Pacific and Indian ocean waters (10^9 km^3) is much greater than that of the low-Cd Atlantic (0.3×10^9 km^3), redistribution of deep-ocean Cd can produce only slight changes in the SS Cd concentration. Transient nonsteady-state mechanisms could alter the oceanic inventory of an element. Broecker (*28*) argued that the δ^{13}C shift in benthic foraminifera could be caused by a transfer of continental-shelf C into the deep ocean and that this C was accompanied by "Redfield ratio" P, increasing the total P inventory by one-third. We argue that such a transfer is less likely for Cd because, during the weathering of organic sediments, much of the Cd originally contained in organic matter will be trapped into Fe and Mn oxides. This assumption is verifiable on the basis of analyses of Cd/Ca in benthic foraminifera from cores in the Pacific and Indian oceans (E. A. Boyle and L. D. Keigwin, in preparation).
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Beryllium-10 in Australasian Tektites: Evidence for a Sedimentary Precursor

Abstract. *Each of seven Australasian tektites contains about 1×10^8 atoms of beryllium-10 (half-life, 1.53×10^6 years) per gram. Cosmic-ray bombardment of the australites cannot have produced the measured amounts of beryllium-10 either at the earth's surface or in space. The beryllium-10 contents of these australites are consistent with a sedimentary precursor that adsorbed from precipitation beryllium-10 produced in the atmosphere. The sediments must have spent several thousand years at the earth's surface within a few million years of the tektite-producing event.*

Accumulating geochemical and isotopic data have buttressed a terrestrial origin for tektites, probably in an impact event (*1*). Meanwhile, the search for cosmic-ray effects in tektites has been abandoned because of several early failures to detect such effects (*2*). Yet tektites could have acquired ^{10}Be, a long-lived product of cosmic-ray interactions, in any of several ways discussed below. Recent developments in accelerator mass spectrometry have lowered 1000-fold the detection limit for ^{10}Be [half-life, 1.53×10^6 years (*3*)]. We therefore decided to resume the search for ^{10}Be in tektites with the aim of constraining more narrowly hypotheses of tektite origin.

We concentrated on the youngest tektites, the 0.7×10^6-year-old australites, because they would have lost by decay the smallest fraction of any ^{10}Be present in their parent material at the time of formation. The 15×10^6-year-old moldavites, in contrast, would retain only about 10^{-3} of the original ^{10}Be. We analyzed a moldavite as one kind of blank. In addition, we measured the ^{10}Be in the two "bediasites" of uncertain provenance. One contained an appreciable amount of ^{10}Be, whereas the other did not. We have excluded these results from Table 1 because of the ease with which nominal bediasites can be confused with australites. Moniot *et al.* (*4*) describe the procedures used to measure ^{10}Be by accelerator mass spectrometry with the Rutgers tandem Van de Graaff and total Be by atomic absorption spectrometry.

The ^{10}Be contents of the australites (Table 1) are 2 to 20 times lower than those of most contemporary sediments, which range from 2×10^8 to 100×10^8 atom g^{-1} (*5–7*). Sediments from Mono Lake have ^{10}Be contents similar to those of the australites (*8*). The moldavite samples gave counting rates indistinguishable from those of the blanks. Various possible sources for the ^{10}Be present in australites are considered below; we favor a source in terrestrial, sedimentary material.

If a meteorite produced the australites, they could have recaptured some fraction of the projectile's ^{10}Be. A meteorite large enough to supply 1×10^8 atoms of ^{10}Be per gram to 10^8 tons of australites (*9*) would present a virtual 2π geometry to irradiation by cosmic rays in space. The surface production rate of ^{10}Be would be about 10 dpm kg^{-1} in stony material (*10*). The production rate would decrease toward the interior with a half thickness of about 40 cm. A projectile with a mass of at least 1×10^8 tons is required to supply this much ^{10}Be. For an iron meteorite the corresponding values are 3 dpm kg^{-1}, 10 cm, and 3×10^9 tons.

If the meteoritic component in tektites were indeed as large as 50 percent, its geochemical signature would be unmistakable; in fact, the trace element data indicate only a small meteoritic component in most samples (*11–13*). Moreover, a projectile of 10^8 tons would probably

Table 1. The Be and ^{10}Be contents of seven australites and one moldavite. Sources of samples: U samples, U.S. National Museum, R. Clarke; indochinite B, R. Fleischer; and SAM 433, V. Barnes.

Sample	Place of origin	Sample mass	Be (ppm)	^{10}Be (10^8 atom g^{-1})	Pre-treatment
		Australites			
U2172	Thailand	10.08 g	2.0 ± 0.2	0.79 ± 0.12	
U2349	Thailand	4.69 g	1.7 ± 0.2	0.74 ± 0.12	
U5424	Thailand*	10.06 g	2.2 ± 0.2	0.97 ± 0.19	
U1953	Santa Mesa, Philippines	8.02 g	2.2 ± 0.2	0.92 ± 0.21	
U1916	Luzon, Philippines	2.22 g	2.6 ± 0.2	1.28 ± 0.15	
Indochinite B (*21*)		1.65 g	2.7 ± 0.6	1.35 ± 0.29	
SAM 433 (*21*)	Kalgoorlie, Australia	<3 mg†		<30(<0.05)‡	24 hours in 0.1*M* HCl
SAM 433		<1 mg†		<50(<0.03)‡	24 hours in 1*M* HCl
SAM 433		0.35 g	1.9 ± 1.1	1.35 ± 0.27	0.3 hours in 49 percent HF
SAM 433		1.45 g	2.7 ± 0.2	2.04 ± 0.27	Residue
		Moldavite			
U2235	Lhenice, Bohemia, Moldavia	2.23 g	1.8 ± 0.2	<0.02	Bulk after 0.5 hour in 0.1*M* HCl
U2235		3.41 g	1.9 ± 0.2	<0.02	Bulk after mechanical abrasion of surface

*Muong Nong type. †Calculated as the difference in mass of the sample before and after leach. ‡Values referred to the total mass of tektite.

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eject 10 to 100 times its own mass as debris (*14, 15*). The uniform apportioning of ^{10}Be in the ejecta or melt products would decrease the average ^{10}Be content to 0.1 to 0.01 of the amount observed in the australites. Neither an increase nor a decrease in the projectile mass can readily solve this problem. The reason is that the amount of ^{10}Be in the projectile scales as r^2 (where r is the radius), whereas the concentration calculated for the ejecta scales approximately as r^{-3} at fixed projectile velocity (*15*). Hence an increase in the projectile mass would increase the quantity of ^{10}Be available but decrease its concentration in tektites; a decreased projectile mass would not yield enough ^{10}Be.

A mechanism that concentrates meteoritic ^{10}Be in tektites might circumvent this difficulty. We doubt that such a mechanism exists because it would have to mix preferentially and homogeneously the outermost few meters of an object hundreds of meters in radius (*12*).

An australite lying at the earth's surface could adsorb ^{10}Be from precipitation or perhaps ground water. The fallout rate (R) for ^{10}Be is about 0.04 atom cm^{-2} sec^{-1} (*5*). At this rate, the surface of a 10-g australite would be struck by the equivalent of 2×10^8 atoms of ^{10}Be per gram in about 500 years. Three lines of evidence suggest that the ^{10}Be in australites was not introduced in this way. First, the moldavite has no ^{10}Be despite exposure to rain and snow. Second, leaching experiments reveal no surface enhancement of ^{10}Be in the australite SAM 433. Third, studies of terrestrial samples indicate a low affinity of silica-rich grains for ^{10}Be (*6, 16*).

We cannot rule out some contamination from country rock embedded in the surfaces of samples not subjected to leaching in the laboratory. We estimate the contribution from this source as less than 10 percent.

Some ^{10}Be must have been produced in the australites by the cosmic-ray secondaries that bombard the earth's surface. We have estimated the maximum production from this source, assuming that the tektites lie at the surface for 0.7×10^6 years. At 30°S and 400-m elevation, high- and medium-energy secondaries produce 2.4×10^{-5} nuclear disintegrations per gram per second (*17*). Production of ^{10}Be is primarily from spallation of ^{16}O, with a yield of 2.5×10^{-2} ^{10}Be nuclei per disintegration (*17*). For matter with an O content of 40 percent, the result is at most 6 percent of the observed ^{10}Be abundance in the australites.

Neutrons can also produce ^{10}Be via the following reactions: ^{9}Be(n,γ); ^{10}B(n,p); ^{11}B(n,np); ^{12}C(n,^{3}He); and ^{13}C(n,α). The cross sections for the (n,γ) and (n,α) reactions are known for neutrons with energies <15 MeV (*18*); upper limits of 100 mbarn were adopted for the others, based on measured values for analogous reaction channels. The concentrations of Be, B, and C were taken as 2, 15, and 100 parts per million (ppm), respectively (*11, 19*). The flux of neutrons at 30°S and 400-m elevation is about 0.3 cm^{-2} sec^{-1}, with a differential energy (E) spectrum approximately proportional to $E^{-0.88}$ for $0.1 \text{ eV} < E < 10$ GeV (*20*). The calculated production of ^{10}Be does not exceed 2 percent of the observed amount. Muon- and neutrino-induced reactions are even less important (*17*).

By a process of elimination, we conclude that the ^{10}Be in australites came from the parent material. Tektites originating in a lunar volcano (*2*) could have acquired the ^{10}Be found only if an appreciable fraction of the parent material had resided at the lunar surface within 15×10^6 years of subduction and ejection. For example, an erupting lunar magma could entrain 2×10^{22} atoms of ^{10}Be by stripping the top 2 m from 0.8 km^2 of the moon or, less plausibly, the top 5 cm from 8 km^2. In the former case, the total assumed mass of 10^{14} g would contain 4 to 5 percent of the surface material. We cannot exclude this possibility but note that it requires the homogeneous mixing of surface and interior material in certain proportions. A severe test of the lunar hypothesis can therefore now be provided by measurements of the ^{53}Mn contents of australites: lunar surface material contains readily measurable amounts of this radioisotope (half-life, 3.5×10^6 years), whereas strictly terrestrial material does not.

Cosmic-ray bombardment in space could not have produced the ^{10}Be. In the australite SAM 433, for example, the 1900-year maximum exposure allowed by the track data (*21*) is 0.1 of the time needed to produce the ^{10}Be, if we assume typical meteoritic production rates.

Our data are most readily consistent with a sedimentary or metasedimentary origin for the australites' parent material. The question of whether the sedimentary deposits were lithified has remained open (*13*). We suggest that an unconsolidated deposit could adsorb ^{10}Be more easily than lithified matter.

Are the quantity and distribution of ^{10}Be in sedimentary matter consistent with the incorporation of ^{10}Be into australites in the amounts observed? As pointed out above, a ^{10}Be content of 1.5×10^8 atom g^{-1} is comparable to or less than those observed in most sediments. If the tektites comprise mainly material from the topmost few meters of the earth, surface sediments can furnish the requisite ^{10}Be without difficulty. David (*22*) has developed a model for the surface production of tektites.

On the other hand, the tektites might well include material from considerable depths in a source crater. As the ^{10}Be arriving in precipitation may penetrate only 10 to 100 cm (*23*), it follows that tektites produced exclusively at depth would have little or no ^{10}Be unless the target region had been deposited within a few million years of impact. We can define several properties of a hypothetical target region simply by assuming that significant ^{10}Be contents occurred at all depths.

Let us suppose for definiteness that the column sampled during tektite formation had a depth (D) of 1 km, a density (ρ) of 2 g cm^{-3}, and an average ^{10}Be content ($^{10}\text{Be}_{\text{ave}}$) of 1.6×10^8 atom g^{-1} at the time of impact. The total amount of ^{10}Be in the column, 3.2×10^{13} atom cm^{-2}, could not have rained down directly; at saturation, the most this source can maintain is 2.8×10^{12} atom cm^{-2} if we assume $R = 0.04$ atom cm^{-2} sec^{-1}. Only transport of material from outside the target zone could have brought in the needed quantity of ^{10}Be. The stipulation that the 1-km column deposit in less than 5×10^6 years sets a minimum sedimentation rate (S) of 0.02 cm year^{-1}. This value is related to $^{10}\text{Be}_0$, the ^{10}Be content of the incoming sediments, through the equation

$$^{10}\text{Be}_{\text{ave}} = \frac{1}{D} \int_0^D {}^{10}\text{Be}_0 e^{-\lambda z/S} dz$$

where λ designates the ^{10}Be decay constant and z denotes the depth below the surface. With $S = 0.02$ cm year^{-1}, $^{10}\text{Be}_0$ becomes 4×10^8 atom g^{-1}. For larger values of S, $^{10}\text{Be}_0$ approaches $^{10}\text{Be}_{\text{ave}}$.

We now consider the source region. Here surface material adsorbs ^{10}Be for some time before erosion carries it to the target region. Erosion proceeds rapidly enough so that decay can be neglected (see below). Consequently, the steady-state concentration of ^{10}Be at the surface is determined by setting R equal to the rate of removal by erosion (ϵ): $R = {}^{10}\text{Be}_0\epsilon$. With the values given above for $^{10}\text{Be}_0$, we find $\epsilon = 1.5 \times 10^{-3}$ to 4×10^{-3} cm year^{-1}.

Mass balance for the source and target

areas (A_s and A_t), gives the relation $A_s\epsilon = A_tS$. Use of the lower limit for S, 0.02 cm year^{-1}, and the upper limit for ϵ, 4×10^{-3} cm year^{-1}, yields a lower limit for A_s/A_t of 5. Higher values for higher sedimentation rates are possible. We do not wish to suggest that these calculated values were in fact realized in the region where the tektites formed. We conclude only that the production of tektites at depth is consistent with the observed ^{10}Be contents.

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Discovery of a Large-Magnitude, Late Pleistocene Volcanic Eruption in Alaska

Abstract. *An extensive blanket of dacitic tephra was deposited across Alaska and the western Yukon Territory by a plinian eruption about 80,000 years ago. The volume of tephra erupted probably exceeded 50 cubic kilometers and the source was probably in the Wrangell Mountains. This widespread layer of tephra serves as an excellent late Pleistocene stratigraphic marker.*

A distinctive layer of dacitic tephra, named the Old Crow tephra (*1*, *2*), occurs across central Alaska and the western Yukon Territory, with localities ranging from the Seward Peninsula of northwestern Alaska to the southwestern corner of the Yukon, a distance of about 1200 km (Fig. 1 and Table 1). It may represent the first extensive Pleistocene tephra to be documented in northwestern North America.

A combination of stratigraphic, petrographic, and geochemical data provides overwhelming evidence for a common source and strong support for equivalence of all Old Crow tephra samples (Table 1) (*2*). The very high values of the similarity coefficients (*3*) of a 14-element array are particularly supportive of this assertion (Table 2). It is possible, however, that the individual samples are not precisely equivalent, but instead are related to several closely spaced eruptions from the same vent (*4*). The highest similarity coefficient is associated with samples from the extremities of the fallout zone (localities 4 and 11 in Fig. 1).

The source is unknown, but several factors suggest the Wrangell Mountains. First, at least three caldera-forming eruptions producing dacitic tephra have occurred there during the past 200,000 years (*5*). Second, patterns of tephra distribution and thickness can be explained by a source in southeastern Alaska. Finally, a northwesterly dispersal of tephra is not incompatible with reconstructions of ice-age atmospheric circulation patterns in Alaska (*6*) because Old Crow tephra—given its association with ground-ice features (*2*) and the pollen content of enclosing sediments (*7*, *8*)—was deposited during a period of cold climate.

The Old Crow tephra is about 80,000 years old. This age estimate is based on

Table 1. Data on location and thickness of Old Crow tephra.

Locality number	Accession number	Location (north latitude, west longitude)	Thickness (cm)
1	UT 1	67°28′, 139°54′	5 to 10
2	UT 50	67°51.5′, 139°49.6′	5
3	UT 361	65°38′, 138°08′	<1
4	UA 339	62°31.5′, 140°57′	1
5	UA 338	62°00.5′, 140°34′	<1
6	UA 739	64°43′, 148°27′	30
7	UT 388	64°52′, 147°56′	7
8	UT 114	66°32.5′, 152°05′	5
9	UT 115	66°31′, 152°15′	2
10		66°39.5′, 151°45′	Thin pods
11	UT 371	65°35′, 163°15′	10
12	UA 348	64°51.5′, 147°56′	13
13	UA 368	64°54′, 148°00′	10

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