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^{10}Be: Recent Applications in Earth Sciences [and Discussion]

L. Brown and P. Damon

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^{10}Be: recent applications in Earth sciences

By L. Brown

Department of Terrestrial Magnetism, Carnegie Institution of Washington,
5241 *Broad Branch Road, N.W., Washington, D.C.* 20015, *U.S.A.*

^{10}Be, a cosmogenic isotope produced by cosmic rays interacting with the Earth's atmosphere and surface, has chemical and physical properties that make it useful as a tracer for some terrestrial processes and a geological clock for a few substances. The rarity of the stable isotope, ^{9}Be, allows ^{10}Be to be detected in natural materials at extremely low levels with backgrounds for rocks, sediments etc. below 10^5 atom g^{-1} now attainable, a value to be compared with an average annual global deposition rate of 1.3×10^6 atom cm^{-2}. The affinity of Be for the components of soil and sediment is sufficiently high that its contact with them effectively immobilizes it, thereby allowing ^{10}Be to function as a tracer of sediment transport. The half-life of 1.5 Ma is convenient for some geological studies. Application has been found in cosmic-ray history, formation of manganese nodules, pelagic sedimentation, island-arc volcanism, soil evolution, soil erosion and rock weathering.

1. Introduction

(*a*) *General*

The existence of ^{10}Be was inferred from the reaction ^{9}Be(d, p)^{10}Be, which was described in a report by Oliphant *et al.* (1935) of the observation of a series of nuclear reactions. When combined with the known mass data, this experiment also predicted ^{10}Be to be unstable, and McMillan & Ruben (1946) reported observing its radioactivity, β-decay to the ground state of ^{10}B with a half life of 1.5 Ma (Yiou & Raisbeck 1972). It was first observed in a natural substance by Arnold (1956), who found it in pelagic sediment. Its production in Nature results almost entirely from cosmic rays interacting directly with N and O, curiosly enough the same process thought to be the origin of all the isotopes of Li, Be and B. It can also be produced by U- and Th-radioactivity in natural materials through the reaction ^{7}Li(α, p)^{10}Be and by neutrons near the Earth's surface from ^{9}Be(n, γ)^{10}Be (Merrill *et al.* 1960). It is also a product of ternary spontaneous fission (Whetstone & Thomas 1967; Cosper *et al.* 1967). These processes have very low probabilities for terrestrial production near the Earth's surface when compared with spallation by cosmic rays; they may produce backgrounds that have been observed in some low-level work, but U- and Th-ores are the only materials in which they are known to be significant (Sharma *et al.* 1986).

Its use as a tracer or as an indicator of natural processes antedates the investigations of accelerator mass spectrometry, although understandably the low-level counting techniques restricted measurement to substances in which concentrations are high. Nevertheless, research carried out with β-counting techniques yielded information about the exposure ages of meteorites, sedimentation in the deep oceans and the ages of manganese nodules, where concentrations exceed 10^9 atom g^{-1}. The introduction of the accelerator method improved the detection sensitivity over low-level counting by orders of magnitude, resulting in various new applications. That the one stable isotope of Be, ^{9}Be, is a trace element present in most materials at the level of one in 10^{6} (Wedepohl 1969) allows concentrations of ^{10}Be to be measured at much lower values than for ^{26}Al, ^{36}Cl or ^{41}Ca, three other isotopes amenable to the accelerator method but whose stable isotopes are abundant.

(*b*) *Atmospheric deposition*

Most of the applications of ^{10}Be to terrestrial studies make use of the isotope that is produced in the Earth's atmosphere and that subsequently descends in rain and snow. Because of its fundamental importance, numerous investigators have studied the deposition rate but not yet with overwhelming success, there being complications that greatly hamper observation. The isotope's concentration varies substantially from one rainstorm to another and can be assumed to have an as-yet unmeasured dependence on latitude and climate.

Stensland *et al.* (1983) pointed out that in measuring the ^{10}Be deposition rate its redeposition into precipitation gauges with dust, a consequence of its high concentration in soil, is a severe source of error. Monaghan *et al.* (1986) have corrected for this by comparing their ^{10}Be measurements for numerous stations with local ^{90}Sr inventories that have accrued from bomb fall-out. The annual deposition rate so obtained from temperate climates is 1.3×10^{6} cm^{-2} for 100 cm of rainfall, uncertain by 21%. Unpublished measurements by the Washington–Philadelphia group in collaboration with G. J. Stensland and D. C. Bogen over a period of a few years tend to confirm this value as well as to underscore the importance of soil contamination. Data from wet-only collectors emptied monthly show marked differences in ^{10}Be concentrations depending on the degree of soil observed in the rain. A station in Illinois, where soil contamination is high, gives 2.3×10^{6} atom cm^{-2} a^{-1}; a station in New Jersey, which has the lowest record of soil contamination of continental U.S. sites, gives 1.7×10^{6} atom cm^{-2} a^{-1}; and a station on Mauna Loa, Hawaii, which has essentially no soil contamination, gives 1.0×10^{6} atom cm^{-2} a^{-1}.

One might well suspect that the deposition rate is not proportional to rainfall in the tropics, but there are no data about this. One might also suspect that dry deposition is important in deserts, but again there are no measurements. Direct measurements of dry deposition are impossible because resuspended ^{10}Be in dust overwhelms. Indirect measurements with ^{7}Be, which is produced in the atmosphere along with ^{10}Be and whose half-life of 53 days allows negligible resuspension in dust, serve to place an upper limit on dry deposition of 10% of that found in precipitation, but again these values have been measured only in temperate climates.

(*c*) *Divisions of terrestrial deposition*

Observation of ^{10}Be in terrestrial locations is conveniently divided into three groups that are effectively decoupled from one another: polar ice, the deep oceans and the continents with their margins. Polar ice preserves a record of the isotope's deposition that extends back hundreds of thousands of years and is being studied assiduously by the Berne–Zürich group for information about the history of cosmic-ray production or of climate or both. This matter is described by H. Oeschger (this symposium). Most of the large flux of ^{10}Be incident on the oceans eventually ends in the pelagic sediment, but in ways far more complicated than one encounters in polar ice. Its residence time of 630 years (Raisbeck *et al.* 1980) allows the ocean currents at all depths to influence its final deposition. Once deposited it can be resuspended and transported yet again by bottom currents. In our self-satisfaction with the accelerator method we should not forget the important and hard-won data about ^{10}Be in pelagic sediments measured with low-level counter techniques; indeed much of our present knowledge of the subject still resides in these data (see Tanaka & Inoue (1980) and references found therein).

(*d*) *Affinity of* ^{10}Be *for soils and sediments*

The chemical property of Be that lies behind all of the applications discussed except polar ice is its affinity for soils and sediments, thereby allowing it to function as a tracer for the movement of particulate matter. For acidities typical of soils and sediment, solid-to-water partition coefficients of the order of 10^5 have been reported from laboratory experiments (Nyffeler *et al.* 1984). This agrees with observations of ^{10}Be inventories in soil profiles where comparison can reasonably be made with deposition and decay. Working from the opposite direction, one finds that the amount of ^{10}Be dissolved in ground and river water indicates losses of only a few percent of a site's inventory through transport in solution. Coarse-grained material does not retain ^{10}Be by mass to the degree that fine-grained material does, but Lundberg *et al.* (1983) observed it to be retained on the surfaces of silicate grains at 5×10^5 atom cm^{-2}; they also found it at concentrations as high as 10^{10} atom g^{-1} in the hand-picked organic fractions of lake sediments. The reader will realize there is ample room for uncertainty, considering the wide variety of soils and sediments. An early study of ^{10}Be in soils (Monaghan *et al.* 1983) reported a residence time of the isotope of 10^4 years. This resulted from sampling a thin layer of soil without continuing deeper into the regolith. Our experience sets the residence time as very long, indeed comparable with the half-life of ^{10}Be.

2. Soil and erosion

(*a*) *The site inventory*

Consider a formation of soil that has evolved out of weathered rock so situated that there is no evidence of sediment having been brought to the location by wind or water within the last few million years. Based on the affinity of Be for soil, one would expect to find in the regolith all of the ^{10}Be that has been deposited from the atmosphere and that has not yet decayed. The large solid–water partition coefficient requires that the isotope will penetrate the soil in solution to depths dependent on the coefficient's value for the various horizons and on the water budget. It may also descend by particulate transport. Two examples of such profiles are given in figure 1 and reveal a somewhat complicated behaviour, but if one considers the integral over depth, the ^{10}Be inventory, N, of the site, the matter takes on a simpler aspect. If all of the isotope is retained in the column and decays there, then for a deposition period that is long compared with the half-life, the inventory is $N_0 = q/\lambda$, where q is the atmospheric deposition rate and λ is the decay rate. Note that this assumes that a steady state exists between ^{10}Be deposition, weathering and erosion. Measurements of inventories at three sites on the Virginia Piedmont, all of which are at locations thought to have had little or no farming and no evidence of sediment transport to their sites, have given values about one third of this inventory. If one assumes the deviation from N_0 to result entirely from solid particle erosion from the surface, one can obtain an estimate of 1 mg cm^{-2} a^{-1}. To evaluate the significance of this result one can compare it with measurements made in the normal manner of sediment yield for catchment basins in the Piedmont, which range from 1 to 20 mg cm^{-2} a^{-1}, depending primarily on land use. The low erosion rate implied from ^{10}Be thus supports the assumption that loss through solution is

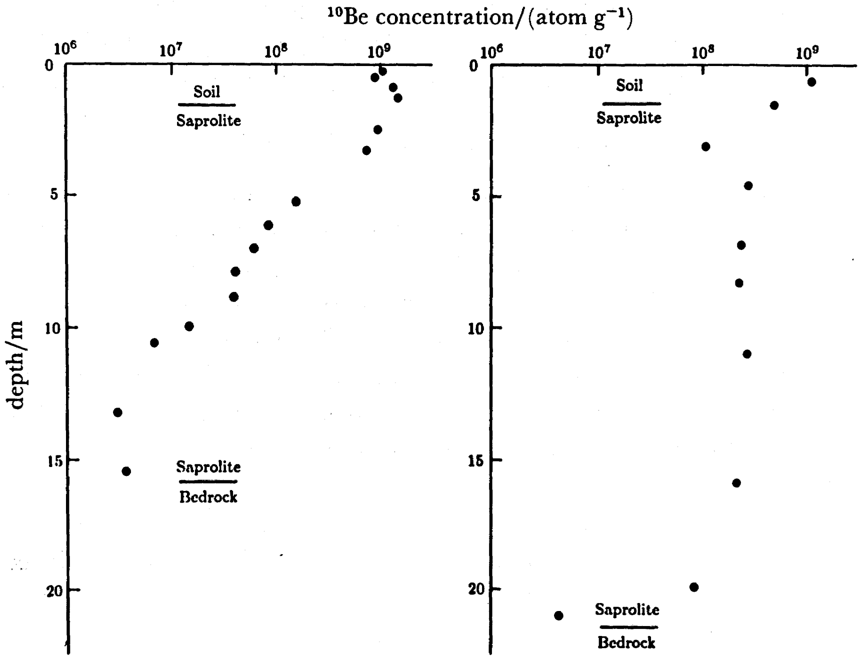

FIGURE 1. ^{10}Be concentrations as functions of depth for two cores taken in Fairfax County, Virginia. The data shown at the left are from a formation that has evolved from a vertically foliated schist, those at the right from a metamorphosed granite. The data at the left are taken from Pavich *et al.* (1985), those at the right are not published elsewhere.

negligible. Measurements of inventory allow the average erosion rate for suitable sites to be determined with a simple, straightforward procedure, a capability heretofore not available to soil scientists. The inventory can, of course, also be used to estimate the extent of alluvial or aeolian transport to the site.

(*b*) *Basin transport*

The normal way of determining erosion is to measure the sediment passing a gauging station daily for long periods, for example, 30 years. It is instructive to see what ^{10}Be has to tell us about this. One can measure the concentration of the isotope in the transported sediment, allowing one to calculate the number of atoms of ^{10}Be leaving the basin annually and to compare this with the number of atoms incident on the basin for the same period. If this ratio, called the ^{10}Be erosion index, is greater than unity, the erosion must be in a transient state.

A study of 46 basins in the eastern United States for which sediment transport data from the Geological Survey are available and whose geology and land-use history are more or less comparable shows striking differences depending on whether the stations are (1) in the Coastal Plain, (2) in the Piedmont uplands, which lie between the fall line (an abrupt change in elevation roughly parallel to the coast) and the mountains, and (3) in the highlands lying to the northwest of the Piedmont. A preliminary report by Brown *et al.* (1986) of the first 28 basins of this group gives details of the measurements and the data needed for the sediment yields. The range of basin size for the group is from 70 to 62400 km^2. There is no correlation between basin size and the ^{10}Be erosion index. Table 1 summarizes the results of measurements of the erosion indices for these three groups. Two anomalously low values have been omitted; they are known to result from dams located upstream from the gauging stations, exceptions that

Table 1

(The ^{10}Be erosion index, defined in the text, is designated by I.)

basin region	number	$I_{\min}$	$I_{\max}$	I_{av}
Coastal Plain	9	0.05	0.6	0.26 ± 0.21
Piedmont⁽¹⁾	17	0.7	8.8	2.40 ± 2.12
Highland subgroups				
Shavers Fork	3	0.6	1.1	0.86 ± 0.29
Guyandotte River⁽²⁾	3	0.6	1.9	1.24 ± 0.66
Coal River⁽²⁾	5	2.8	6.2	4.36 ± 1.32
Pennsylvania highland	4	0.4	1.2	0.59 ± 0.38
miscellaneous⁽³⁾	3	0.5	3.0	

(1) Two basins from the Piedmont are omitted, owing to the presence of dams upstream that have greatly reduced the erosion index.

(2) These two groups are relatively close geographically, but the Coal River group has had extensive mining.

(3) This group has a wide geographical distribution and varying land use.

test the rule. We see that for the Coastal Plain, where low topographic gradients prevail, the indices are all less than unity with an average value of 0.26, in marked contrast to the Piedmont group with an average almost ten times higher. This agrees with conclusions reached by Trimble (1974) and Meade (1982) about the large amount of soil set in motion in the Piedmont by intemperate farming in the preceding two centuries but that has not yet gone far into the Coastal Plain. The highlands group is more varied, owing to a more diverse land use that includes farming, timber, grazing and mining. Four subgroups of the highlands that are similar in geology and land use each have consistent sets of indices, with low indices correlating with conservative land use.

The consistency of the results for these basins allows one to begin cautiously applying ^{10}Be to the history of erosion and to the correction of denudation rates from present, presumably transient values to rates closer to long-term averages.

(c) *Soil age*

In principle, a site inventory can be used to determine the age of a soil, but in practice such an application is difficult because it requires a soil protolith with no inherited ^{10}Be to be exposed to rain starting at a well defined time and that it subsequently evolves into soil as it absorbs the isotope. There are terraces along the Merced River, California, that do approximate this requirement and for which ages have been determined by Pavich *et al.* (1986). These terraces formed out of granitic alluvium obtained through the weathering and erosion of the Sierra Nevada Mountains and have been uplifted over the past few million years. The alluvium currently brought down from the mountains has a low ^{10}Be concentration, similar to values we have observed from other mountain streams; we can reasonably assume the concentration was also low when the terraces were laid down. The ages obtained for the seven Merced terraces agree with ages previously obtained by various radiometric methods and range from 40 ka to 3 Ma. This agreement in age confirms that our understanding of the manner in which ^{10}Be interacts with the Earth's regolith is basically correct. An earlier study (Pavich *et al.* 1984) of a less well-defined set of terraces on the Rappahannock River, Virginia, also led to consistent ages. Where the conditions for soil dating can be met, ^{10}Be provides constraints on recent tectonism and uplift.

(*d*) *Loess*

It appears that long-standing, unresolved questions concerning the origin of loess (see Smalley (ed.) 1975 for a review of this topic) may receive answers from the kind of ^{10}Be data that H. Oeschger has just presented. One oft-cited explanation for this material is that it is rock dust manufactured by glaciers, accumulated in outwash plains, and then transported by wind to its present location. Studies of ^{10}Be in rock, some of which will be discussed shortly, show that any kind of unaltered rock has a very low ^{10}Be concentration compared with the data given by H. Oeschger, and the same is true for our own data for two other sites in China. All have concentrations typical of soils with ages much older than the times separating us from the recent ice ages, making the 'rock flour' hypothesis difficult, although not impossible, to maintain. Loess is distributed world wide, and hypotheses about it are often regional in character, so the constraints imposed by ^{10}Be data may prove useful in attempting to understand the puzzles presented by this material.

(*e*) *Agricultural history implied by* ^{10}Be

A study of three sediment cores taken from the tributaries of the Chesapeake Bay by Valette-Silver *et al.* (1986) shows effects attributed to European agriculture on the ^{10}Be concentrations as functions of depth. The three were selected from 107 piston cores because they showed no evidence of any disturbance of the original stratigraphy and because they sampled small catchment basins where land-use history is well known. Soils just below the surface generally have the highest ^{10}Be concentration, and their erosion and subsequent transport to the core site has presumably caused the sharp increase in the isotope's concentration coincident with the onset of cultivation. The ^{10}Be profile of figure 2 shows much more clearly than the sedimentation rate the period of intensive farming and the final reversion of the land to grass and timber when farming began its decline in the early part of this century. The steady

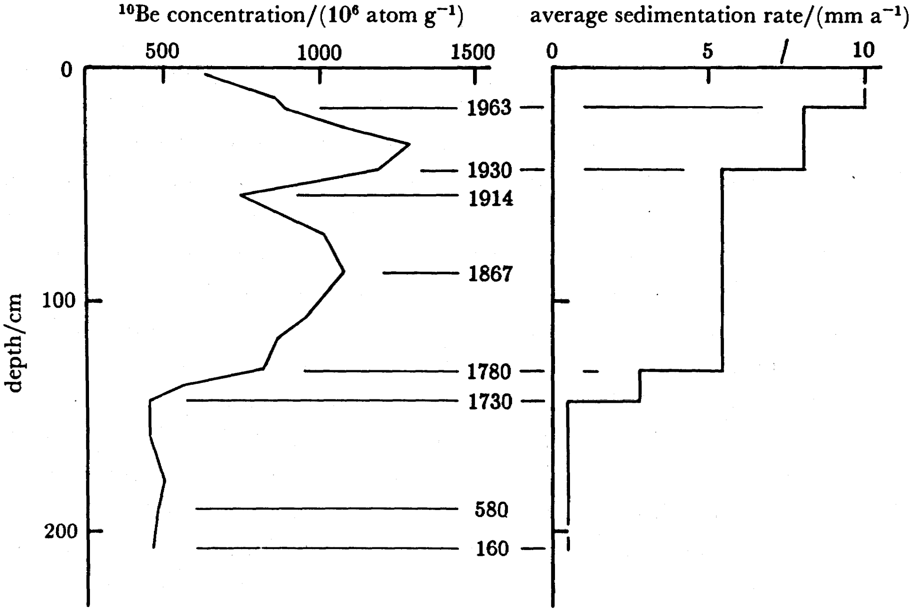

FIGURE 2. ^{10}Be concentration and average sedimentation rate as functions of depth for a core taken at Furnace Bay of the Chesapeake Bay. Dates are noted for various depths. Data are taken from Valette-Silver *et al.* (1986).

increase in sedimentation rate contrasts with the ^{10}Be concentration and correlates with an increase in particle size; this probably results from the larger, ^{10}Be-poor particles having longer transit times than the ^{10}Be-rich clays.

The profile before colonization has remarkably little structure, but a small peak in another profile (not shown) correlates with the presence of bits of charcoal, suggesting that enhanced erosion followed a forest fire. Again the effect shows up more sharply in ^{10}Be than in the sedimentation rate, where there is nothing anomalous.

(*f*) *Off-shore scavenging*

The high solid-to-water partition coefficient of Be determines the way in which ^{10}Be inventories are built up at ocean margins. The isotope's concentration and residence time in the ocean can be a source of high deposition rate where ^{10}Be-laden currents encounter continental run-off or other sources of particulate matter. In the sea off southern California, this mechanism produced deposition rates an order of magnitude above the atmospheric rate, and a Deep Sea Drilling Project core taken 150 km west-southwest of Mazatlan, Mexico, yielded an even higher value (Brown *et al.* 1985). Scott *et al.* (1983) had observed the same phenomenon earlier with Pu. This scavenging proved to have unexpected application to volcanism, as we shall now see.

3. Island-arc volcanism

At regions of the Earth where lithospheric plates are being subducted, ^{10}Be is being used to trace a geological process that involves both the chemistry and the physics of the subducted materials. The geometry of subduction is imaged by the location of numerous earthquakes that mark the boundary between the descending plate and the overlying mantle wedge and is manifested geographically by a deep ocean trench and a line of volcanoes 100–200 km landward of the trench. Once it became clear during the 1960s that some cause–effect relation held between subduction and island-arc volcanism, the origin of the lavas automatically became a new scientific question, and a possible role for subducted sediment became a major controversy. A layer of pelagic sediment, usually a few hundred metres thick, accompanies the plate at least during the early stages of subduction. Located as it is between the plate and the mantle wedge, this sediment layer has been seen by many as a possible key to understanding the origin of the island-arc magmas. Being able to show whether this sediment is or is not incorporated into arc lavas allows one to place important constraints on possible origins and subduction-zone processes. Evidence based on chemical and isotopic composition has not resolved the matter of sediment incorporation to the satisfaction of all investigators.

F. Tera & I. S. Sacks suggested in 1978 that the high concentration of ^{10}Be known to exist in pelagic sediments (typically 5×10^9 atom g^{-1}) might be utilized as a sediment tracer for this problem. In addition to its affinity for sediment it has the remarkable advantage of a half-life that is long enough to follow the course of subduction yet short enough to prevent confusion through subsequent recycling. If it could be found in island-arc lavas and not in the lavas of volcanoes unrelated to subduction, sediment incorporation would be proved; the problem ultimately showed itself to admit of such an answer.

Because atmospheric deposition is the ultimate origin of ^{10}Be, the observer must ensure that the effects measured are not the result of surface contamination. This has been addressed in various ways: (1) measuring the ^{10}Be concentration in many samples with origins unrelated to subduction; (2) by using wherever possible samples picked up immediately after eruption; (3) examining thin sections for evidence of alteration and looking for correlations between degree of alteration and ^{10}Be concentration; (4) ascertaining whether the volumes of rain water needed to produce the levels observed are reasonable; and (5) extending our knowledge of the distribution of the isotope in rain, soils, sediments and ground water to evaluate various surface incorporation mechanisms. Sediment might also be assimilated into the ascending magmas as they pass through strata on top of which the volcanoes have formed. To evaluate this mechanism one must examine the details of the local geology, but here the half-life of ^{10}Be eliminates any sedimentary layer except relatively young ones.

The measurement of the isotope's concentration in samples of lava unrelated to subduction form a control group with which one may compare data from various island arcs. The data for the control group are shown graphically in figure 3 by indicating measurements of individual lava flows; there are no values greater than 10^6 atom g^{-1}. This is to be compared with the results shown in figure 4 of six arcs, in the North Pacific, Central America and South America, for which much higher concentrations are encountered. Three other arcs, the Halmahara, Marianna and Sunda, are indistinguishable from the control group. These raw data argue for pelagic-sediment incorporation as the source of ^{10}Be in the six arcs that show the effect.

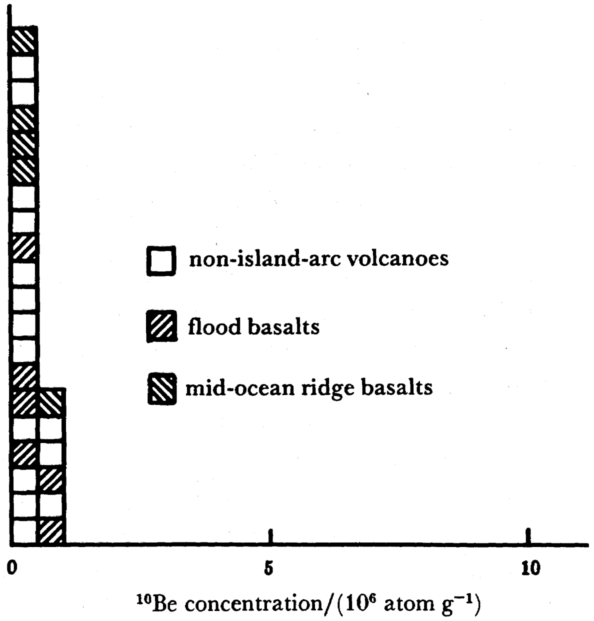

FIGURE 3. A histogram of ^{10}Be concentration measurements for lavas from sources unrelated to subduction. Division of the bins is 5×10^5 atom g^{-1}. Data are taken from Tera *et al.* (1986).

The presence or absence of ^{10}Be in the lavas of various arcs can be modelled in a preliminary manner with two variables to describe each arc: (1) the travel time of the plate from the trench to the roots of the volcanoes and (2) a ^{10}Be inventory determined from the product of the Plio-Pleistocene sedimentation rate and the sediment's ^{10}Be concentration outboard of the trench. The latter approximates the inventory available for subduction, which may be affected by particle scavenging and is often quite different from the atmospheric deposition inventory, N_0. For details of these matters see Tera *et al.* (1986) and Morris *et al.* (1987).

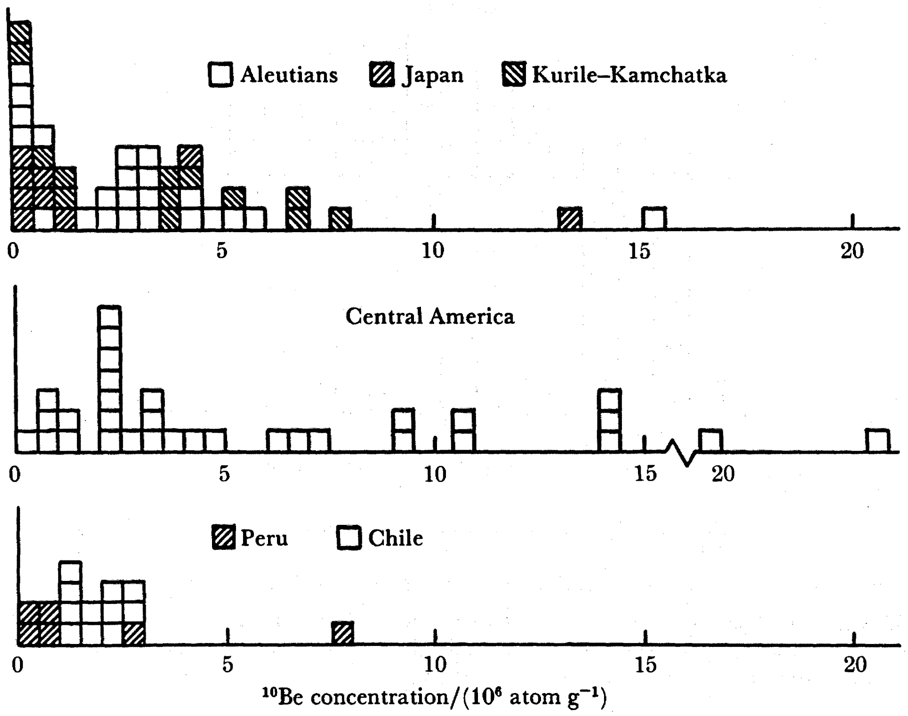

FIGURE 4. A histogram of ^{10}Be concentration measurements from lavas of volcanoes from six Pacific Ocean arcs. Requirements of sample freshness are essentially the same as for the control group of figure 3. The data are from Tera *et al.* (1986) and Morris *et al.* (1987).

4. TEKTITES

There are a few regions of the Earth's surface on which glassy objects of varying sizes, but typically with dimensions of a centimetre or so, can be found scattered about the surface. Prehistoric Man observed and presumably discussed them, but probably without the contention as to their origin that has marked their study in modern times. Tektites have a chemical composition similar to soil and sediment, have virtually no entrapped gases, and have shapes indicating their solidification while passing through the atmosphere. Of the various origins proposed, two have retained adherents to the present: (1) they are the result of some object striking the Earth and (2) they are in some way ejected from the Moon. This is clearly not the place to examine the various arguments on this matter in detail, which the reader may learn from Koeberl (1986). Suffice it to say that a large majority of geochemists accept a terrestrial origin primarily because tektites are chemically and isotopically similar to the Earth and not the Moon.

An important objection to the terrestrial origin has been the absence of an impact crater that could account for the huge strewn field covering much of Australia and southeast Asia. It is to this point that ^{10}Be has evidence to offer. Pal *et al.* (1982) reported observing the isotope in a few Australian tektites. This was followed by the measurement of ^{10}Be in 42 tektites by Tera *et al.* (1983), revealing a relatively tight distribution of the isotope's concentration shown by the histogram of figure 5. It appears to have a bimodal geographic dependence, with the Australian tektites forming one group and those of southeast Asia forming the other. What is of interest here is that the average concentration, when corrected for the age of 0.7 Ma, is typical

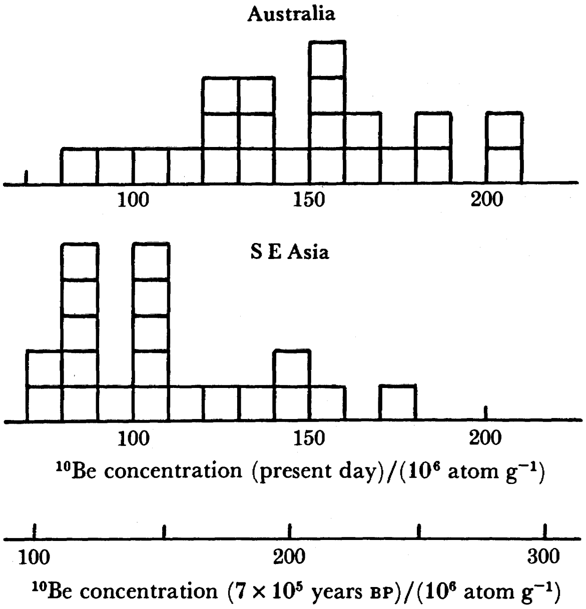

FIGURE 5. A histogram of ^{10}Be concentration measurements from tektites of Australia and southeast Asia. Division of the bins is 10^7 atom g^{-1}. A second, horizontal axis gives the concentrations at the time of the event that produced the tektites. Data are from Tera *et al.* (1983).

of what one finds in continental margin sediments. These sediments tend to have a much narrower range of ^{10}Be concentration than soils, no doubt the result of their being the averages of large land masses. (Such concentrations are about two orders of magnitude lower than found at the surface of the Moon.) This suggests that the impact may have been in the large expanse of continental run-off sediments reaching to the far northwest of Australia. In this region, an ocean regression of a few tens of metres would expose vast target areas of sediment. The return of the ocean could eradicate the evidence of a crater.

5. MANGANESE NODULES

The pelagic equivalent of tektites are manganese nodules and crusts. These objects are ferromanganese oxide concentrations that are scattered profusely about many regions of the ocean floor. Since their discovery during the Challenger expedition of the last century they have been subjected to extensive study, yet their origins are still uncertain. The report (Pettersson 1943) of ^{226}Ra unsupported by ^{230}Th, i.e. derived directly from sea water, on a very thin surface layer introduced a new puzzle, for it implied an annual growth rate of less than 10^{-3} mm a^{-1}, a value lower than the local sedimentation rate. When examined by other methods the growth rate decreased substantially from this upper limit, leaving the intriguing question of why so many of the nodules are not buried, although many are found imbedded in the sediment. ^{10}Be has furnished the most conclusive evidence yet that the annual growth rates are indeed very low, less than 10^{-5} mm a^{-1} (Turekian *et al.* 1979; Sharma & Somayajulu 1982). An explanation for this curious situation has not yet come from the ^{10}Be data, but they do hint at some significant change in oceanic conditions 7–9 Ma ago (Ku *et al.* 1982), and so the game goes on.

6. Conclusions

The change from low-level β-counting to accelerator mass spectrometry has altered the science done with ^{10}Be as remarkably as the change from proportional counter to nuclear particle accelerator has altered the instrumentation. ^{10}Be has had only a few successes as a geological clock, a use repeatedly suggested in the papers describing the invention of the accelerator technique. It has been useful in determining exposure and terrestrial ages of meteorites, and its application to pelagic sediment and manganese nodules allows dating, if the concentration falls off as a function of depth in a well-behaved manner. It settled the matter of growth rate for manganese nodules and in so doing certified the puzzling nature of these objects. But on the continental land masses its use as a clock seems to be restricted to a few soil terraces whose ages are known from other methods. Because its decay product is the ubiquitous ^{10}B, it is not possible to determine an isochron. Beryllium, not being a gas, is not taken up and homogenized by ^{9}Be as is ^{14}C by elemental C. Things will probably be dated from time to time by ^{10}Be, but it seems unlikely that it will become a standard way of determining ages.

Before the accelerator method, a large effort (Moeller & Wagener 1967) had produced only a single datum showing that the isotope was indeed to be found in soil. Such measurements are now routine, accomplished at the rate of two or three an hour. The new technique is allowing us to observe the isotope's migration about the surface of the Earth and thereby to approach with a new probe the problem of erosion and sediment transport by wind and water. It has shown itself capable of disclosing information about agricultural history. The application to tektites hints strongly at an explanation of why no crater has been found for the extraterrestrial body that is presumed to have formed the Australasian strewn field. The observation of ^{10}Be in the lavas of some island arcs and its absence in sources unrelated to subduction is a clear decision on the side of those who have long claimed to see evidence for sediment incorporation. That there is significant variation in ^{10}Be concentration from arc to arc possibly explains some of the past disputes between investigators of this subject and points to the isotope's utility in understanding the details of sediment incorporation and magma genesis.

In applications described in other papers in this symposium, ^{10}Be has been shown to be of use to investigators addressing the particularly difficult and important questions of the histories of the cosmic-ray irradiation of the Earth and of its climate, matters clearly related in the data and probably related in the cause. In pelagic sediments, the isotope is yielding remarkably unambiguous information about the nature of geomagnetic reversals. Combined with ^{26}Al it is opening new methods of examining rock weathering and glaciation, and who can guess what unforeseen applications await us.

References

Arnold, J. R. 1956 *Science, Wash.* **124**, 584.
Brown, L., Klein, J. & Middleton, R. 1985 *Geochim. cosmochim. Acta* **49**, 153–157.
Brown, L., Tera, F., Valette-Silver, N., Pavich, M. J., Klein, J. & Middleton, R. 1986 In *Proceedings of the Fourth Federal Interagency Sedimentation Conference*, section 4, pp. 10–19.
Cosper, S. W., Cerny, J. & Gatti, R. C. 1967 *Phys. Rev.* **154**, 1193–1206.
Koeberl, C. 1986 *A. Rev. Earth planet. Sci.* **14**, 323.
Ku, T. L., Kusakabe, M., Nelson, D. E., Southon, J. R., Korteling, R. G., Vogel, J. & Nowikow, I. 1982 *Nature, Lond.* **299**, 240–242.
Lundberg, L., Ticich, T., Herzog, G. F., Hughes, T., Ashley, G., Moniot, R. K., Tuniz, C., Kruse, T. & Savin, W. 1983 *J. geophys. Res.* **88**, 4498–4504.

McMillan, E. M. & Ruben, S. 1946 *Phys. Rev.* **70**, 123–126.
Meade, R. H. 1982 *J. Geol.* **90**, 235–252.
Merrill, J. R., Lyden, E. F. X., Honda, M. & Arnold, J. R. 1960 *Geochim. cosmochim. Acta* **18**, 108–129.
Moeller, P. & Wagener, K. 1967 In *Low level dating and methods of low-level counting*. Vienna: International Atomic Energy Agency.
Monaghan, M. C., Krishnaswami, S. & Thomas, J. H. 1983 *Earth planet. Sci. Lett.* **65**, 51–60.
Monaghan, M. C., Krishnaswami, S. & Turekian, K. K. 1986 *Earth planet. Sci. Lett.* **76**, 279–287.
Morris, J., Harmon, R. S., Tera, F., Lopez-Escobar, L., Klein, J. & Middleton, R. 1987 *Chem. Geol.* (In the press.)
Nyffeler, U. P., Li, Y.-H. & Santschi, P. H. 1984 *Geochim. cosmochim. Acta* **48**, 1513–1522.
Oliphant, M. L. E., Kempton, A. E. & Rutherford, Lord 1935 *Proc. R. Soc. Lond.* A **150**, 241–258.
Pal, D. K., Tuniz, C., Moniot, R. K., Kruse, T. H. & Herzog, G. F. 1982 *Science, Wash.* **218**, 787–789.
Pavich, M. J., Brown, L., Klein, J. & Middleton, R. 1984 *Earth planet. Sci. Lett.* **68**, 198–204; addendum **70**, 445–446.
Pavich, M. J., Brown, L., Valette-Silver, J. N., Klein, J. & Middleton, R. 1985 *Geology* **13**, 39–41.
Pavich, M. J., Brown, L., Harden, J., Klein, J. & Middleton, R. 1986 *Geochim. cosmochim. Acta* **50**, 1727–1735.
Pettersson, H. 1943 *Meddn. oceanogr. Inst. Göteborg* **B2**, 1–39.
Raisbeck, G. M., Yiou, F., Fruneau, M., Loiseaux, J. M., Lieuvin, M., Ravel, J. C., Reyss, J. M. & Guichard, F. 1980 *Earth planet. Sci. Lett.* **51**, 275–278.
Scott, M. R., Salter, P. F. & Halverson, J. E. 1983 *Earth planet. Sci. Lett.* **63**, 202–222.
Sharma, P., Klein, J. & Middleton, R. 1986 *Eos, Wash.* **67**, 414 (abstract).
Sharma, P. & Somayajulu, B. L. K. 1982 *Earth planet. Sci. Lett.* **59**, 235–244.
Smalley, I. J. (ed.) 1975 *Loess: lithology and genesis*. Stroudsburg, Pennsylvania: Dowden, Hutchinson & Ross.
Stensland, G. J., Brown, L., Klein, J. & Middleton, R. 1983 *Eos, Wash.* **64**, 283 (abstract).
Tanaka, S. & Inoue, T. 1980 *Earth planet. Sci. Lett.* **49**, 34–38.
Tera, F., Brown, L., Klein, J., Mason, B. & Middleton, R. 1983 *Meteoritics* **18**, 405 (abstract).
Tera, F., Brown, L., Morris, J., Sacks, I. S., Klein, J. & Middleton, R. 1986 *Geochim. cosmochim. Acta* **50**, 535–550.
Trimble, S. W. 1974 *Man-induced soil erosion on the southern Piedmont*. Ankeny, Iowa: Soil Conservation Society of America.
Turekian, K. K., Cochran, J. K., Krishnaswami, S., Lanford, W. A., Parker, P. D. & Bauer, K. A. 1979 *Geophys. Res. Lett.* **6**, 417–420.
Valette-Silver, J. N., Brown, L., Klein, J. & Middleton, R. 1986 *Earth planet. Sci. Lett.* **80**, 82–90.
Wedepohl, K. H. 1969 *Handbook of geochemistry*. Heidelberg: Springer-Verlag.
Whetstone, S. L. & Thomas, T. D. 1967 *Phys. Rev.* **154**, 1174–1181.
Yiou, F. & Raisbeck, G. M. 1972 *Phys. Rev. Lett.* **29**, 372–375.

Discussion

P. Damon (*University of Arizona, Arizona, U.S.A.*). Marc Monaghan reported at the San Francisco AGU (Monaghan *et al.* 1985) the results of a study of ^{10}Be:^{9}Be ratios in mineral separates from an Aleutian lava. His results suggested that ^{10}Be and ^{9}Be were not in isotopic equilibrium in all phases of the rock, and he interpreted this as evidence that ^{10}Be was not incorporated through sediment subduction but rather through sample alteration. Would Dr Brown comment on this?

Reference

Monaghan, M. C., Klein, J. & Middleton, R. 1985 *Eos, Wash.* **66**, 1111 (abstract).

L. Brown. Monaghan's study is based on just four measurements from one rock. His measurements were at the very limit of the ^{10}Be technique and have large uncertainties. They have not been reproduced. Unless, and until, the results are reproduced and extended to a larger sample set, the significance of this study is not clear. In contrast, our studies of oceanic island basalts show that even altered rocks from regions not associated with subduction do not contain ^{10}Be, whereas lavas collected immediately after eruption in island arcs often do. This is hard to explain by alteration but is easily explained by a subduction mechanism.