Improving In-situ Cosmogenic Chronometers

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New radiocarbon ages for Sierra Nevada deglaciation, the first 10Be measurements from the Laurentide terminal moraine, and calculations of magnetic field strength have the potential to substantially improve the accuracy of cosmogenic age estimates. Specifically, three new constraints apply to the interpretation of measured abundances of in situ cosmogenic 10Be and 26Al: (1) A suite of minimum-limiting radiocarbon dates indicates that the Sierra Nevada was deglaciated at least several thousand years earlier than assumed when Nishizumi et al. (1989) first calibrated 10Be and 26Al production rates based on polished bedrock surfaces in the range, with retreat beginning by 18,000 cal yr B.P. and completed by 13,000 cal yr B.P. (2) Concentrations of 10Be in moraine boulders and glacier-polished bedrock in New Jersey show little variance (10%, 1σ) and can be used to calculate a preliminary 10Be production rate (integrated over the past 21,000–22,000 cal yr B.P. at 41°, 200–300 m altitude) that is about 20% lower than currently accepted. (3) Calculations of the effect of past geomagnetic field-strength variations on production rates suggest that the use of temporally averaged production rates may generate age errors of >20%; however, to cosmogenic exposure ages can be corrected for this effect, although the corrections currently are imprecise. Many previously reported late-Pleistocene 10Be and 26Al exposure ages are probably too young and are less accurate and less precise than implied by reported uncertainties. The discrepancy between accepted production rates and those calculated from Laurentide exposures, when considered together with the Sierra declaglacial chronology and the model results, suggest that correlations between cosmogenic and other numerical ages, especially brief events like the Younger Dryas and Heinrich events, will not be robust until temporal variations and the altitude/latitude scaling of production rates are fully understood and quantified at levels comparable to current analytic uncertainties (−3%). ©1995 University of Washington.

INTRODUCTION

Measurement of nuclides produced by cosmic-ray bombardment of surficial deposits and exposed bedrock is rapidly becoming an important tool in paleoclimatology, geomorphology, and other physical sciences. In particular, such measurements have been used to determine the age of otherwise undatable landforms, to estimate rates of surface processes, and to correlate geologic, climatologic, and tectonic events (e.g., Bierman, 1994; Cerling and Craig, 1994a; Nishizumi et al., 1993). As the precision of isotopic measurements, and thus the apparent precision of calculated exposure ages, has improved in the past several years, studies have increasingly attempted to date and correlate short-lived, particularly climate-related, events across wide regions (e.g. Clark and Bartlein, 1995; Easterbrook, 1994; Evenson et al., 1994; Gosse et al., 1995; Phillips and Zreda, 1992). The reliability of such dating, and of any resulting correlations, depends directly upon the accuracy and precision of the isotope production rates from which exposure ages are calculated.

Typically, time-integrated, “average” isotope production rates are determined empirically from geomorphic surfaces of “known” age (Cerling and Craig, 1994b). Those production rates are assumed to be constant when calculating exposure ages. Because geomagnetic field strength, and therefore isotope production rates, at latitudes <50° have varied in the past (Cerling and Craig, 1994a, 1994b; Kurz et al., 1990; Mazaud et al., 1991; McElhinny and Senanayake, 1982, Weeks et al., 1995), the use of average production rates will, in most cases, generate systematic errors in calculated cosmogenic exposure ages. Furthermore, geomagnetically induced production rate variability and the associated systematic errors in calculated exposure ages are complexly related to the latitude, altitude, and exposure age of sample and calibration sites.

Our research shows that uncertainties in ages of calibration surfaces and geomagnetic field strength variations contribute substantial and typically unstated errors to cosmogenic age estimates. New radiocarbon ages demonstrate that the assumed exposure age of glaciated Sierra Nevada rocks, used to calibrate late-Pleistocene and Holocene production rates for 10Be and 26Al (Nishizumi et al., 1989), is probably at least 20% too young. Preliminary 10Be data from the Laurentide terminal moraine in New Jersey support this finding and, along with the Sierra radiocarbon data, imply that many exposure ages calculated using previously accepted production rates are also too young. Calculations based on proxy records of geomagnetic field strength suggest that even if calibration sites were cor-
rectly dated, field-strength and attendant production-rate variations may generate age errors >20% over the past ~100,000 yr for all in situ isotope systems if time-averaged production rates are used to calculate exposure ages.

These findings indicate that inaccuracy in calculated cosmogenic exposure ages is significantly greater than previously suggested by analytic precision (typically 3--8%) or by the lowest variance so far associated with multiple samples from a monogenetic landform (4%, Gosse et al., 1995, p. 1330). We conclude that the variety and magnitude of systematic uncertainties, illustrated by our data and calculations, currently prohibit rigorous cosmogenic dating or correlation of short-lived events such as the Younger Dryas climatic reversal or North Atlantic Heinrich events.

**10Be and 26Al production rates and a revised glacial chronology for the Sierra Nevada**

_in situ_ isotope production rates have been estimated in two ways: theoretically using excitation functions (Lal, 1991) and empirically by analyzing samples exposed to the cosmic ray flux for discrete time periods. For the latter method, Yokoyama et al. (1977) estimated a variety of short-term (years) production rates on the basis of Na isotopes produced in Al targets at high altitudes. Long-term production rates (millennia), which we discuss in this paper, have typically been calibrated on glacially polished bedrock, morainal boulders, or lava flows. Several assumptions underlie such long-term calibrations: (1) the calibration site was instantaneously exposed at a known time in the past; (2) the site has no isotopic inheritance from previous exposure; (3) the sample has not been significantly buried after exposure (e.g., by loess, till, or snow); and (4) the sampled surface has not eroded since exposure. In this section, we discuss the effect that changes in the first criterion may have on previously accepted production rates for 10Be and 26Al.

Nishizumi et al. (1989) made the first calibration of _in situ_ cosmogenic 10Be and 26Al by collecting samples of glacially polished granite in the Sierra Nevada and by assuming that their three sample sites (37°59' N, 3180 m altitude; 37°25' N, ~3550 m; 38°52' N, ~2440 m; Fig. 1) were deglaciated 11,000 calibrated (or sidereal) years ago (11,000 cal yr B.P.). This exposure-age estimate was based on minimum-limiting conventional radiocarbon ages of ~10,000 14C yr B.P. on basal bulk sediments from two sites, a lake and a meadow, dammed behind Tioga (last late-Wisconsin maximum) recessional moraines (Table 1; Adam, 1967; Mezger and Burbank, 1986). On the basis of this estimated age, Nishizumi et al. reported sea-level, high-latitude production rates in quartz of 6.03 and 36.8 atoms g^-1 year^-1 for 10Be and 26Al, respectively, assuming that the modern geomagnetic latitude of the samples (44°) was representative of their geomagnetic latitude since exposure. Although Nishizumi et al. reported uncertainties (p. 17,913) in both the timing of deglaciation (±5%) and the temporal stability of the geomagnetic field (potential production rate decrease of ~15%), most subsequent 10Be and 26Al studies rely on Nishizumi et al.'s production rates without acknowledging the full geologic and geomagnetic uncertainties inherent in the original calibration, despite commonly discussing in detail other sources of potential error (e.g., Evenson et al., 1994; Gosse et al., 1993; Macfarloli et al., 1994; McCuaig et al., 1994; Nishizumi et al., 1993).

New 14C ages for Sierra Nevada deglaciation suggest that the production rates of Nishizumi et al. are at least 20% too high because the age of exposure they chose was too young. Calibrated ages (Bard et al., 1990; Stuiver and Reimer, 1993) of twelve radiocarbon dates, of basal or near-basal lake sediments from cores of 10 postglacial lakes, show that Sierra Nevada deglaciation was underway by 19,000--16,000 cal yr B.P. and that the mountain range was deglaciated before ~13,100 cal yr B.P. (Table 1). All coring sites listed in Table 1 lie inside the maximum Tioga ice limits, as do the two used by Nishizumi et al. and thus provide minimum ages for onset of deglaciation (Fig. 1). It is the highest sites, however, near the crest of the range, that provide minimum ages for the complete deglaciation of the range and thus minima for the exposure age of sites sampled by Nishizumi et al.; furthermore, many are closer to the 10Be and 26Al calibration sites than are the two coring sites cited by Nishizumi et al. Together, the twelve radiocarbon dates indicate that Tioga deglaciation in the Sierra Nevada occurred at least 2000 cal yr before 11,000 cal yr B.P.

The timing of full deglaciation is particularly important for evaluating the actual exposure age of Nishizumi et al.'s calibration sites and is demonstrated by a pair of high-precision AMS radiocarbon dates from Baboon Lakes, a series of tarns formed behind a set of small moraines in the headwaters of Middle Fork Bishop Creek (Fig. 2). The moraines surrounding these lakes correlate with the Recess Peak advance (Birman, 1964; Clark et al., 1994; Clark and Gillespie, 1994, in press), previously thought to be a late-Holocene Neoglacial event (e.g., Burke and Birkeland, 1983; Davis, 1988). The new ages from the two Baboon Lakes cores demonstrate that Recess Peak is actually a late-Pleistocene advance.

Clark and Gillespie (1994; in press) have mapped Recess Peak deposits along the crest of the Sierra from Lake Tahoe to the southern limit of glaciation (Fig. 1), and the sites sampled by Nishizumi et al. (1989) all lie downstream from Recess Peak moraines in those drainages. Thus all sites used to calibrate the production of _in situ_ 10Be and 26Al were deglaciated before the onset of the Recess Peak advance. The minimum limiting dates from Baboon Lakes, in conjunction with the other dates in Table 1, indicate that Tioga ice in the Sierra retreated to the crest of the range, and Recess Peak glaciers then advanced and disappeared, all before ~13,100 cal yr B.P. (Clark, 1976; Clark and Gillespie, 1994, in press).

The accuracy and precision of the Baboon Lakes dates are supported by seven other internally consistent AMS radiocarbon dates that are higher in the two cores. Moreover, dates on adjacent gytta, wood chips, and charcoal are indistinguishable
within analytic error (typically <1%, 1σ), indicating the gyttja has been neither disturbed nor contaminated since deposition. Sixteen internally consistent dates on macrofossils, gyttja, peat, and tephra from cores of four other similar tarns elsewhere in the Sierra further support the accuracy of such lake sediments for radiocarbon dating (Clark and Gillespie, 1994; in press). The lack of any significant sources of "old" carbon in the granitic basins upstream of the lakes indicates that all dates of Clark and Gillespie are minima for deglaciation.

Considering the new age limits for Recess Peak glaciation and deglaciation and the other minimum limiting dates for substantial Tioga deglaciation (e.g., Highland Lakes on the Sierran crest by 15,500 cal yr B.P.; R. Byrne, written communication, 1994; Table 1), we infer that late-Wisconsin deglaciation of the Sierra was completed by 13,000 to 15,000 cal yr B.P., rather than 11,000 cal yr B.P. Therefore, exposure ages calculated from Nishiizumi et al.'s (1989) production rates are systematically too young unless compensated by other unrecognized errors. Using the conservative estimate that Nishiizumi et al.'s sites were deglaciated 13,000 cal yr B.P., integrated production rates (sea level, high latitude) for 10Be and 26Al would be 5.10 and 31.1 atoms g⁻¹ yr⁻¹, respectively, about 20% lower than those reported by Nishiizumi et al. Considering that Nishiizumi et al.'s sites were probably exposed earlier than the minimum age for the Recess Peak advance (Clark and Gillespie, 1994, in press), we feel 14,000 cal yr B.P. is a better estimate for their deglaciation, indicating production rates of 4.74 and 28.9 atoms g⁻¹ year⁻¹ for 10Be and 26Al, respectively.

**LAURENTIDE TERMINAL MORAINE**

As an independent test of our revision of the Sierra Nevada 10Be and 26Al production-rate calibrations, we measured 10Be concentrations in a suite of rock samples from on and near the late-Wisconsin terminal moraine in west-central New Jersey. Radiocarbon dates, stratigraphic evidence, and palynological studies from lacustrine and bog-bottom sediments near the moraines provide minimum limiting ages for deglaciation of the area, and thus for exposure of our sample sites.

We analyzed 15 rock samples from the Laurentide moraine, including five replicates (Table 2). Five samples are from striated and polished outcrops of quartzite, as well as gneissic outcrops that show glacier-shaped forms but which are no longer polished or striated; five samples are from the tops of large (>2 m) quartzite and gneissic boulders, none of which preserve polish but all of which show minimal weathering-related erosion (probably <5 cm) as indicated by the relief of phenocrysts and quartz veins. We sampled areas where surrounding till was thin in order to minimize the possibility that an outcrop had been covered for part of its exposure history.

Samples were prepared at the University of Vermont and accelerator mass spectrometric analyses were made at Lawrence Livermore National Laboratory. Quartz was purified by density separation and ultrasonic acid-etching. Twenty to thirty grams of quartz was dissolved with 250–400 μg of commercial Be carrier. Be and Al were separated using cation exchange. Measured isotopic ratios, corrected for interfering isotopes, ranged from 46 to 235 × 10⁻¹⁵ after subtraction of our long-term measured carrier and massing blank of 24.5 ± 9.4 × 10⁻¹⁵. Geometrical corrections were applied for dipping surfaces according to the flux relationship of sin 2θ.

Several lines of evidence place limits on the age of the Laurentide terminal moraine in New Jersey. Cotter (1984) determined that the Ontario Lobe of the Laurentide ice sheet began to retreat before 18,500 14C yr B.P. on the basis of radiocarbon-dated basal lacustrine sediments that were characterized by a tundra pollen assemblage. Cotter's samples were collected north of ours and should thus underestimate the exposure age of our samples. Oldale and Stone (1987) concluded that the ice in New Jersey reached its maximum limit 21,000–
TABLE 1

Minimum Limiting Radiocarbon Dates for Deglaciation of the Sierra Nevada, California

<table>
<thead>
<tr>
<th>Location</th>
<th>Lab. number</th>
<th>N Latitude</th>
<th>W Longitude</th>
<th>Altitude (m)</th>
<th>Geologic setting of cored lake</th>
<th>Dated material</th>
<th>Basal date (14C yr B.P.)</th>
<th>Basal date (cal yr B.P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swamp Lake, N. Fork</td>
<td>Unknown</td>
<td>38°22'</td>
<td>120°08'</td>
<td>1957</td>
<td>Dammed within Tioga lateral moraines</td>
<td>Outwash silts</td>
<td>15,565 ± 820†</td>
<td>17,638–19,294</td>
</tr>
<tr>
<td>Stanislaus River†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dammed within Tioga lateral moraines</td>
<td>Organic silt</td>
<td>14,750 ± 500†</td>
<td>17,080–18,180</td>
</tr>
<tr>
<td>Lake Morain, N Fork</td>
<td>Unknown</td>
<td>38°30'</td>
<td>120°08'</td>
<td>2017</td>
<td>Dammed within Tioga recessional moraines</td>
<td>Organic silt and sand</td>
<td>13,690 ± 340†</td>
<td>15,948–16,838</td>
</tr>
<tr>
<td>Stanislaus River†</td>
<td>Beta-27895</td>
<td>37°57'</td>
<td>119°49'</td>
<td>1554</td>
<td>Dammed within Tioga recessional moraines</td>
<td>Organic sediments</td>
<td>15,230 ± 470†</td>
<td>17,652–18,604</td>
</tr>
<tr>
<td>Swamp Lake, Tuolumne River</td>
<td>Beta-27895</td>
<td>37°57'</td>
<td>119°49'</td>
<td>1554</td>
<td>Dammed within Tioga recessional moraines</td>
<td>Organic silt (~530 cm sediment depth)</td>
<td>15,230 ± 470†</td>
<td>17,652–18,604</td>
</tr>
<tr>
<td>&quot;Granite Gorge&quot; pond,</td>
<td>CAMS-11388</td>
<td>36°59'</td>
<td>119°00'</td>
<td>1980</td>
<td>Damaged at Tioga recessional moraines</td>
<td>Glaize (267 cm sed. depth)</td>
<td>11,700 ± 60†</td>
<td>13,531–13,766</td>
</tr>
<tr>
<td>N. Fork Kings River†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Glaize (259 cm sed. depth)</td>
<td>11,690 ± 60†</td>
<td>13,520–13,754</td>
</tr>
<tr>
<td>Bunker Lake, Rubicon River</td>
<td>Unknown</td>
<td>39°00'</td>
<td>120°20'</td>
<td>1995</td>
<td>Dammed at Tioga recessional moraines</td>
<td>Organic silt</td>
<td>11,240 ± 180†</td>
<td>12,910–13,230</td>
</tr>
<tr>
<td>Upper Echo Lake</td>
<td>USGS-1076</td>
<td>38°50'</td>
<td>120°03'</td>
<td>2260</td>
<td>Damaged at Tioga recessional moraines</td>
<td>Organic silt</td>
<td>11,100 ± 70†</td>
<td>12,929–13,094</td>
</tr>
<tr>
<td>Upper Truckee River†</td>
<td>Unknown</td>
<td>31°49'</td>
<td>119°48'</td>
<td>2625</td>
<td>Damaged at Tioga recessional moraines</td>
<td>Organic silt</td>
<td>11,360 ± 70†</td>
<td>13,218–13,619</td>
</tr>
<tr>
<td>Highline Lk., N. Fork</td>
<td>A-4456</td>
<td>37°56'</td>
<td>119°00'</td>
<td>2816</td>
<td>Damaged at Tioga recessional moraines</td>
<td>Organic silt</td>
<td>11,730 ± 430†</td>
<td>13,204–14,204</td>
</tr>
<tr>
<td>Stanislaus River†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Glaize (259 cm sed. depth)</td>
<td>11,190 ± 70†</td>
<td>13,015–13,187</td>
</tr>
<tr>
<td>Barre Lake, Mammoth Creek</td>
<td>CAMS-11382</td>
<td>37°10'</td>
<td>118°37'</td>
<td>3385</td>
<td>Damaged at Tioga recessional moraines</td>
<td>Glaize (267 cm sed. depth)</td>
<td>10,880 ± 60†</td>
<td>12,727–12,882</td>
</tr>
<tr>
<td>Babcuk Lk. 1, Middle Fork</td>
<td>CAMS-11382</td>
<td>37°10'</td>
<td>118°37'</td>
<td>3385</td>
<td>Damaged at Tioga recessional moraines</td>
<td>Glaize (259 cm sed. depth)</td>
<td>10,880 ± 60†</td>
<td>12,727–12,882</td>
</tr>
<tr>
<td>Bishop Creek†</td>
<td>CAMS-11383</td>
<td>37°10'</td>
<td>118°37'</td>
<td>3385</td>
<td>Damaged at Tioga recessional moraines</td>
<td>Glaize (259 cm sed. depth)</td>
<td>10,880 ± 60†</td>
<td>12,727–12,882</td>
</tr>
<tr>
<td>Osgood Swamp†, Upper</td>
<td>A-345</td>
<td>38°51'</td>
<td>120°02'</td>
<td>1985</td>
<td>Damaged at Tioga recessional moraines</td>
<td>Glaize (259 cm sed. depth)</td>
<td>10,890 ± 60†</td>
<td>12,730–12,882</td>
</tr>
<tr>
<td>Truckee River†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Glaize (259 cm sed. depth)</td>
<td>10,990 ± 60†</td>
<td>12,730–12,882</td>
</tr>
<tr>
<td>Cottonwood Lk*</td>
<td>Beta-??</td>
<td>36°28'</td>
<td>118°10'</td>
<td>2880</td>
<td>Damaged at Tioga recessional moraines</td>
<td>Glaize (259 cm sed. depth)</td>
<td>10,640 ± 160†</td>
<td>12,383–12,738</td>
</tr>
</tbody>
</table>

* Sites used for calibration of Nishizumi et al. (1989).
† Conventional radiocarbon age.
‡ AMS radiocarbon age.
§ Batchelder (1980).
‡ Smith and Anderson (1992).
& Clark (this study).
(3) Adam (1985).
(4) Byrne (1994; written communication).
(6) Clark and Gillespie (in press).
(7) Adam (1985).
(8) Merz and Burbank (1986).

20,000 14C yr B.P., using 14C dates on wood, bone, horn, peat, shells, and bulk-sediment samples. Evenson et al. (1983) used radiocarbon dates, stratigraphic relationships, and palynological evidence to argue that ice began to retreat from the terminal moraine in New Jersey before 18,000 14C yr B.P. Matsch (1987) also concluded that the growth of the Laurentide ice sheet ceased by 20,000 14C yr B.P. and that parts of the southern margin were retreating by 18,000 14C yr B.P. Sirkin (1977), estimating deposition rates for sediments below radiocarbon-dated sedimentary horizons, suggested that recession from northern New Jersey began about 18,000 14C yr B.P. On the basis of the data cited above, we tentatively adopt an exposure age of at least 18,500 14C yr B.P. for the boulders and outcrops we sampled; our adoption of this minimum exposure age is based primarily on the minimum limiting ages of Cotter (1984). We believe such a minimum limiting age is a conservative interpretation. Data recently presented by Stone (1995) suggest that Laurentide retreat from New Jersey may have begun prior to 20,000 14C yr B.P. Correcting the Cotter age for variation in atmospheric 14C content (Bard et al., 1990; Stuiver et al., 1991; Stuiver and Reimer, 1993) indicates a calibrated exposure age for our samples of 21,000–22,000 cal yr B.P. We therefore have adopted an exposure age of 21,500 cal yr B.P. for our production-rate calibration.
We chose sample sites based on several criteria that could significantly affect the abundances of cosmogenic nuclides, including (1) the absence of till cover, (2) boulder stability since deposition, and (3) little or no erosion of the rock surface since deglaciation. To ensure that a boulder had not been moved or covered with till since deglaciation, only the largest boulders and those sitting atop ridges were sampled. Bedrock sample sites all lie on prominent ridge tops where till is less likely to have persisted. These characteristics also lessened the chance of shielding due to significant snow cover. Ubiquitous and well-preserved glacial striations on the quartzite indicate that it is more resistant to weathering than is gneiss, the other sampled lithology. The sample quartzite is extremely hard and dense; few quartzite surfaces are significantly weathered. Rough surfaces, lack of preserved striations, and relief of quartz veins indicate that gneissic boulders and outcrops are
more weathered; however, similar isotopic abundances in the quartzite and gneiss samples suggest that the magnitude of such weathering (and consequent erosion) has been negligible since deglaciation.

The average concentration of 10Be in the five boulder and five bedrock samples is similar (Table 2) and averages 1.02 ± 0.10 × 10^5 atoms g^-1 (1σ). Replicate measurements of five samples agree within 1σ uncertainties. If two sigma errors are considered, all ten bedrock and boulder samples are indistinguishable. If the exposure age of these samples is 21.500 cal yr, we calculate a preliminary sea-level, high-latitude production rate of 4.76 ± 0.47 10Be atoms g^-1 yr^-1 (1σ of mean). We caution that this estimate is tentative and that the values we calculate may change as we analyze additional samples. The full data set including detailed site descriptions will be published elsewhere.

The sea level, high-latitude 10Be production rate we calculate is 21% lower than that calculated by Nishiizumi et al. (1989; 6.03 10Be atoms g^-1 yr^-1) and could be variously interpreted to indicate that: (1) radiocarbon minimum limiting ages of the Laurentide moraine in New Jersey are too old; (2) Laurentide boulders and outcrops have been covered by till or snow, or have eroded so as to lower measured isotope abundances; or (3) the rate of 10Be production over the past 21,500 yr is lower than previously thought. The latter interpretation seems most likely because: (1) the limiting ages on the Laurentide moraine are basal bog dates that probably underestimate rather than overestimate the true age of retreat; (2) the likelihood of a variety of outcrops and boulders, some polished, others unpolished, some gneissic, others quartzite, recording similar isotope abundances seems small if such abundances were partly controlled by idiosyncratic effects such as erosion, snow cover, or till cover; and (3) the production rate we calculate from the Laurentide moraine agrees closely with our revised Sierran calibration.

### Table 2: 10Be Samples from the Laurentide Terminal Moraine

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lithology</th>
<th>Location</th>
<th>Elevation (m)</th>
<th>Thickness (cm)</th>
<th>Elevation correction</th>
<th>Slope (degrees)</th>
<th>Quartz (g)</th>
<th>Carrier (μg)</th>
<th>10Be/Be (x10^-16) (sea level, high latitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWR-B-8</td>
<td>Gneiss</td>
<td>Weldon Rd.</td>
<td>375</td>
<td>3</td>
<td>1.32</td>
<td>0</td>
<td>20.04</td>
<td>243</td>
<td>159 ± 12</td>
</tr>
<tr>
<td>SWR-B-4X</td>
<td>Gneiss</td>
<td>Weldon Rd.</td>
<td>375</td>
<td>3</td>
<td>1.32</td>
<td>0</td>
<td>29.86</td>
<td>232</td>
<td>235 ± 13</td>
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<tr>
<td>SMR-B-9</td>
<td>Gneiss</td>
<td>Lk. Denman</td>
<td>253</td>
<td>2.5</td>
<td>1.19</td>
<td>15</td>
<td>15.66</td>
<td>235</td>
<td>103 ± 12</td>
</tr>
<tr>
<td>SMR-B-9X</td>
<td>Gneiss</td>
<td>Lk. Denman</td>
<td>253</td>
<td>2.5</td>
<td>1.19</td>
<td>15</td>
<td>32.69</td>
<td>254</td>
<td>215 ± 14</td>
</tr>
<tr>
<td>SAP-B-10</td>
<td>Gneiss</td>
<td>Allamuchy</td>
<td>323</td>
<td>2.5</td>
<td>1.25</td>
<td>25</td>
<td>18.05</td>
<td>233</td>
<td>135 ± 13</td>
</tr>
<tr>
<td>SAP-B-11</td>
<td>Gneiss</td>
<td>Allamuchy</td>
<td>323</td>
<td>5</td>
<td>1.25</td>
<td>0</td>
<td>22.36</td>
<td>249</td>
<td>185 ± 13</td>
</tr>
<tr>
<td>SAP-B-12</td>
<td>Gneiss</td>
<td>Allamuchy</td>
<td>323</td>
<td>3</td>
<td>1.25</td>
<td>0</td>
<td>28.23</td>
<td>391</td>
<td>144 ± 12</td>
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<td>SPA-O-2X</td>
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<td>46 ± 11</td>
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<tr>
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<td>1.28</td>
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<tr>
<td>SPA-O-6X</td>
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<tr>
<td>SAF-O-13</td>
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<td>30</td>
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<td>90 ± 11</td>
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<td>1.24</td>
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<td>17.06</td>
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<td>113 ± 11</td>
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<tr>
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<td>27.68</td>
<td>243</td>
<td>244 ± 23</td>
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</tbody>
</table>

Note. B, boulder; O, outcrop; X, replicate sample; L, 165 g cm^-2; rock density assumed to be 2.7 g cm^-3.

**Modeling Changes in Production Rates**

The accuracy and precision of calculated production rates are affected not only by the assumed exposure age of calibration sites, as shown above, but also by temporal changes in the strength of Earth's geomagnetic field, which modulates the flux of incoming primary cosmic radiation; e.g., high field strength diminishes the abundance of cosmic rays penetrating the atmosphere and reaching the Earth's surface and thus lowers in situ isotope production rates. Many studies have documented field strength changes during the Pleistocene and the impact of these changes on isotope production rates, primarily in the atmosphere (Bard et al., 1990; Mazaud et al., 1991; McElhinny and Senanayake, 1982; Meynadier et al., 1992; Weeks et al., 1993). Only a few studies have explicitly considered the effect of field strength changes on the production of cosmogenic nuclides in situ (Kurz et al., 1990; Cerling and Craig, 1994a, 1994b).

In order to estimate the magnitude of geomagnetically induced exposure age errors and to demonstrate that model corrections can be applied to reduce these errors, we calculated the effect of changing geomagnetic field strength on in situ production rates of cosmogenic isotopes using several simple models available in the literature. Our resulting model combines the paleointensity records of Mazaud et al. (1991), McElhinny and Senanayake (1982), and Meynadier et al. (1992) to quantify the sign and approximate magnitude of field strength changes over the past 137,000 yr (Fig. 3A). To calculate instantaneous in situ production rates from the continuous paleointensity data, we used the formulation of Nishiizumi et al. (1989) to express each geomagnetic intensity change as an effective paleolatitude of cosmic ray dosing (Fig. 3B). Such a calculation assumes that a change in geomagnetic field strength can be represented by a change in geomagnetic latitude of a sample site. For example, a stronger field is equivalent to the
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Figure 3C compares these instantaneous production rates to the long-term average production rate (P_{cal}) measured by Nishizumi et al. (1989). The Nishizumi et al. approach of equivalent paleolatitudes is useful only for sample sites poleward of 20° latitude.

Our calculations indicate that field-strength-induced changes in isotopic production rates are greatest at low latitudes and high altitudes, as suggested by Cerling and Craig (1994a). For example, using the approximate paleointensity record we have accepted (Fig. 3A), the maximum deviation of instantaneous production rates (P_i) from current production rates over the past 137,000 yr for samples exposed at sea level is 22% at 30° latitude and 4% at 50°. For samples exposed at 3 km altitude, the maximum deviation is 56% at 30° latitude and 9% at 50°. Of course, once exposed, rocks on the Earth's surface integrate these changing production rates and thus dampen the effect of instantaneous production rate changes.

Despite the integration of changing production rates by rocks exposed on the Earth's surface, assuming a static geomagnetic field strength can lead to substantial errors in age estimates (Fig. 3D). Specifically, any production-rate calibration made at latitudes lower than 50° will integrate temporarily changing production rates and will strictly be representative only of the integrated cosmic-ray exposure at that specific latitude, altitude, and duration of exposure. Applying such a calibration to samples collected at the same latitude and altitude but exposed for different lengths of time will result in misestimation of the actual exposure age. For the Sierran calibration (Nishizumi et al., 1989), an age-error of -10% occurs for exposure ages greater than 40,000 yr (Figs. 3 and 4). For calibrations made on sites exposed longer, such as Meteor Crater, Arizona, the greatest relative age error occurs for young samples, those initially exposed during the high field strength, low production rate period in the Holocene (Fig. 4).

Although the accuracy of paleointensity records on which our calculations are based is uncertain (Raisbeck et al., 1994), we emphasize that many late-Pleistocene records indicate that substantial changes in field strength have occurred, that to the first order the records from widely separated areas are consistent in the sign and magnitude of those changes (e.g., Weeks et al., 1995), and therefore that a static late-Quaternary geomagnetic field is unlikely. Even if the magnitude and timing of field strength changes are later shown to differ from the paleointensity records we have used (Mazaud et al., 1991; McElhinny and Senanayake, 1982; Meynadier et al., 1992), our calculations still illustrate the substantial effects field strength changes will have on in situ cosmogetic ages. By accepting a paleointensity record, calculations such as we have made can be used to correct cosmogenic exposure ages for temporally varying geomagnetic field strength. Obviously, such corrections currently are approximate and their accuracy remains uncertain.

If calibration sites and samples for dating are collected at different altitudes and latitudes, calculating site- and time-specific production rates is even less straightforward. Such
different altitudes and latitudes requires assuming or estimating a variety of parameters, including the exposure age of the calibration surface, the time-averaged geomagnetic latitude of the sample sites, corrections for exposure geometry, scaling factors for elevation and latitude, and the efficiency of various isotope production pathways. Varying these parameters can generate significant differences in production rates (Table 3). For example: (1) Nishizumi et al. (1989) assume that the current geomagnetic latitude of their calibration samples (44°) is representative of the average geomagnetic latitude since Tioga deglaciation. However, if the average geomagnetic latitude since exposure is taken as the current geographic latitude (38°), as was done for Meteor Crater data (Nishizumi et al., 1991) and as is indicated by measurements of late-Holocene shifts in the geomagnetic dipole (e.g., Merrill and McElhinny, 1983, p. 100), calculated high latitude/sea-level production rates would be 15% higher than currently reported. In effect, such a difference in integrated paleomagnetic latitude for the Sierran calibration sites would have the same result as a 15% overall decrease in integrated paleomagnetic field strength. (2) The contribution of muons to 10Be and 26Al production remains uncertain but is probably minor (Brown et al., 1995). Knowing the rates of muon-induced production is important because the muon flux is attenuated more slowly with increasing atmospheric depth than the neutron flux which is responsible for the dominant, spallation-production pathway. If we consider the extreme case where production is entirely by spallation, recalculated sea-level, high-latitude production rates are 11% lower than Nishizumi et al.’s for geomagnetic latitude 44° but do not change if the average geomagnetic latitude is 38°. (3) Using 14,000 cal yr B.P. rather than 11,000 cal yr B.P. for the exposure age of the Sierran calibration samples, as seems reasonable from our study, lowers all production rates by more than 20%.

The 10Be production rate we estimate from the Laurentide data (4.76 atom g⁻¹ yr⁻¹, assuming a 21,500 yr exposure age) is most consistent with Nishizumi et al.’s (1989) data if Sierran deglaciation occurred between 13,000 and 14,000 cal yr B.P. (Table 3) regardless of which geomagnetic latitude or muon contribution is used. It is important to note that the latitude of the Laurentide samples is similar to that of Nishizumi et al. but that the altitudes are much lower. As a result, altitude/latitude corrections required to normalize the Laurentide data (factors of 1.2–1.3) to sea level and high latitude are

**TABLE 3**

<table>
<thead>
<tr>
<th>Exposure age (cal kyr)</th>
<th>Location</th>
<th>Geomagnetic latitude during exposure</th>
<th>Sample elevation (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Tioga, Sierra Nevada</td>
<td>44°</td>
<td>38°</td>
</tr>
<tr>
<td>13</td>
<td>Tioga, Sierra Nevada</td>
<td>6.03</td>
<td>6.85</td>
</tr>
<tr>
<td>14</td>
<td>Tioga, Sierra Nevada</td>
<td>5.10</td>
<td>5.80</td>
</tr>
<tr>
<td>21.5</td>
<td>Laurentide, NJ</td>
<td>4.74</td>
<td>5.39</td>
</tr>
</tbody>
</table>

* Production rate scaled assuming all production by spallation.
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many times less than those required to normalize the Sierran data (a factor of 10.2). The small correction needed for the Laurentide samples minimizes the uncertainty related to estimating muon production rates and scaling of production rates to sea level at high latitudes.

Paleointensity-based calculations can also be used to support the conclusion that the calibration sites of Nishizumi et al. (1989) were deglaciated before 11,000 cal yr B.P. Data from Meteor Crater (Nishizumi et al., 1991) are consistent with longer term average sea-level, high-latitude $^{10}$Be and $^{26}$Al production rates of about 6 and 36 atoms g$^{-1}$ (Nishizumi et al., 1989). Using the paleomagnetic intensity record we have adopted, it is difficult to reconcile the 11,000 cal yr B.P. Sierran calibration with the Meteor Crater data. Assuming an average geomagnetic latitude of 38° for the Sierran calibration samples and assuming that the 11,000 cal yr B.P. calibration and the paleomagnetic record we adopted were both correct, Meteor Crater should appear to be about 58,000 yr B.P. However, Meteor Crater has been independently dated by thermoluminescence at 49,000 ± 3000 yr B.P. (Sutton, 1985); it is more likely, therefore, that the 11,000 cal yr B.P. calibration age is in error. If one applies a production rate calculated from the Meteor Crater data and uses the paleointensity-based forcing we have proposed (Fig. 3), the exposure age of the Tioga calibration surfaces would be about 12,900 cal yr B.P., independently supporting the new radiocarbon data presented above.

CONCLUSIONS

The calculations we present, together with the new Sierran deglacial record, Laurentide data, and other significant geologic uncertainties (Bierman and Gillespie, 1991; Hallet and Putkonen, 1994) show that age estimates based on the abundance of in situ produced cosmogenic isotopes are not yet certain enough to warrant their use in correlating brief (500–1000 yr) geomorphic or climatic events, such as the late-Pleistocene Younger Dryas climatic reversal or Heinrich events.

The revised chronology of deglaciation in the Sierra Nevada emphasizes the need for accurate, independent age control at all calibration sites. Exposure ages accurate to within several percent are required to define accurately short-lived events or to correlate reliably cosmogenic ages with other well-dated time series. To achieve this level of both accuracy and precision, several other parameters will also need to be understood better, including the effective long-term geomagnetic latitude of a sample site, altitude and latitude scaling corrections, and the relative contribution to muons to $^{10}$Be and $^{26}$Al production. In addition, instantaneous production-rate corrections, such as those we have demonstrated, will need to be refined to take into account the changing intensity of the geomagnetic field. Cosmogenic exposure ages will be more accurate and useful if independent production-rate calibrations are performed at a variety of sites spanning a range of altitudes, latitudes, and durations. Our calculations show that errors in relative and numerical ages, related to the varying intensity of the geomagnetic field, will be minimized if calibrations are made and samples are collected at high latitudes and low altitudes. Errors related to applying locally derived production rates to distant sampling sites will decrease if the altitude and latitude of sample and calibration sites are similar. Finally, errors related to geomagnetic forcing will be reduced if samples and calibration sites are exposed for similar durations.

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