Bierman

Long-Term, Basin-Wide Erosion Rates Determined From In Situ Produced Cosmogenic Isotopes In Sediments

A Basis For Assessing Rates Of Human And Climate Induced Landscape Change

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Erik Matthew Clapp

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Introduction

Rates of erosion are an important indicator of both human and naturally occurring landscape change. As the demand for land as a natural resource increases, it becomes critical to understand the impacts on Earth's surface of diverse land use practices as well as changes in climate. In order to interpret short-term changes in contemporary rates of erosion, long-term erosion rates must be quantified. This study, in conjunction with the Department of Defense Army Research Office and US Geological Survey, will advance recently developed methods for determining long-term, basin-wide erosion rates, as well as set a baseline against which to measure human-induced landscape change. It is also possible that the effects indicative of environmental changes in Earth's recent past will be detected.

For the past decade, nuclides produced in quartz by cosmic rays, termed cosmogenic radionuclides, have been used to estimate residence times (or exposure ages) of bedrock at or near Earth's surface. These exposure ages have in turn been used to approximate erosion rates of bedrock surfaces (Bierman, 1995; Bishop, 1985; Nishiizumi et al. 1991), timing of glacial retreat (Brook et al., 1993; Gosse et al., 1995; Phillips & Zreda, 1992), and recurrence intervals of earthquakes (Bierman et al., 1995). More recently, cosmogenic radionuclides in sediments have been examined as an indicator of rates of erosion within a drainage basin (Brown et al., 1995; Bierman & Steig, 1996; Granger et al., 1996). Because cosmogenic radionuclides accumulate over the exposure history of a rock or sediment sample, there should be a relationship between the rate at which sediment is being derived and transported within a drainage basin (erosion), and the abundance of cosmogenic radionuclide (Bierman & Steig, 1996). More specifically, if a drainage basin is eroding slowly, sediments will reside at Earth's surface for a longer period of time and will thus accumulate relatively high abundances of radionuclides. Alternatively, a rapidly eroding basin, where sediments are generated and transported quickly, will allow less time for radionuclide accumulation. If the assumption is made that the sediments leaving a drainage basin via a stream channel are a completely mixed and representative sample of the sediments within the basin, then the abundance of radionuclides within these sediments should indicate the average exposure time and thus the basin-wide average rate of erosion. Mixing models, taking into consideration the various sources and storage of the sediments within a basin, will be necessary to interpret the isotopic signatures of the stream channel sediments leaving a basin.

I propose the first, comprehensive, basin-wide, cosmogenic exposure age study in sediments, aimed at determining long term-rates of erosion while advancing and improving the field of cosmogenic radionuclide exposure dating. This study will examine a series of three drainage basins each in a different climatic region. Within each of the three drainages, I will sample the stream channel sediments, the bedrock uplands, and the critical sediment storage compartments of the landscapes. Through a series of modeling exercises, I will use the isotopic data from the bedrock uplands and the sediment storage compartments to interpret the isotopic signature of the stream channel sediments leaving each of the drainage basins. This study will provide managers of natural and cultural resources a history of landscape change within a basin and a better understanding of the long-term impacts related to changes in land use and climate in Earth's recent past.

Statement of Hypothesis

1) Basin-wide rates of erosion can be determined by measuring the cosmogenic radionuclide signature of the stream channel sediments leaving a drainage basin (Bierman & Steig 1996). The interpretation of samples collected from various reservoirs within the basin (bedrock, colluvium, alluvium) requires an understanding of the geomorphic processes at work within the basin.

2) Mixing models representing isotopic signatures of sediment reservoirs throughout a drainage basin can be used to understand and interpret the isotopic signature of the stream channel sediments leaving a drainage basin.

3) Detailed analysis of isotopic signatures of sediments deposited within a basin can show changes in rates of sedimentation over time, indicative of changes in climate and/or land use. Sediment layers with low isotopic abundances should indicate periods of more rapid erosion and more direct transport pathways than sediment layers with higher isotopic abundances.

Specific Objectives

1) I will measure in situ produced cosmogenic isotopes in samples collected from upland bedrock, sediment storage compartments, and stream channel sediments to test the hypothesis put forth by Bierman and Steig (1996) that cosmogenic radionuclides in stream channel sediments can be used as an indicator of basin wide erosion rates.

2) I will use cosmogenic isotope measurements to:

a) determine basin-wide erosion rates in Yuma Wash, Arizona, to establish a baseline by which the Army can compare current erosion rates in areas disturbed by military exercises to long-term sediment yield from the basin to the Colorado River.

b) determine basin-wide erosion rates in Arroyo Chavez Basin, New Mexico and estimate rates of basin infilling, rates of arroyo cutting, and basin sediment yield to the Rio Puerco to aid the Bureau of Land Management (BLM) in establishing best management practices for arid lands on the Southern Colorado Plateau.

c) determine basin-wide erosion rates and long-term sediment yield for the watershed of Nahal Yael, Southern Negev, Israel to aid the Israeli government and researchers at the Hebrew University of Jerusalem in better understanding landscape evolution in hyper-arid environments.

4) I will determine if sediment grain size has a significant impact on the abundance of cosmogenic isotopes and the interpretation of the isotopic signatures.

5) I will improve the interpretation of cosmogenic exposure ages and erosion rates by modeling the effects of historical fluctuations in Earth's magnetic field strength.

Cosmogenic Radionuclide Production

"Cosmogenic" isotopes are nuclides produced when cosmic rays interact with materials in the atmosphere and at Earth's surface (e.g. ^{10}Be, ^{14}C, ^{26}Al). Primary cosmic rays or high-energy protons continuously enter Earth's atmosphere where they interact with various stratospheric atoms producing a rain of secondary cosmic rays (generally neutrons) which bombard Earth's surface (Bierman, 1994; Friedlander, 1989; Faure, 1986). These neutrons collide and react with target atoms in rock and sediment to produce cosmogenic isotopes "in situ" (Bierman, 1994; Friedlander, 1989). The incoming flux of cosmic rays and the subsequent production of cosmogenic isotopes at Earth's surface are moderated primarily by the strength of Earth's magnetic field and the mass (proportional to distance) of atmosphere through which a cosmic ray must travel (Bierman, 1994; Lal 1991). Deflection of primary cosmic rays is greater at the equator than at the poles with magnetic field effects becoming negligible at latitudes greater than 60°. Secondary cosmic rays are more abundant at higher altitudes, diminishing with atmospheric depth through interactions with atmospheric gases (Bierman, 1994; Lal, 1991; Nishiizumi, 1989). Thus, cosmogenic isotope production at Earth's surface is greatest at high altitude and high latitude.

The variation of cosmogenic isotope production with altitude and latitude has been described by Lal's (1991) third order polynomial (Figure 1) as well as by other researchers (Yokoyama et al., 1977; Lingenfelter, 1963; Pomerantz and Agarwal, 1962; Rose et al., 1956). From Lal's (1991) relationships, a correction factor can be calculated which can be multiplied by a literature value for cosmogenic production rates normalized to sea level and a latitude greater than 60°. For ^{10}Be and ^{26}Al, the most widely accepted, normalized production rates to date are 6.03 atoms g^{-1} yr^{-1} and 36.85 atoms g^{-1} yr^{-1} respectively (Nishiizumi et al., 1989).

Cosmogenic isotopes are produced by a variety of reaction pathways, including spallation, muon capture, neutron activation, and alpha particle interaction all dependent on the depth of material, and the characteristics of the isotope. For this study, and the isotopes ^{10}Be and ^{26}Al, spallation is the dominant production pathway with muon contribution being small to negligible (Brown et al., 1995; Lal, 1991). Muons are low mass, deeply penetrating, negatively charged particles which may contribute from 1% (Brown et al, 1995) to as much as 18% (Nishiizumi et al., 1989; Lal, 1988) of cosmogenic isotope production at Earth's surface.

Spallation occurs when a high energy, cosmic-ray neutron collides with a target atom, splitting this target atom and producing a specific isotope. ^{10}Be is produced primarily through spallation of ^{16}O

$$[^{16}O(n,3n4p)\,^{10}Be], \qquad (1)$$

but can also be produced from Si, Mg, Fe, and through muon capture (Lal, 1988). In the spallation of ^{16}O, the high energy neutron (n) collides with the target atom (^{16}O) which loses four protons (p) and three neutrons (net loss is 2n) to yield a ^{10}Be atom. ^{26}Al is produced through the spallation of Si, Al, and Fe as well as through muon capture (Lal, 1988). Isotope production through spallation decreases exponentially with depth of surficial material, described by the equation:

$$P_x = P_o e^{-(x\rho/\Lambda)} \qquad (2)$$

Where: P_x = production rate (atoms g^{-1} yr^{-1}) at depth x (cm)

P_o = production rate (atoms g^{-1} yr^{-1}) at surface

ρ = density of material (= 2.7 g cm^{-3} in rock)

Λ = characteristic attenuation length for fast neutrons (150-170 cm^2 g^{-1})

Spallation production rates approach zero at about 2.5 meters depth, while production by muon capture is significant up to 10 meters below Earth's surface.

Measurement of Cosmogenic Isotopes

The cosmogenic isotopes ^{10}Be and ^{26}Al are produced in all silicate rocks. These isotopes are typically measured in quartz because it is ubiquitous, it weathers slowly, its resilienee make it easy to isolate from other minerals, and the composition is simple and consistent. Measurement of ^{10}Be and ^{26}Al requires isolation of quartz from other minerals which comprise the rock or sediment that is being analyzed. Samples of ^{10}Be and ^{26}Al are prepared through HF dissolution of quartz to produce targets which are then analyzed using Accelerator Mass Spectrometry (AMS).

Interpretation of Cosmogenic Isotopic Abundances

Interpretive Models

Interpretation of cosmogenic isotope abundances in rock or sediment requires the use of mathematical models representing possible landscape evolution scenarios. Two end member scenarios represent: 1) a landscape that has been rapidly exposed to cosmic rays yet has extremely low to negligible rates of erosion; and 2) a landscape that is slowly eroding in a steady state condition. For the rapidly exposed, low-erosion end member, a sample will sit at Earth's surface and accumulate cosmogenic isotopes at a rate governed by isotope production and decay. For the steady-state-erosion end member, a sample or particle of material begins accumulating cosmogenic isotopes at depth, and the rate of accumulation increases as Earth's surface erodes towards and approaches the sample. Most locations will have an evolution history which is some combination of the two end member scenarios.

In the most simple case of rapid exposure and no erosion, the time of exposure of a sediment or rock sample is determined by measuring the abundance of specific cosmogenic isotopes in a sample of rock or sediment and dividing this isotopic abundance by a known rate of production; for unstable isotopes decay must also be considered. In this no erosion scenario, the abundance of atoms (N) present in a sample is a function of the isotope production rate (P), the decay rate (λ), time (t) and the background level of the isotope (B) in the material when completely shielded from incoming cosmic rays (Bierman, 1994; Lal, 1988).

$$N = \frac{P}{\lambda}\left(1 - e^{-\lambda t}\right) + B \qquad (3)$$

The case of a steadily eroding landscape, is better described by calculating a steady state erosion rate (ε) than an exposure age. The abundance of atoms (N) in a sample eroding at a constant rate (ε) is a function the isotope production rate (P), the density of the material (ρ), the characteristic attenuation length of the cosmic rays (Λ), the decay rate (λ), and the background level of the isotope (B) in the material when completely shielded from incoming cosmic rays (Bierman, 1994; Lal, 1988).

$$N = \frac{P}{\varepsilon\rho\Lambda^{-1} + \lambda} + B \qquad (4)$$

Gillespie and Bierman (1995) have shown that simultaneous solution of equations 3 and 4 for erosion rate and exposure age give excessively large errors (>2 standard deviations from the mean) for young samples (< 200,000 years (200ky)) and two isotope systems with similar half lives (e.g. ^{10}Be & ^{26}Al). Preliminary results show that exposure ages in the three proposed study basins are much more rapid than 200 ky. It is therefore necessary to use the data collected in this study to generate limits. Higher erosion rates will result in lower isotopic concentrations, thus there will be a maximum rate of erosion possible that will still allow the accumulation of the measured abundance of atoms. Conversely, measured abundances can be interpreted as a minimum time of exposure needed to accumulate the nuclide inventory.

Two Isotope Systems

The use of ^{10}Be and ^{26}Al together allow for interpretation of the history of a given sample. Measured abundances of ^{10}Be are plotted against the ratio ^{26}Al/^{10}Be (Figure 2) on a two isotope plot. The two isotope plot consists of 1) an upper line representing modeled abundances for materials which are rapidly exposed and accumulate isotopes at Earth's surface (e.g., a landscape scoured by a glacial advance and then rapidly exposed during glacial retreat), and 2) a lower line representing modeled abundances for a sample with steady state erosion (e.g., a basin in which nuclide abundance is controlled by steady chemical and physical weathering). Those samples which fall on the upper exposure line represent samples for which exposure history can be described by equation three; those which fall on the lower line represent samples for which equation four provides a viable model. Any sample that plots below the lower line must have been buried at some point during its exposure history; the more rapid decay of ^{26}Al (half life = 0.7 million years) relative to ^{10}Be (half life = 1.5 million years) causes the ^{26}Al to ^{10}Be ratio decrease during burial. For young samples (< 300 ky), differences in ^{10}Be and ^{26}Al decay rates will not be perceptible.

Production Rates

The interpretive models described above use average, integrated production rates and assume that rates of production of cosmogenic isotopes have been constant throughout Earth's history. Integrated production rates have been determined by sampling bedrock surfaces of known exposure ages (by other dating methods), measuring the cosmogenic isotopic abundances, and dividing total abundances over the time of known exposure (Nishiizumi et al., 1989; Larsen, 1995). Although some controversy still exists, production rates are known within ±15-20%. Recently, efforts have been made to improve upon the accuracy of these production rates by increasing the accuracy of the dating of production rate sampling sites (Clark et al., 1995), and by taking into consideration changes in production rates over time caused by fluctuations in Earth's magnetic field strength (Clapp and Bierman, 1996).

Rates of Denudation

Direct Measurements of Denudation

Rates of denudation have been explored by hundreds of researchers (Selby, 1982) and a comprehensive review of over 400 denudation related studies is presented by Saunders and Young (1983). Traditionally these studies have been based on either determining the mass of material deposited over time within a given basin (Reneau & Dietrich, 1991; Hicks et al., 1990; Clague, 1985; Church and Ryder, 1972; Judson, 1968; and Langbein & Schumm, 1958), measuring current rates of fluvial sediment export and extrapolating over the entire drainage basin and back over time (Dole & Stabler, 1909; Judson & Ritter, 1964; Holeman, 1968; Gurnell et al., 1988; and Harbor & Warburton, 1993), or by directly measuring changes in surface elevations caused by soil creep, surface wash, and chemical weathering (Leopold et al., 1966; Selby, 1974; Dunne, 1977; Gellis, 1996).

Sediment accumulation studies are ideal in basins that are well defined and have a discrete sediment accumulation sink such as a glacial lake or dammed reservoir, but for larger basins where sediments are often exported and accumulation is spatially variable, it is difficult to draw conclusions on the evolution of an entire basin. Many studies of larger basins measure the current export of material through major drainages over short periods of time (several to tens of years). Stream export studies give good short-term estimates of sediment loading, but may grossly over or under-estimate long-term rates of erosion if a stream is currently incising or if the basin has significant sediment storage in river terraces, alluvial fans, lakes, and many other sediment sinks throughout a basin. Direct measurements of surface lowering also suffer from the uncertainty inherent in measuring small changes over a short period of time and extrapolating the results. The use of cosmogenic isotopes to estimate rates of denudation may be the tool which will allow for large-scale, long-term erosion rate studies that can consider both long-term average erosion rates as well as long periods of accelerated or decreased rates of erosion.

Cosmogenic Isotope Determination of Denudation

The possibility of determining basin-wide erosion rates through the use of cosmogenic isotopes in sediments has been discussed in great detail by Bierman and Steig (1995). Bierman and Steig (1995) discuss the assumptions which are necessary to interpret stream channel sediment isotopic signatures, and suggest mathematical models for determining basin-wide erosion rates. The most critical assumption put forth and perhaps the most difficult to justify is that a basin must be in isotopic equilibrium with the number of atoms of a given isotope being produced within the basin being equal to the number of atoms being exported from a basin either with the sediments, in solution, or by decay if the isotopes are not stable. It is unlikely that this assumption holds true over short periods of time (years to decades) where bank failures, slides, and slumps may contribute large amounts of sediments and associated isotopes over short periods of time. It is however more likely to be valid over longer periods of time and larger spatial scales where integration will smooth short-lived events in the system. For systems with long sediment residence times, one would expect that storage in river terraces, alluvial fans, or colluvial hollows would decrease the export of isotopes because isotopes will tend to accumulate within the basin along with sediment accumulation. For basins with short sediment residence times, it is unlikely that a significant amount of nuclides will accumulate while the sediment is in storage where a large percentage of substrate will be buried and thus shielded from cosmic ray exposure.

A second assumption made by Bierman and Steig (1995) is that the basin must be in erosional steady state or must be eroding at a constant rate over time. Although few basins could be assumed to be eroding at a steady state over short time frames (years to decades), this is a valid assumption for many basins when erosion rates are integrated over longer time frames (thousands of years). A basin that erodes at a constant rate will also achieve isotopic equilibrium, because all sediments will have the same residence time, and will have the same cosmic ray exposure as they move from the bedrock through the basin, to the basin outlet. Erosional steady state can be shown through isotopic analysis of depth profiles in sediment accumulation zones. If a column of sediment is analyzed, and shows a profile change which is in contrast to a standard isotopic depth profile, it is likely that the sediment accumulated at varying rates over time. If sediments accumulate and are buried at a constant rate, the isotopic abundance of the sediment should be the same at depths below 1.5-2.0 meters where spallation reactions become negligible. Above this level, there should be a decrease in abundance representing the dosing during deposition and burial. Because most basins do not have rectangular cross sections, the basin width will increase with increased sediment accumulation and thus the sediment thickness will decrease for the same amount of total sediment generated from the basin; the isotopic abundance must therefore be modeled to represent these changes.

Determination of basin wide erosion rates from sediments has been explored by few researchers. Brown et al. (1995) used cosmogenic ^{10}Be in sediments to determine basin-wide erosion rates in the Luquillo Experimental Forest of Puerto Rico. They use a limited number of samples to characterize the erosional histories of the bedrock uplands, upland soils, a local landslide, and Icacos river bedload. Brown et al. (1995) begin to address many of the problems inherent to a basin-wide erosion rate study including contribution of non-quartz bearing lithology, soil stirring, grain size effects, and quartz dissolution, but the limited number of samples preclude any conclusions on many of these concerns. Brown et al. (1995) also measured only a single isotope which makes it impossible to identify samples with complex burial histories. This proposed study should better answer many of these questions through a larger and more rigorous sampling and analysis strategy.

Granger and Kirchner (1996) studied two basins in the Fort Sage Mountains of California and determined basin wide erosion rates from cosmogenic ^{10}Be and ^{26}Al in stream channel sediments. They compared these rates to volumetric calculations based on dated alluvial fan deposits. The cosmogenic rates of erosion are slightly greater than those determined from the fan deposits indicating that perhaps material has been lost from the fan, or that there is sediment contribution from other parts of the basin with faster rates of erosion.

Granger et al.(1997) used differential decay of ^{10}Be and ^{26}Al in cave-deposited river sediments to determine downcutting rates of the New River, Virginia. As the New River downcuts through limestone, caves are left high above the current river channel and river sediments deposited in these caves were therefore deposited at the time at which the river was at the cave level. These cave sediments are shielded from cosmic rays, and therefore begin decaying with time. The differential decay rates in the two isotopes begins to be discernible after about 300 ky allowing for the time since deposition to be determined. The predominant problem with this study is that the clasts which where analyzed may have a very complex exposure history making the differences in isotopic abundances between ^{10}Be and ^{26}Al difficult to interpret. The study also concentrates on about twenty quartz clasts which will may give biased results because the samples may not be as representative of the entire basin and are certainly not as well integrated as samples comprised of finer grained sediments in which millions of grains are analyzed.

Project Description

This study, determining long-term erosion rates from in situ produced cosmogenic ^{10}Be, ^{26}Al, and ^{14}C in sediments and bedrock, will be conducted at three study sites.

The three study sites have been chosen to represent a variety of climatic conditions while avoiding interpretive problems caused by probable long-term snow cover. These sites contain quartz-bearing lithologies necessary for cosmogenic ^{10}Be and ^{26}Al exposure age studies. For each of the three study sites, I have or will sample the bedrock uplands, the dominant geomorphic features, sediment storage compartments, and the channel sediments of the drainage network. Simulation models will then be constructed that vary the isotopic contribution from each of the storage compartments in order to interpret the isotopic signature of channel sediments.

Site 1- Arroyo Chavez

Arroyo Chavez (an arroyo being a steep sided ephemeral stream channel) is a tributary to the Rio Puerco which ultimately drains to the Rio Grande north west of Albuquerque, New Mexico (Figure 3). Arroyo Chavez and the Rio Puerco are the location of a major research effort by the US Geological Survey (USGS), the Bureau of Land Management (BLM) and University of New Mexico to assemble geomorphic and socioeconomic data in a Geographic Information System (GIS). The Arroyo Chavez Basin has been a major contributor of alluvial sediment to the Rio Puerco and Rio Grande over the past century. It is unclear whether increased sedimentation and arroyo formation is due to increased grazing of lands, or is a cyclical occurrence due to long term changes in climate. Deciphering these signals in the sedimentary record will help guide management decisions about road construction, grazing intensity, impoundment construction, and many other land use issues.

The Arroyo Chavez basin (Figure 4) is relatively small (17.3 km^2) and well constrained geologically, having a homogeneous lithology and easily identifiable geomorphic features. The Arroyo Chavez basin is located at approximately 2 km above sea level, and in a semi-arid climate (average annual precipitation 21.5 cm). Bedrock in the Arroyo Chavez basin is predominantly a quartz-rich arkosic sandstone with occasional layers of dolomite and limestone. Sediments deposited within the basin are generally medium to fine sand, silts, and clays (Figure 5). It is assumed for this study that sediments < 250 microns have a strong possibility of aeolean transport from other basins and thus will not accurately represent sediments generated within the Arroyo Chavez basin. A total of 28 samples have been collected for the Arroyo Chavez Basin (Table 1).

Preliminary sample analysis from the Arroyo Chavez Basin show minimum effective model exposure ages of stream channel sediments range from 3,000-6,500 years (3-6.5 ky) which indicate maximum, model, basin-wide erosion rates of 80 to 150 meters per million years (m My^{-1}) (Table 2; Figure 6). Sediments sampled from the hillslopes had lower exposure ages (2.5 - 3.3 ky) and higher erosion rates (187 - 245 m My^{-1}), indicating that overall, material from the uplands is being generated at a higher rate than is indicated by the channel sediments but may continue to be dosed during transport to the stream channel. It is likely that the isotopic abundances found in the stream channel sediments is a mix of low abundance (younger) hillslope material and higher abundance(older) valley fill.

Preliminary sample analysis of a depth profile from the walls of the main channel indicate a possible increase in isotopic abundance with depth (Figure 7). If published attenuation rates of cosmogenic isotope production with depth are assumed, this increasing trend with depth may indicate longer exposure times and thus slower erosion rates at the time of deposition of the basal sediment layer than that of the upper layer.

Site 2-Yuma Wash

Yuma Wash, located on the U.S. Army Base, Yuma Proving Grounds, in Southwestern Arizona is a tributary to the Colorado River (Figure 8). Yuma Wash is the focus of a major research effort by the Department of Defense to reclaim and restore military lands and their ecosystems after decades of intensive use during military training exercise. Yuma Wash in particular has been recently disrupted by unauthorized tank maneuvers on fragile desert pavement surfaces.

The Yuma Wash basin is constrained by the Chocolate mountains to the East, and the Trigo mountains to the West and North (Figure 9). This basin is much larger (130 km^2) than the Arroyo Chavez Basin (17.3 km^2) which allows for an analysis of the effects of basin size on the determination of basin wide erosion rates from cosmogenic isotopes in sediments. Yuma Wash ranges in elevation from 60 to 850 meters asl and represents a low elevation, hyper-arid environment (average annual precipitation is 9.11 cm).

Yuma Wash Basin is lithologically and geomorphologically complex. Lithologies range from Rhyolitic volcanics bearing less than 5% quartz, to metamorphosed marine shists and granites bearing as much as 20% quartz. The stream channel sediments produce approximately 8% to 13% quartz by weight. The lowlands of Yuma Wash Basin are dominated by piedmont surfaces or bajadas made up of a complex mallange of debris and mud flow deposits, alluvial fan deposits, volcanics, and stream terrace deposits. The bajada and terraces surfaces are highly dissected, yet the remaining surfaces show significant long-term stability (thousands of years) because desert pavements are well developed.

Yuma Wash will be studied at two different scales. A large scale analysis of the entire basin will be conducted by sampling stream channel sediments in the three major branches of the wash. A total of 85 samples have been collected to represent the entire basin (Table 1). A small scale analysis will be conducted on the sub-basin drained by the Southwestern branch of Yuma Wash. This basin is dominated by granite and quartz-bearing schist, is well constrained topographically, and is small enough to allow for collection of a representative number of samples from each of the major geomorphic units. This sub-basin should allow for the comparison of erosion rates in the lower elevation, lower precipitation, steeper terrained Yuma wash with the results from Arroyo Chavez Basin in New Mexico, without the complexities of working in basins of different scales.

Site 3-Nahel Yael

Nahal Yael Research Watershed (0.6 km^2) is a heavily monitored basin in the hyper-arid southern Negev, Israel (average annual precipitation is 3.2 cm) (Figures 10 & 11). The basin hydrology and geomorphology have been monitored since 1966 in order to better understand responses of desert environments to precipitation events and changes in climate. This project is in conjunction with the Government of Israel and the Hebrew University of Jerusalem, to help establish the temporal variability in sediment export and determine a long-term average rate of erosion with the basin. The monitoring of sediment discharge from the Nahal Yael Research Watershed over the past several decades will allow for detailed calculations of short-term erosion rates within the basin. These short-term erosion rates will provide an ideal comparison to the long-term, integrated erosion rates determined through cosmogenic exposure age dating.

Nahal Yael is an ephemeral tributary to Nahal Roded which connects to the Arava Rift Valley and the Gulf of Aqaba, Red Sea. The basin has been described as "bare, rocky desert" (Schick, 1974) composed of quartz-bearing pellitic schists, granitic gneisses, some quartz-poor amphibolites, and abundant quartz rich dykes and sills (Aryeh Shimron in Schick, 1974). Most slopes range are exposed bedrock; some are covered by a thin (5-20 cm) layer of talus (Schick, 1974). A total of 20 samples will be collected in the Nahal Research Watershed (Table 1).

Sample Collection

For each site, samples will be taken from hillslope soils, terraces, alluvial fans and stream channels distributed as shown in Table 1.

Hillslopes

For each major hillslope section, several soil profiles will be sampled as well as a transect of samples along the slope. A hillslope soil profile will entail sampling the entire soil column at even depth intervals to determine the importance of soil stirring in the overall isotopic signature. Samples are integrated over a 5 to 10 cm range. For soils less than 10 cm, it is assumed that the soils are completely mixed, and only a single integrated sample will be taken. At Arroyo Chavez, soil depths were only about 10-15 cm, therefore three 5 cm sections were sampled.

At each sample location, approximately three kilograms of sediment are collected in order to obtain 100 grams of quartz in each of three size fractions. Sample location (GPS latitude and longitude), elevation, orientation, slope, depth, and shielding of incoming cosmic rays are noted as well as a detailed sketch and a photograph of the sample site. Sample sites are marked on topographic maps or aerial photographs for future return visits.

Geomorphic Features

Terraces and alluvial fans will be sampled primarily near the surface. The top 20-30 cm will be sampled and completely mixed. For terraces and fans with channel incisions, a detailed profile will be collected. An incised fan at Arroyo Chavez was sampled at 50 cm increments, with each sample integrating approximately 20 cm of sediment.

Stream Channel Sediments

Stream channel sediments are also sampled to a depth of 20-30 cm and completely mixed. For wide channels such as those found in Yuma Wash, A transect is made across the channel collecting sediments every several meters. All sediments from a given transect are then combined and completely mixed.

Bedrock

Bedrock samples are collected from the basin uplands to determine a rate of bedrock lowering. Bedrock surfaces are found which show the least likelihood of recent burial (usually the highest points in the basin) and which have no evidence of recent rapid erosion. This method will tend to under-estimate bedrock erosion rate because of the biased sampling of resistant surfaces. Bedrock is sampled by chiseling thin (0-5 cm) slabs of rock from the bedrock outcrop while trying to stay greater than one meter from any edge to avoid contribution of cosmic rays from the side.

Sample Distribution

Sample distribution is shown in Table 1. For Arroyo Chavez, the majority of the sediment is medium to fine grained sands. Preliminary data show that isotopic abundance may be a function of sediment grain size (Figure 12), however, the limited grain size distribution found in the Arroyo Chavez basin and the large standard deviation associated with the samples suggests that a detailed grain size dependence study is not advantageous. Therefore, multiple grain sizes will not be run, so the samples for Arroyo Chavez can be spread out over many sample sites. Conversely, Yuma Wash has a wide distribution of grain sizes (Figure 13), and thus necessitates a more detailed grain size dependent isotopic analysis. Most of the Yuma Wash samples will require at least 3 size fractions thus limiting the number of sample locations possible. At least one detailed grain size analysis will be conducted on the Yuma Wash samples. The grain size dependence and exact distribution of samples from Nahal Yael is yet to be determined.

Sample Preparation

All sediment samples are dry sieved into seven size fractions. For Arroyo Chavez, a high clay content necessitated a pre-wash in 1N HCL before sieving could be conducted. Samples are sieved into size fractions of: 0.00-0.125mm, 0.125-0.250mm, 0.250-0.50mm, 0.50-1.00mm, 1.00-2.00mm, 2.00-4.00mm, 4.00-12.70mm, and greater than 12.70 mm. Bedrock samples and all sediment samples are then crushed and sieved to yield an optimal particle size of 0.25-0.80 mm for further processing. Samples are next etched in 6N HCL and then 1% HF & 1%HNO3 in order to isolate quartz grains and remove any atmospheric ^{10}Be or ^{26}Al. Samples are then prepared for isotopic analysis through a series of digestions which isolate Be and Al. Isotopic abundances are determined through accelerator mass spectrometry at Lawrence Livermore National Lab. For A detailed description of laboratory methods , please see our web page at:

http://beluga.uvm.edu/geowww/cosmolab.html

Modeling

Modeling of geomorphic processes and cosmic ray dosing will play an important role in this project. In order to interpret the isotopic data, I will construct detailed mixing models. Such models will further our understanding of cosmogenic exposure dating and cosmogenic mechanics including effects of changes in production rates through time, erosion rate determination, and error analysis.

Mixing Models

Models to describe the movement of sediments in and out of storage reservoirs as well as through specific basins will be critical to understanding the isotopic signature of stream channel sediments. A dynamic simulation modeling software system, STELLA, will be used construct models describing the mixing of sediments from various geologic sources and having various isotopic signatures and differing lithologies. Isotopic data from each of the measured geomorphic units as well as geomorphic details gathered in the field will be used to constrain the models. A series of theoretical hillslope evolution models will be constructed based on the relative importance of features found in the field.

Cosmogenic Exposure Age Calibration Model

The greatest uncertainties in cosmogenic exposure ages of samples for which exposure history is well constrained are nuclide production rates as a function of time, altitude, and latitude. For example, over the past seven years researchers have calculated ^{10}Be and ^{26}Al exposure ages using the time-averaged production rates of Nishiizumi et al. (1989). Recent work has suggested that ages calculated using these established production rates may he inaccurate for several reasons: (1) Nishiizumi et al.'s calibration sites (38°, 3440 m) have been recently re-dated, effectively decreasing calculated, integrated production rates by 15-20% (Clark et al., 1995); (2) the contribution of muons to ^{10}Be and ^{26}Al production at sea level appears to have been overestimated (Brown et al., 1995) changing the altitude/latitude scaling used by most workers; (3) the geomagnetic rather than the geographic latitude was used to scale the Nishiizumi et al. (1989) data to sea level and high latitude, a convention not followed in later works (e.g. Nishiizumi et al., 1991); (4) a production rate calibration from the Laurentide terminal moraine (41°, 300 m; Larsen et al., (in review); Larsen, 1995) gave a sea-level, high-latitude production rate 20% less than Nishiizumi et al. (1989); and most importantly, (5) the use of site specific, integrated production rates, for dating samples of different ages and exposed at different altitudes and latitudes, does not take into account production rate modulation by Earth's dynamic, magnetic field (Kurz et al., 1990).

In order to begin addressing the temporal variation in production rates, I have created a Macintosh-based computer program (COSMO-CALIBRATE) which uses a model based on generally accepted geomagnetic paleointensity records and empirical relationships to account for cosmogenic isotope production rate variations over the last 140 ky. I have applied my program to cosmogenic nuclide data from recent literature in order to demonstrate the effect of calibrating exposure ages. Such calibration generally increases cosmogenic exposure ages and appears to reconcile apparently disparate ^{10}Be and ^{26}Al production rates, suggesting our approach is valid. 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.

Conclusions & Expected Findings

This study will be the first comprehensive, basin-wide cosmogenic isotope study aimed at determining long-term rates of erosion. By sampling three different study sites in three different climatic and geomorphic settings, the study should allow for:

1) the determination of long-term, basin-wide rates of erosion and the establishment of background erosion rates for comparison to human induced rates.

2) better management through informed decisions based on scientific evidence

3) proof of methods and validation of assumptions necessary for cosmogenic isotope interpretations in sediments.

4) identification of periods of increased or decreased sediment movement indicative of changes in climate and land use.

5) the determination of the relationship between sediment particle size and isotopic abundance.

6) the determination of the importance of soil stirring on the bulk isotopic signature of the sediments.

7) An improvement in the use and interpretation of cosmogenic isotopes in landscape interpretation.

Schedule To Complete Degree Program

October 1997	Dissertation Proposal & Seminar
	Completion of Arroyo Chavez Sample Analysis
November 1997	Comprehensive Exams
	Begin write-up of Arroyo Chavez Project
December 1997	Israel Field Work
January 1998	Completion of Yuma Wash Sample Analysis
	Begin write-up of Yuma Wash Project
April 1998	Completion of Nahal Yael Sample Analysis
	Completion of Arroyo Chavez & Yuma Wash write-ups
June 1998	Completion of Nahal Yael write-up
August 1998	Completion of Dissertation
September 1998	Dissertation Defense

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Table 1. Allocation of samples for each of the three proposed study sites.

Arroyo Chavez		
sample	# samples generated	Description
ECAC1	1	upper basin bedrock
ECAC4	1	upper basin bedrock
ECAC6	1	upper basin bedrock
ECAC8	2	Arroyo channel sediments
ECAC9	1	Arroyo channel sediments
ECAC10	1	Arroyo channel sediments
ECAC11	3	Arroyo channel sediments
ECAC12	1	Hillslope transect -depth profile
ECAC14	3	Hillslope transect
ECAC16	1	Hillslope transect
ECAC18	1	Hillslope transect
ECAC19a	2	Profile sample main channel cut through basin fill
ECAC19b	1	Profile sample main channel cut through basin fill
ECAC19d	2	Profile sample main channel cut through basin fill
ECAC19f	1	Profile sample main channel cut through basin fill
ECAC19g	2	Profile sample main channel cut through basin fill
ECAC20a	1	Profile cut through alluvial fan
ECAC20c	1	Profile cut through alluvial fan
ECAC20d	1	Profile cut through alluvial fan
ECAC21	1	Profile sample main channel cut (integrated)
TOTAL ANALYSIS	28	

Nahal Yael		
sample	# samples generated	description
NY1-3	3	Bedrock Uplands
NY4-8	5	Stream Cut Profile
NY9-13	5	Hillslope Transects
NY14-20	7	Stream Channel Seds
TOTAL ANALYSIS	20	

Yuma Proving Grounds		
sample	# samples generated	description
YPG2-1	1	Main wash channel seds (0.25-0.5mm)
YPG2-2	1	Main wash channel seds (0.5-1.0mm)
YPG2-3	1	Main wash channel seds (1.0-2.0 mm)
YPG2-4	1	Main wash channel seds (2.0-4.0mm)
YPG2-5	1	Main wash channel seds (4.0-12.7mm)
YPG2-6	1	Main wash channel seds (12.7-50mm)
YPG2-6quartz clast	1	Main wash channel seds (35 x 70 mm quartz clast)
YPG3	3	Main wash channel seds
YPG4	3	Main wash channel seds
YPG5	3	Main wash channel seds
YPG7	1	upland bedrock in south western study basin
YPG8	1	upland bedrock in south western study basin
YPG9	1	upland bedrock in south western study basin
YPG10.3	3	Terrace cut profile in sw study basin (meters from top-9)
YPG10.5	3	Terrace cut profile in sw study basin (meters from top-6)
YPG10.7	3	Terrace cut profile in sw study basin (meters from top-3)
YPG10.9	3	Terrace cut profile in sw study basin (meters from top-1)
YPG11	3	SW study basin channel seds
YPG12	3	SW study basin channel seds
YPG13	3	SW study basin channel seds
YPG14	3	SW study basin channel seds
YPG15	3	SW study basin channel seds
YPG16	3	Main wash channel seds
YPG17	3	Main wash channel seds
YPG18	3	Main wash channel seds
YPG19	3	Main wash channel seds
YPG20	3	Main wash channel seds
YPG21	3	Main wash channel seds
YPG22	3	Main wash channel seds
YPG23	1	Hillslope colluvium in sw study basin
YPG24	1	Hillslope colluvium in sw study basin
YPG25	1	Hillslope colluvium in sw study basin
YPG26-0.5	3	terrace/fan profile low in sw study basin
YPG26-1.5	3	terrace/fan profile low in sw study basin
YPG26-2.5	3	terrace/fan profile low in sw study basin
YPG27	3	Main wash channel seds
YPG28	3	Main wash channel seds
TOTAL ANALYSIS	85	

Table 2. Average model cosmogenic exposure ages and erosion rates for Arroy Chavez, NM.
Averages include both 10-Be and 26-Al samples which had an Al/Be ratio of approximately 6.

		average exposure		average erosion rate	
sample	environment	age (k yrs)	(+/-)	(m/My)	(+/-)
AC8-2	stream channel	7.4	1.6	83	19
AC11-1	"	5.0	1.1	121	27
AC11-2	"	4.9	1.0	126	28
AC11-3	"	4.2	1.1	145	37
	average	5.4	1.2	119	28
AC14-1	hillslope	3.0	0.8	210	58
AC14-2	"	2.9	0.7	216	52
AC14-3	"	2.9	0.7	215	56
	average	2.9	0.7	214	56
AC19A-1	arroyo wall	7.2	1.6	85	20
AC19A-2	"	6.6	1.6	94	24
AC19D-1	"	6.6	1.5	94	21
AC19D-2	"	6.8	1.4	90	20
AC19G-3	"	4.5	1.1	136	35
	average	6.3	1.4	100	24

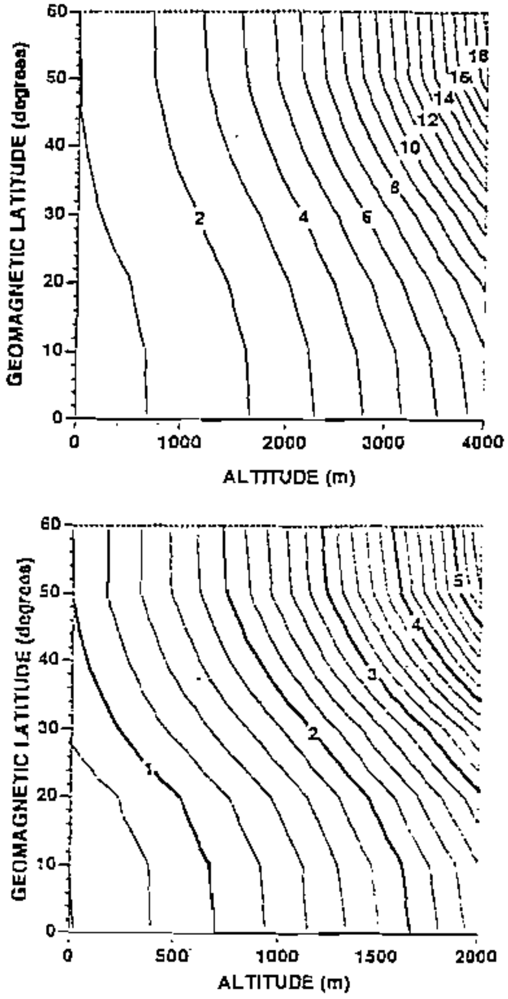

Figure 1. Relationship of cosmogenic isotope production rates to sample altitude and latitude (Lal, 1991 in Bierman, 1994). The numbers on lines within the plots are scaling factors which are multiplied by normalized production rates (normalized to sea level and >60° latitude) to get a site specific production rate. The correction factors are greatest at high altitudes and low latitudes.

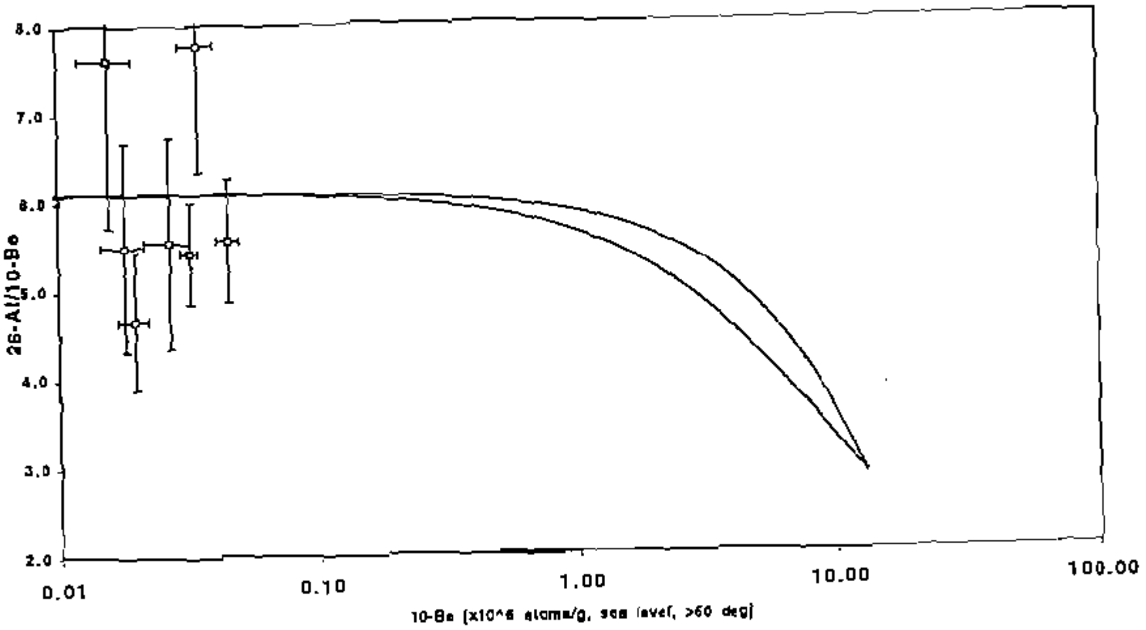

Figure 2. Two isotpope plot (10-Be and 26-Al) for Arroyo Chavez sediment samples. Upper line represents model for constant exposure. Lower line represents model for constant erosion rate. Any values falling below the lower line have been buried sometime during or after exposure to cosmic rays.

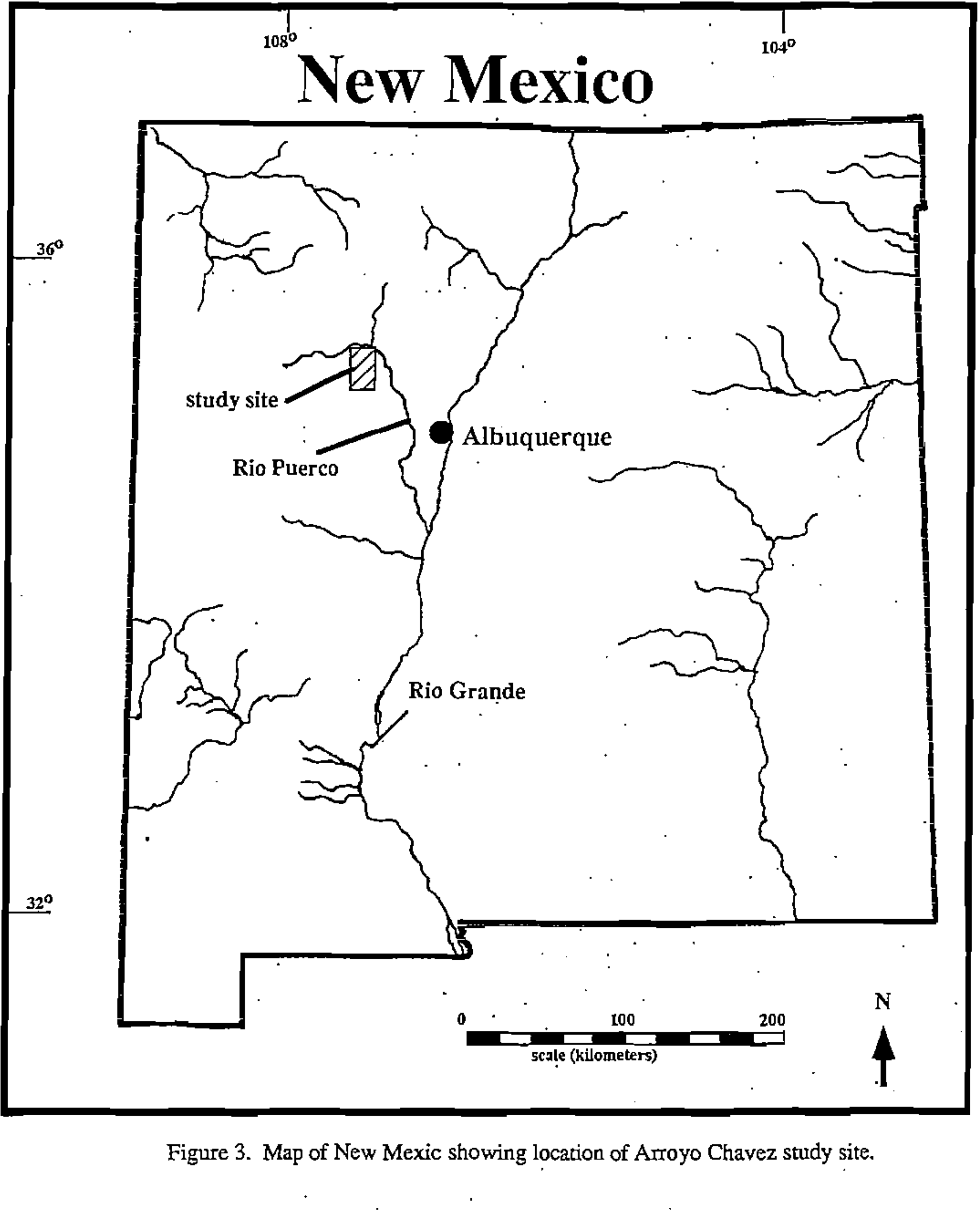

Figure 3. Map of New Mexic showing location of Arroyo Chavez study site.

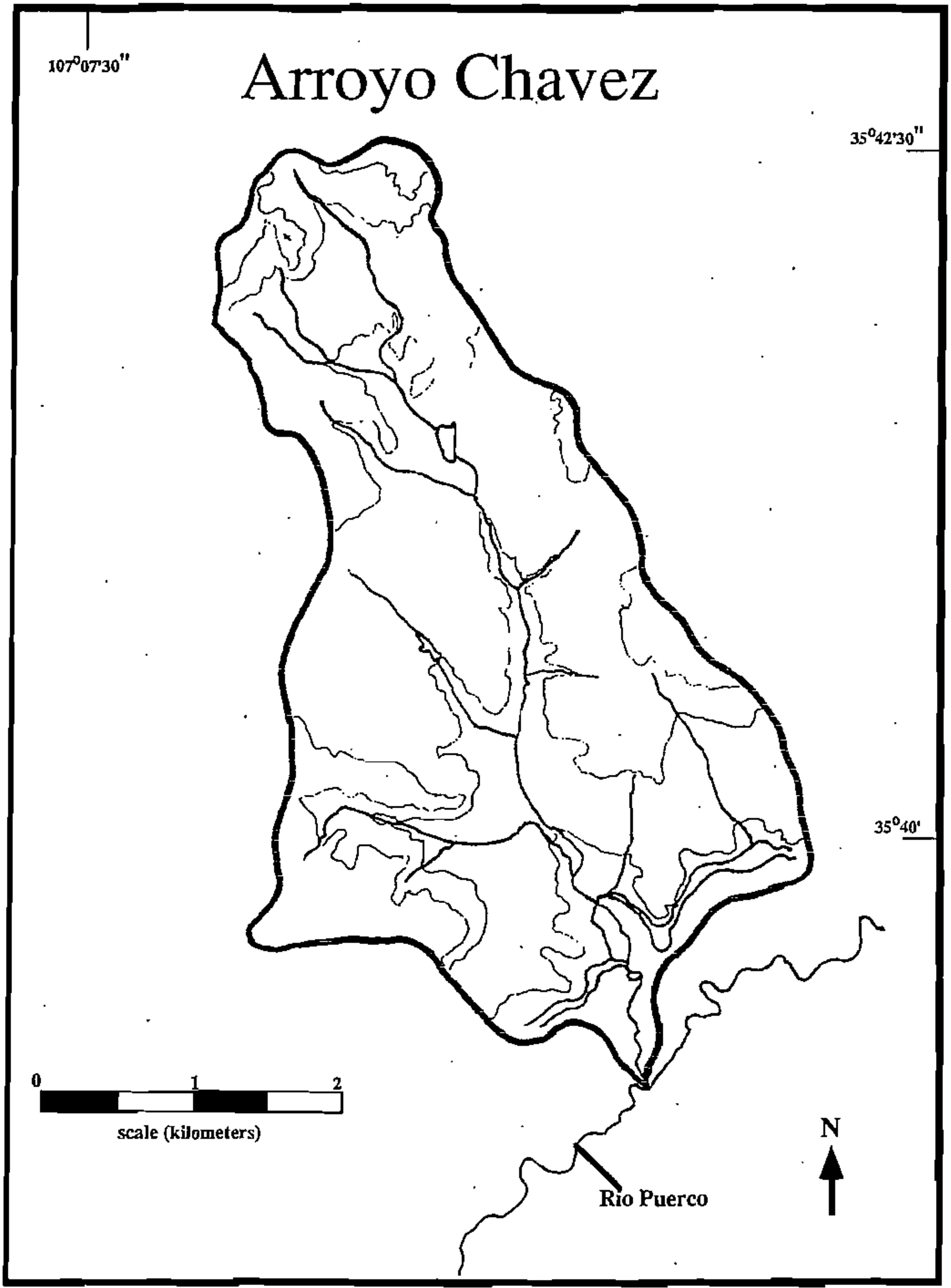

Figure 4. Map of Arroyo Chavez drainage basin.

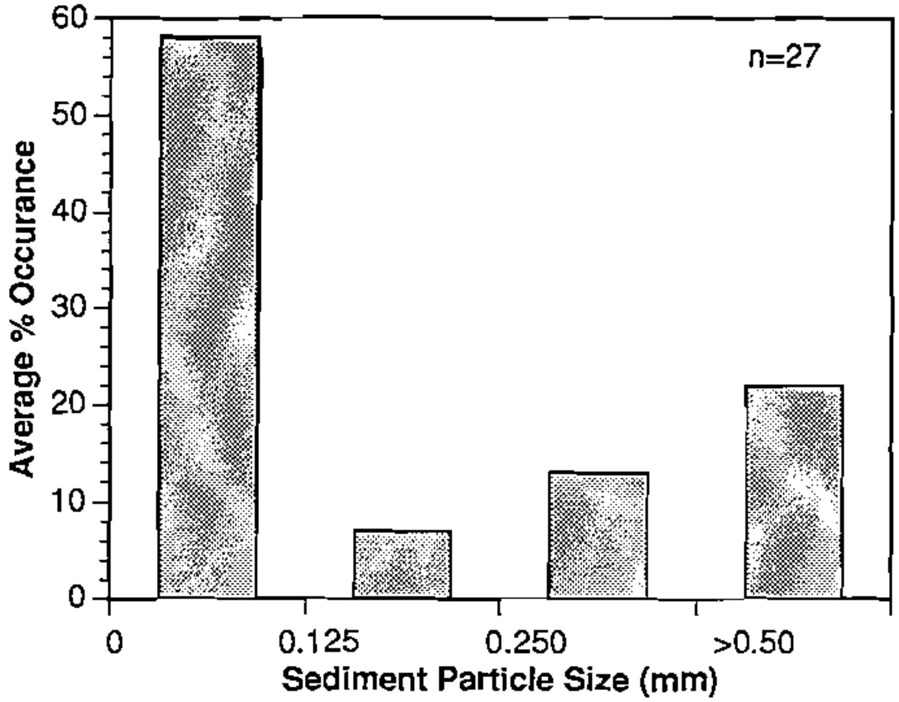

Figure 5. Average frequency (%) for sediments sampled at Arroyo Chavez, New Mexico. Sediment particle sizes are listed as an average between two sieve sizes. The fine fraction (less than 0.125 mm) dominates the sediment distribution in the basin, but must be discarded due possible aeolean inputs.

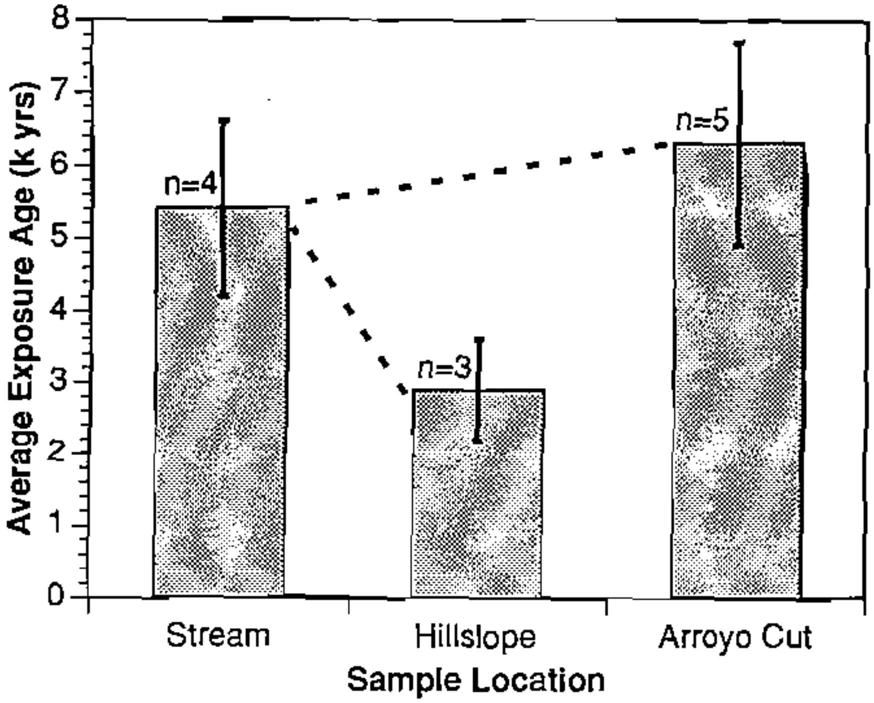

Figure 6. Average cosmogenic exposure age measured in stream channel sediments, hillslopes, and a wall of the main arroyo cut at Arroyo Chavez, New Mexico. Channel sediments are likely a mix of higher abundance arroyo cut sediments and lower abundance hillslope sediments. Values are averages of both 10-Be and 26-Al measurements which all had Al/Be ratios near 6. Error bars=1sigma. For actual values, see Table 1.

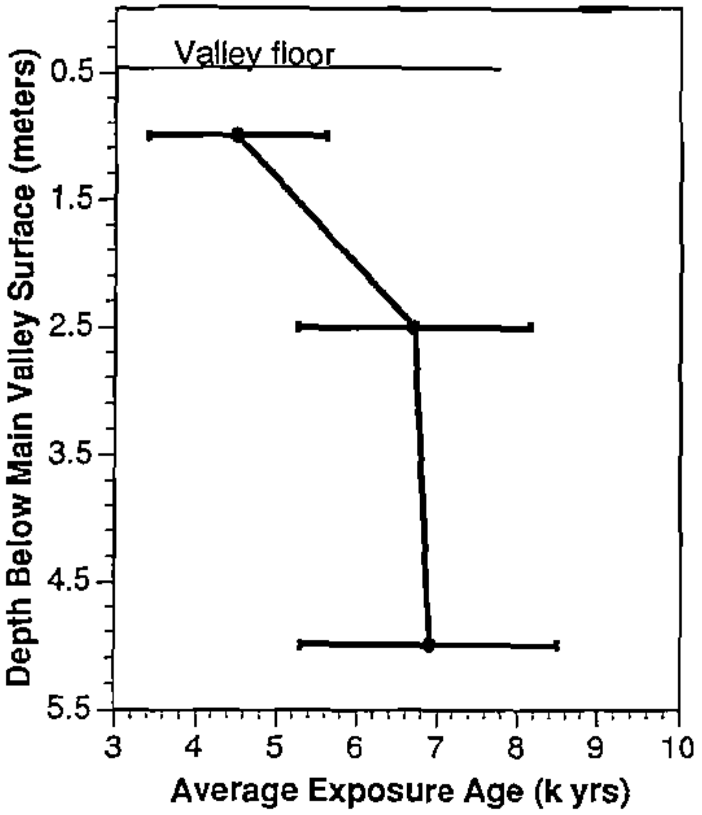

Figure 7. Average cosmogenic exposure ages taken from an arroyo wall at Arroy Chavez, New Mexico. There appears to be an increase in age and isotopic abundance with depth, which is likeley due to *in situ* production during burial for the upper 2.5 meters, but could also indicate an increase in deposition rate in recent years or could be the result of increasing basin width at higher elevations. Below 2.5 meters, the relationship of increased abundance with depth is not significant. It should be noted that highest sample is for coarse material only which could account for the lower ages (see figure 12). Error bars=1 sigma. Samples were collected over at 10 cm depth interval. Samples are the average of both 10-Be and 26-Al data which had al/Be ratios near 6.

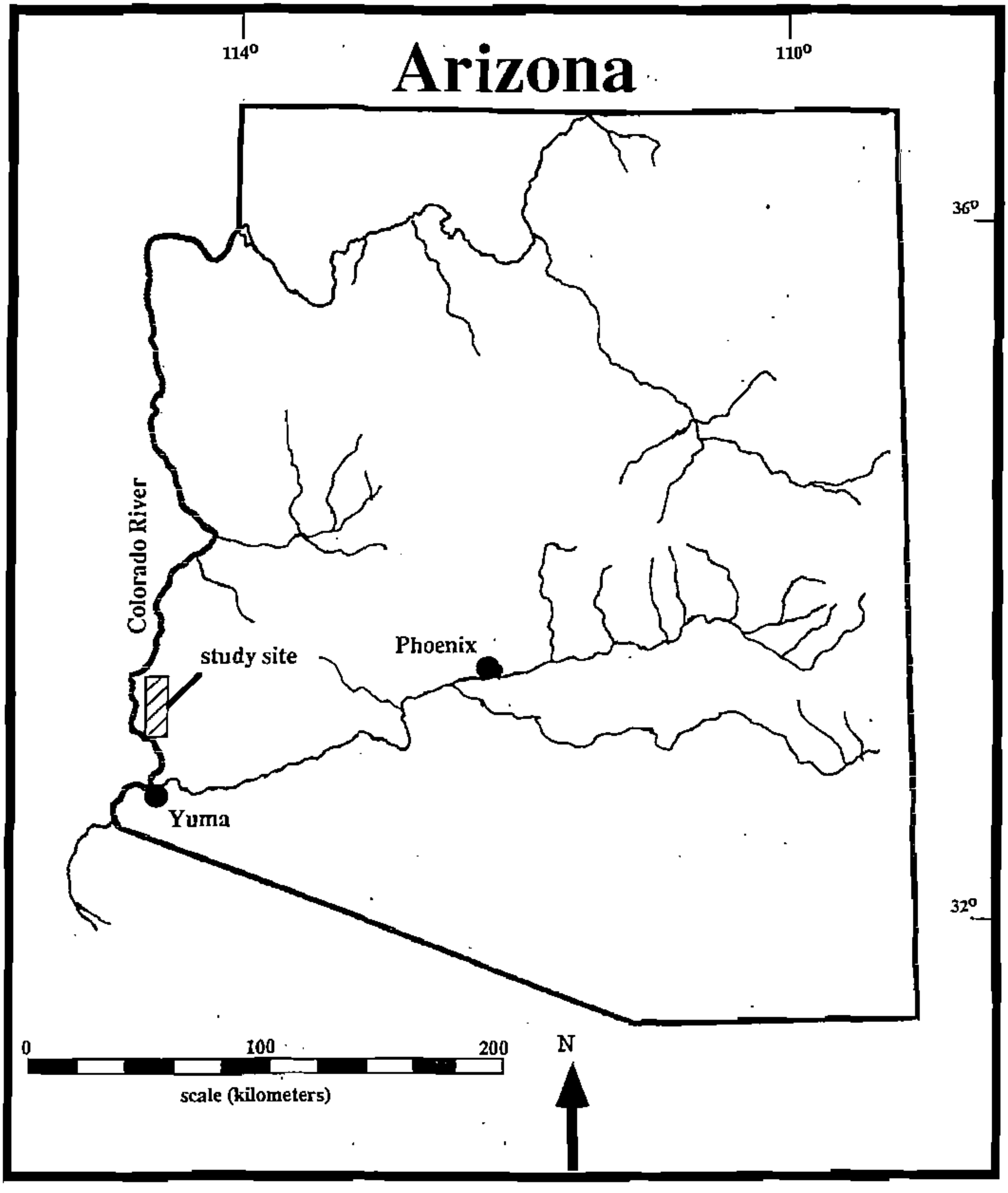

Figure 8. Map of Arizona showing Yuma Wash study site location.

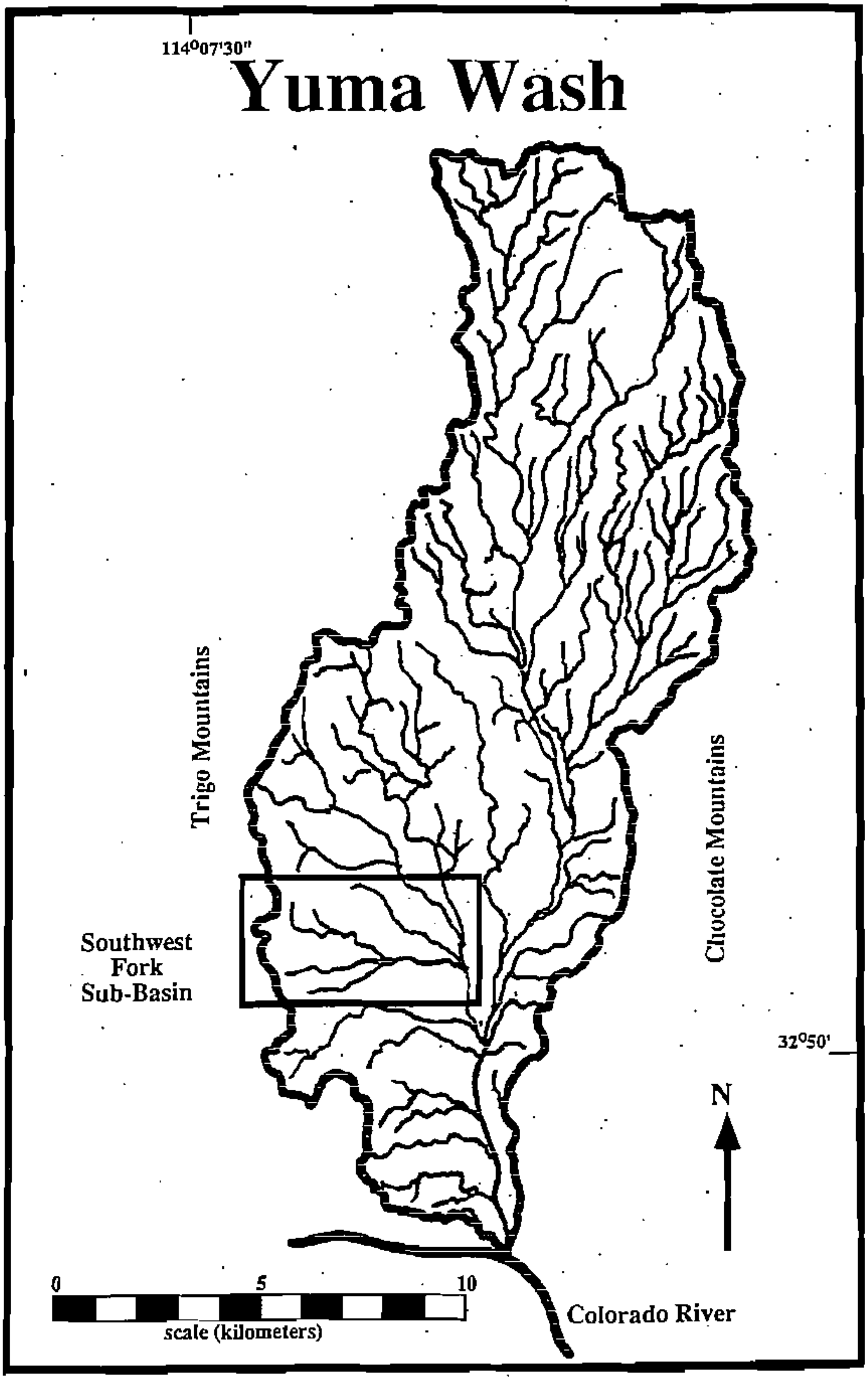

Figure 9. Map of Yuma Wash study site.

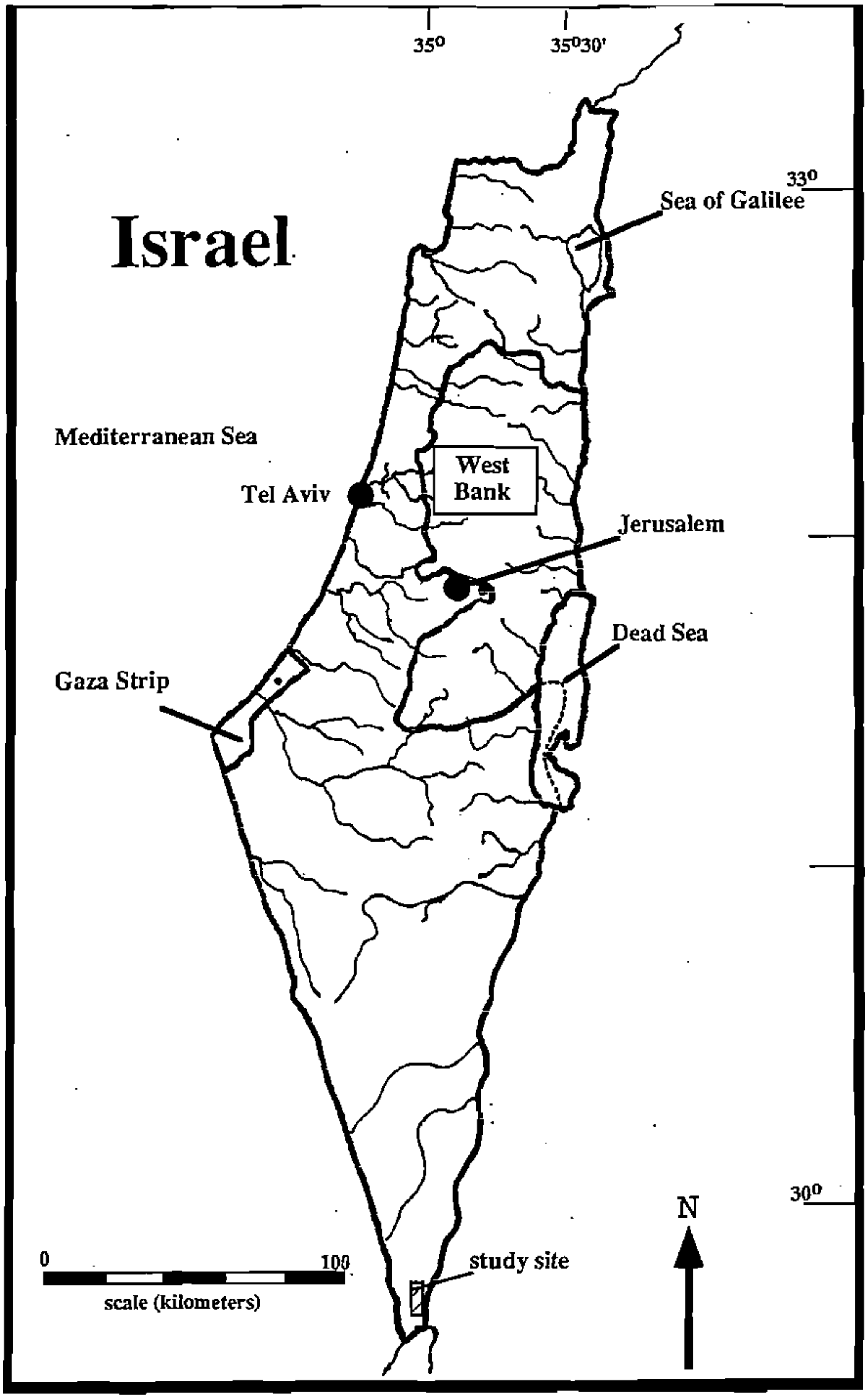

Figure 10. Map of Israel showing Nahal Yael study site.

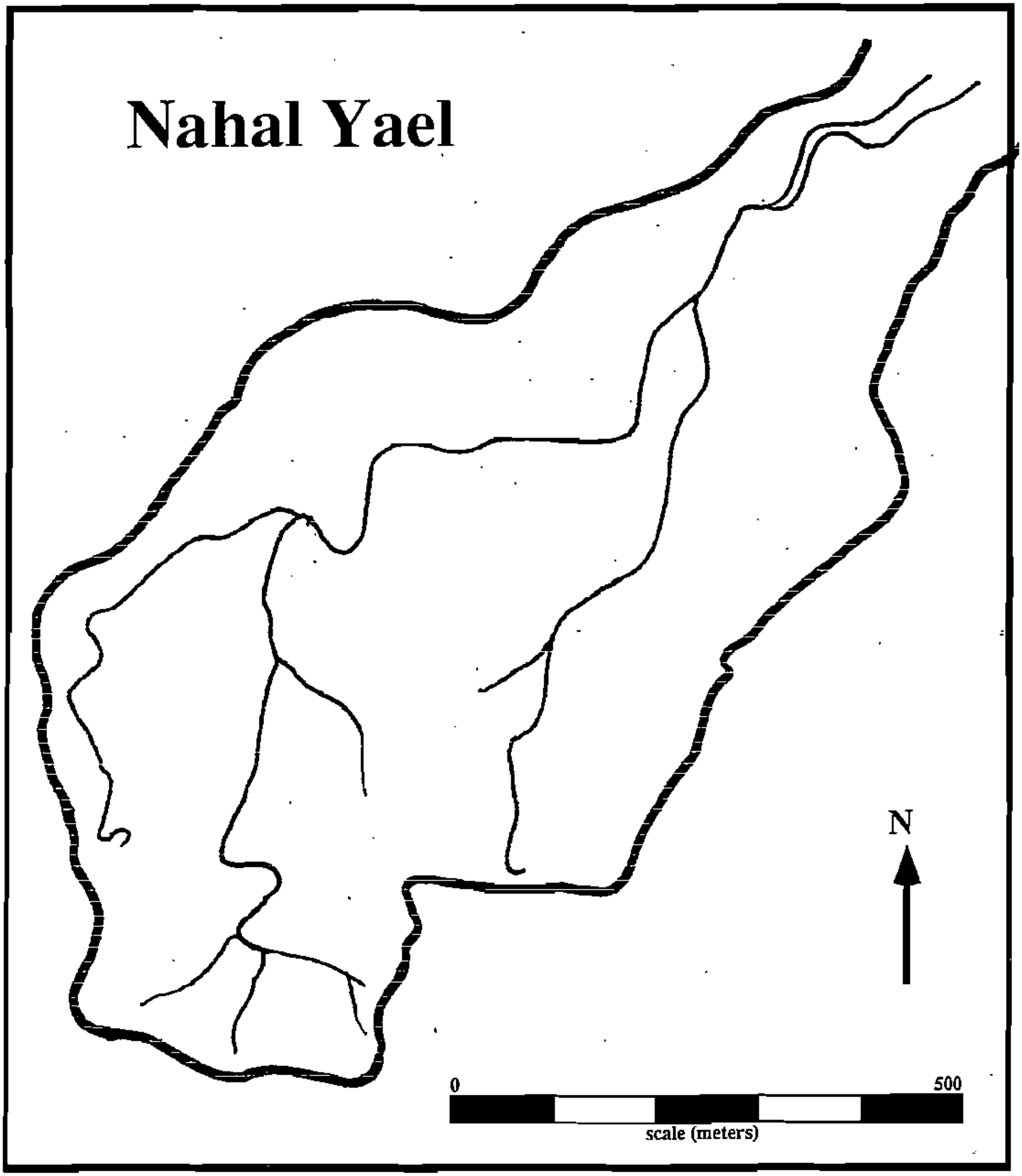

Figure 11. Map of Nahal Yael study site.

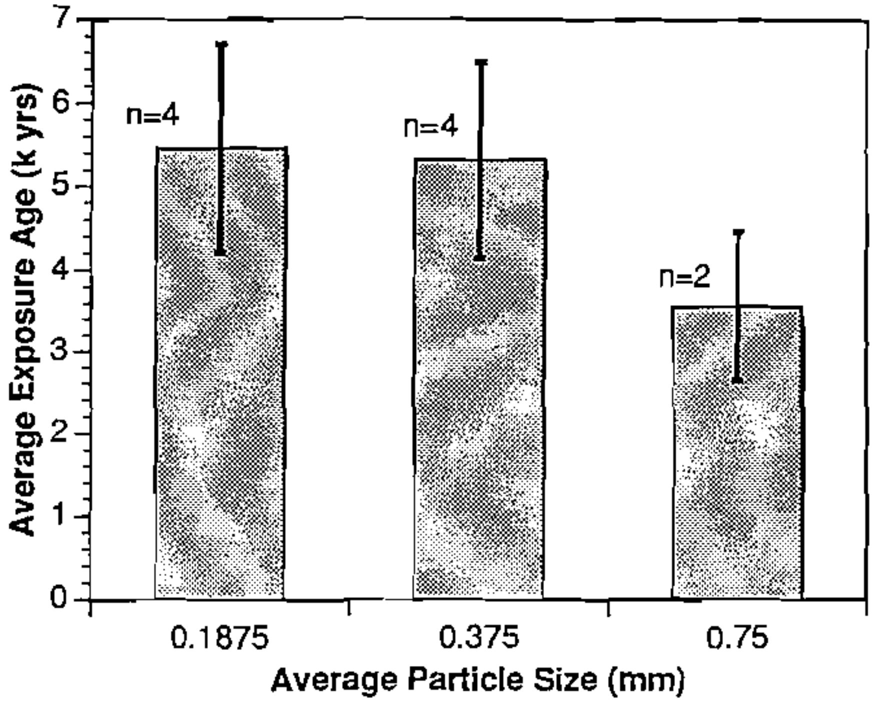

Figure 12. Average cosmogenic exposure age measured in three different size sediments of Arroyo Chavez, New Mexico. There appears to be a slight decrease in abundance and calculated exposure age with an increase in particle size, however, the differences are less than 1 sigma (error bars=1 sigma). Samples are an integration between sieve sizes of 0.125-0.250 mm, 0.250-.050 mm, and >0.50 mm. For actual values, see Table 1.

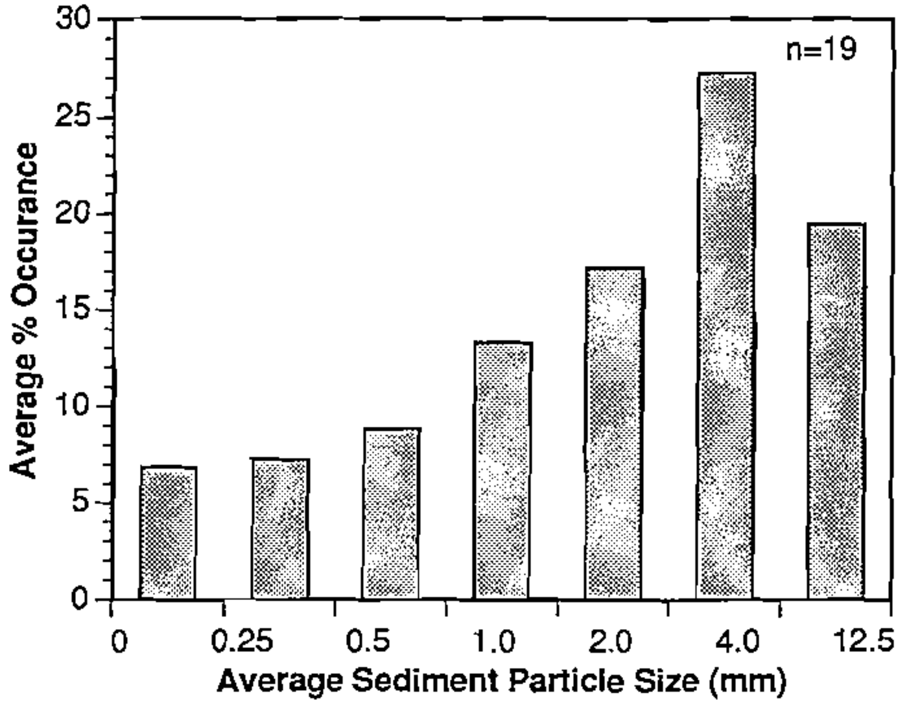

Figure 13. Average frequency (%) for sediments sampled at Yuma Wash, Arizona. Sediment particle sizes are listed as an average between two sieve sizes.