PRODUCTION RATES OF COSMOGENIC ^{10}BE AND ^{26}AL OVER THE PAST 20 KY

A Proposal Presented

by

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Abstract

Cosmogenic isotopes are being used with increasing frequency in a variety of geomorphic applications despite the fact that the production rates of these isotopes are not well constrained with respcct to time. As a result of recent advances in the detection capabilities for cosmogenic isotopes, the dominant error in exposure age and erosion rate calculations becomes the production rates, therefore, I am proposing to estimate the average production rate of ^{10}Be and ^{26}Al over the last 20 ky by sampling quartzite boulders from the Laurentide icesheet's terminal moraine.

The production rates of cosmogenic isotopes must be well constrained if they are to be a useful tool in geomorphological studies; calculations of cosmogenicly based erosion rates or exposure ages rely on interpretive models which require estimates of isotope production as a function of time. Most previous studies have assumed that production rates are temporally constant; however, several lines of geophysical evidence suggest that rates of in-situ isotope production may have changed by a factor of ≥ 1.5 over the past 20 ky. Even though exposed rocks integrate these changes over the timc, preliminary calculations suggest that variations in production rates could significantly affect the accuracy of cosmogenic model cxposure ages and erosion rates.

Despite increasing use of ^{26}Al and ^{10}Be for studies of erosion, climate change and glaciation in the Late Pleistocene (Evenson and Gosse, 1993; Nishiizumi et al., 1993), there exists no direct calibration of ^{26}Al and ^{10}Be production rates over the 20 ky time frame. I am proposing to determine, empirically, the production rates of ^{10}Be and ^{26}Al from morainal boulders having an associated ^{14}C age of about 18.5 ky based on the dating of associated organic material. This study will address a fundamental uncertainty in thc application of cosmogenic isotopcs to geologic studies and will tell us more about the behavior of Earth's magnetic field in thc geologic past.

Introduction

Cosmogenically produced nuclides are finding a wide range of applications in the earth sciences and are becoming a valuable and ubiquitous tool for geomorphic studies. Cosmogenic isotopes have been used to calculate bedrock-to-soil conversion rates (Monaghan et al., 1992), exposure ages of glacial moraines (Brown et al., 1991), and rates of weathering (Sarda et al., 1993; Raisbeck et al., 1983; Nishiizumi et al., 1986; Nishiizumi et al., 1989; Klein et al., 1986; Middleton and Klein, 1987). This burgeoning popularity of in-situ produced cosmogenic isotopes is primarily due to increased analytical capabilities, a unique time frame over which such isotopes are potentially useful, and a selection of isotopes with varying half-lives.

With recent advances in the detection capabilities of cosmogenic isotopes, it is now possible to measure ratios for the isotopes $^{26}Al/^{27}Al$ and $^{10}Be/^{9}Be$ as low as several parts in 10^{-15} (Bierman, in press). Given these significant advancements in accelerator mass spectrometry (AMS) technology, the emphasis must now be concentrated on further quantifying the production rates of cosmogenic isotopes over time. Production rates for ^{26}Al and ^{10}Be have been established over 11 ky (Nishiizumi et al., 1989) and seemingly confirmed over 50 ky (Nishiizumi et al., 1991b) but production rates between and outside this range have only been estimated or based on average values.

Cosmic rays

The earth is continuously being bombarded by charged particles most of which are smaller than an atom. These charged particles are known as cosmic rays and it is the effects of these cosmic rays on the surface of the earth which provides the foundation for this study.

The cosmic rays entering at the top of Earth's atmosphere are predominantly protons (85%). Very few of these protons (primary cosmic rays) reach the surface of Earth. Essentially all primary cosmic ray protons collide with atmospheric nuclei producing atmospheric radionuclides as well as a shower of additional particles (secondary cosmic rays) and result in what is referred to as a 'nuclear cascade'. These secondary particles have sufficient energy to reach the Earth's surface and create, in-situ, a variety of nuclides including ^{10}Be and ^{26}Al (Fabryka-Martin, 1988). The origin of cosmic rays is still a subject of some debate; however, evidence suggests that there are two major sources: stars within the Milky Way galaxy reaching the explosive supernova stage, and less significantly, a solar source (Friedlander, 1989).

Production mechanisms of cosmogenic isotopes

There are several commonly measured cosmogenic isotopes which are created in-situ, by several different mechanisms, when cosmic rays interact with target nuclei in rock and soil. Six cosmogenic isotopes that are commonly used in geomorphic studies are ^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, and ^{36}Cl. The four main types of isotope production interactions are spallation, muon capture, neutron activation, and alpha particle interaction (Fabryka-Martin, 1988), of which the first two are the most relevent production pathways with respect to this study.

Spallation, which is the primary production pathway of cosmogenic ^{10}Be and ^{26}Al, occurs when a target nucleus is split into several particles as a result of bombardment by a high energy neutron. Spallation reactions are generally negligible at depths more than a few meters below the surface. ^{10}Be is produced as a result of the spallation of O, Mg, Si, and Fe, and ^{26}Al is produced by the spallation of Si, Al, and Fe.

Muon capture, a less significant isotope producing interaction, involves charged particles with a low mass. Muons, which are secondary particles caused by interaction of primary cosmic rays with atmosphere and soil, are captured by a proton in the target nucleus. The production rates for muon capture are lower than spallation near the surface but they penetrate to greater depths than high-energy neutrons. An example of an isotope created by muon capture would be ^{26}Al from ^{28}Si.

Factors affecting production rates

Production rates of cosmogenic isotopes can be calculated using one of two equations. If the exposure age of the outcrop is less than the half-life of the radiogenic isotope by at least an order of magnitude, then the production rate (P, atoms g^{-1} yr^{-1}) is a function of the number of atoms of the isotope (N, atoms g^{-1}) and the exposure age (t, yrs):

$$P = N / t \qquad \textbf{(Eq. 1)}$$

If the nuclide is unstable and the exposure age of the outcrop approaches its half-life, then the production rate is a function of the decay constant (λ, yr^{-1}) as well as the exposure age (t, yrs):

$$N = \frac{P}{\lambda} e^{-\lambda t} \qquad \textbf{(Eq. 2)}$$

Although the flux of galactic or primary cosmic rays is generally assumed to be constant with respect to time, there are several factors that affect the production rates of cosmogenic isotopes at Earth's surface. The three primary variables are strength of Earth's magnetic field, sample elevation, and the depth of the target below the surface.

As previously mentioned, primary cosmic rays are positively charged particles. As such, they are going to be affected by magnetic fields according to the equation :

$$F = qv \times B \qquad \textbf{(Eq. 3)}$$

where the magnitude of the force on the particle (F) is the cross product of the charge (q) times the velocity (v) and the component of magnetic field strength (B) perpendicular to velocity. The magnitude of this force is expressed as

$$F = |q| vB \sin\theta \qquad \textbf{(Eq. 4)}$$

where θ is the angle between **v** and **B**. From this equation, it can be seen that the force acting on the charged particle will be greatest when θ equals 90 degrees, or when the velocity vector is perpendieular to the magnetic field. The magnetic field of the earth is analogous to the magnetic field of a bar magnet; equipotential lines are parallel to the surface of the earth at the equator and is perpendicular to the surface of the earth at the poles (Figure 1). The result of this phenomena is that production rates of cosmogenic isotopes are going to be less at the equator than at the poles, due to the decreased angle of incidence (θ) between the velocity vector and the field equipotential lines. There is also an abundance of evidence which suggests that the strength of Earth's magnetic field has not remained constant over the history of the earth (Meynadier et al., 1992; Figure 2), thereby making magnetic field intensity a two-dimensional variable which varies over time and space.

Cosmic rays also interact with atmospheric gases. Due to the attenuation of the cosmic ray flux by atmospheric gases, the isotope production rates will be higher at higher elevations where the influence of atmosphere will be negligable, and deerease at lower elevations where atmospheric pressure is higher. The altitudinal variations in cosmogenic isotope production rates are described by the equation

$$P_a = P_b e^{[(b-a)/L]} \qquad \textbf{(Eq. 5)}$$

where P_a and P_b represent production rates at atmospheric depths a and b (g cm^{-2}) and L is the attenuation pathlength of ~160 g/cm^2 (Brown et al., 1991).

Lastly, production rates are dictated by the depth of the target below the surface of the earth, with production rates being highest at the surface and decreasing exponentially with depth. It has bcen observed that half of the cosmic-ray-neutrons havc been absorbed above the depth of 45 cm in rock. The equation representing production rates as a function of depth is

$$P_x = P_o e^{-\left(x\rho/\Lambda\right)} \qquad \textbf{(Eq. 6)}$$

where P_x = production rate (atoms g^{-1} yr^{-1}) at depth x (cm), P_o = surface production rate, x = depth (cm), ρ = density of rock (g/cm^3), and Λ = attenuation length for cosmic ray neutrons (150-170 g cm^2).

Significance of Proposed Research

Existing cosmogenic exposure age and erosion rate calculations are based on the assumption that isotope production rates are constant or are well represented by average values. However, numerous studies have shown that the strength of Earth's magnetic field and thus the production rate of cosmogenic nuclides have fluctuated over 20 ky (Bard et al., 1990; Kurz et al., 1990; Mazaud et al., 1991; Meynadier et al., 1992; Tric et al., 1992). Because accelerator mass spectrometer measurements can now be made with relatively high precision (several percent, 1σ), uncertainty in the rate of isotope production can easily become the dominant error term in any model used to interpret isotope abundances as exposure ages or erosion rates.

^{26}Al and ^{10}Be are two widely used cosmogenic nuclides for which production rates have been estimated using samples collected from glacially eroded bedrock surfaces. The exposure ages, based on two bog-bottom radiocarbon dates, were estimated to be 11 ky (Nishiizumi et al., 1989). While it seems reassuring that exposure ages calculated with these production rates are consistent with several other age estimates (50 ka, (Nishiizumi et al., 1991b)) and approaching saturation (>2 my, (Nishiizumi et al., 1991a)), geophysical data suggest that exposure ages calculated for samples younger or older than the calibration age (11 ky) should be in error. Such discrepancy is suggested by the observation that on average, Earth's magnetic field was weaker and thus cosmic ray fluxes were higher over the past 30 ky than over the past 11 ky (Figure 2). Conversely, average cosmic ray fluxes and isotope production rates during periods of the Holocene have been significantly lower than the average value taken over the past 11 ky. Production rate data for ^{3}He are consistent with changing field strength and isotope production rates (Kurz et al., 1990).

Despite increasing use of ^{26}Al and ^{10}Be for studies of erosion, climate change and glaciation in the Late Pleistocene (Evenson and Gosse, 1993; Nishiizumi et al., 1993), there exists no direct calibration of ^{26}Al and ^{10}Be production rates over the 20 ky time frame. I am proposing to determine empirically the production rates of ^{10}Be and ^{26}Al from morainal boulders having a ^{14}C age of about 18.5 ky based on the dating of associated organic material. The boulders will be sampled from the terminal moraine of the Laurentide ice sheet in northwestern New Jersey (Figure 3) where the Laurentide's Hudson-Champlain Lobe reached its terminus. This site was chosen based on the well constrained exposure age of the terminal moraine as well as the composition of the glacial erratics, predominantly quartz (SiO_2). This study will address a fundamental uncertainty in the application of cosmogenic isotopes to geologic studies and will tell us more about the behavior of Earth's magnetic field in the geologic past.

Previous Cosmogenic Production Rate Studies

Production rates of cosmogenic ^{10}Be and ^{26}Al were calculated over the 11 ky time period by Nishiizumi et al. (1989) and confirmed by a study done in Antarctica as well as an independent 50 ky calibration (Nishiizumi et al., 1991b). The production rates at sea level and > 50° latitude for ^{10}Be and ^{26}Al were determined to be 6.0 atoms g^{-1} yr^{-1} and 36.8 atoms g^{-1} yr^{-1}, respectively, assuming that the 11 ky calibration is correct.

The 11 ky calibration was done on glacially polished granitic outcrops in the Sierra Nevada, California (Nishiizumi et al., 1989). The glacial surfaces used by Nishiizumi were assigned to the Tioga glaciation, approximately 11 ka, and the glacial polish provided evidence that surface erosion was negligible since the intial exposure. With respect to absolute production rates, no correction was made for possible changes in the intensity of the earth's dipole field, nor were corrections made for uncertainty in the absolute age of the samples. The dismissal of these two corrections could potentially result in as much as a 20% error in absolute production rates. Perhaps the greatest uncertainty of this calibration, however, is that associated with the dating of the exposure age of the polished surfaces. Nishiizumi's age estimates, upon which the validity of their results rests, are based wholly on two bog-bottom radiocarbon dates.

The empirically derived production rates were verified by two studies, one on Antarctic rocks with exposure ages of >2 my (Nishiizumi et al., 1991a), and the other on rocks with exposure ages of 50 ky (Nishiizumi et al., 1991b). The latter, an independent study utilizing in situ ^{10}Be and ^{26}Al, constrained exposure ages of dolomitic ejecta blocks at Meteor Crater, Arizona (Nishiizumi et al., 1991b), thereby dating the cratering event. The determined exposure age, approximately 50,000 years, was similar to that obtained by thermoluminescence, which was assumed to be correct, and cosmogenic ^{36}Cl dates. The isotope production rate for 50,000 years appears to be similar to the production rate estimated for 11,000 years.

There have been two studies which directly and distinctly correlate changing isotope production rates with the changing magnetic field intensity. The first attempted to determine cosmogenic ^{3}He production rates in young Hawaiian lava flows (Kurz et al., 1990), and the second focused on changes in the production of atmospheric ^{14}C over the last 30 ky (Bard et al., 1990).

Kurz et al (1990) used cosmogenic ^{3}He to calculate production rates in young Hawaiian lava flows. Despite the complete absence of soil cover and negligible erosion rates, determined by flow morphology, they found considerable variation in production rates with respect to time. From present to 2000 years they found a production rate of 125+-30 atoms g^{-1} yr^{-1}. The production rate was 55+-15 atoms g^{-1} yr^{-1} from 2000 to 7000 years, and for 7000 to 10,000 years the 3He production rate was found to be 127+-19 atoms g^{-1} yr^{-1}. The minimum values for the 2000 to 7000 year time period correspond to a maximum in the earth's dipole field, as can be seen in the archaeomagnetic measurements compiled by McElhinny and Senanayake (1982) as well as Meynadier et al.,(1992) (Figure 2).

Another study which relates varying production rates with changing magnetic field strength was done by Bard et al., (1990). They compared U-Th ages with atmospheric ^{14}C ages over the last 30,000 years and found the ^{14}C ages before 9000 years ago to be systematically younger than the U-Th ages, indicating increased production rates of atmospheric ^{14}C over the time period. The U-Th ages, which are not influenced by the cosmic ray flux, were determined to be accurate as they were in accord with a dendrochronological calibration (Figure 4). Ultimately, the authors determine that the discrepency between U/Th ages and ^{14}C ages are the result of a time-variant magnetic field.

Research Plan/Methodology

Site selection

I am proposing to estimate the average production rate of ^{10}Be and ^{26}Al over the last 20 ka by sampling quartzite boulders from the Laurentide icesheet's terminal moraine. The study area consists of a portion of western New Jersey which was glaciated by the Hudson-Champlain Lobe of the Laurentide ice sheet during the latest Wisconsinan glaciation. The southernmost extent of the Laurentide ice sheet can be identified by the terminal moraine, which varies in morphology and composition throughout its length. In New Jersey, ice retreat from the terminal moraine to the New York border has been well documented. Ridge (1983) mapped the positions of the ice using the morpho-sequence concept and in addition, three moraines have been recognized, the Franklin Grove Moraine, the Sparta Moraine, and the Ogdensburg-Culvers Gap Moraine, the last of which is considered to be the Late Wisconsinan terminal position of the Laurentide ice sheet (Connally, 1979).

I have selected the terminal moraine of the Laurentide ice sheet in northwestern New Jersey (Figure 3) as a calibration site because it meets four specific criteria: 1) Samples have well-constrained exposure ages (Figure 5). 2) The effect of erosion is probably negligible. 3) Rocks are quartz-bearing and 4) the geomorphic setting is well understood. Below, I document the published ice-sheet recession ages of several authors, all of which are in radiocarbon years unless specified as calibrated radiocarbon dates (crc), as well as elaborate on the importance of quartz as a target composition.

Approximately 21 ka (crc), the Laurentide ice sheet began to retreat from northern New Jersey depositing, among various lithologies, quartzite glacial erratics. The age of the terminal moraine and glacial retreat has been determined by several independent investigators (Figure 5). Cotter, (1984) determined that deglaciation of the Ontario Lobe of the Laurentide ice sheet had begun prior to 18.5 ka. This age estimate was based on radiocarbon dates from basal lacustrine sediments after tundra pollen spectra were identified in sediments from the same depth. Oldale and Stone, (1987) also determined that the ice reached its terminal position 21-20 ka using ^{14}C dates on wood, bone, horn, peat, shells and whole sediment samples. According to Oldale, the maximum error in the age of retreat is a few thousand years. Evenson et al. (1983) used radiocarbon dates, stratigraphy, palynology and morphologic sequence mapping to determine that ice began to retreat from the terminal moraine in New Jersey prior to 18 ka. Matsch (1987) also concluded that the growth of the Laurentide ice sheet ceased by 20 ka and that parts of the southern margin were retreating by 18 ka. Sirkin (1977), estimating deposition rates for sediments below radiocarbon dated sedimentary horizons, suggested that recession from northern New Jersey began about 18 ka. The quoted dates are in radiocarbon years, uncorrected for the change in ^{14}C production rates. Corrected ages would be several thousand years older (Figure 4). In summary, I believe that the actual exposure age of the quartzite morainal boulders lies between 21 and 22 ky (crc).

The quartzite boulders found on and within the moraine are ideal for measurements of in-situ produced cosmogenic ^{10}Be and ^{26}Al for two reasons. 1) Quartzite is very hard and highly resistant to chemical and physical weathering; thus I suspect that surface degradation has been minimal over the exposure time. 2) Quartzite is compositionally simple, reducing the potential for contamination by atmospheric, or 'garden variety' ^{10}Be, and therefore ideal for the measurement of ^{26}Al and ^{10}Be.

Sample Collection Strategy

Samples will be collected from the upper surface (0-3 cm) of quartzite boulders with a hammer or rock drill. I will be sampling from horizontal, up-facing, outcrops. Based on the geographic latitude of the field site, I believe that the shielding effect of seasonal snow cover will be negligible, thereby allowing for the sampling of horizontal surfaces. At least 0.5 kg of rock will be obtained from each sample site in order to ensure sufficient quartz for reliable measurement of ^{10}Be and ^{26}Al. I will be analyzing the spatial variance of isotope abundance on several scales. Initially, I will collect multiple samples from each of several boulders. I will then sample several boulders at a variety of sites on the moraine. Lastly, I will compare mean isotope abundance for these different populations. By stratifying the sampling, I hope to learn more about the causes of variability in isotope abundance and more accurately constrain the uncertainty in the calculated production rates. Samples will also be taken from boulders that have been shielded from cosmic rays in order to determine the importance, if any, of isotope inheritance from previous cosmic-ray exposure.

Sample Preparation and Analysis

Samples will be prepared for mineral separation using equipment located in the Geology Department at UVM. After initial acid-etching to eliminate atmospheric ^{10}Be, quartz will be separated using heavy liquids. Quartz clean-up and additional etching will be done ultrasonically. Quartz dissolution, column separations and preparation of Be and Al targets for mass spectrometry will be done at UVM using protocols based on those developed at Lawrence Livermore National Laboratory. Both replicate and blank samples will be run to ensure the reliability of sample preparation.

I anticipate analyzing 20-25 samples on the FN Tandem accelerator mass spectrometer (AMS) at Lawrence Livermore National Laboratories. Analytic uncertainties for ^{10}Be are typically only several percent (1 sigma); uncertainties are slightly higher for ^{26}Al. Isotopic analyses made at Livermore will be corrected both for laboratory and machine blanks. Isotopic analyses will be done in collaboration with scientists at Livermore and without cost to this project. Time averaged production rates will be calculated using the measured isotope abundance and the exposure age of the glacially polished surfaces · (Equation 1).

Possible Outcomes

There are three potential scenarios I can envision with respect to the outcome of this study, cach having a different interpretation. 1) the production rates for ^{10}Be and ^{26}Al over the last 20 ky are higher than the production rates for the same isotopes over the last 11 ky, as hypothesized. 2) the production rates over 20 ky appear to be the same as those published by Nishiizumi, and 3) the production rate values over 20 ky appear to be less than those published by Nishiizumi. I will discuss each of these possible outcomes and the resulting interpretations in turn.

Case 1

My hypothesis asserts that the integrated production rates at 20 ky will be higher than Nishiizumi's 11 ky production rate. Based on calcularions of cosmogenic isotope production rate variations, and magnetic field data over the last 140 ky (Figure 2), the integrated production rates over the last 20 ky could be as much as 15-20% higher than those published by Nishiizumi, whose production rate calibration was based on assumed exposure ages of 11 ky. This result can be expected due to the relatively weak magnetic dipole over the last 20 ky and the theoretical calculations of cosmogenic isotope production rate variation based on Mazuad et al., (1991) (Figure 6a and 6b).

Case 2

Another potential outcome is the scenario where Nishiizumi's 11 ky integrated production rate is equal to the integrated production rate obtained by this study. There are several possible interpretations if the 20 ky production rates are similar to Nishiizumi's 11 ky average values.

A. This result, like the first scenario, could also be supported by theoretical production rate calculations. Using a different method of calculating the dependence of cosmogenic isotope production on field strength (Nishiizumi, 1989), it was determined that the error in age estimates using Nishiizumi's 11 ky average production rate would not exceed 5% over 140 ky (Figure 7).

B. Another possible explanation for this scenario would involve either a history of cosmic ray shielding or higher than expected erosion rates. Both of these phenomena would result in production rates less than the expected values. The least likely interpretation of less than expected production rates would be an overestimated exposure duration.

Case 3

The third scenario, 20 ky production rates less than published values, is the least likely outcome. If the third scenario comes to fruition, it would most likely indicate an error in either the field interpretation of erosion rates (higher than expected), the estimate of exposure age (shorter than expected), or lab/analytical technique.

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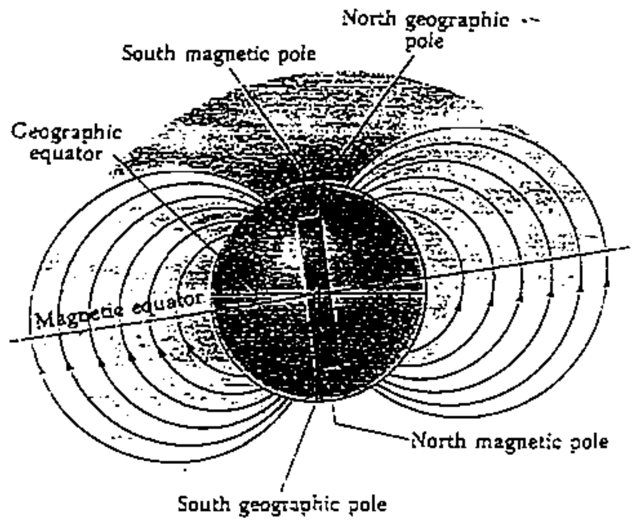

Figure 1. from Physics for Scientists and Engineers, Serway (1990)
This figure illustrates the nature of Earth's magnetic field. The field lines are parallel with Earth's surface at the equator, and perpendicular to the surface of Earth at the poles. From this diagram, it can be seen that the maximum force exerted on cosmic rays ($F = qvB\sin\theta$) will occur at the equator, and the magnitude of that force will decrease as latitude increases.

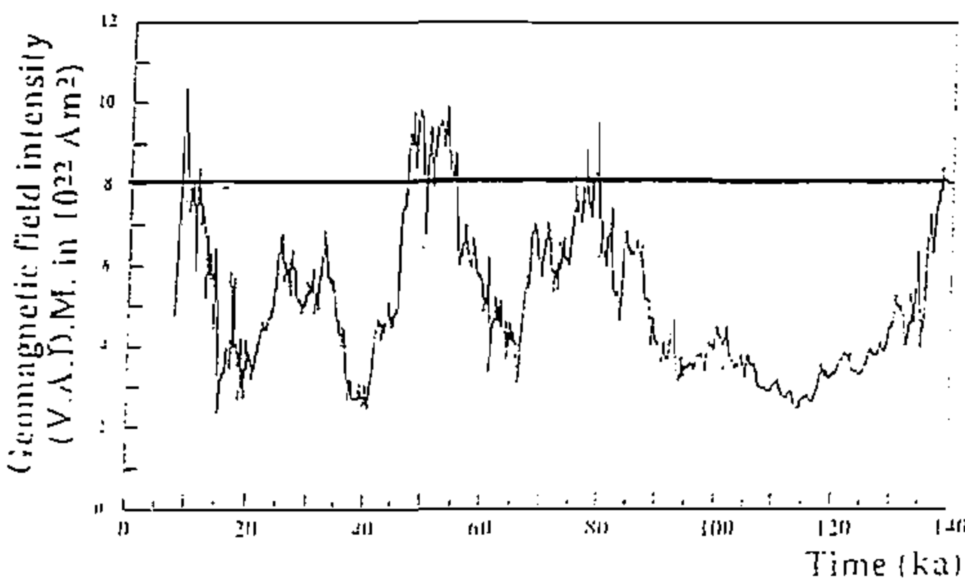

Figure 2. (Meynadier et al., 1992)
This figure shows the relative geomagnetic field intensity over the last 140 ky. Today's field is illustrated by solid line at 8 V.A.D.M. (10^{22} A m^2)

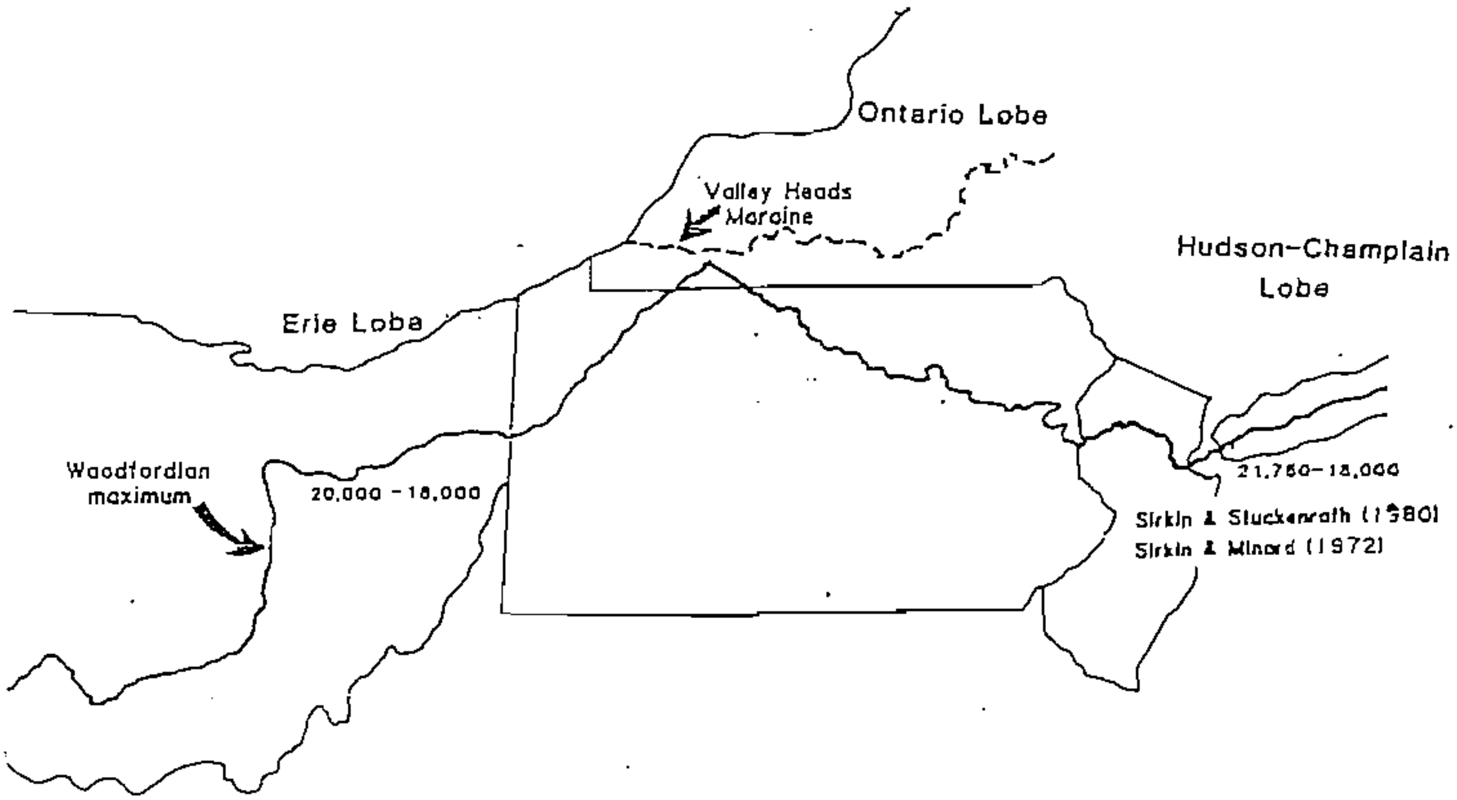

Figure 3. This figure shows the position of the Laurentide ice sheet's terminal moraine in Pennsylvania and New Jersey. The proposed study locality is in northwestern New Jersey, where the Hudson-Champlain Lobe reached its terminus. Dates shown are absolute ages of Woodfordian deposits (Cotter, 1984).

14C Calibration (Bard et al.,1990)

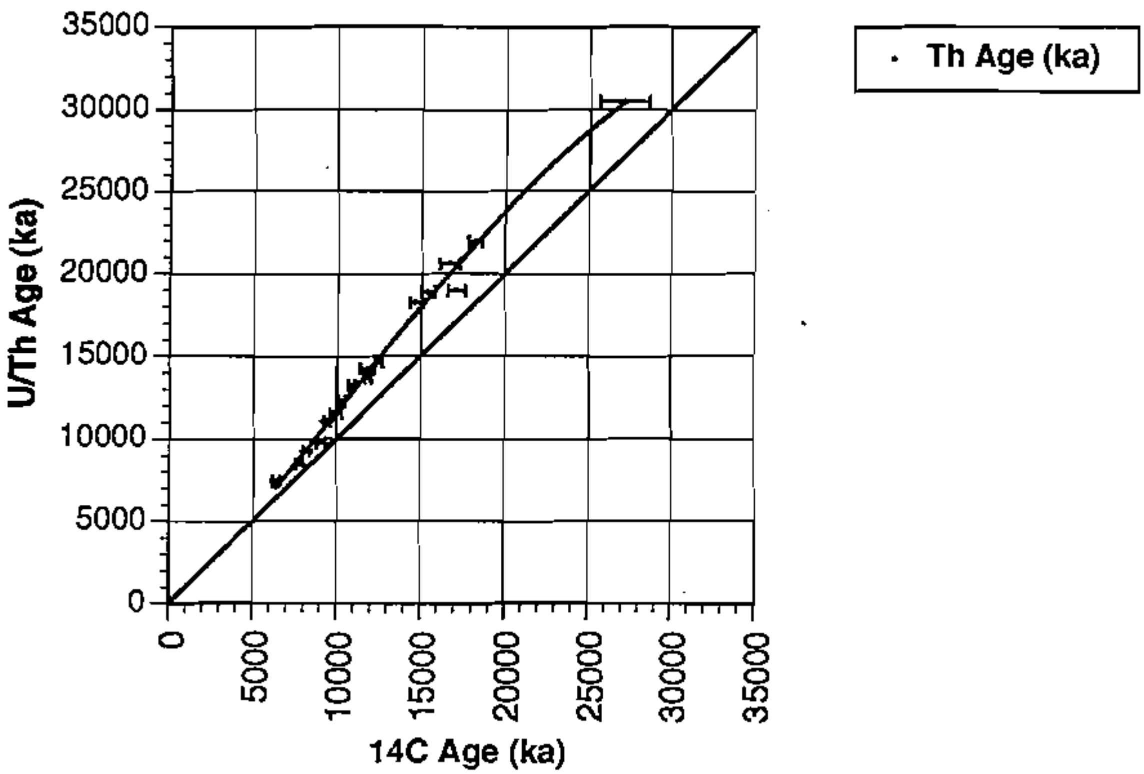

Figure 4.
Reproduced from Bard et al., (1990).
Cross symbols represent the U-Th ages plotted against the 14C ages (calculated with the 5730 year half-life). The age errors are quoted at 2 σ (U-Th errors are invariably smaller than the size of the symbol). This calibration was used to obtain a "corrected" 14C date for the recession of the Laurentide ice sheet from the terminal moraine in northwestern New Jersey.

Age of retreat of Laurentide ice from NW New Jersey

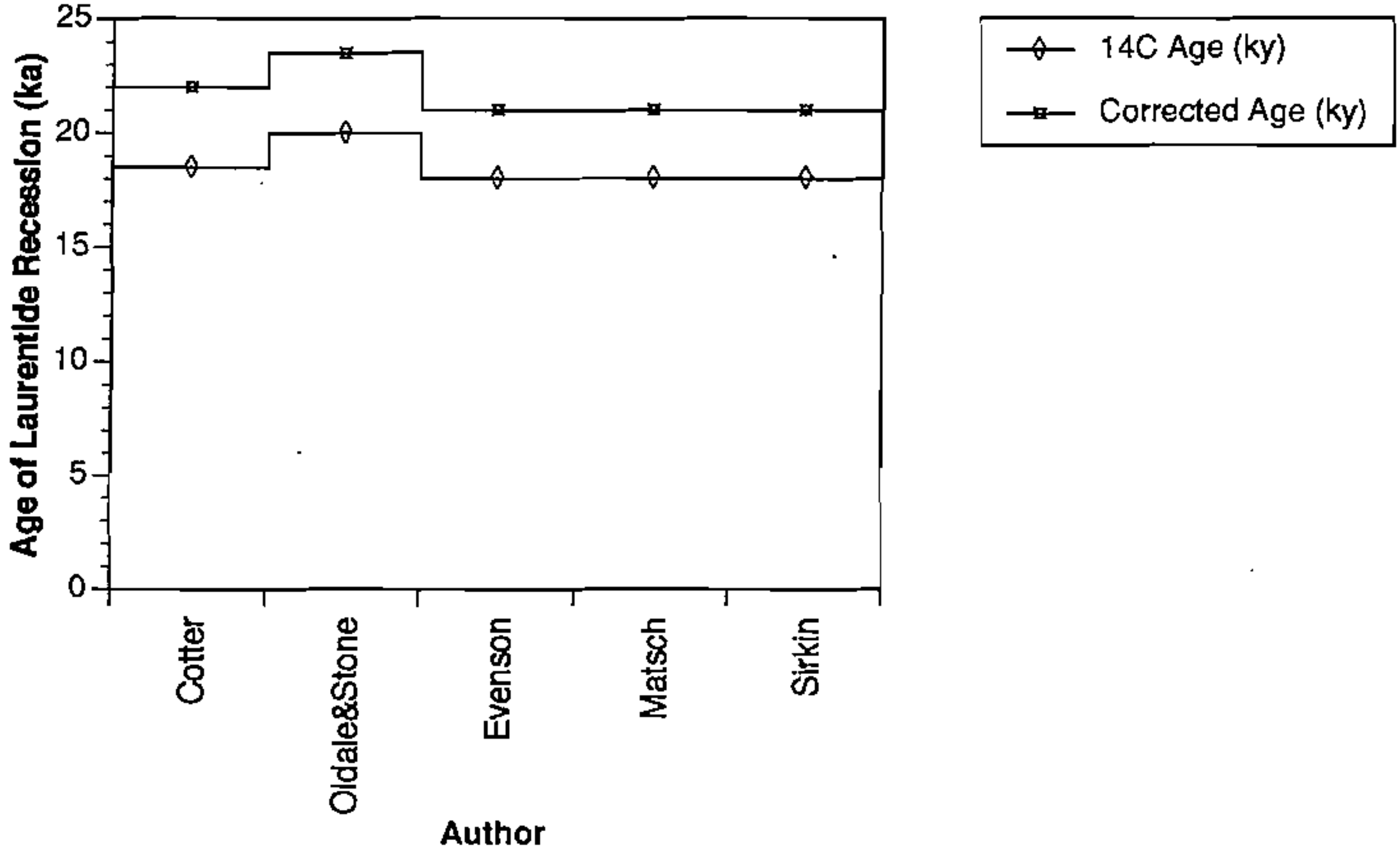

Figure 5.
This figure shows the 14C ages of five independent investigators for the recession of the Laurentide ice sheet from the terminal moraine in northwestern New Jersey, and the corrected age using Bard's (1990) calibration (Figure 3). In all cases, error bars were either smaller than the symbol or not reported by the author.

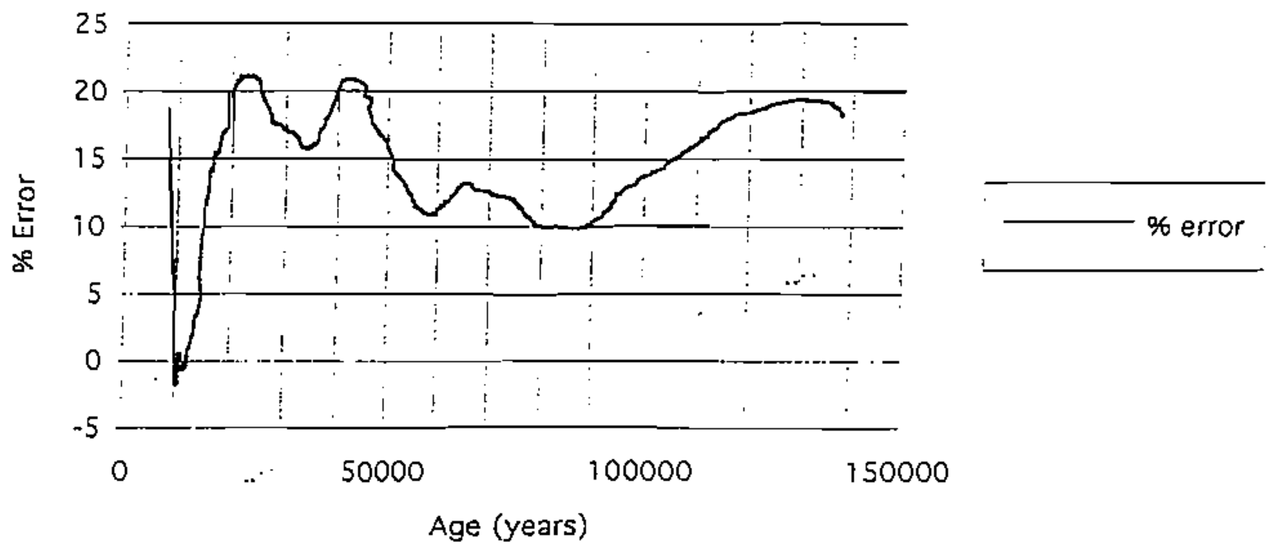

Figure 6a. (Mazaud method of calculating production rate dependence on field strength) This figure shows the percent error of a 10Be exposure age estimate for differing exposure ages if Nishiizumi's 11 ky calibration (Nishiizumi et al., 1989) is assumed to be correct. This graph compares the theoretical time-integrated production rate with Nishiizumi's 11 ky average production rate.

To generate this figure, the magnetic field data of Meynadier et al., (1992) were converted into a production rate curve using the results of Lal, (1988). The theoretical production rate was calculated using $\sqrt{\frac{M_0}{M}}$ where $\mathbf{M_0}$ = present day magnetic field, and **M** = dipole moment at the time considered (Mazaud et al., 1991). Isotope production was integrated over time and compared with that expected from Nishiizumi's integrated average production rate.

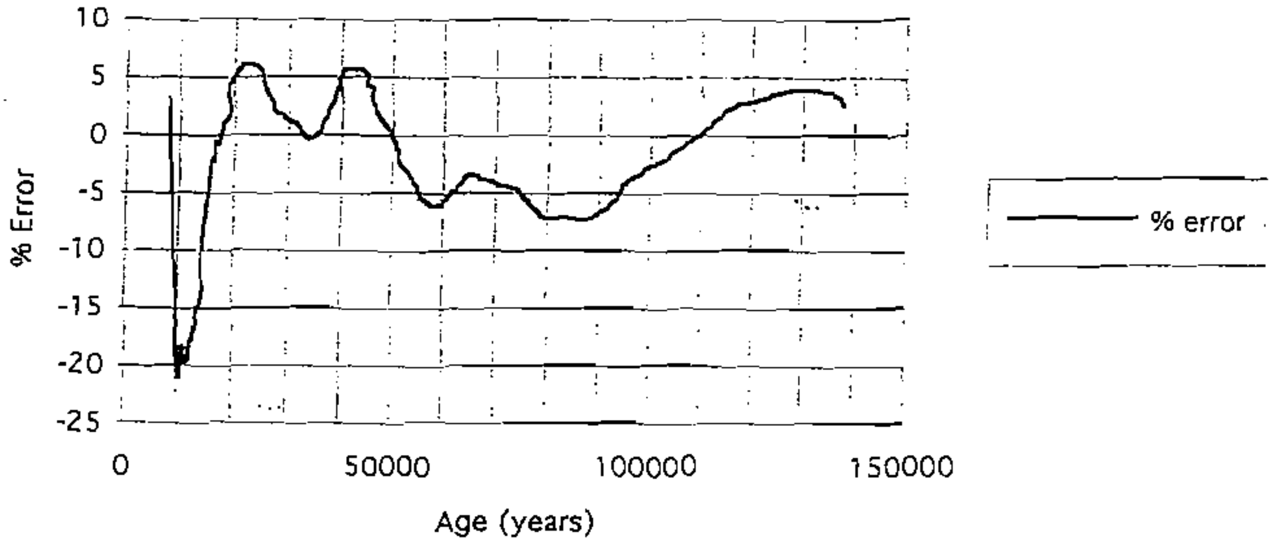

Figure 6b.
This figure, using the same dirivation as figure 6a, shows the percent error in the age estimation with respect to time if Nishiizumi's 50 ky calibration is assumed to be correct.

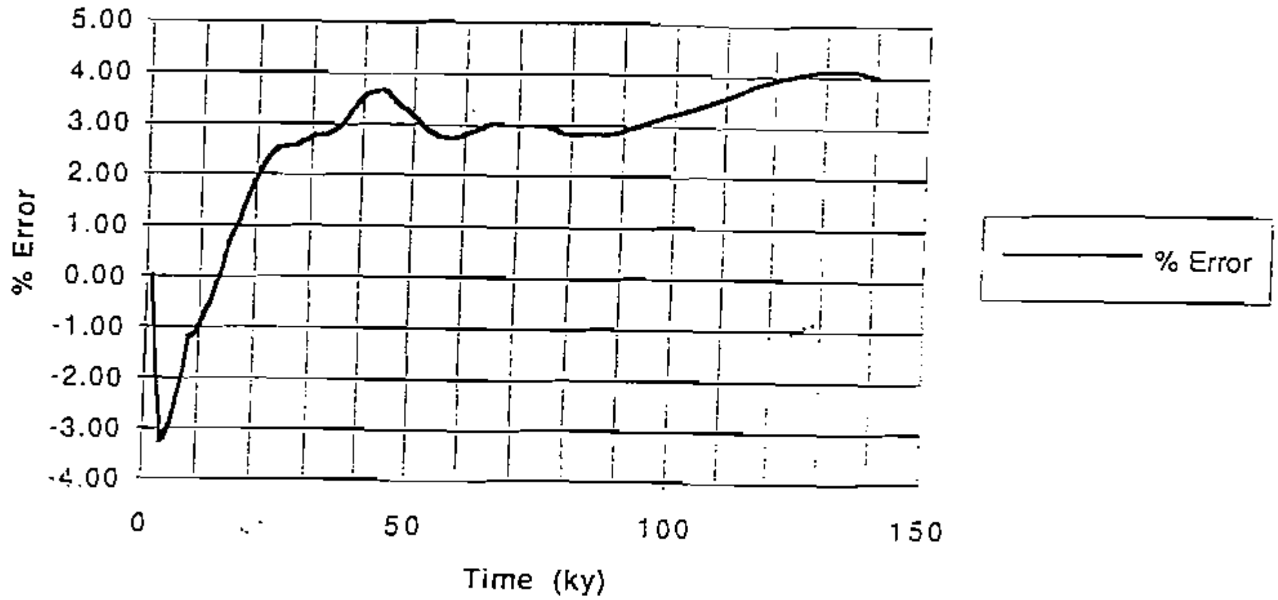

Figure 7. (Nishiizumi method of calculating production rate dependence on magnetic field strength) This graph illustrates the % error in age estimate with respect to time if Nishiizumi's 11 ky production rate is assumed to be correct. It suggests that production rate variation causes only small errors at the latitude of New Jersey.

Steps followed to create this graph:

1) Meynadier's et al. (1992) magnetic fired data for last 140 ky was digitized to obtain specific dipole field strength with respect to time.

2) These values were then used to determine the effective latitude, at any point in time, with the equation $\cos\Lambda_M = [M/M_O]^{.25} * \cos(\Lambda_S)$. (Nishiizumi, 1989). M = past dipole field, M_O = present dipole field, Λ_M = effective latitude at field strength M, Λ_S = latitude of field site.

3) The effective latitudes were then used to determine a new production rate using the polynomial $f(x) = -9.444444E\text{-}6*x^3 + 8.476190E\text{-}4*x^2 + -7.888889E\text{-}3*x + 6.926190E\text{-}1$, where x = latitude and f(x) is the new production rate factor as a function of latitude. This polynomial was created using the results of Lal (1991) and reflects the change in production rate as a function of latitude.

4) The new production rates were then integrated over 140 ky and compared with Nishiizumi's 11 ky production rate, also integrated over 140 ky (corrected for New Jersey altitude and latitude).