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SANTA FE WORKSHOP ABSTRACTS[1]

REFINING ESTIMATES OF ^{10}Be AND ^{26}Al PRODUCTION RATES

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We have taken a variety of approaches to refine the existing ^{10}Be and ^{26}Al production rate estimates of Nishiizumi *et al.* (1989), including measuring nuclide abundances on boulders and bedrock surfaces exposed on the relatively well-dated Laurentide moraine, making altitude and latitude corrections using different, now currently accepted protocols, and modeling the effect of changing geomagnetic field strength on production rates over time.

In north-central New Jersey, we collected 16 samples of quartzite and gneiss from striated and/or glacially molded outcrops and large glacial erratics on or just behind the terminal moraine of the Laurentide ice sheet (Larsen 1995). The exposure age of the moraine is estimated to be ~21.5 ky sidereal years on the basis of several limiting ^{14}C ages. The calibration of these ^{14}C ages is based on the recommendations of Stuiver *et al.* (1991). Average concentrations and standard errors of the mean of $1.37 \pm 0.04 \times 10^5$ (n=12) atoms g^{-1} SiO_2 for ^{10}Be and $8.03 \pm 0.29 \times 10^5$ (n=14) atoms g^{-1} SiO_2 for ^{26}Al can be used to calculate integrated sea level, high-latitude production rates and associated standard errors of the mean of 5.17 ± 0.15 and 30.40 ± 1.01 atoms g^{-1} yr^{-1} for ^{10}Be and ^{26}Al, respectively. The isotope abundances show no significant variation between boulder and outcrop sample locations and quartzite and gneiss sample lithologies, implying that the effects of erosion and till cover are negligible. We have scaled these abundance data to sea level and high latitude using the neutron data of Lal (1991) following the finding by Brown *et al.* (1995) that muon production is insignificant; however, because our samples were collected at relatively high latitude (41°) and low altitude (300 m), the choice of scaling protocol is unimportant. The integrated production rates calculated over the past 21.5 ky are *ca.* 18% lower than previously determined integrated production rates over the 11 ky (Nishiizumi *et al.* 1989) and 50 ky (Nishiizumi *et al.* 1991b) time frames.

Comparing these three different production rate estimates is not straightforward. Each was calculated from samples exposed for varying lengths of time at different altitudes and latitudes. Scaling the lower-latitude, higher-altitude measurements from the Sierra Nevada and Meteor Crater to sea level and high latitude involves choosing an effective geomagnetic latitude for the duration of exposure, determining the contribution of muons to ^{10}Be and ^{26}Al production as a function of altitude and latitude, and determining how instantaneous production rates have changed over the duration of exposure at each site.

We find that by assuming muon production is inconsequential at sea level (Brown *et al.* 1995), scaling the three data sets for spallation only, and incorporating a geomagnetically driven production rate forcing model (Clark *et al.* 1995; Clapp and Bierman, in review), the three different production rate estimates can be reconciled to within several percent if the exposure age of the Sierra Nevada calibration sites is taken to be 13.5 ky as suggested by Clark *et al.* (1995). Although such agreement is promising, additional data must be gathered to test these findings. Until those data have been gathered, nuclide production rates as a function of altitude, latitude and exposure duration will remain a significant uncertainty in the interpretation of nuclide abundance data.

[1]See Bibliography on pp. 142–147 for references not separately provided in following abstracts.

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AN ANTARCTIC PERSPECTIVE ON *IN-SITU* COSMOGENIC NUCLIDE PRODUCTION

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Long-term average production rates of some nuclides can be constrained by examining slowly eroding, old rock surfaces. At steady state with respect to production and radioactive decay, production rates are simply calculated from concentration data (*e.g.*, $P=N\lambda$), as long as erosion is negligible (Brook *et al.* 1995) The possibility that erosion is non-negligible makes these production rates minimum values. Examination of our and other published ^{26}Al data (half-life 7.2×10^5 yr) from a total of 15 Antarctic rock surfaces with ^{10}Be exposure ages older than 2 Ma (and therefore model erosion rates <~7 cm/Ma) yields ^{26}Al production rates that agree well with the published Sierra Nevada rates (Nishiizumi *et al.* 1989), assuming the altitude/latitude scaling of Lal (1991). The samples span an altitude range of 1380 to 2650 m and at each sample altitude the calculated production rates agree with the scaled Sierra Nevada rates within ~10%. The sea level production rate derived from the data (Lal 1991) is 35 ± 2 at/g/yr, close to the predicted value (Lal 1991) of 37 at/g/yr. These observations suggest that the long-term average ^{26}Al production rate is not higher than, and is probably close to, the value determined for glaciated bedrock in the Sierra Nevada exposed over the last ~11 ka[2]. The results also imply that the scaling factors (Lal 1991) are accurate within the latitude and altitude range considered here (excepting the possibility of compensating errors). As there is no reason to expect temporal variations in the $^{26}Al/^{10}Be$ production ratio, the long-term ^{10}Be production rate is also probably close to the Sierra Nevada rate (Nishiizumi *et al.* 1989). These conclusions are similar to those of Nishiizumi (this issue).

We have also collected two 1–1.5 m drill cores in Antarctic sandstone bedrock to examine the depth dependence of ^{10}Be, ^{26}Al, and ^{3}He production. ^{10}Be and ^{26}Al profiles from one core were reported previously (Brown *et al.* 1992). Both cores have exponential profiles; scale lengths are close to expected values and are 152 ± 5 and 145 ± 5 g/cm^2 for ^{10}Be and 153 ± 13 and 152 ± 5 g/cm^2 for ^{26}Al. Contrary to the calculations of Nishiizumi *et al.* (1989), these data indicate that muons produce <1–3% of total ^{10}Be and ^{26}Al at the altitudes and latitude of these cores, consistent with previous conclusions (Brown *et al.* 1995) based on a depth profile of ^{10}Be at low altitude near the equator.

The situation for ^{3}He is more complicated. One of the two cores exhibits an exponential decrease in cosmogenic ^{3}He with a scale length of ~150 g/cm^2. The second has a distinctly higher scale length, 227 ± 14 g/cm^2, over a similar depth interval. Studies of different size quartz grains in each core show that the discrepancy, which can be thought of as "extra ^{3}He" at depth, or loss of ^{3}He at the surface, is not an artifact of diffusion. It also does not appear to be caused by the presence of a non-cosmogenic ^{3}He component. Production of ^{3}He by muons is a remaining possibility. A model that includes the processes of erosion, diffusion, and ^{3}He production by neutrons and muons can approximately reproduce the observed profile with reasonable parameters, if exposure times are very long (*e.g.*, of order 20 Ma or greater), and if production of muons is ~10% of total production at 1700 m. While we are uncertain if this explanation of our data is correct, our observations suggest that further investigation of production rates of ^{3}He due to muon interactions is warranted.

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DIRECT EXAMINATION OF TERRESTRIAL COSMOGENIC NUCLIDE PRODUCTION RATES OF ^{10}Be, ^{3}He AND ^{3}H

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We have determined production rates of ^{10}Be, ^{3}He, and ^{3}H in tanks of water exposed for a period of 15 months at a range of altitudes (620 m, 3810 m, and 4745 m) in the French Alps. Measurements of ^{3}He and ^{3}H were undertaken by static mass spectrometry at Laboratoire de Modelisation du Climat et de l'Environnement in Saclay, France, while ^{10}Be determinations were made at the Tandetron Accelerator Mass Spectrometry Facility in Gif-sur-Yvette, France. Corrections were made for low levels of ^{10}Be and ^{3}H present in the water, for incomplete degassing of atmospheric He, and for production of the three nuclides within the tanks in the laboratory before and after installation at altitude. Further minor corrections were made for self-shielding within the tanks and for skyline shielding by local topography. Our results indicate production ratios for oxygen spallation of ~2:1 for ^{3}He:^{3}H and ~20:1 for (^{3}He+^{3}H):^{10}Be. Strategies for application of our production rates to longer time periods and other locations, as well as to specific mineral phases, will be discussed.

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COSMO-CALIBRATE: A PROGRAM FOR CALIBRATING COSMOGENIC EXPOSURE AGES

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In order to account for geomagnetically induced changes in cosmogenic nuclide production rates *in situ*, and thereby increase the potential accuracy of exposure age dating, we have developed a numerical model that generates geomagnetically calibrated exposure ages. Currently accepted, model-age calculations are based on time-averaged production rates. Use of time-averaged production rates bay introduce systematic errors >20% in exposure ages causing cosmogenically dated events to be correlated incorrectly with events dated by other means (Clark *et al.* 1995). Applying our model to existing nuclide abundance data generally increases calculated exposure ages (Fig. 1), supports the ^{10}Be-based assertion of Gosse *et al.* (1995) that a glacial advance in the Rocky Mountains may have occurred during the Younger Dryas, and most importantly, reconciles three apparently disparate production rate estimates for ^{26}Al and ^{10}Be.

We have created a computer program (COSMO-CALIBRATE) that uses generally accepted geomagnetic paleointensity records (Meynadier *et al.* 1992; McElhinny and Senanayake 1982) and empirical relationships to account for cosmogenic isotope production rate variations over the last 140 kyr. Magnetic field strengths are converted to apparent paleolatitudes using the formulation of Nishiizumi *et al.* (1989) after which instantaneous production rates are calculated using the third degree polynomial of Lal (1991). Muon contribution is currently assumed to be minimal, as suggested by Brown *et al.* (1995). Samples exposed at lower latitudes and high altitudes will have experienced greater production rate variation (Fig. 2).

Our program calculates instantaneous ^{10}Be and ^{26}Al production rates at any given sample site (altitude and latitude) and outputs both geomagnetically calibrated and uncalibrated exposure ages from sample isotopic abundance data. Calibration, such as we propose, will likely increase the accuracy of exposure ages and once verified by additional data, may allow for more robust cosmogenic dating and correlation of relatively brief geomorphic and climatic events. Our program is available as user-friendly, compiled Macintosh code by anonymous ftp from `beluga.uvm.edu`.

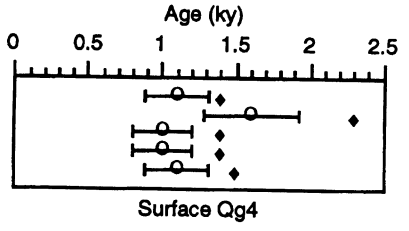

Fig. 1. Calibrated ^{10}Be exposure ages from COSMO-CALIBRATE 1.7 (diamonds) and uncalibrated ^{10}Be exposure ages (Bierman *et al.*) calculated using production rates of Nishiizumi *et al.* (1989), for 11,000 cal yr BP (open circles).

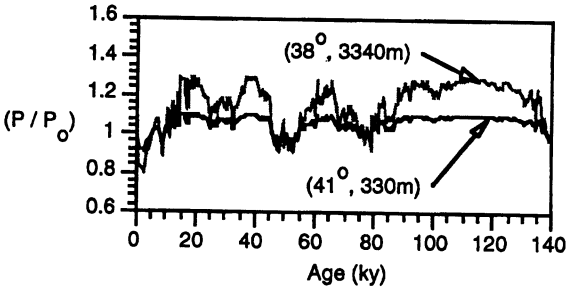

Fig. 2. Relative instantaneous production rates calculated by COSMO-CALIBRATE for two study sites: Sierra Nevada (38°, 3340 M) and the Laurentide Terminal Moraine (41°, 330 m)

^{10}Be AND ^{26}Al PRODUCTION RATES AND A REVISED GLACIAL CHRONOLOGY FOR THE SIERRA NEVADA

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New ^{14}C ages for Sierra Nevada deglaciation suggest that currently accepted late-Pleistocene production rates of *in-situ* cosmogenic ^{10}Be and ^{26}Al are ~20% too high because the assumed age of exposure is too young. The original production rates for the isotopes were calibrated based on measurements of glacially polished granite from the Sierra Nevada, assumed to have been deglaciated ~11,000 calibrated (or sidereal) years ago (11,000 cal yr BP) (Nishiizumi *et al.* 1989). This exposure age was estimated from minimum-limiting conventional radiocarbon ages of ~10,000 ^{14}C yr BP for basal bulk sediments from two sites, a lake and a meadow, dammed behind Tioga (last late-Wisconsin maximum) recessional moraines (Adam 1967; Mezger and Burbank 1986).

Calibrated ages (Bard *et al.* 1990; Stuiver and Reimer 1993) of 12 new ^{14}C dates, of basal or near-basal lake sediments from cores of ten postglacial lakes, show instead that Sierra Nevada deglaciation was underway by 16,000–19,000 cal yr BP (~13,500–16,000 ^{14}C yr BP) and that the range was effectively deglaciated before ~13,100 cal yr BP (11,190 ^{14}C yr BP) (Clark *et al.* 1995; Clark and Gillespie, in press). The coring sites all lie inside the maximum Tioga ice limits, as do the two cited by Nishiizumi *et al.* (1989), and thus provide minimum ages for onset of deglaciation. The highest sites near the crest of the range, however, provide minimum ages for complete retreat of Tioga glaciers and thus minima for the exposure age of sites sampled by Nishiizumi *et al.* for calibration. The highest lakes we cored, in the headwaters of Bishop Creek, are formed behind moraines of the Recess Peak advance, which ended before 13,100 cal yr BP (Clark and Gillespie, in press). We have

mapped and correlated Recess Peak moraines along the crest of the Sierra from southern to northern limits of the advance, and find that all calibration sites of Nishiizumi *et al.* lie downstream from Recess Peak moraines in those drainages. Thus, our minimum age control for the Recess Peak advance in Bishop Creek also provides a firm minimum age for exposure of the calibration sites. The accuracy of the AMS ^{14}C dates from the Bishop Creek cores is supported by: 1) other dates from higher in the same cores that are internally consistent; 2) parallel dates between adjacent gyttja and macrofossils in the cores that are indistinguishable within 1-sigma analytic error (typically <1%); 3) similar findings in dates of cores from other areas that also are internally consistent; and 4) absence of sources of contamination, especially "old" carbon, in the drainage basins upstream from the lakes. These observations substantiate the stability of carbon in high Sierran lake basins. Together, the new limiting ^{14}C dates indicate that Tioga deglaciation occurred at least 2000 cal yr before 11,000 cal yr BP.

Recalculating the production rates using the formulation and measured abundances of Nishiizumi *et al.* (1989) but assuming the sites were deglaciated 13,500 cal yr BP yields sea-level, high-latitude production rates that are ~20% lower than in the original calibration for both isotopes. This difference agrees within several percent of an independent late-Pleistocene calibration from the Laurentide terminal moraine in New Jersey (Larsen 1995), if appropriate latitudinal scaling and the affects of geomagnetic field-strength fluctuations on production rates are considered (Clark *et al.* 1995; Clapp and Bierman 1995). Our results emphasize the need for accurate, independent age control and geologic context as primary foundations for production-rate calibrations of cosmogenic nuclides.

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PLANS FOR CALIBRATION OF THE COSMIC RAY FLUX OVER THE PAST 500,000 YEARS USING VOLCANIC ROCK

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While recent measurements of neutron fluxes can be combined with nuclear reaction data using Monte Carlo simulation techniques to predict the current production rates of cosmogenic nuclides, such techniques cannot be used to explore the past history of the cosmic ray flux (CRF). Although certain effects are fairly well understood or modeled, such as short-term cycling of the CRF at the surface of the Earth in response to variations in the Earth's magnetic field, other variations are not as well categorized. While some ice cores and similar historical record-keepers provide some insight into the past, it is the intent of this project to calibrate the method of ^{36}Cl rock exposure dating, and hence the cosmogenic production rates, back through 500 ka by comparing the ^{36}Cl concentrations with $^{40}Ar/^{39}Ar$ data in collected samples from the central Andes.

The central Andes is an ideal location for a study such as this. This hyper-arid and isolated environment offers samples that have remained undisturbed and effectively uneroded in a location that has had little or no water or vegetation cover. In addition, the high altitude of the region insures very high nuclide concentrations. The effectively instantaneous creation of the lava flows aids in correlating the $^{40}Ar/^{39}Ar$ to the measured ^{36}Cl concentrations, and the long-term development of the volcano by successive flows will provide a moderately wide span of dates for the calibration. As an additional incentive, Tata Sabaya, the specific volcano to be studied, underwent a cone collapse that resulted in an easily identifiable debris flow. This extra "instantaneous" event provides another point on the calibration curve.

When combined with the existing calibration data, which focus on more recent time periods, these new data should provide a broader perspective on long-term variations in the CRF. Analysis will incorporate Monte Carlo neutron transport simulations to account for rock geometry and water content in addition to the standard scaling factors such as geometric shielding, altitude and latitude variations, and erosion effects. With the higher frequency variations from magnetic field fluctuations effectively averaged out after only a few cycles, any long-term variations in the CRF, and hence, the radioisotope production rates, will be identifiable, making the results of the project useful to any method or procedure that relies on cosmogenic nuclides.

PRODUCTION RATE OF *IN-SITU* COSMOGENIC ^{10}Be IN QUARTZ AT HIGH ALTITUDE AND MID LATITUDE

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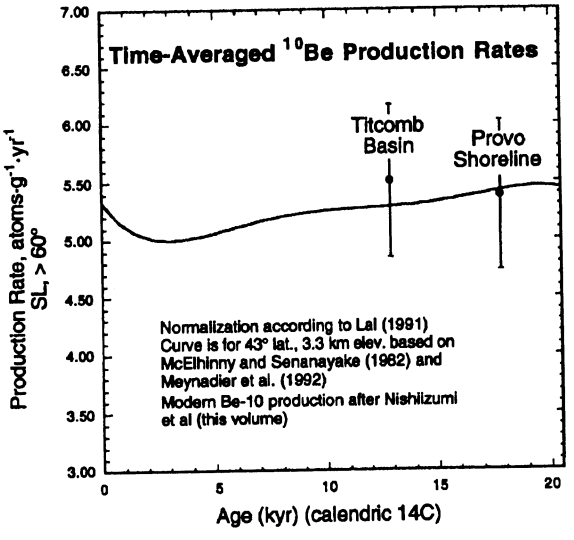
Several considerations must be made when attempting to empirically calibrate a cosmogenic nuclide time scale to the calendric time scale. The sampled surface should not have been buried or eroded during exposure, the initial cosmogenic concentration of the nuclide must be zero (*i.e.*, no inheritance from prior exposure), there should be no significant shielding or geometry problems, and the lithology must be suitable. The duration of the exposure of the surface must also be accurately known. Finally, the geomagnetic latitude and duration at which calibrations are done should be taken into account because at some latitudes even a small uncertainty in geomagnetic latitude can produce a large uncertainty in the production rate. For calibration sites having <10 kyr exposure, the uncertainty in geomagnetic latitude due to pole position secular variation may be a factor because the dipole axis may not have been geocentric. If the change in production rate due mainly to geomagnetic field intensity variation is the focus, it may be useful to concentrate our measurement of production rates at sites within the latitudinal zone (~15°–45°) where these geomagnetic uncertainties have the most significant effects.

We have sampled 10 boulders from the inner Titcomb Basin moraine in the Wind River Range, Wyoming (3.3 km, 43°N), which has been correlated to the Temple Lakes moraine, dated by Zielinski and Davis (1987) and Davis (1994), at ~11.4 to 11.7 ^{14}C kyr. The site production rate of ^{10}Be in quartz assuming 12.9 cal kyr (Stuiver and Reimer 1993) for the moraine age is 51.7 atoms $\cdot$ g^{-1} yr^{-1}, 53.6 atoms $\cdot$ g^{-1} yr^{-1} if adjustments are made for the effects of snow and one of the ten samples is considered an outlier. The production rate at sea level, high latitude (using Lal 1991) is *ca.* 5.5 atoms $\cdot$ g^{-1}

yr^{-1} based on nine samples and adjusted for snow cover. Considering the uncertainties in the exposure time, snow density, and muonic scaling, the uncertainty in this production rate is ±12%.



Preliminary results based on ^{10}Be measurements of two samples collected from a Provo Lake wave cut shoreline (1.5 km, 41°N) will also be presented. The results suggest the time-averaged ^{10}Be production rate for 14.4 ^{14}C kyr (Oviatt, Currey and Sak 1992; 17.6 cal kyr) of exposure at sea level >60° latitude is 5.4 ± 0.6 atoms · g^{-1} yr^{-1} (uncertainty assigned as above).

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THE ^{21}Ne PRODUCTION RATE IN A SI TARGET AT MOUNTAIN ALTITUDES

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The isotopic signature of cosmic ray produced Ne was first measured in Antarctic rocks (Graf *et al.* 1991; Niedermann *et al.* 1993). Production rates of cosmogenic Ne were determined in quartz from glacially polished Sierra Nevada rocks which were exposed for only *ca.* 10^4 yr (Niedermann *et al.* 1994). However, past and present production rates of ^{21}Ne and other relevant cosmic ray produced nuclides are still poorly known. Temporal variations in the production rates can be studied by determinations of the products in well dated rocks and minerals thereof. The present production rates can

be measured on exposed targets at mountain altitudes. We report first ^{21}Ne results obtained from a Si target exposed on Mt. Evans, Colorado.

We used an experimental melt (Corning Glass) substituting a small amount of Li for Na. The glass (2091 g) was placed in a 13 × 31 cm stainless steel cylinder. The stem was double valved to prevent leakage. To reduce self-shielding, the cylinder was designed to be only about half filled and lie on its side. The glass was degassed by heating numerous times above the softening temperature. Reaction of the glass with the stainless steel cylinder was apparent by glass analysis after the Ne study. The sample was exposed to cosmic rays for *ca.* 3 yr on the summit of Mt. Evans, Colorado before it was transported to La Jolla for analysis.

Calibrations of the $^{40}Ar^{++}$ and CO_2^{++} interferences on masses 20 and 22, respectively, revealed that the ratios of doubly to singly charged ^{40}Ar and CO_2 ions are not constant. Our Ne analytical procedure monitors the peaks at masses 2, 18, 19, 20, 21, 22, 40, 42, and 44. The ratios $^{40}Ar^{++}/^{40}Ar^{+}$ and CO_2^{++}/CO_2^{+}, respectively, are calculated according to Graf *et al.* (1994) and the appropriate calibrations. The resulting interference corrections are subtracted individually for each cycle. We also need to calibrate the Ne sensitivity of the instrument as changes in the charge states and charge density in the ion source affect concentration measurements.

A significant fraction of the cosmic-ray produced Ne (36%) was in the gas phase of the cylinder. Ne was then extracted in 3 steps at increasing temperatures and a re-extraction step at 950°C was added. Trapped Ne in all steps was fractionated up to 2% per amu, an effect that is presumably due to the extensive degassing prior to exposure. The total excess ^{21}Ne observed in the glass corresponds to 1500 atoms g^{-1} (SiO_2) and we calculate a production rate P_{21} (SiO_2)= 410 ± 60 atoms $a^{-1}g^{-1}$ (SiO_2) at Mt. Evans (4250 m) altitude. The uncertainty includes current uncertainties in the Ne sensitivity and in mass discrimination which were added quadratically. The procedure of Lal (1991) is used to calculate the production at sea level, and P_{21} (SiO_2)=19.3 atoms $a^{-1}g^{-1}$ (SiO_2) for latitudes >60° is obtained. No corrections have yet been applied for self-shielding and for flux variations during the solar cycle (the exposure occurred during maximum solar activity). This value may be compared to a production rate P_{21} = 21 atoms $a^{-1}g^{-1}$ (quartz) obtained by Niedermann *et al.* (1994) for Sierra Nevada quartz samples.

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RECENT AND PLANNED RESEARCH IN COSMOGENIC ISOTOPES AT GNS

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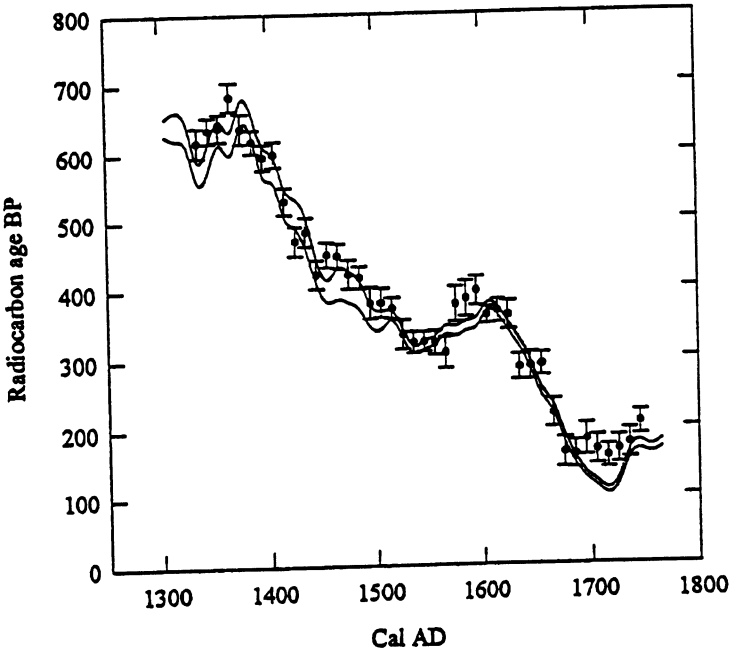
The AMS laboratory at GNS was set up some ten years ago and has established an international reputation in ^{14}C analysis directed mainly towards archaeometry and atmospheric studies. A recently obtained calibration curve has provided a more secure basis for radiocarbon measurement. Tree rings from a section of native *Matai* covering the period AD 1335 to 1745 have been dated and used to generate a ^{14}C calibration for Southern Hemisphere wood. Comparison of this curve with calibration data for Northern Hemisphere woods shows no systematic difference.



Research into other cosmogenic isotopes (^{10}Be, ^{26}Al and ^{36}Cl) at GNS is still in its infancy. Analysis of ^{10}Be in marine sediments, loess and Antarctic soils has yielded some interesting but inconclusive results. Planned research for 1996 involves direct measurement of ^{10}Be fluxes and *in-situ* production rates across a wide range of Southern Hemisphere geomagnetic latitudes (3°S to 79°S). On-site measurement of neutron and/or muon flux is also planned. Sampling sites have been investigated and some preliminary rain collections made and measured.

DEPTH PROFILES OF COSMOGENIC NUCLIDES AND ACCELERATOR SIMULATION EXPERIMENTS WITH STOPPED NEGATIVE MUONS AND FAST MUONS

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In-situ production of cosmogenic nuclides is important for the determination of background events in all low-level detection experiments, *e.g.*, cryogenic dark matter detectors or geochemical experiments such as the geochemical solar neutrino experiment $^{205}Tl(\nu_e, e^-)^{205}Pb$ (Neumaier, Nolte and Morinaga 1991), and in many geophysical applications such as the determination of erosion rates.

The *in-situ* production of radionuclides has been calculated as the function of the depth z, taking into account spallation reactions, reactions with captured negative muons, reactions with fast muons and background reactions. The production rate due to μ^- capture can be expressed by $P_{\mu^-}(z) = I_{\mu^-}(z) \cdot f_C \cdot f_D \cdot f^*$ with the rate of stopped negative muons $I_{\mu^-}(z)$, the chemical compound factor f_C, the probability of nuclear capture f_D and the probability f^* of the reaction channel after nuclear μ^- capture to the investigated nuclide or isomeric state.

The production due to fast muons is given by $P_{\mu,fast}(z) = \Phi_{\mu,fast} \cdot \sigma$ with the flux of fast muons $\Phi_{\mu,fast}$. The energy-dependent cross section σ is given by $\sigma = \sigma_0 \cdot E_{mean}^{0.7}$ according to the Wolfendale rule with the mean muon energy E_{mean} in GeV at the depth considered.

These contributions due to μ^- capture and fast muons were studied by accelerator simulation experiments at PSI, Villigen, with slow negative muons and at CERN with 190 GeV muons. The following probabilities f^* of particle emission channels after μ^- capture have been measured in addition to earlier measurements (Dockhorn *et al.* 1991, Strack *et al.* 1994): $f^* = (5.2 \pm 0.6) \cdot 10^{-3}$ for $O(\mu^-, \nu_\mu \alpha pxn)^{10}Be$ [x = 1–3], and $f^* = (1.4 \pm 0.4) \cdot 10^{-3}$ for $S(\mu^-, \nu_\mu \alpha xn)^{26}Al$ [x = 2–4,6]. From the result of the oxygen irradiation and the earlier result obtained for ^{26}Al from the irradiation of silicon, the production ratio of ^{26}Al to ^{10}Be after μ^- capture in quartz has been deduced to be $P(^{26}Al)/P(^{10}Be) = 7.3 \pm 1.2$ (Heisinger *et al.*). For the determination of the fast muon cross section σ_0 of ^{10}Be (in O), ^{14}C (in O), ^{26}Al (in Si, S and Al), ^{36}Cl (in Ca), ^{53}Mn (in Fe) and ^{205}Pb (in Tl) several targets have been irradiated at CERN. This work is still in progress.

In addition, natural depth profiles of ^{10}Be and ^{26}Al in quartz have been measured in Northern Bavaria up to depths of 250 m and have been compared, taking erosion into account, with calculated profiles. From this comparison, the erosion rate for the last million years has been determined to be *ca.* 5 μm yr^{-1} (Heisinger *et al.*).

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NEUTRON-INDUCED PRODUCTION CROSS SECTIONS FOR LONG-LIVED NUCLIDES AND RARE GASSES: SOME EXPERIMENTAL DATA

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We present data on neutron-induced nuclear cross sections for the production of long-lived radionuclides of ^{3}H, $^{7,10}Be$, ^{14}C, ^{26}Al and ^{36}Cl and rare gases $^{21,22}Ne$, which have been measured by our group in the last several years, using semi-monoenergetic neutrons from the $^{9}Be(p,n)$ and/or $^{7}Li(p,n)$ reactions.

Cosmogenic nuclide production rates depend on chemical composition of the sample material and on particle fluxes of cosmic ray secondaries. Neutrons with energies up to a few hundreds MeV are the major contributing particles in terrestrial environments. Since the neutron energy spectrum depends considerably on the chemical composition of surrounding materials, knowledge of cross sections is indispensable for understanding the production rates in various terrestrial environments. Production cross sections are determined in most cases by counting the number of atoms produced from the known number of target atoms by irradiating with a known particle fluence. Because of the absence of an appropriate monoenergetic source, there have been very few experimental data on neutron-induced cross sections for energies above 20 MeV. Above 20 MeV, the most practical way is to use semi-monoenergetic neutrons from secondary emission through the $^{9}Be(p,n)$ and $^{7}Li(p,n)$ reactions.

We have two facilities available for semi-monoenergetic neutron irradiation: the SF cyclotron facility at the Institute for Nuclear Study (INS), University of Tokyo for 10–38 MeV, and the AVF cyclotron facility at the Japanese Atomic Energy Research Institute (JAERI) in Takasaki for 40–90 MeV (Nakamura *et al.* 1994). In addition, we have used the Van de Graaff accelerator at the Fast Neutron Laboratory (FNL) at Tohuku University for <1–16 MeV monoenergetic neutrons. Because of the limited machine time, many of the cross section studies are still underway. In the workshop I will present the data (including the published ones) on production of ^{3}H from oxygen (<40 MeV), $^{7,10}Be$ from C, N and O (<70 MeV), ^{26}Al from Al and Si (<40 MeV), $^{21,22}Ne$ from Mg and Al (<40 MeV).

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A COMPARISON OF ^{10}Be, ^{26}Al, ^{36}Cl IN BOULDERS FROM A YOUNGER DRYAS MORAINE, JULIER PASS, GRAUBÜNDEN, SWITZERLAND

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^{10}Be, ^{26}Al, and ^{36}Cl measured in six boulders from an Egesen moraine complex at Julier Pass, Switzerland, gave a mean age of *ca.* 11,000 yr. Radiocarbon dating, geomorphologic evidence and regional correlation constrain Egesen moraines to have been formed as Alpine glaciers advanced during the Younger Dryas (YD) cold event (11,000 to 10,000 ^{14}C yr ago). Corrections for thickness of sample and topographic shielding have been made, but snow and erosion corrections have not.

With the latitude and altitude corrections stated in Lal (1991) as a basis, production rates for the three isotopes can then be examined. Overall, the agreement of the surface exposure ages from different isotopes in single boulders, between all six boulders and with the known age of the YD is very good. This leaves little room for significant changes in production rates over the last *ca.* 12,000 yr and indicates that present production rates (Nishiizumi *et al.* 1989; Phillips *et al.* 1996) are not that far off.

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PRODUCTION OF ^{14}C AND ^{10}Be IN THE ATMOSPHERE AND ON THE EARTH'S SURFACE

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In recent years, there has been growing interest in the production of cosmogenic nuclides in rock surfaces as well as in the atmosphere, because of possible applications to a variety of fields. Geophysical and temporal variations in the production rates of cosmogenic nuclides must be understood in order to be useful for such diverse applications as estimating the exposure ages of a geomorphic surface based on *in-situ*-produced cosmogenic nuclides and calibration of ^{14}C ages.

Jull *et al.* (1988) reported the first measurements of cosmogenic ^{14}C in terrestrial rocks based an extension of earlier work on meteorites (Jull *et al.* 1989). Measurable levels of *in-situ*-produced cosmogenic ^{14}C have been found in rocks collected from 3300 to 5452 m from North and Central America and Hawaii (Jull *et al.* 1988, 1992, 1994; Donahue, Jull and Toolin 1990). These measurements allowed us to estimate differences in sea-level production rate on the basis of latitude. Temporal changes in atmospheric and *in-situ* ^{14}C production rates are also significant. Tree-ring data suggest that substantial variations in the production rate of ^{14}C in the atmosphere occur (Damon and Sonett 1991). We know that the production 10,000 yr ago was of the order of 10% higher than today. Bard *et al.* (1990) argue for larger variations of up to 40% in the Late Pleistocene, based on comparisons of ^{14}C ages with U-Th ages of corals. Long-term variations in the tree-ring ^{14}C are probably due to geomagnetic variations, although short-term variations are thought to be solar (Damon and Sonett 1991). Bard *et al.* (1990) argue that same geomagnetic influences can explain the larger ^{14}C effects seen in late Pleistocene coral results. Edwards *et al.* (1993) studied ^{14}C in Late Pleistocene corals and found larger effects than can be ascribed to geomagnetic effects. Oceanic effects must have a strong, if not dominant, effect on atmospheric ^{14}C variations.

For *in-situ* produced isotopes, however, geomagnetic effects are expected to predominate. Estimating geomorphic surface exposure ages or erosion rates using *in-situ* cosmogenic nuclide measurements requires us to know the average production rate over the exposure time of the surface. The record of ^{10}Be produced in the atmosphere, observed in deep-sea sediments and ice, gives us a possible way of estimating these integral variations. Integration of ^{10}Be in a marine sediments suggests that the effect of "spikes" at 30, 43 and 60 Ka due to cosmic-ray fluctuations possibly due to supernova or other transient phenomena (McHargue *et al.* 1995) will not have much effect on ^{14}C. The total effect on *in-situ*-produced ^{14}C is <10%. Similarly, such "spikes" cannot explain the deviations of ^{14}C and U-Th observed by Bard *et al.* (1990), which are probably a combination of oceanic and

geomagnetic influences. However, transient changes in the cosmic-ray flux would likely have greater effects on longer-lived nuclides.

TABLE 1. Production Rates of *In-Situ*-Produced ^{14}C as a Function of Latitude

Sample	Geomagnetic latitude	P at sea level (^{14}C/g/yr)	Reference
Mt. Massive, Colorado	49°N	21 ± 2	Jull *et al.* (1988); Donahue, Jull and Toolin (1990)
Tabernacle Hill, Utah	49°N	20 ± 2	Jull *et al.* (1992)
La Malinche, Mexico	28°N	16 ± 2	Jull *et al.* (1988)
Popocatepetl, Mexico	28°N	12 ± 2	Jull *et al.* (1988)
Mauna Loa, Hawaii	18°N	15 ± 2	Donahue, Jull and Toolin (1990)

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TERRESTRIAL FACTORS THAT INFLUENCE PRODUCTION RATES

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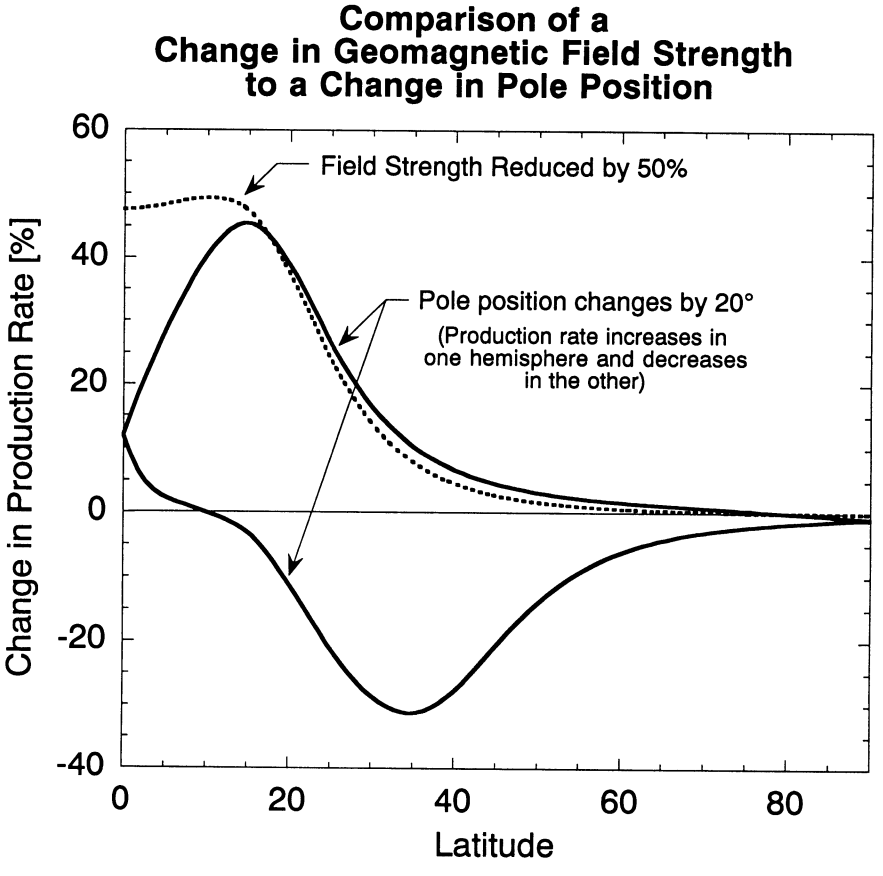
Production rates of cosmogenic nuclides on Earth undergo temporal variations. These variations are caused by extraterrestrial factors that are expected to affect production rates uniformly everywhere on Earth and by terrestrial factors that cause changes in production rates that vary with location. Accurate age determinations using techniques that rely on the accumulation of cosmogenic nuclides require a knowledge of production rates for the periods during which the samples were exposed. Measurements are now made with sufficient precision that the uncertainty of an age determination is often set by limitations in our knowledge of time-varying production rates. Knowing what causes the changes in production rates is important when transferring production rates measured in one location to other places on earth. Additionally, an appreciation of the possible causes of variations in production rates should inform the selection of locations chosen for calibrations.

For example, the terrestrial factor that has been blithely assumed to have the greatest effect on production rates is the strength of the Earth's magnetic field. However, the figure on the following page shows that at latitudes above 20° an equally important factor may be the position of the magnetic pole relative to the geographic pole. The distinction between field strength and pole position is an important one, not only because different latitudinal profiles must be used to calculate production rates from known changes in field strength and pole position, but also because additional data are needed to determine the position of the pole at the site used for calibration. These additional data may be magnetic declination and inclination measurements at the sampling location, or measurements of relative production rates at positions of similar age and latitude but at different longitude. A recognition of the importance of pole position changes the approach one uses to establish the calibration data.

Other factors that will be addressed include local changes in atmospheric density resulting from sea-level lowering and terrestrial-ice buildup during periods of glaciation and long-term effects of isostatic compensation.



MONTE CARLO SIMULATION OF *IN-SITU*-PRODUCED COSMOGENIC NUCLIDES

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Cosmogenic nuclides produced *in situ* in terrestrial surface samples provide an important tool for dating and determining erosional histories of landforms. Reliable interpretation of the measured nuclide contents requires a good understanding of fundamentals of nuclide production mechanisms. We present a pure physical model (Masarik and Reedy 1995) for the simulation of the relevant processes enabling an investigation of nuclide production dependence on depth, composition, atmospheric thickness, and geomagnetic field intensity.

In our simulation model (Masarik and Reedy 1994, 1995), the spectra of particles inducing reactions that produce cosmogenic nuclides are calculated by Monte Carlo numerical simulations using the LAHET Code System (LCS) and the GEANT code. Having calculated neutron fluxes with these codes, the production rates of nuclides are determined by integrating over energy the product of these fluxes with experimental and evaluated cross sections for the reactions producing each nuclide. Technical details of the LCS model and our approach are described in Masarik and Reedy (1995). This approach is similar to that often used and well tested by us for cosmogenic-nuclide production rates in lunar samples and meteorites (*e.g.*, Masarik and Reedy 1994).

We simulated the irradiation of Earth with an isotropic GCR particle flux with an energy distribution corresponding to the GCR primary particle flux averaged over a solar cycle. The Earth was modeled as a sphere with a 6378-km radius and an average crustal elemental composition. The model atmosphere has a 1030-g/cm^2 thickness and its standard composition, density, and temperature profiles (Masarik and Reedy 1995). Running 10^7 primary particles, we obtained surface neutron fluxes with statistical errors of ~8%. Although we calculated muon fluxes, their contribution to the production rate was not considered by us because of the lack of the data needed to convert muon fluxes to production rates.

Except for H and Fe, most changes in the surface composition or the addition of other elements to the assumed composition have very little effect on the calculated fluxes (Masarik and Reedy 1994). Therefore elemental production rates valid for many types of rocks can be obtained from these fluxes. The total production rates (in atoms per gram-element per year) only by neutrons and for high latitudes and sea level are given by

$$P(^{10}Be) = 10.87[O] + 0.52[Mg] + 0.39[Si] + 0.45\,[Al] + 0.16[Fe]$$

$$P(^{14}C) = 31.3[O] + 5.3[Mg] + 4.2[Al] + 4.3[Si] + 1.2[Fe]$$

$$P(^{26}Al) = 225[Al] + 77\,[Si] + 0.15\,[Fe]$$

$$P(^{36}Cl) = 129[K] + 65[Ca] + 16[Ti] + 0.9[Fe]$$

$$P(^{21}Ne) = 98[Na] + 131[Mg] + 65[Al] + 39[Si] + 4[Ca] + 0.20[Fe]$$

$$P(^{3}He) = 135[O] + 116[Mg] + 107[Al] + 111[Si] + 61[Ca] + 40[Fe]$$

in which the target-element concentrations, such as [O], are in weight fractions. The calculated rates for most minor target elements are not well tested and could have considerable uncertainties. Latitude-altitude production rates for all above listed nuclides were also calculated. The results of our model calculations are in good agreement with most recent measurements (Masarik and Reedy 1995).

PRODUCTION RATE OF ^{10}Be AND ^{26}Al ON THE SURFACE OF THE EARTH AND UNDERGROUND

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To apply *in-situ* produced cosmogenic nuclides to the study of Earth surface processes, production rates at the surface of the Earth and the attenuation length of the production underground must be known. I review present understanding of ^{10}Be and ^{26}Al production rates from quartz, based on different methods and covering various time scales. Each method has its merits and limitations that must be understood in order to assess the reliability of the production rates.

A. *Geological Methods*: Geological methods require that the exposure conditions of the samples studied be constant and that they be well known. Production rates are averages over changes of the Earth's magnetic field and of the primary cosmic ray flux.

1. Concentration of ^{10}Be and ^{26}Al in quartz from glacially polished rocks (Nishiizumi *et al.* 1989): Since samples are uneroded, nuclides with various half-lives can be compared in the same sample (Neidermann *et al.* 1994). Uncertainties in the exposure age (glaciation age) and in the geomagnetic latitude correction must be considered.
2. Concentration of ^{10}Be and ^{26}Al in saturated rocks (Nishiizumi *et al.* 1991; Brown *et al.* 1991): The high concentrations of cosmogenic ^{21}Ne (Hudson *et al.* 1991) insure that the activities of ^{10}Be and ^{26}Al in certain Antarctic rocks are saturated (decay rate is the same as the production rate). Effects of changing geomagnetic intensity can be ignored for these high latitude samples. Because of the possible influence of erosion, the production rate estimates are lower limits. In addition, there is an uncertainty arising from uplift of the samples during the million year exposure period.

B. *Theoretical Calculation* (ex. Masarik and Reedy 1995): The accuracy of calculated production rates depends on the model and on knowledge of excitation functions. The increasing availability of laboratory data (Imamura *et al.* 1990; Reedy *et al.* 1994) improves the reliability of the results. The method can be applied to samples of various size and shape.

C. *Direct Measurements of ^{10}Be Production in a Water Target* (Nishiizumi *et al.* 1995): Exposure conditions are unambiguous but the exposure age is very short compared to the geological time scale. There is an uncertainty arising from secular variations of the Earth's magnetic field and of the primary cosmic ray flux.

TABLE 1. Comparison of ^{10}Be Production Rates (atom/gSiO_2/yr at sea level, >50°)

Method	Time scale	^{10}Be production rate (atom/gSiO_2/yr)	Reference
Water targets	4 solar cycles	5.32 ± 0.27	Nishiizumi *et al.* 1995
Water targets (after geomagnetic correction)	11,000 yr	6.1 ± 0.3	Nishiizumi *et al.* 1995
Glacially polished rocks at Sierra Nevada	11,000 yr	6.03	Nishiizumi *et al.* 1989
Antarctic Rocks	≥ 4 My	6.13	Nishiizumi *et al.* 1991
Antarctic Rocks	≤ 2.5 My	6.4	Brown *et al.* 1991
Theoretical calculation	> several My	5.97	Masarik and Reedy 1995

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COSMIC-RAY NEUTRONS AT GROUND LEVEL: TEMPORAL AND GEODETIC VARIATIONS

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Ground-level cosmic-ray neutrons are the major producer of near-surface cosmogenic isotopes. The inventory of a cosmogenic isotope at a particular location at a particular time depends on the past temporal variation of the neutron flux at that location. To obtain the sensitivity of terrestrial ground-level neutron fluxes on time and space, ground-level fluxes have been calculated using LUIN94 (O'Brien 1995) as a function of geodetic coordinates, altitude, solar activity and magnetic field intensity. The geomagnetic field was treated in considerable detail, using the 1980 Epoch vertical cutoff calculations of Shea and Smart (1983), obtaining the non-vertical cutoffs by means of the approach of Rösler (personal communication) and Heinrich and Spill (1979). Solar modulation was treated in the heliocentric potential approximation. Results are presented graphically. The tabular data underlying these data or the codes used to generate them will be given to anyone interested.

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MORE REVEALING HISTORIES OF EXPOSURE: THE RAT URINE STORY

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Accurate surface exposure dating using cosmogenic nuclides will require correcting for the effects of secular variations in the production rates of cosmogenic nuclides, presumably mostly due to fluctuations in the intensity of the geomagnetic field. The two main sources of data about these variations are paleomagnetic intensity reconstructions (mostly from sediment cores) and documented discrepancies between ^{14}C ages and independent ages. Unfortunately, environmental conditions during deposition can affect the accuracy of paleomagnetic intensity reconstructions, and their reliability is difficult to assess. Variations in cosmogenic production can be back-calculated from the ^{14}C discrepancies, but the magnitude of these discrepancies is strongly affected by changes in oceanic circulation. We have measured ^{36}Cl in fossil packrat urine in order to provide an independent basis for reconstructing variations in cosmogenic nuclide production. The record of ^{36}Cl fluctuations thus obtained shares many features with the ^{14}C and paleomagnetic reconstructions, but indicates a larger and more abrupt decrease in cosmogenic production at the end of the last glacial period.

COMPARISON OF DATES FOR YOUNG BASALTS FROM THE $^{40}Ar/^{39}Ar$ AND COSMOGENIC HELIUM TECHNIQUES

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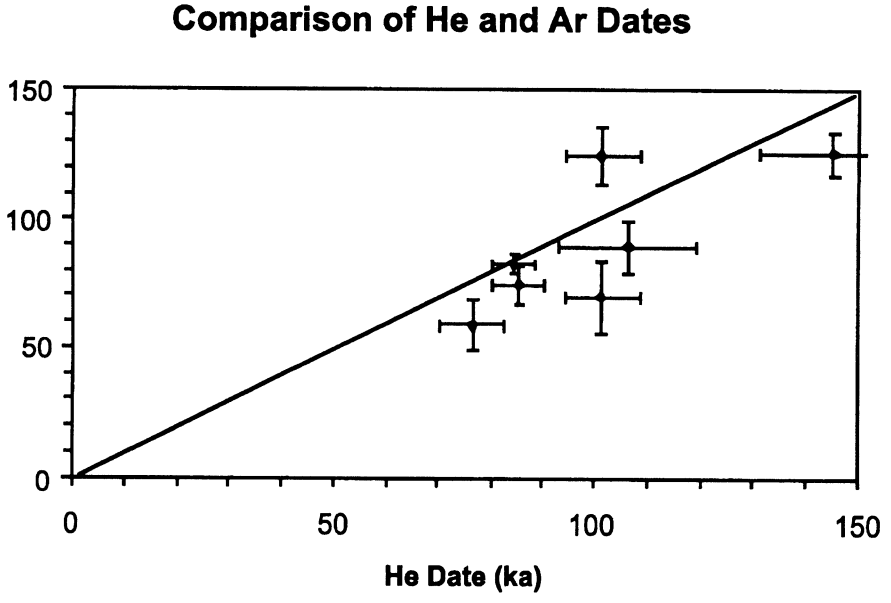
We have ^{3}He surface exposure dates and $^{40}Ar/^{39}Ar$ dates for a number of lavas from three volcanic fields: Potrillo (New Mexico), Lathrop Wells (Nevada), and San Quintin (Baja California, Mexico). The dates span from 20 ka to 150 ka. While agreement among the two types of dates is encouraging, it is not universal. Both types of dates have their associated assumptions that can bias the results: He dates for older lavas may be lower than the eruption age due to erosion, while $^{40}Ar/^{39}Ar$ dates at low radiogenic yields are sensitive to assumptions about the trapped component. A particularly encouraging approach is $^{40}Ar/^{39}Ar$ dating of sanidine separated from xenoliths. At Lathrop Wells, a subset of these xenoliths yields an upper limit for the age of the Q12 flow of 75 (±2) ka, slightly younger than the ^{3}He date (85 ± 5 ka). This observation, as well as the general comparison of Ar and ^{3}He dates (figure below), suggests that the integrated production rate for ^{3}He is slightly higher at *ca.* 80 ka, compared to that derived from Tabernacle Hill at 17 ka.



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PRODUCTION SYSTEMATICS OF COSMOGENIC NUCLIDES IN THE EARTH

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The high-energy (GeV) particles in the galactic cosmic rays (GCR) produce nuclides deep in any object exposed to them. Cosmogenic nuclides have been well studied since the 1950s in meteorites and lunar samples. In extraterrestrial matter, several approaches have been used to determine cosmogenic-nuclide production systematics. The work being done for terrestrial cosmogenic nuclides (*e.g.*, Reedy *et al.* 1994a) follows the approach used for extraterrestrial nuclides.

For extraterrestrial cosmogenic nuclides, initial studies used activities of radionuclides to infer production rates. (For a long, constant exposure to cosmic rays, a radionuclide's decay rate approaches equilibrium with its production rate.) Irradiations of thick targets at high-energy accelerators were done to experimentally simulate GCR irradiations in space and helped in understanding the nuclear processes involved. Accelerators were also used with thin targets to measure cross sections for making these cosmogenic nuclides. Several models were developed for predicting the systematics of the production of cosmogenic nuclides, mainly semi-empirical fits. Recently, numerical simulations based only on physics have been used to study nuclear reactions and allow us to examine the details of how GCR particles interact with matter (Masarik and Reedy, this issue).

The terrestrial case is more complicated because of the Earth's atmosphere and strong geomagnetic field. Most GCR particles interact in the Earth's atmosphere, making mainly ^{14}C. The Earth's thick (1033 g/cm^2) atmosphere attenuates the flux of particles reaching the surface by several orders of magnitude. The large difference in the composition and density of the atmosphere compared to extraterrestrial matter makes it difficult to use data from extraterrestrial matter for nuclides made deep in the atmosphere. One major difference is that most pions made in dense extraterrestrial matter interact before they can decay, while most pions in the thin atmosphere decay to muons. These muons are weakly-interacting particles and can go much further than strong-interacting particles such as neutrons and pions. Below a few meters in the Earth's surface, muons are a major source of cosmogenic nuclides. Another complication is that the production rates of a nuclide in the Earth's surface can vary much with the sample's elevation and the location's geomagnetic latitude.

Most production rates of nuclides made in the Earth are now based on a few measurements made with natural samples. Generally, the production rate of a cosmogenic nuclide is converted from that determined at the location's elevation and geomagnetic latitude to the rate at sea level and a high geomagnetic latitude (>60°) with no cutoff of GCR particles. Most measurements have been done on material with a simple composition, often quartz (SiO_2) or calcite ($CaCO_3$).

Several studies have been done at accelerators on production systematics of terrestrial cosmogenic nuclides. Some irradiations were done at the Los Alamos Meson Physics Facility, usually using secondary neutrons near a beam-stop. These irradiations have yielded some production ratios, such as $^{10}Be/^{14}C/^{26}Al$ in SiO_2 (Reedy *et al.* 1994b), and could be used to get relative production rates from pure elements. Some accelerators are also sources of muon beams. Work is also being done on measuring yields of nuclides from fast muons or muons stopping in various targets (Reedy *et al.* 1994c).

As the ratio of neutrons to protons in the Earth's surface is higher than in most meteorites and lunar samples, cross sections for the production of terrestrial cosmogenic nuclides by energetic neutrons are very important. However, only a few neutron cross sections have been measured for the nuclides

of interest, mainly at energies below 20 MeV. More cross sections are needed for terrestrial cosmogenic nuclides, especially for neutron energies above 20 MeV.

Neutron-transport codes, such as the Monte Carlo N-Particle (MCNP) code, can be used to study nuclides made by neutron-capture reactions and have shown that rates for the $^{35}Cl(n,\gamma)^{36}Cl$ reaction depend on the rock's composition and water content. The LAHET Code System (LCS) and similar codes have been used very successfully for studying cosmogenic nuclides in extraterrestrial matter. LCS was recently to study production of nuclides in the Earth (Masarik and Reedy, this workshop).

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WORKSHOP ON SECULAR VARIATIONS IN THE RATES OF PRODUCTION OF COSMOGENIC NUCLIDES ON EARTH: PALEOMAGNETIC AVERAGES OF GEOMAGNETIC LATITUDE

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The production rate of cosmogenic nuclides depends on the geomagnetic cutoff rigidity, which in turn depends upon geomagnetic latitude. The geomagnetic dipole moment axis moves over time, one of the characteristic patterns of secular variation. Over the past 300 yr, the latitude of the northerly end of the dipole axis has decreased from *ca.* 83°N to 78°N, while longitude has drifted westward from 320°E to 290°E (Merrill and McElhinny 1983). On the other hand, a critical assumption of paleomagnetism is the geocentric axial dipole field hypothesis, whereby the magnetic direction at any locality will average over several millennia to that of an axial geocentric dipole.

Data of Ohno and Hamano (1992) were used to model the effect of dipole secular variation on average geomagnetic latitude. This compilation gives average pole positions at 500-yr increments for the past 10,000 yr, based on archaeomagnetic and sediment paleomagnetic data. For several sites on the Earth's surface, the average pole position was integrated back in time from the present to 10,000 yr ago. Differences between geomagnetic and geographic latitudes (here called the latitude difference) were calculated for the time-integrated average pole positions at 500-yr increments. Averaging from the present back to 1–4 ka gives a median difference of 1.7°; from 4–7 ka, it is 1.4°; from 7–10 ka, it is also 1.4°. A similar analysis was carried out using pole positions of Merrill and McElhinny (1983: Table 4.1) at 100-yr increments back to 2000 yr BP. Averaging from the present back to 200–800 BP gives a median difference of 4.2°. Thus, for exposure times longer than several centuries, the latitude error is typically 1.5°.

The Laschamp excursion, involving anomalous paleomagnetic directions and intensities, has been observed in some but not all data sets between 30 and 50 ka (Thouveny and Creer 1992). If such an excursion were due to a tilt of the dipole axis, its effect on average geomagnetic latitude could also be calculated. If the pole moves linearly to a latitude of 45° and back during a 5-ka long excursion (ignoring changes in dipole moment), the integrated average latitude difference is down to 2° after 50,000 yr; for a short 200-yr excursion (Thouveny and Creer 1992), the difference is down to 2° after 200 yr.

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COSMOGENIC CHLORINE-36 PRODUCTION RATES FROM CALCIUM AND POTASSIUM

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Advantages of exposure dating with cosmogenic Chlorine-36 are high ^{36}Cl production rates in a number of common minerals, and the high sensitivity of AMS Cl isotopic analyses. A disadvantage is the variety of ^{36}Cl-producing reactions—spallation reactions on K and Ca, muon capture reactions on these elements, and capture (by ^{35}Cl) of secondary neutrons produced in spallation, muon capture and fast muon interactions. Complications arise through the different latitude, altitude, depth and compositional dependences of these reactions. Also, errors in calibration of any one reaction tend to propagate into calibration of the others. In estimating ^{36}Cl production rates from geological surfaces, our strategy has been to: 1) work with separated minerals—calcite, Ca-feldspar and K-feldspar—to maximize target element abundances (enhancing analytical sensitivity) and Ca/Cl and K/Cl ratios (enhancing contributions from spallation relative to slow neutron capture); 2) use high altitude sites for calibrating spallation reactions and deep sub-surface samples for calibrating muon reactions; and 3) suppress ^{36}Cl measurement errors and reduce dependence on accurate Cl analyses by adding Cl carrier to samples.

Results are summarized below. Quoted uncertainties are $\pm 1\ \sigma$ (68% confidence) based on analytical errors and indicated uncertainties in calibration surface ages. Uncertainties refer to production rates at the calibration sites; additional errors in scaling to sea-level and high latitude have not been propagated here. Spallation and muon reactions have been scaled separately using the procedures of Lal (1991: EPSL 104, 424). Latitude corrections are based on effective geomagnetic latitudes (λ_{eff}) of the calibration sites over their exposure times. Sidereal ages are used for calibration, to avoid errors due to non-linearity in the radiocarbon timescale.

1. *Ca Spallation*: Our primary calibration is based on Ca-feldspar from the Tabernacle Hill basalt (t_{exp} = 17.3 ± 0.5 ka), which gives a Ca spallation rate of 152 ± 5 atom (g Ca)$^{-1}$ a^{-1} at 1445 m, λ_{eff} = 40.9°. Five measurements were made on feldspar from three separate rock samples. Ca-spallation accounts for 86–88% of ^{36}Cl in the samples, with 5% due to $^{40}Ca(\mu^-, \alpha)^{36}Cl$, 7% due to K reactions and 1–2% due to neutron capture. The equivalent rate at sea level and high latitude is 48.8 ± 1.7 atom (g Ca)$^{-1}$ a^{-1}.
2. *Muon Reactions in Calcite*: ^{36}Cl measurements on a 20-m profile in calcite marble at Wombeyan in SE Australia (620 m, λ = 34.3°) give a $^{40}Ca(\mu^-, \alpha)^{36}Cl$ production rate of 0.011 ± 0.0013 atom ^{36}Cl per stopped negative muon and a secondary neutron yield of 0.41 ± 0.1 neutrons per stopped negative muon in calcite. Assuming a negative muon stopping rate of 175 μ^- g^{-1} a^{-1} at sea-level and high latitude, the surface production rate for the $^{40}Ca\ (\mu^-, \alpha)^{36}Cl$ reaction is 4.8 ± 0.5 atom (g Ca)$^{-1}$ a^{-1} (*i.e.*, 9% of total production from Ca). The natural calibration avoids the need to know values for muon reaction parameters such as the chemical compound factor and α-emission probability. Estimates of these factors are required to apply the results to

minerals other than calcite, however. Assuming a Fermi-Teller ("z-law") distribution of muon captures between Ca, C and O in calcite, we derive an α-emission probability following muon capture of 0.033 ± 0.004, well within the range of existing measurements and calculations ($0.004 < P\alpha < 0.15$).

3. *^{36}Cl production from K*: So far only surface samples of K-feldspar have been measured, precluding a breakdown of total production from K (PK) into component reactions. Samples from glacial pavements in the Sierra Nevada, Scotland and Antarctica have been measured. Assuming t_{exp}=13.1 ka, samples from the Sierra Nevada give PK=1460 ± 88 atom (g K)$^{-1}$ a^{-1} at 3000 m and λ_{eff}=37.4°. Concordant results (χ^2/n=0.8, n=10 measurements) are obtained from samples at 4 sites, at elevations between 3000 and 3600 m and with chloride concentrations from 10–310 ppm. Reactions on K account for 76–99% of production in the samples. Consistency between samples with low and high Cl contents is obtained assuming a surface neutron capture rate of 2450 n g^{-1} a^{-1} at 3000 m and 37.4°, close to the scaled value of Zreda *et al.* (1991: EPSL 105: 94–109). Assuming 5% of K production at sea level is due to muon capture, these data give PK = 180 ± 11 atom (g K)$^{-1}$ a^{-1} at sea level and high latitude. Samples from pavements exposed by retreat of Loch Lomond (Y. Dryas) Stage ice (t_{exp} = 11.5 ± 0.3 ka) in Scotland give PK = 313 ± 25 atom (g K)$^{-1}$ a^{-1} at 520 m and λ =58.5°. Neutron capture corrections are 18–22% for these samples. Again assuming 5% of total K production due to muon capture, these data give PK = 189 ± 15 atom (g K)$^{-1}$a^{-1} at sea level and high latitude, in excellent agreement with results from the Sierra Nevada. Two samples of K-feldspar from the Trans-Antarctic Mountains (λ = 77.5°), apparently saturated with ^{36}Cl, give production rates of 1350 ± 50 atom (g K)$^{-1}$ a^{-1} at 2050 m and 1230 ± 40 atom (g K)$^{-1}$ a^{-1} at 2000 m, with negligible (<2%) corrections for neutron capture on ^{35}Cl. Equivalent rates at sea level, scaled as above, are PK = 239 ± 10 and 227 ± 8 atom (g K)$^{-1}$ a^{-1}. The samples have been measured repeatedly to confirm that the 25% discrepancy with the scaled values from Scotland and the Sierra Nevada is real and must be accounted for either by the scaling procedure, or secular variation in the cosmic ray flux.

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TEMPORAL VARIATIONS IN GLOBAL ATMOSPHERIC ^{14}C AND ITS PRODUCTION

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The atmospheric radiocarbon record of the past 20,000 yr is an integrated response to climatic, solar and geomagnetic forcing. The time dependencies of the forcing functions play an important role in shaping the atmospheric ^{14}C profile. Geomagnetic forcing manifests itself mainly on millennia time scales, whereas solar forcing is more restricted to decadal and century time intervals. Oceanic thermohaline circulation change (and associated climate perturbation) sufficiently large to induce atmospheric ^{14}C change operates on decadal to millennia time scales.

^{14}C age calibration is needed because conventional ^{14}C dates do not take atmospheric ^{14}C variability into account. Use of our knowledge of forcing factors in carbon reservoir models will generate "hypothetical" calibration curves, but the limitations of our knowledge, especially of solar and oce-

anic variability, are such that calculated calibration curves lack much of the detail found in measured Holocene tree-ring ^{14}C.

The record of ^{14}C change can be extended beyond the interval covered by tree rings by using ^{14}C and U/Th dated corals. However, the marine surface waters greatly attenuate production-rate induced ^{14}C variations, and thus the calibration curve extension loses much century-type production rate detail.

DETERMINATION OF ^{36}Cl PRODUCTION RATES FROM THE DEGLACIATION HISTORY OF WHIDBEY AND FIDALGO ISLANDS, WASHINGTON

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Cosmogenic ^{36}Cl is produced in surface rocks by thermal neutron activation of ^{35}Cl, spallation of ^{39}K and ^{40}Ca and slow negative muon capture by ^{40}Ca. Production parameters for the ^{36}Cl isotopic system were refined using the well-constrained deglaciation history of Whidbey and Fidalgo Islands, Washington, USA. Calculated production rates due to spallation are 1770 ± 121 atoms ^{36}Cl (kg^{-1} rock) (percent K_20^{-1}) yr^{-1} and 641 ± 20 atoms ^{36}Cl (kg^{-1} rock) (percent $Ca0^{-1}$) yr^{-1}. The calculated effective thermal neutron absorption rate is (3.53 ± 0.07) × 10^5 neutrons kg^{-1} of rock yr^{-1}. Production due to muon capture by ^{40}Ca was estimated using previously calculated values scaled to high geomagnetic latitude and sea level.

Consistency between calculated ^{36}Cl ages using the production rates reported here, and independent ^{14}C ages that constrain the timing of deglaciation of the Cordilleran Ice Sheet over three disparate locations, substantiates the validity of the ^{36}Cl production rates for high-latitude (>60°) locations, integrated over the last ~15,200 cal yr. Evaluation of potential sources of error indicate that uncertainty of AMS and total Cl measurements are the dominant factors controlling the overall uncertainty of the ^{36}Cl ages. Geologic factors such as surface erosion and/or prior exposure history are also important sources of error that were addressed by this study; however, independent testing of the production rates on independent surfaces of known age suggest that these potential problems were minor for the 64 calibration samples.

Analytical uncertainties of ±5–6% (1 σ) for the calibration samples indicate that it should be possible to resolve late-glacial landforms from those of full-glacial age using the ^{36}Cl dating method, providing the analytical uncertainty of AMS and total Cl measurements is <5% and geological problems are accurately constrained. However, without greatly improving the precision of AMS and total Cl measurements, it is unlikely that the ^{36}Cl dating method will be able to resolve ages of, or correlate landforms associated with, short-term climatic episodes such as the late-glacial Younger Dryas event.

RECENT ADVANCES IN DETERMINING ABSOLUTE AND RELATIVE PALEOINTENSITY VARIATIONS OF THE GEOMAGNETIC FIELD

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For the past 30 yr, the focus in paleomagnetism has been on the direction of the paleomagnetic vector rather than on its intensity. The reason for this "two-dimensional" view of a three-dimensional quantity is that determination of the paleointensity is inherently more complex, more difficult, and less reliable than determination of the paleomagnetic direction. This situation may be changing as new techniques and new instrumentation are brought to bear on these problems.

For determinations of the absolute paleointensity of the geomagnetic field, the standard methodology has, for many years, been the Thellier-Thellier double heating experiment. This approach can be used with material that carries a thermal remanent magnetization, such as lava flows, hearths and pottery. Unfortunately, the Thellier-Thellier experiment is very time-consuming, and the percentage of samples that give unsatisfactory results can be quite high. As a result, the database of absolute paleointensity determinations is still relatively small. Recently, several research groups have tried to develop mineral magnetic screening criteria for identifying, in advance, those samples that were likely to produce satisfactory results in the Thellier-Thellier experiment. Although this work promises to increase the success rate for absolute paleointensity determinations, it does not address another important problem, namely, the available material seldom represents a continuous sampling of the geomagnetic field through time. This problem is particularly acute for studies involving lava flows but it can also arise when archaeological materials are involved.

Sediments, on the other hand, offer the possibility of a continuous record of geomagnetic intensity variations. For sediments, however, the intensity of magnetization depends on the intensity of the geomagnetic field at the time the magnetization was acquired and on several other factors, including the concentration and grain size of the magnetic carriers. Many years ago it was proposed that the relative intensity of the geomagnetic field intensity could be determined with a normalization based on the intensity of a laboratory-induced magnetization. It was soon recognized that too much variation in the size or concentration of the magnetic grains could be a problem, and various selection criteria were proposed. In recent years, a globally consistent picture of relative paleointensity variations is beginning to emerge, at least for the last 250,000 yr. In addition, there has been the intriguing suggestion that variations in relative paleointensity over the past four million years are linked to polarity transitions. However, there is still disagreement about the interpretation of significant spatial and temporal variations that are seen in relative paleointensity records over both time scales. In addition, it is not clear whether the absolute and relative paleointensity records are mutually consistent.

With regard to the determination of production rates of cosmogenic nuclides, it is important to recognize that both absolute and relative paleointensity determinations are not easy to make nor simple to interpret, and that the inherent problems and complexities could lead to problems in calculations based upon them. On the other hand, the most important observation may be that geomagnetic intensities during the past 10,000 yr have been somewhat higher than the average for the past 250,000 yr. If this conclusion is correct, then temporal and spatial variations that are present over the longer time interval could have had a relatively minor influence on production rates.