

Use of a new ^{10}Be and ^{26}Al inventory method to date marine terraces, Santa Cruz, California, USA

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ABSTRACT

Marine terraces along active continental margins reflect the interplay between sea-level oscillations and rock uplift. Well-dated marine terraces record the timing of sea-level highstands and delimit both uplift and geomorphic rates. Cosmogenic radionuclides provide a new tool for dating previously undatable terraces. Because the five marine terraces north of Santa Cruz, California, are capped by well-developed soils formed in regressive marine sands, both predepositional cosmogenic radionuclide inheritance and bioturbation of the profile must be accounted for. We present a new cosmogenic radionuclide inventory method that uses the depth-integrated cosmogenic radionuclide concentration to determine the terrace age. This method yields terrace ages that correlate well with sea-level highstands of marine oxygen isotope stages 3, 5a, 5c, 5e, and 7. The implied uplift rate is steady at 1.1 mm/yr, and is two to three times higher than rates suggested by earlier studies.

Keywords: marine terraces, geochronology, cosmogenic elements, Santa Cruz County, California.

INTRODUCTION

Marine terraces are striking stepped geomorphic features, common along actively uplifting continental margins, that form through the interaction of rock uplift and rapid, large-scale sea-level oscillations (Alexander, 1953). Dated marine terraces record the timing of sea-level highstands (e.g., Lajoie et al., 1991; Muhs et al., 1994; Rockwell et al., 1989) and can place limits on the pace of rock uplift (e.g., Bradley and Griggs, 1976; Muhs et al., 1990), landscape evolution (e.g., Hanks et al., 1984; Mizutani, 1996; Rosenbloom and Anderson, 1994), and pedogenesis (e.g., Merritts et al., 1992; Singer et al., 1992).

U-Th disequilibrium provides the least ambiguous absolute dating method, but suitable fossils such as the solitary coral *Balanophyllia elegans* are rare at middle to high latitudes. Other less precise dating methods also rely on scarce fossil material (e.g., amino acid racemization, $\delta^{18}\text{O}$ stratigraphy, and faunal assemblage correlations) primarily found in modern seacliff exposures. On flights of terraces where only the lowest terrace can be dated or dates are completely lacking, steady uplift is often assumed and the altitudinal spacing of the terraces is used to assign sea-level highstand ages (e.g., Muhs et al., 1990; Merritts and Bull, 1989; Weber, 1990). This steady-uplift model has several uncertainties: (1) the uplift rate might not have been steady over 10–100 k.y. time scales; (2) given the uncertainty in sea-level highstand ages and elevations (Muhs et al., 1994), several steady-uplift models can usually be constructed; and (3)

wave attack can completely remove a terrace (e.g., Anderson et al., 1999), eliminating the one to one correspondence between marine terraces and sea-level highstands.

Although the superbly preserved flight of five marine terraces near Santa Cruz (Fig. 1) has attracted researchers for half a century, their absolute ages have remained an open question. The marine platforms are beveled into Miocene mudstone and fine-grained sandstone and are mantled by 1–4 m of medium- to coarse-grained regressive beach sediment. No *B. elegans* fossils have been found for U-Th disequilibrium dating south of the landfall of the San Gregorio fault, and mollusks have

been found only on the first terrace. Previous researchers assign the first terrace to sea-level highstands ranging from marine oxygen isotope stage (MIS) 5a to 5e, or ca. 80–125 ka, on the basis of amino acid racemization dates (130 ± 50 ka; Lajoie et al., 1975), faunal assemblages combined with amino acid racemization measurements (5a; Kennedy et al., 1982), early U-series dating in mollusks (68–100 ka; Bradley and Addicott, 1968), terrace width (5e; Bradley and Griggs, 1976), best fit to a steady-uplift model (5a; Weber, 1990), and modeled rates of landform evolution (5e; Hanks et al., 1984). Corresponding uplift-rate estimates vary from 0.21 to 0.45 mm/yr.

Cosmogenic radionuclides (CRNs) produced in situ in the terrace cover deposits provide a new tool for dating marine terraces, because ^{10}Be and ^{26}Al accumulation in quartz acts as a clock (e.g., Nishiizumi et al., 1989). All of the terraces can potentially be dated, allowing a test of the steady-uplift assumption. We describe here the first use of CRNs to date marine terraces and the first use of CRN profiles in sandy deposits with well-developed soils (see Philips et al., 1998, for application in arid soils), where the issues of both CRN inheritance and postdepositional bioturbation must be addressed.

COSMOGENIC RADIONUCLIDE METHODOLOGY

Highly energetic cosmic rays interact with atomic nuclei at Earth's surface to create radionuclides such as ^{10}Be (time, $t_{1/2} = 1.5$ m.y., from O and Si) and ^{26}Al ($t_{1/2} = 0.7$ m.y., from Si) (Cerling and Craig, 1994). On a non-eroding surface, the production rates of ^{10}Be and ^{26}Al can be modeled as decreasing exponentially with depth (after Lal, 1988):

$$P(z) = P_0 e^{-z/\lambda^*} \quad (1)$$

where P_0 is the nuclide production rate (atoms $\text{g}^{-1}\text{yr}^{-1}$) by spallation at the surface and λ^* is a characteristic length scale of 60–110 cm for common rock and soil densities ($= \Lambda/\rho$, with $\Lambda \approx 160 \text{ g cm}^{-2}$; e.g., Brown et al., 1992). For ages much shorter than the CRN half-life, radioactive decay may be ignored. Stable rock or soil surfaces ought to display CRN concentration profiles that are the product of this exponential profile with the age of the surface.

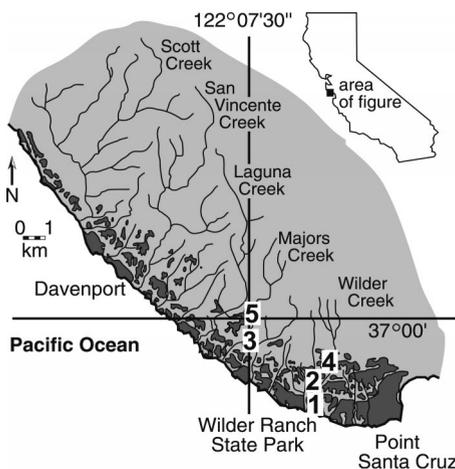


Figure 1. Location of Santa Cruz terraces, California. Gray indicates areas with capping terrace sediment and numbers indicate sample locations; 1 is youngest terrace.

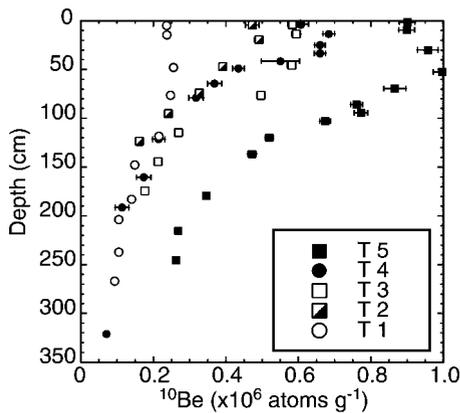


Figure 2. Measured ^{10}Be concentrations for Santa Cruz terraces T1–T5. Reported depths are averages of each ~10 cm sampling interval.

A depositional surface with a well-developed soil presents two complications: (1) inheritance of CRNs generated in the sediment during exhumation and transport, and (2) postdepositional bioturbation. With no bioturbation, a minimum of two samples is required to correct for the inheritance, one sample from the surface and the other from deep enough to have been largely shielded from postdepositional CRN production (Anderson et al., 1996; Hancock et al., 1999; Repka et al., 1997). Bioturbation complicates this simple picture by altering the postdepositional exponential profile. However, if no erosion or deposition has taken place, and soil-strain and density changes are minor, bioturbated soils should retain the same depth-integrated CRN concentration as undisturbed sediments. In other words, the inventory of in situ-produced CRNs should be conserved. To document this CRN inventory, a full concentration depth profile must be measured.

CRN INVENTORY METHOD

Determining the age T of the surface requires both the measured inventory S of CRNs and a single concentration C_d from deep enough within the profile to be undisturbed. The CRN concentration in this latter sample is

$$C_d = C_i + P_0 T e^{(-z_d/z^*)}, \quad (2)$$

where C_i (atoms g^{-1}) is the inherited CRN concentration and z_d (cm) is the depth of the sample. The measured CRN inventory S (atoms cm^{-1}) is the sum of the integrals of inheritance and postdepositional CRN ingrowth. Assuming that the inheritance is uniform throughout the profile, which should hold for rapidly deposited sediments, this inventory is

$$S = C_i z_d + T \int_0^{z_d} P_0 e^{(-z/z^*)} dz. \quad (3)$$

TABLE 1. COSMOGENIC RADIONUCLIDE INVENTORY METHOD RESULTS

Terrace	Number of samples*	Mean inheritance [†] (^{10}Be 10^4 atoms g^{-1})	Mean age [§] (ka)	Marine isotope stage (MIS)	Age (ka)
1	3	8.0 ± 0.6	65.4 ± 3.3	3	58
2	4	10.5 ± 8.6	91.6 ± 24.6	5a	84
3	3	5.5 ± 0.9	137.4 ± 3.2	5c	105
4	6	2.2 ± 3.4	138.7 ± 12.3	5e	125
5	5	16.4 ± 7.5	226.2 ± 22.4	7	212

*In undisturbed, exponential part of profile (Table B; see text footnote one).

[†]Mean and standard deviation using equation 5.

[§]Mean and standard deviation using equation 4.

Combining the measurable quantities, the age of the surface is then

$$T = \frac{S - C_d z_d}{P_0 z^* [1 - e^{(-z_d/z^*)}] - P_0 z_d e^{(-z_d/z^*)}}. \quad (4)$$

Once the age is calculated, the inheritance can be estimated by rearranging equation 2:

$$C_i = C_d - P_0 T e^{(-z_d/z^*)}. \quad (5)$$

This CRN inventory method is very general; it can be performed by using any subsurface sample below the zone of bioturbation, and is useful in both bioturbated and nonbioturbated profiles for determining the age and inherited CRN concentration of a surface.

METHODOLOGY

We sampled each of the five terraces best expressed along the coast immediately north of Santa Cruz (Fig. 1) on flat interfluvies well away from eroding cliffs. We subsampled vertical profiles of sandy soil with a hand auger at ~10 cm intervals to typically greater than 2 m depth (either down to bedrock or until encountering gravel or silica hardpan). Wet and dry soil densities were determined from piston cores collected near the sample sites. We separated quartz from the 250–500 μm grain-size fraction (Kohl and Nishiizumi, 1992) and used standard procedures to prepare ^{10}Be and ^{26}Al targets for measurement on the Lawrence Livermore National Laboratory accelerator mass spectrometer. Measured $^{10}\text{Be}/\text{Be}$ and $^{26}\text{Al}/\text{Al}$ ratios were normalized to the ICN ^{10}Be and the National Bureau of Standards (NBS) ^{26}Al standards.

RESULTS

Higher terraces display greater surface CRN concentrations, consistent with increasing age with elevation (Fig. 2). The ^{26}Al and ^{10}Be concentrations are mutually consistent, exhibiting the expected spallation production ratio of ~6:1 (Clark et al., 1995; Nishiizumi et al., 1996). The measured profiles display exponentially decreasing concentrations below a relatively homogeneous 0.5–1.5-m-thick near-surface layer. The predepositional CRN inheritance deduced from the asymptotic concentrations at depth varies among the terraces.

Although the youngest terrace has a nearly uniform near-surface concentration, the other profiles display a subtle maximum in the middle of this nonexponential layer.

INTERPRETATION

We first use the in situ CRN inventory method to estimate ages (equation 4) and inheritance (equation 5) (Table 1). This calculation is made for all samples (Tables A and B¹); S is determined by numeric integration. The undisturbed part of each profile is then defined as including those samples that display similar age and inheritance. We assume a long-term sea-level, high-latitude ^{10}Be production rate in quartz of 5.55 atoms $\text{g}^{-1}\text{yr}^{-1}$, ~7% higher than the short-term sea-level, high-latitude production rate of ~5.2 atoms $\text{g}^{-1}\text{yr}^{-1}$ over 10–13 k.y. (e.g., Kubik et al., 1998; Nishiizumi et al., 1996). These calculations do not include the density changes associated with soil strain; scaling suggests that these effects would alter the apparent ages of the Santa Cruz terraces by at most a few thousand years.

Terrace ages are assigned by averaging the CRN inventory method-based ages for all samples within the exponential profiles. These match the sea-level highstands of marine isotope stage (MIS) 3, 5a, 5c, 5e, and 7 to within 10%, with the exception of terrace 3. It is important to note that the pattern of ages—tight clustering of ages of the lowest four terraces and a much older age of the fifth terrace—can only be matched by these particular sea-level highstands. Even considering uncertainties in CRN production rates and cosmic ray absorption length, the match of ages with known highstands is very good. These ages correspond to a nearly steady uplift rate of ~1.1 mm/yr (Fig. 3).

Terrace 3 appears to be too old for MIS 5c, despite its proper elevation. Extensive removal of terrace 3 along the coastline due to cliff backwearing greatly limited sample site selection. The import of terrace sediment from the

¹GSA Data Repository item 2001102, Depth profile ^{10}Be concentrations and CRN inventory method calculations, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

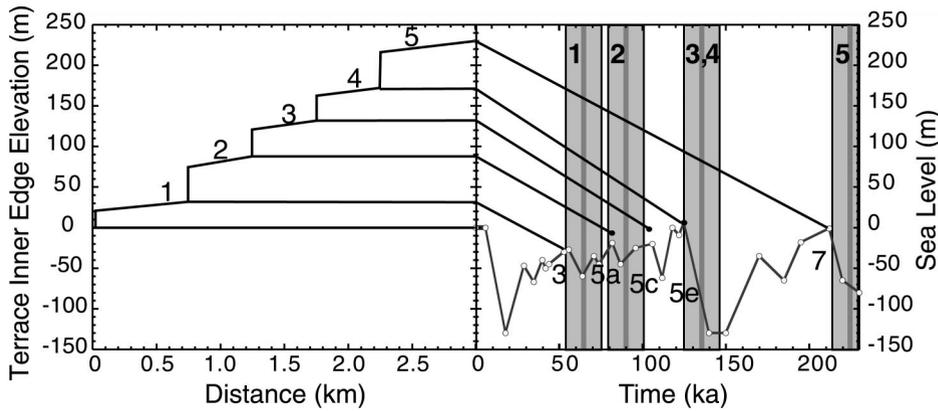


Figure 3. Uplift model using terrace ages corresponding to marine isotope stages (MIS) 3, 5a, 5c, 5e, and 7. **Left:** Terrace inner edge elevations near sample sites (Anderson and Menking, 1994) and approximate local terrace widths. **Right:** Sea-level history since 225 ka from Papua New Guinea (Chappel and Shackleton, 1986), augmented (black circles) with MIS 5 sea-level elevations for California (Muhs et al., 1994). Dark gray lines: cosmogenic radionuclide ages with light gray error boxes of ± 10 k.y. Slope of lines connecting present inner edge elevation with appropriate sea-level highstand elevation give uplift rates, indicating steady uplift of 1.1 mm/yr over past 250 k.y.

strong degradation of terrace 4 immediately above this site could explain the higher calculated age. The CRN concentration profile of terrace 2 displayed the poorest exponential form at depth, the sediment cover at the sample site being perhaps too thin to preserve a distinct undisturbed part of the profile.

Several meters of erosion would be required to reconcile the measured CRN inventories with the previously proposed older ages of the terraces. Such erosion is unlikely because (1)

we specifically chose sites that do not show topographic evidence of significant erosion, and (2) the original capping regressive marine sands were initially only a few meters thick (Bradley, 1957), whereas our profile samples are typically at least 2 m deep. Sediment cover does not decrease on older terraces. We can also make use of the CRN profile shape to define the degree to which erosion might have altered the inventory. On undisturbed surfaces, erosion strips off the high-CRN concentra-

tion surface, reducing the CRN inventory while not affecting the exponential profile. However, bioturbation moves low CRN concentration sediments upward so that erosion will strip away less of the CRN inventory. Erosion therefore creates a mismatch between the integral of the CRN concentration in the bioturbated layer and the integral expected by extrapolating upward the exponential part of the profile. We see no such mismatch in our measured profiles (Fig. 4).

We argue that the nonexponential near-surface part of the profile is due to bioturbation, rather than input of eolian sand or colluvium from degradation of older terraces. First, the nonexponential part of the profile is typically 0.5–1.5 m, which corresponds well with typical maximum depths of gopher burrows (e.g., Litaor et al., 1996). Evidence against eolian input includes (1) no morphological evidence for sand dunes, except within meters of the modern seacliff edge, (2) no sharp change in grain size or chemical composition between the exponential and nonexponential parts of the profile (Art White, 2000, personal commun.), and (3) measurement of CRN concentrations in 250–500 μm grains that are much larger than typical eolian material. Evidence against blanketing of the entire terrace with colluvium includes (1) distinct colluvial apron morphology, which we have avoided in our sampling, and (2) lack of progressive decline in marine sediment cover

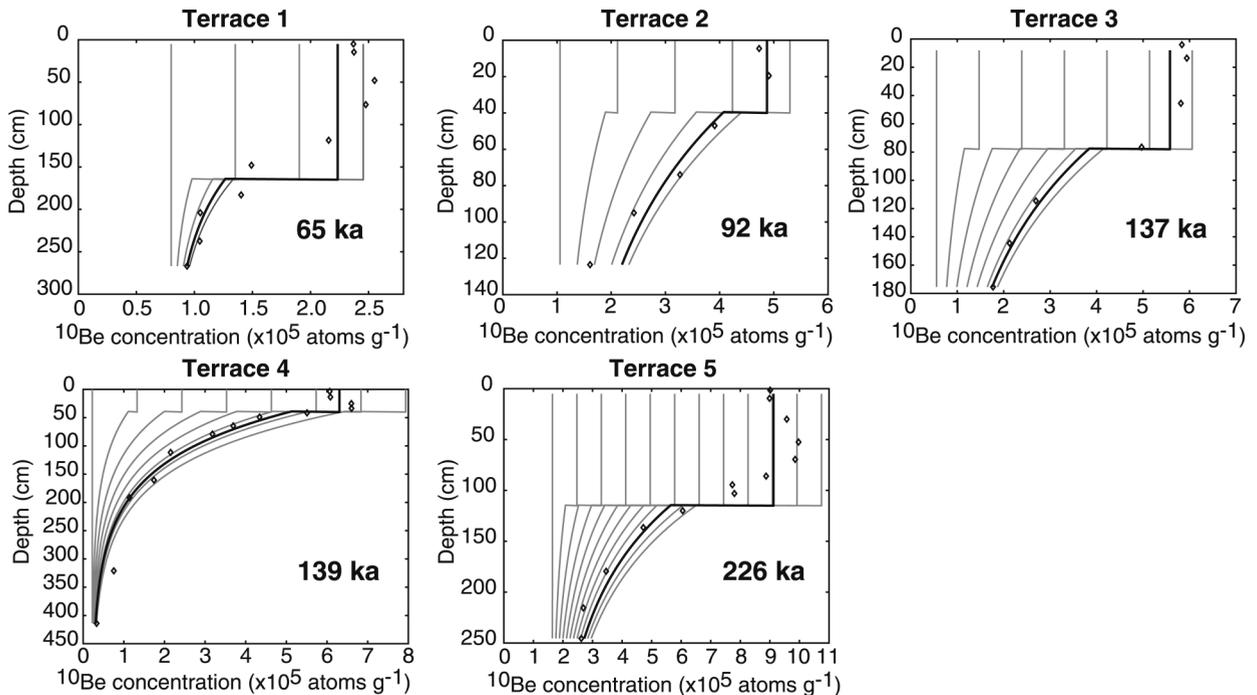


Figure 4. Numerical model of ^{10}Be profile evolution, shown at 25 k.y. intervals (gray lines), with measured cosmogenic radionuclide (CRN) profiles (black diamonds). Model includes uniform inheritance, steady CRN production, and bioturbation, assumed to homogenize CRN concentrations over fixed depth. Inheritance is set using mean inheritance calculated from equation 5 (Table 1; gray line labeled 0 ka). $P_{0,\text{SLHL}} = 5.55 \text{ atoms g}^{-1}\text{yr}^{-1}$; $z^* = 84\text{--}100 \text{ cm}$, depending on average density of soil profile (see text). Bold black line indicates analytic model ages (equation 4; Table 1).

thickness with terrace age. We believe that deposition of exactly the quantity and concentration of sediment needed to match the CRN inventory expected from the exponential portion of all five profiles is highly unlikely.

The CRN concentration in the modern Santa Cruz littoral cell ($5\text{--}10 \times 10^4$ ^{10}Be atoms g^{-1}) provides a comparison for the inherited component in the terrace sands ($2\text{--}16 \times 10^4$ ^{10}Be atoms g^{-1} , Fig. 4). The modern littoral cell has two sandy inputs: rivers (2×10^4 ^{10}Be atoms g^{-1}) and terrace deposits capping seacliffs (18×10^4 ^{10}Be atoms g^{-1}). The variability in concentration of past beaches could be explained by differences in the CRN concentrations of the recycled terrace sediments that depend on the exposure age of the terrace being cannibalized at that time.

CONCLUSIONS

We have shown that the CRN inventory method works in bioturbated sandy soils. It can be employed on a wide range of otherwise undatable depositional surfaces. The Santa Cruz terrace dates are internally consistent. They are younger than estimated in previous studies: the youngest terrace correlates with the MIS 3 highstand rather than with any of the stage 5 highstands. The implied uplift rate of 1.1 mm/yr is several times higher than inferred in earlier studies, and appears to have been steady over at least 250 k.y. This higher uplift rate is in accord with geodetic studies of the Santa Cruz Mountains: local coastline uplift rates of 0.8 mm/yr, plus 40 mm of uplift in the 1989 Loma Prieta earthquake (e.g., Bürgmann et al., 1994). These younger terrace ages also imply faster degradation rates for the Santa Cruz terraces, including as much as two-fold increases in estimated rates of paleocliff degradation (Hanks et al., 1984), pedogenesis (Singer et al., 1992), and stream incision (Rosenbloom and Anderson, 1994).

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