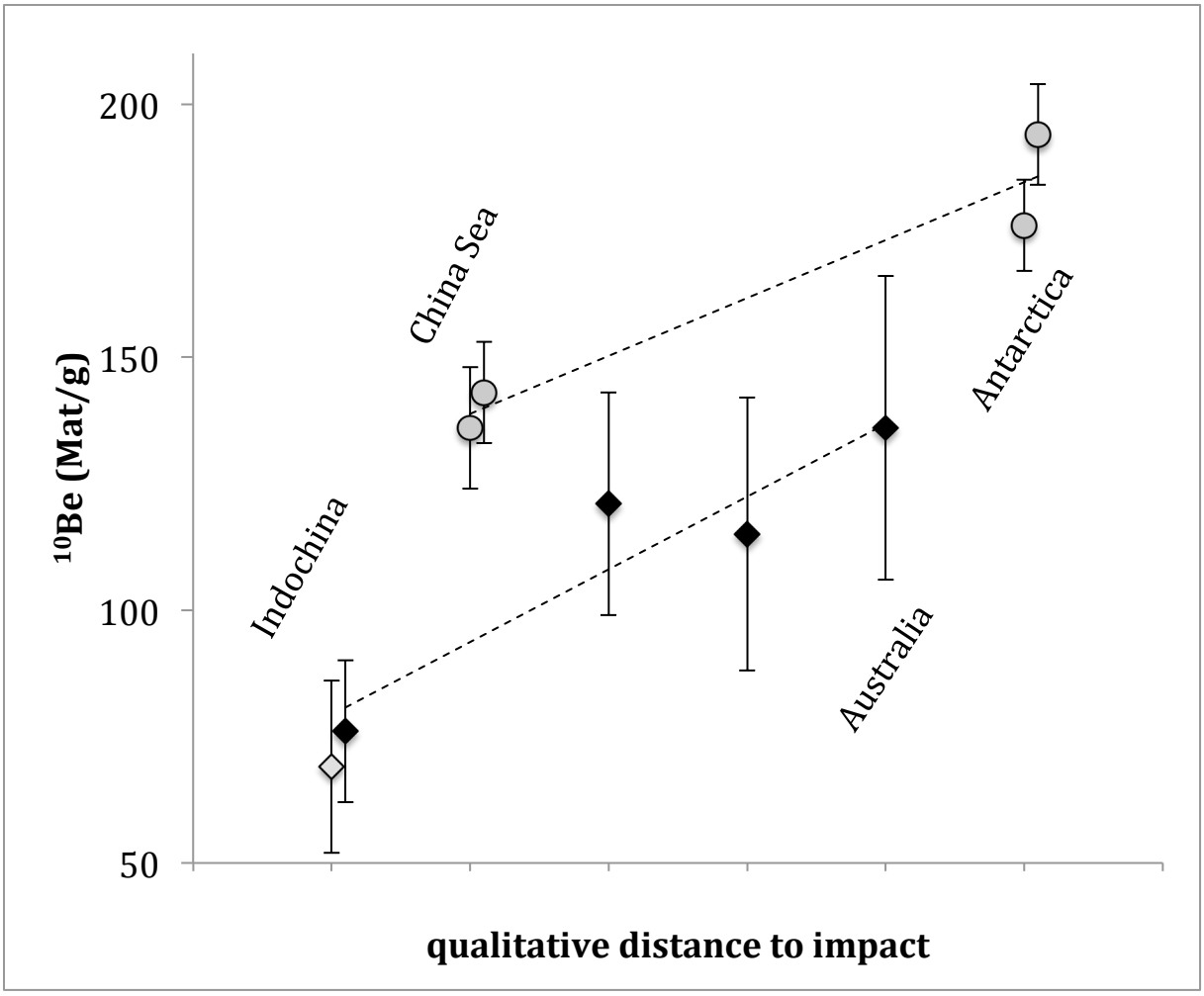

Table 1: ^{10}Be results from this study (underlined is corrected from in situ-production) and *geographical averages from Ma et al. (2004). D is the estimated distance to source (based on Glass and Pizzuto, 1994). Splash form = SF; Muong Nong=MN.

Tektite	**^{10}Be (Mat/g)**	**s.d.**	**N**	**D (10^3 km)**
*Indochina MN	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)**
China Sea 1	136	12	3.8	1.6
China Sea 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