QUANTIFYING HUMAN IMPACTS ON NATURAL RATES OF EROSION ALONG CONTINENTAL MARGINS

A Dissertation Proposal Presented

by

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Introduction:

Understanding natural rates of sediment generation and landscape erosion is imperative for the design and implementation of realistic resource management strategies. However, measurements of such background rates with traditional techniques are difficult to make and of uncertain validity (Meade, 1969, Trimble and Crosson, 2000). Estimates for the natural pace of sediment movement down hillslopes and through river systems around the globe are subject to numerous biases, and are often markedly influenced by the activities of people. Stated all too well by Roger Hooke (2000), "…we have become arguably the premier geomorphic agent sculpting the landscape…"

Whether it be from the conversion of forests to croplands, the harvesting of timber from hillslopes, intensive mining, or the spread of impermeable pavement, erosional processes change, and the volume of sediment delivered to and carried by surrounding rivers no longer reflect natural conditions (e.g. Kirchner and others, 2001, Meade, 1969, Trimble, 1977). Human-landscape interactions can yield sediment loads and inferred erosion rates elevated over background rates by as much as an order of magnitude (Meade, 1969). In addition, contemporary sediment yield records are often short (on the order of years to decades) and may not incorporate large volumes of sediment delivered to rivers during high-magnitude, low-frequency events (e.g. Wolman and Miller, 1960) such as intense storm activity capable of mobilizing otherwise stable material (Hicks, Gomez, and Trustrum, 2000, Kirchner and others, 2001).

In short, records of sediment yields are highly variable in space and time, leading to uncertain and probably biased estimates for rates of landscape change. Basing effective resource management and hazard assessment protocols on such data can be both difficult and dangerous. Alternative geologic techniques for measuring erosion, such as fission-track thermochronometry (e.g. Cockburn and others, 2000, Naeser and others, 2004), integrate mass loss over millions of years, spanning vastly different climate and land-cover conditions than today. Taken alone, as with sediment yield data, these long-term estimates provide little useful information for resource management.

Over the past decade, concentrations of the rare isotope, ^{10}Be, have been measured in sediment collected from active river channels. With appropriate models, these isotopic data can be used to calculate natural rates of sediment generation and erosion over millennial time scales (Bierman and others, 1995, Brown and others, 1995, Granger, Kirchner, and Finkel, 1996). When compared to modern sediment yields, these isotopic measurements constitute an indispensable tool for assessing human impacts on natural process rates, a comparison which can lead to more informed land-use planning decisions

My dissertation work will build upon the work of others who have used cosmogenic ^{10}Be to make comparisons between short-term rates of sediment delivery and long-term rates of sediment generation (Brown and others, 1998, Clapp and others, 2000, Ferrier, Kirchner, and Finkel, 2005, Gellis and others, 2004, Hewawasam and others, 2003, Kirchner and others, 2001, von Blackenburg, Hewawasam, and Kubik, 2004). In contrast to the site-specific nature of most previous studies, this research will span large portions of continental margins, including several New Zealand and North American river basins ravished by the erosional effects of land clearance (Figures 1 & 2). My three study sites represent widely differing tectonic and climatic environments, and have diverse land-use histories. Results from these studies will provide researchers and planners with a more comprehensive understanding of the impacts of human-landuse practices on natural rates of surface processes across broad geographic regions.

Primary Research Objectives:

There are two primary objectives of my research. First, analysis of ^{10}Be measurements will provide estimates of natural rates of sediment generation and erosion for comparison to modern-day rates of sediment delivery, fundamental data for evidence-based resource management. Through careful comparison of these long-term rates to modern sediment yield data, the impacts of human land-use practices can be assessed and the potential implications for resource management can be considered. Second, erosion rate data from nearly 200 samples will constitute one of the largest ^{10}Be datasets to date and will improve our understanding of the natural pace of landscape erosion across geographic regions subject to different and pronounced tectonic and climate gradients. Specific testable hypotheses germane to each region are laid out in detail and discussed in following sections.

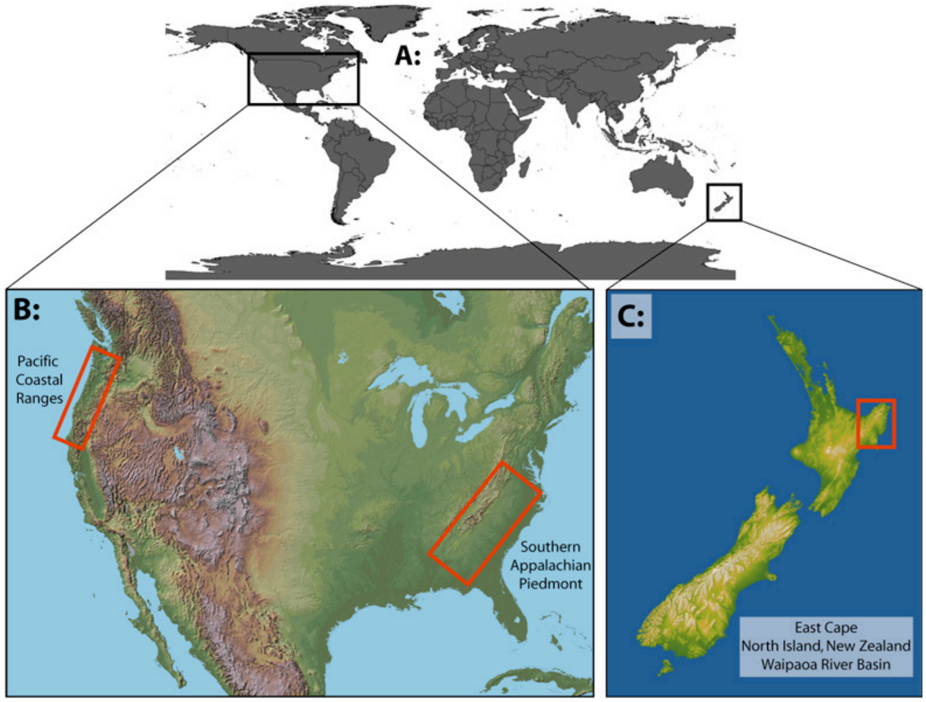

FIGURE 1: Location map showing all study sites. (A) global overview. (B) Middle North American Continent. Red boxes highlight the Pacific Coastal Transect along the active North Pacific Coast and the southern Appalachians along the passive U.S. Atlantic Coast. (C) North and South Islands of New Zealand. Red box highlights the East Cape region and Waipaoa Basin on the North Island.

Background:

Cosmogenic Isotopes and Erosion Rate Modeling :

Although the discovery of cosmic radiation in 1912 provided numerous insights in the field of particle physics at the time (Gosse and Phillips, 2001), more than four decades passed before the geologic applications of the interaction of such radiation with earth-surface materials to produce the cosmogenic isotope ^{36}Cl was realized (Schaeffer and Davis, 1955). While the existence of several other cosmogenic isotopes (^{3}He, ^{10}Be, ^{26}Al, and ^{21}Ne) produced in near-surface terrestrial materials was hypothesized, their routine detection and measurement did not become feasible until advances in analytical chemistry and accelerator mass spectrometry were made in the 1980's (Elmore and Phillips, 1987). Because these rare isotopes are produced at known rates in rocks and sediments exposed at Earth's surface primarily by the bombardment of cosmic rays, measurement of their concentration in geologic samples can be used to estimate exposure histories and to quantify surficial process rates. For the past several decades, *in situ* produced cosmogenic isotopes have been utilized to investigate a wide array of

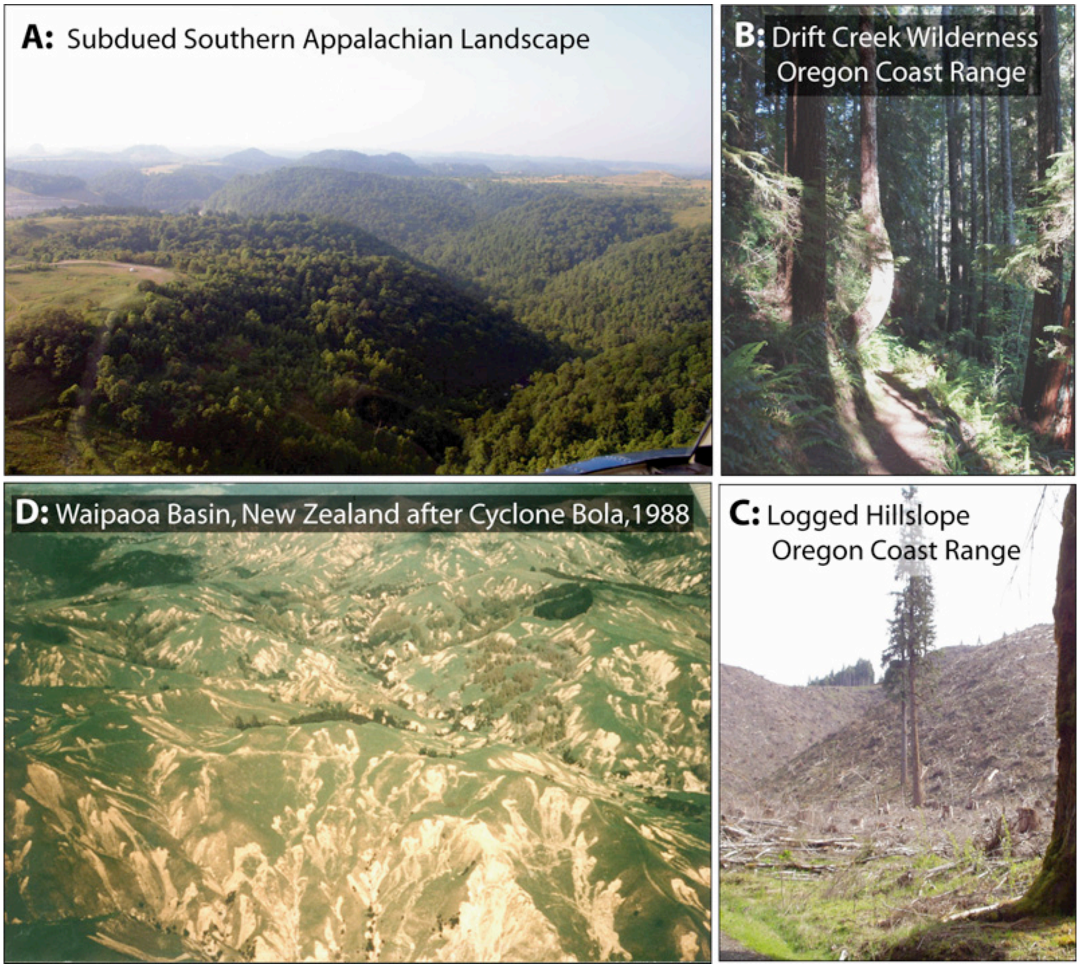

FIGURE 2: Characteristic pictures from the three study sites. (A) Image showing a typical southern Appalachian landscape. Note the subdued topography, and thick vegetation punctuated by patches of cleared land. (B) Steep rugged slopes characteristic of the Oregon Coast Range. Picture is from the Drift Creek Wilderness Area, one of the only remaining patches of natural vegetation. (C) Clearcut hillside in the Oregon Coast Range. (D) Landslides in the western Waipaoa Basin, New

geologic problems such as; estimating the exposure and erosional histories of bedrock landforms (e.g. Bierman and Turner, 1995, Bierman and Caffee, 2002b), reconstructing glacial chronologies (e.g. Marsella and others, 2000, Phillips and others, 1990), calculating fault displacement rates (e.g. Gran and others, 2001), estimating the timing and rate of bedrock channel incision (Burbank and others, 1996, Leland and others, 1998, Reusser and others, 2006, Reusser and others, 2004, Schaller and others, 2005), determining transport rates across desert piedmonts and rates of arroyo formation (Clapp, Bierman, and Caffee, 2002, Clapp and others, 2000, Nichols and others, 2002), and modeling rates of soil production and transport (e.g. Heimsath and others, 2001, Jungers and others, 2006). The application most germane to my dissertation work is the measurement of cosmogenic isotopes in river sediment for the purpose of estimating

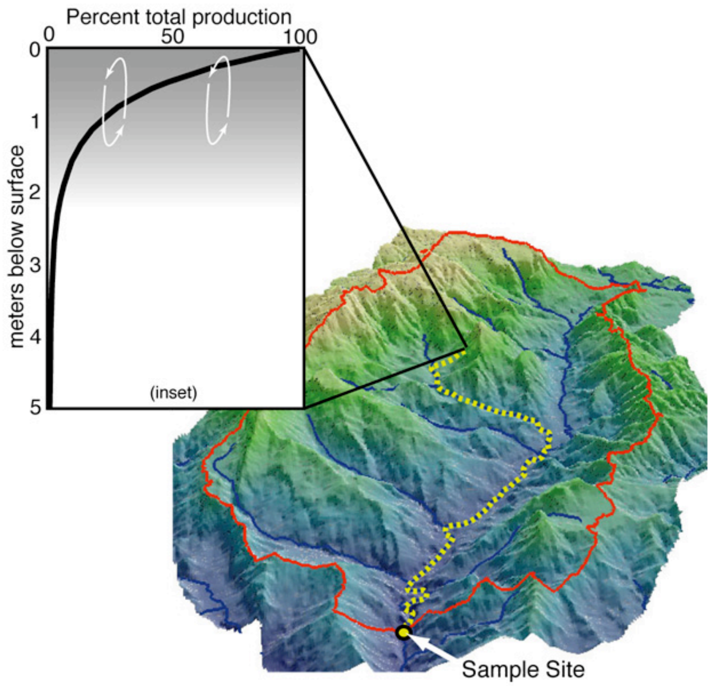

FIGURE 3: Schematic illustrating the conceptual framework of long-term erosion rates modeled from the accumulation of ^{10}Be. Contributing drainage basin outlined in red. Yellow dashed line represents the trajectory of an individual grain of sediment from its origin on a hillslope to the basin outlet. "Inset" illustrates the integrated history of exposure of hillslope material as it is exhumed from bedrock as hillslopes erode. Shaded area shows the zone of ^{10}Be hillslope production and accumulation. White arrows demonstrate the homogenization of ^{10}Be inventories within the upper several meters caused both by biotic and abiotic processes of soil stirring.

spatially averaged basin-wide erosion rates (Bierman and Steig, 1996, Brown and others, 1995, Granger, Kirchner, and Finkel, 1996).

^{10}Be, an isotope often employed in erosion rate studies, is produced in quartz by the bombardment of near-surface materials by cosmic rays (Lal and Peters, 1967). Collisions between the continual flux of high-energy neutrons and oxygen atoms within quartz mineral grains result in the formation of ^{10}Be. The rate of production of all cosmogenic isotopes varies as a function of the sampled location's altitude, latitude, and earth's geomagnetic fields strength (Clark, Bierman, and Larsen, 1995, Nishiizumi and others, 1989). Similarly, production rates vary exponentially as a function of depth (Lal, 1991), with 100% production at the surface dropping to ~20% production at a depth of 1 m in rock. At a depth of 3 meters, production rates drop to nearly zero illustrating the ability of cosmogenic isotopes to isolate processes active at earth surface only (Figure 3 inset). With a half-life of ~1.5 million years, and a sea level, high latitude production rate of ~5.2 atoms g^{-1} $year^{-1}$, ^{10}Be is well suited for investigating geologic processes operating over millennial time scales.

Each grain of sediment in a river channel has a unique history, beginning at some point in the past as bedrock far beneath the surface. As hillsides erode, what will become sediment grains, move closer to the surface eventually entering the zone of exposure to cosmic radiation (2 to 3 meters below the surface). Based on the rate of erosion and thus its near surface residence time, the grain will accumulate more or less ^{10}Be as it enters and move through the soil column, makes its way to the surface of a hillside, travels down slope to the river channel, and is then carried downstream in the water column. If this process as a whole is rapid, the concentration of ^{10}Be will be lower; if slow, the concentration will be correspondingly greater. In this way, each quartz grain acts as a dosimeter, recording its near-surface history of exposure, erosion, transportation, and in some instances periods of channel storage. Rivers collect, transport, and mix millions of grains from the upstream portion of a drainage basin contributing to any point along the channel. The concentration of ^{10}Be in a sample of river sediment reflects the integrated history of exhumation and erosion of the drainage basin over time and space (Bierman and Steig, 1996) (Figure 3).

Comparing Modern Sediment Yields to ^{10}Be Rates of Sediment Generation:

Erosion rates derived from concentrations of cosmogenic isotopes are integrated over thousands of years; thus, they provide a valuable means by which to consider the effects of human activities on natural rates of surface processes. Through mixing in the upper horizons of a soil profile, the inventory of ^{10}Be is homogenized in the zone where most cosmic ray dosing occurs (Figure 3 inset). In the absence of large-scale geomorphic events, such as gullying or deep landsliding capable of removing meters of soil and bedrock, cosmogenically modeled erosion rates are relatively insensitive to human-induced disturbance of natural landscapes (Heimsath and others, 2002, Hewawasam and others, 2003). If episodic delivery of large volumes of sediment, such as landslides, is a natural erosional process inherent to a region, the averaged isotopic signal of such phenomena will be reflected in long-term ^{10}Be erosion rate estimates (Niemi and others, 2005), whereas such occurrences tend to confound short-term sediment yield records (Hewawasam and others, 2003, Kirchner and others, 2001).

A number of researches have utilized these physical properties of ^{10}Be production to directly compare modern-day sediment yields to long-term rates of sediment generation. The tectonic and climatic settings represented by these studies vary considerably, and while the expected outcome has often been that short-term rates would greatly outpace long-term rates, this was not always the case. Owing largely to modern land-use practices, sediment yields were found to be moderately faster than background rates in arid desert regions (Clapp and others, 2000, Gellis and others, 2004), and up to ~100 times faster in agricultural tropical regions subject to monsoonal weather patterns (Brown and others, 1998, Hewawasam and others, 2003). In contrast, results from several comparison studies in the Oregon Coast Ranges show relatively good agreement between sediment yields and long-term sediment generation (Bierman and others, 2001, Ferrier, Kirchner, and Finkel, 2005), suggesting either that long- and short-term rates are in equilibrium, or that short sediment yield records do not reflect infrequent episodes of high sediment delivery. On the other end of the spectrum, long-term rates were found to be up to 17 times greater than sediment yield data in mountainous Idaho streams (Kirchner and others, 2001). These findings emphasize the importance of incorporating infrequent catastrophic events when interpreting short-term sediment yield data that may reflect only slow and steady erosional processes, and account for a small portion of the sediment leaving a catchment over longer time frames. Such temporal bias can have serious implications when assessing the potential erosional impacts of proposed land-use changes (Brown and others, 1998, Montgomery and others, 2000), predicting the effects of sediment loading on aquatic ecosystems, or calculating infilling rates and life spans for reservoirs.

<u>Study Sites:</u>

My research focuses on three regions, all of which drain from continental margins to sea, and represent landscapes governed by different climatic, tectonic, and human-influenced processes. These sites include: the stable and subdued southern Appalachian Piedmont stretching from Virginia to Georgia, the active and rugged coastal ranges stretching from southern Washington to northern California, and the active East Cape region of New Zealand's North Island.

<u>*Southern Appalachians – Blue Ridge and Piedmont Erosion Rates:*</u> The Appalachian Mountains stretch from Newfoundland, Canada in the north, to Alabama in the south along the eastern margin of the North American Continent. Today, the ancient roots of the range are one of the most stable environments around the globe, and have inspired more than a century of research into what the longevity of the Appalachians can tell us about the growth and decay of landscapes (Ahnert, 1970, Davis, 1889, Hack, 1960,

Judson and Ritter, 1964), and the interaction of human land-use practices with these natural processes and rates (Trimble, 1977). In the southern regions of the range, most research utilizing cosmogenic isotopes has focused on high elevation and high relief areas, such as the Great Smoky Mountains (Duxbury and others, 2006, Matmon and others, 2003a, Sullivan and others, 2006). While long-term erosion rates have been measured in the low relief Piedmont in the north-central Appalachians and clearly demonstrate that agricultural practices elevate modern day sediment delivery rates above long-term averages (Reuter, 2005), a paucity of such data exists in the southern Piedmont. Prior to European settlement, erosion across the vegetated and low relief Piedmont is believed to have been minimal, with most sediment delivery originating from episodic mass movements in the upstream and higher relief Blue Ridge province (Trimble, 1974 and references therein).

Table 1:

	Southern Appalachian Piedmont	Pacific Coastal Ranges	North Island New Zealad
Tectonic Environment:	Passive margin	Active subduction margin: North American, Pacific, and Juan de Fuca Plates Convergence Rate ~30 mm/yr	Active subduction margin: Australia and Pacific Plates Convergence Rate ~40 mm/yr
Geology:	Mix of PreCambrian metamorphic rocks, Cambrian eugeosynclinal and volcanic rocks, and triassic marine deposits (sandstones to shales)	North and central: mostly Tertiary sedimentary rocks with minor amounts of volcanics and intrusives. To the south: combination of slightly older metamorphics, intrusives and volcanics.	Exposed latest Cretaceous to Tertiary forearc sedimentary rocks; mostly calcareous silt to mud stones, interbedded with thin sandstone and limestone lenses.
Climate:	Humid Temperate	Temperate Rain Forest	Maritime Climate
Average Annual Temp:	14 to 18 °C	0 to 12 °C	~14 °C
Average Annual Precipitation:	1100 to 1400 mm	1500 to 6000 mm	1000 to 1500 mm
Seasonality:	Summer thuderstorms are common, Winter tropical cyclones occasionally reach inland to the Piedmont.	Highly seaonal with most precipitation falling in Winter months.	Highly seasonal with most precipitation falling in June and July. Periodic intense cyclonic activity.
Topographic Terrain:	Piedmont topography is generally subdued and low slope (~1 to ~10 deg). Upstream Blue Ridge regions are more rugged and less suitable for agriculture.	Terrain of the coastal ranges is typically rugged with steep hillslopes and deeply incised river valleys.	Terrain is typically rugged in the headwater regions, and virtually flat in the heavily aggraded valley bottoms. In middle parts of the basin, hillslopes are either gently rolling or steep.
Land use history:	Extensive agriculture (mainly cotton to the south and tobacco to the north) began in the early 1700's. Landscape erosion peaked between 1860 and 1920. Between 1920 and the present, agriculture and erosion have decreased dramatically.	Intensive forestry practices commenced in the mid 1800's with Euro-American settlement. Industrial logging and road construction began in the 1940's, substantially impacting erosional regime.	Widespread clearance of the landscape began in the early 1800's mainly for sheep and cattle grazing. By 1880, the downstream portion of the Waipaoa basin was cleared, and by 1920, the headwaters were cleared. Today, only 3% of the basin remain uder native vegetation.
Uplift Rates:	N.A.	0 to 1 mm/yr	~1 to ~4 mm/yr - East Cape Region ~0.5 to ~1 mm/yr - Waipaoa Basin

Due to the humid temperate climate (Table 1), subdued topography, rich soils, and long growing season characteristic of the southern Piedmont, the region was subjected to intensive agricultural practices beginning in the 1700's (Trimble, 1974). Cotton and tobacco production increased dramatically during the 1800's and early 1900's, resulted in widespread and severe erosion of hillslopes and aggradation of river channels (Phillips, 1992, Trimble, 1974, Trimble, 1977). At the peak of agricultural use

(1860 to 1920), virtually the entire southern Piedmont was cultivated resulting in an average depth of upland hillslope erosion of ~180 mm (Trimble, 1977). Despite the scope of landscape disturbance, sediment yields representing the peak agricultural period from 10 large catchments draining the majority of the southern Piedmont could account for only about 6 percent of the material eroded from hillslopes (Figure 4) (Dole and Stabler, 1909, Trimble, 1977). Because the low gradient stream systems of the southern Piedmont were under fit to transport the overwhelming volumes of sediment shed from hillslopes, the majority of material went into storage across the landscape in river valleys and dam reservoirs (Phillips, 1992, Trimble, 1977). The apparent disconnect between hillslope erosion and the transportation of sediment by rivers highlights the dangers of estimating the degree of human-induced landscape erosion, as well as the design and implementation of resources management strategies from the load of sediment in streams. Previous studies of long-term erosion suggest that, as a whole, the Appalachians are eroding slowly (~0.02 m/ky; Reuter, 2005; Matmon, 2003). While in the higher slope Blue Ridge and Valley and Ridge provinces of the range, natural long-term and human-influences short-term rates of erosion are often in balance, heavy agricultural use in the northern Piedmont over the past several hundred years appears to have elevated short-term rates of

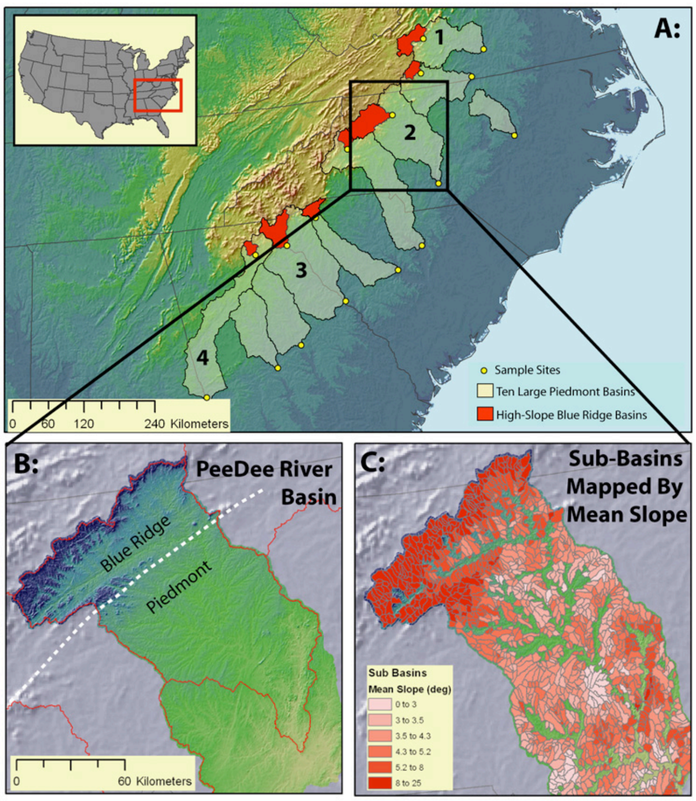

FIGURE 4: Field area for the southern Appalachian Piedmont project. (A) Overview showing the 10 large catchments studied by Trimble (1977). Yellow polygons represent the combined Piedmont – Blue Ridge proposed sample basins, while red polygons represent the higher slope Blue Ridge portions of each basin that will be samples. Samples will be collected from small sub-basins (5-15 km^2) within the larger catchments labeled as 1 through 4; Roanoke, Pee Dee, Savannah, and Chattahoochee basins respectively). (B) Blow up of the Pee Dee catchment showing the subdued topography of the Piedmont, and the higher relief of the Blue Ridge. (C) Example of sub-basins within the PeeDee mapped by mean slope.

sediment delivery over long-term rates of sediment generation and erosion (Reuter, 2005). ^{10}Be measurements from this study will provide an opportunity compare natural, background rates of sediment generation with the effects of landuse disturbance across the expansive southern Piedmont at the peak of agricultural use (late 1800's), as well as assess the effectiveness of current land management strategies.

U.S. North Pacific Coastal Transect: In contrast to the southern Appalachian Piedmont, the topography of the coastal ranges, stretching from northern California to the Olympic Mountains in Washington State (Figure 5), is rugged with steep hillslopes and deeply incised river valleys resulting from active subduction along the Cascadian subduction zone (Kelsey and others, 1994). In the temperate rainforest climate, mean annual precipitation ranges from ~1500 to ~6000 mm/yr throughout the ranges, and is highly seasonal with most rainfall falling in the winter months (Gendaszek

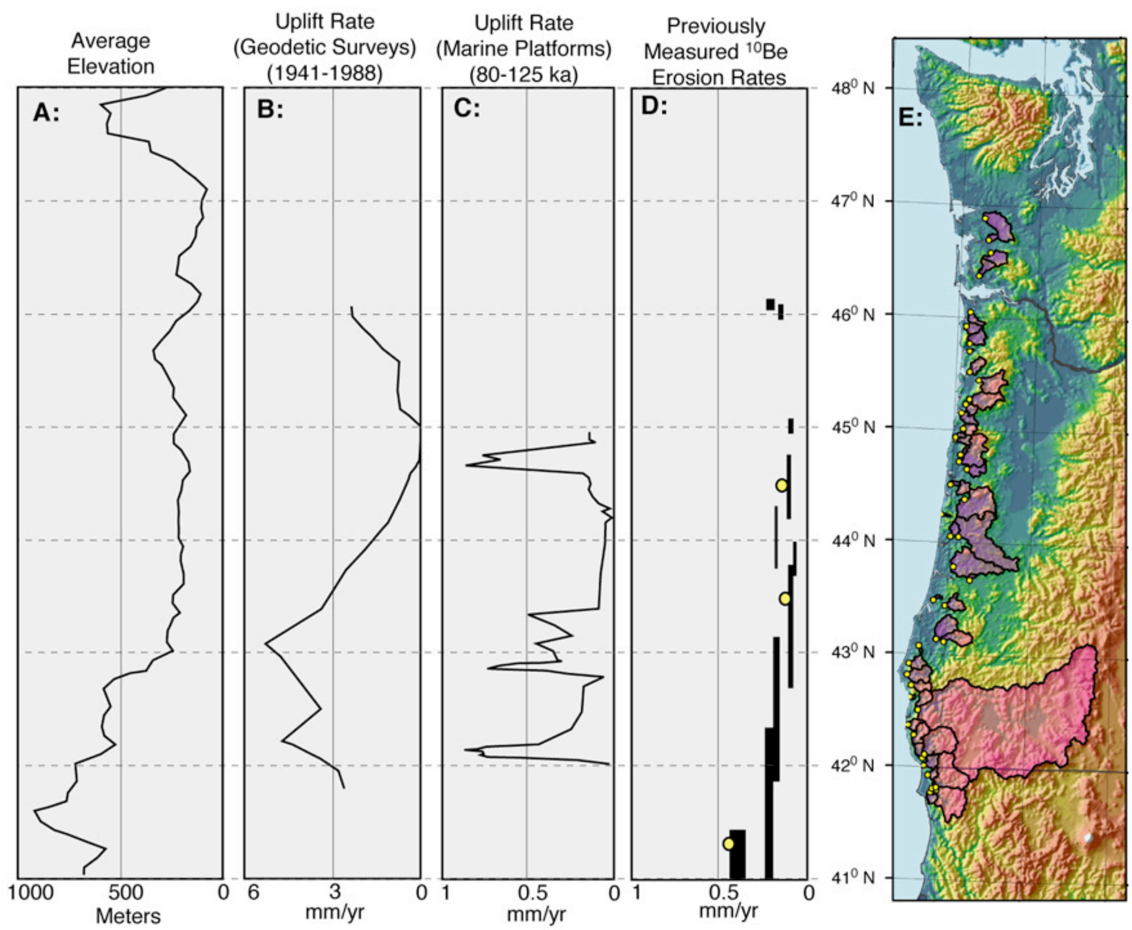

FIGURE 5: Compilation of previously published data from the Pacific Coastal ranges, and drainage basins sampled for ^{10}Be erosion rate modeling in this study. (A) Average elevation. (B) Maximum uplift rates from geodetic surveys along coastal highway. (C) Maximum uplift rates from uplifted marine cut terraces (A, B, and C, are modified from Kelsey, et al., 1994). (D) Previously published ^{10}Be erosion rate data. Black bars from Gendaszek, et al., in press. Yellow circles from Bierman, et al., 2001; Heimsath, et al., 2001; and Ferrier, et al., 2005). (E) Coastal ranges from Washington to northern California showing the sample locations (yellow circles) and contributing drainage basins (purple polygons) for this study.

and others, in press, Heimsath and others, 2001). Under natural conditions, sediment typically accumulates in topographic hollows along steep hillslopes as soil creeps downslope, and is discharged episodically to channels by debris flows and landslides (Dietrich and Dunne, 1978, Reneau and Dietrich, 1991). In the coastal ranges, inferring erosion rates, or assessing the geomorphic effects of land-use practices from short-term records of sediment yield is exceedingly difficult owing to the naturally episodic nature of the movement sediment through fluvial systems.

The primary landuse practice in the coastal ranges has been, and continues to be, the harvesting of timber. Forestry commenced in the mid 1800's with European settlement, and hit full stride around 1940 (from Forest Service site: www.fs.fed.us/land/pubs/ecoregions/toc.html), shortly following the invention of the chainsaw in 1935. Today, relatively few patches of undisturbed natural vegetation remain against which to assess the impacts of logging; among these, the Drift Creek Wilderness Area stands out as a prime example. In 1993, a suite of samples was collected for ^{10}Be analysis from the Drift Creek area. Results from this study, published several years later, suggest that the southern-central Oregon Coast Range is naturally eroding at a rate of ~0.14 m/ky (Bierman and others, 2001). Subsequent studies of ^{10}Be long-term erosion rates from northern California to northern Oregon, range from ~0.08 to 0.44 m/ky and are in relatively good agreement given the vast latitudinal range they represent (Ferrier, Kirchner, and Finkel, 2005, Gendaszek and others, in press, Heimsath and others, 2001). ^{10}Be data from this study will characterize long-term erosion along 100's of km of the coastal ranges, against which to compare records of short-term sediment yield derived erosion rates, as well as the temporal reproducibility of ^{10}Be erosion rate modeling for previously sampled basins. In addition, through comparison to dated uplifted marine terraces (Kelsey and others, 1994), these data will provide a picture of the relative influence of differing tectonic uplift rates along the coast to rates of landscape erosion and sediment production.

Waipaoa River Basin, North Island, New Zealand: The Waipaoa is one of several large catchments draining the tectonically active northeast coast of New Zealand's North Island (Figure 6). Rapid uplift rates along the subduction margin (~1 to 4 mm/yr) (Berryman and others, 2000, Brown, 1995, Mazengarb and Speden, 2000, Ota and others, 1992), heavily fractured and weakly cemented rocks (Black, 1980, Mazengarb and Speden, 2000), and periodic intense cyclonic activity (Hessell, 1980, Hicks, Gomez, and Trustrum, 2000) render the East Cape region of the North Island exceptionally susceptible to erosion. In the Waipaoa River Basin, these natural conditions, acting in concert with widespread landclearance for agriculture purposes have resulted in some of the most dramatic erosional features in the world, causing the Waipaoa River's specific sediment yield (t/(km^2 * yr)) to be among the highest recorded in New Zealand, as well as around the globe (Gomez and others, 2003, Hicks, Gomez, and Trustrum, 2000, Milliman and Robert, 1983).

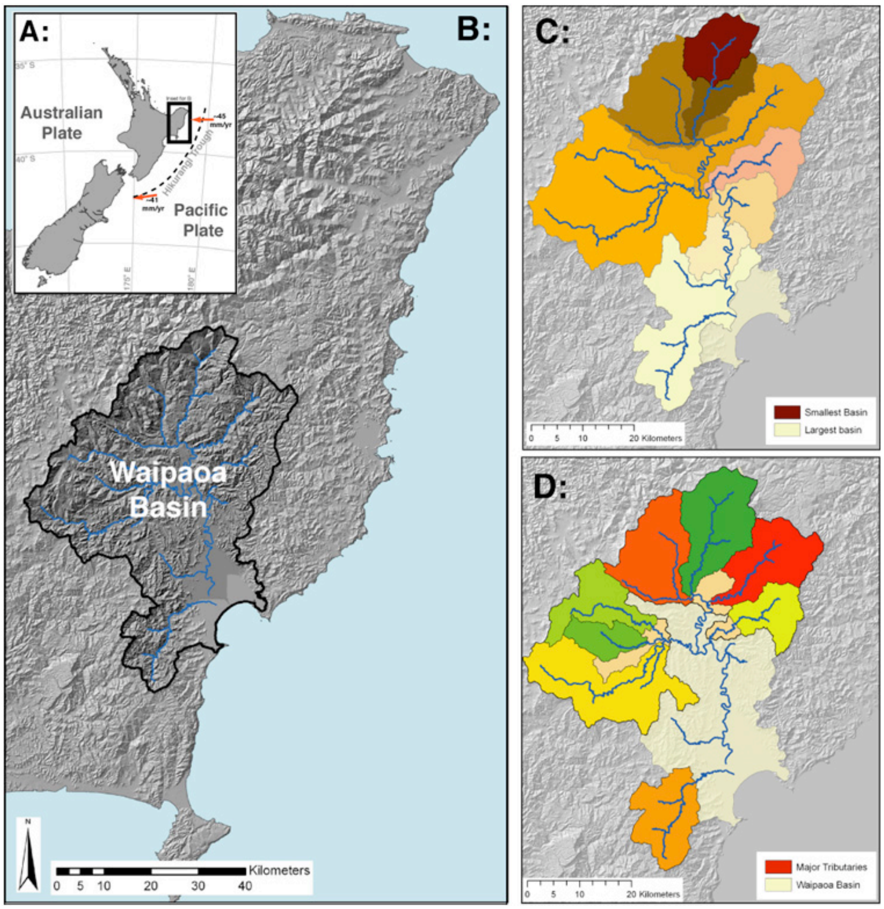

FIGURE 6: Layout of the New Zealand project. (A) regional map showing both islands and the general tectonic geometry of the Hikurangi Subduction Margin. (B) Blow up of the East Cape region on east coast of New Zealand's North Island. Other basins sampled lie to the north and south of the Waipaoa. (C) Long-profile mixing model for the Waipaoa Basin. Samples collected from larger and larger catchments downstream to investigate the ^{10}Be concentration as sediment is mixed while traveling downstream. (D) Tributary mixing model for the Waipaoa Basin. Samples collected from most major tributaries to investigate rates of sediment generation and erosion in different regions of the basin.

The region was first settled by the Mauri ~700 ybp, however widespread clearance of the land didn't commence until the early 1800's with the arrival of European Settlers. By 1880, the downstream portion of the basin was largely cleared, and by the

1920's most of the headwaters were cleared as well, resulting in extensive hillslope erosion and massive aggradation in river channels (Hicks, Gomez, and Trustrum, 2000). Today, only 3 percent of the basin remains under native vegetation. Modern-day erosion rates (~3.5 m/ky; Table 2 and Figure 7) derived from sediment yield data are several times greater than rates of uplift across the region suggesting that today, erosion outpaces uplift along this active margin. While these current erosion rates are predominately a reflection of elevated stream loads from landclearance, it is difficult to say with any certainty what the background rate of erosion is. Although the Waipaoa is an extremely active environment and challenges several assumptions underlying ^{10}Be modeling, data from this study will provide the first glimpse of long-term erosion on the North Island of New Zealand, and enable a more realistic assessment of the magnitude of human-induced landscape disturbance.

Testable Hypotheses:

While the primary objectives for this work as a whole pertain to all areas of study, specific testable hypotheses are best laid out for each study site separately.

For the stable southern Appalachians Mountains:

- ^{10}Be erosion rates for the ten basins analyzed by Trimble (1977) support assertions that increased erosion of sediment from hillslopes resulting from human landscape disturbance is masked by valley storage and sediment trapping by dams in the southern Appalachian Piedmont.
- There are discernable differences between background ^{10}Be rates of sediment generation in the higher slope Blue Ridge and the lower slope Piedmont portions of each of the ten large basins studied by Trimble (1977).
- Measured differences in ^{10}Be concentrations are related to slope characteristics of the basins, as has been observed in several previous studies of the Appalachian Mountains.

For the active U.S. North Pacific Coast:

- Along the North Pacific Coast, long-term ^{10}Be, and short-term sediment yield derived erosion rates will agree well, as demonstrated in several previous cosmogenic studies in the Oregon Coast Range.
- ^{10}Be rates of sediment generation and landscape erosion agree with rates of land uplift measured with raised marine terraces (long-term, tens to thousands of years) and geodetic surveys (short-term, several decades) suggesting stead-state between uplift and erosion along this active continental margin.

- ^{10}Be rates of sediment generation and erosion from certain basins in this study agree with previous ^{10}Be measurements from the same basins, indicating that ^{10}Be erosion rates are temporally reproducible and do in fact reflect erosion rates integrated over thousands of years.

For large catchments draining the east coast of New Zealand's North Island:

- In basins draining the east coast of the North Island, subject to extraordinary erosion problems resulting from intensive land clearance, highly erodible lithologies, and rapid uplift rates, ^{10}Be estimates for background rates of sediment generation and erosion are lower than modern day sediment yields.
- Weighted averages of ^{10}Be erosion rate estimates from prominent tributaries of the Waipaoa River agree with the aerially averaged erosion rate for the basin as a whole, confirming that sediments are well mixed as they travel through the fluvial system.
- Concentrations of ^{10}Be can be used as isotopic fingerprints of landscapes dominated by different erosional processes or vegetation conditions (e.g. basins dominated by severe gullying, vs. landsliding, vs. native vegetation, vs. paddock).

Work Plan:

Sampling Strategies and Sample Site Selection:

In order to address each of these hypotheses while designing sampling strategies for the projects, I drew from a variety of resources including overlay analysis and hydrologic modeling with ArcGIS, paper and digital topographic maps at the 1:24,000 and 1:100,000 scale, geologic maps, aerial photographs, and results from previous works.

Southern Appalachian Mountains: In December of 2006, we collected 49 samples from 7 of the 10 large (18,000 to 2,500 km^2) watershed studied by Trimble (1977) that drain the southern Appalachian Piedmont, and small portions of the Blue Ridge province stretching form the Roanoke River Basin in Virginia, to the Chattahoochee Basin in Georgia. We will collect samples from the remaining three southernmost basins in early Spring, 2007. From each of the ten large basins, we collected, or are soon to collect, one sample where each trunk stream crosses the fall-zone separating the Piedmont and Coastal Plain in order to compare long- (^{10}Be), and short-term erosion rates (Trimble, 1977) across the southern Piedmont. These ten samples will help determine whether the effects of landscape disturbance during the peak of agricultural use (1860 to 1920) on sediment yield data are masked by alluvial storage in valley bottoms and impoundment of sediment in dam reservoirs. We collected an additional sample in each of the ten basins where they cross the Blue Ridge – Piedmont transition. These seven samples will determine if the upstream and higher slope Blue Ridge portions of each basin naturally erode differently than the lower slope Piedmont regions. If differences are detected, these samples will also allow us to isolate natural erosion rates in the Piedmont portions of the basins where, due to the gentler topography, most agricultural practices were, and continue to be focused. At three sites across the region, we sampled just downstream from prominent dams, as well as upstream of the dam reservoirs in order to ensure that the impoundment of sediment behind dams has no discernable effect on ^{10}Be concentrations and erosion rate modeling. Finally, in four of the ten basins (Roanoke, PeeDee, Savannah, and Chattahoochee), we collected, or are soon to collect, a total of 40 samples from small sub-basins (5 to 15 km^2) representing a range of mean slopes (~2° to ~25°). Across the expansive Piedmont portions of each of the 4 large basins, we collected 7 samples from small basins with mean slopes ranging from 2° to10°. In the higher relief, headwater (Blue Ridge) regions of each of the 4 large basins, we collected three samples from small basins with mean slopes ranging from ~12° to ~25°. In these four large basins, in addition to collecting the customary grain size fraction (medium to coarse sand), we also collected a coarse fraction at the lowest slope basin (~2°), an intermediate slope basin (~10°), and at the highest slope basin (~22°). The distribution of ^{10}Be erosion rates from these small-basin samples will allow us to assess how representative erosion rate estimates are from samples collected at the outlets of the ten large basins, as well as to further investigate the influence of slope upon erosion rates across the southern Appalachian mountain chain as a whole.

U.S. Pacific Coast: In May and June of 2005, we collected 51 samples from river basins draining the Coastal Ranges west to the Pacific Ocean. These basin range from ~15 to ~750 km^2 in area, and represent a latitudinal extent stretching from ~46.5° N to ~41.5° N, with the northernmost basins residing just south of the Olympic Mountains in Washington State, and south of the maximum southern extent of the last glaciation (Wisconsinan), and the southernmost basins lying in northern California (Figure 5). Where individual basins had been sampled previously for cosmogenic erosion rates (Bierman and others, 2001, Ferrier, Kirchner, and Finkel, 2005, Gendaszek and others, in press, Heimsath and others, 2001) we attempted to resample these basins at the same locations in order to assess the temporal reproducibility of ^{10}Be rates of sediment generation and erosion. In basin where sediment yield data are available, direct comparisons between short- and long-term rates of erosion can be made and considered in context of the landuse history of each sampled basin. Our ^{10}Be data will also be compared to dated and uplifted marine terraces in order to investigate the tectonic influence of differing uplift rates along the Pacific coast on millennial scale rates of erosion.

Basins along the east coast of New Zealand's North Island: In February and March of 2005, we collected 68 samples from the Waipaoa river basin, as well as several other basins draining the east coast of the North Island. 37 of these samples are from sub-basins within the Waipaoa watershed, 8 are from the outlets of large catchments to the north and south of the Waipaoa, 15 are from alluvial and strath terraces bordering the Waipaoa River, and 8 are from various bedrock outcrops within the basins (Figure 6). Samples collected from the outlets of the large catchments (several of which have good sediment yield data) will provide directly comparable rates of long (^{10}Be) vs. short (sediment yield) sediment generation and erosion. Within the Waipaoa catchment, 23 of the 37 samples are from prominent tributaries and/or are from points along the mainstem Waipaoa River. These sample basins range in area from 79 to 2150 km^2, and will help determine which parts of the basin naturally erode more quickly than others, as opposed to which parts of the basin yield more sediment as a result of erosion problems associated with modern land-use practices. The remaining samples are collected from smaller basins ranging in size from 2 to 65 km^2 that are overwhelmed by severe erosional processes (gullying vs. shallow landsliding), or are underlain by specific lithologies (all sandstone vs. all mudstone), or are characterized by certain vegetation types (paddock vs. monoculture reforestation plantations vs. native vegetation). The two basin (WA16 and WA20, 2 and 9 km^2 respectively) that drain the only remaining patches of undisturbed native vegetation will hopefully serve as a control, against which to compare samples from all other regions which have been subject to some form of human impact in this rapidly uplifting and eroding environment.

Field Methods:

Potential sample locations selected prior to fieldwork for each of the three projects were assessed in the field, and adapted when necessary. If the geometry of the channel or refusal of permission to enter private lands prevented access to the riverbed, or maps inaccurately represented the landscape, a more suitable site up or downstream was sought. Once a site was selected, we collected ~2kg of sand (850 to 250 micron) from active mid-channel bars or the active channel bed. For pictures and field descriptions of sample sites, refer to: http://www.uvm.edu/cosmolab/projects/waipaoa/waipaoa_home.html.

At some locations, in addition to the 850 to 250 micron grain size fraction, we also collected a coarser grain size fraction (~ several mm) to compare the ^{10}Be activity in different types of bed material. While it is uncertain at present whether these samples will be processed and measured (funding limitations, and low quartz yields) they could potentially provide intriguing information regarding different hillslope erosion and transport processes. Coarser bed material could be sourced from landslides delivering more deeply seated material quickly to the river channel thus yielding lower ^{10}Be concentrations and higher model erosion rates (Brown and others, 1995). Alternatively, coarser material could originate from lesser weathered soil particles located low on hillslopes and closer to river channels that received less cosmic ray dosing and were subject to less physical disintegration during transport down slope to the channel (Matmon and others, 2003b).

Laboratory Methods:

Following each field session, we brought all samples to the University of Vermont, where they were oven dried. Because many of the samples from New Zealand and the U.S. Pacific Coast were collected from basins draining lithologies containing very little quartz, I adapted several of the quartz purification protocols we typically use (Kohl and Nishiizumi, 1992) to more efficiently process the lower yield samples. For full processing, each sample was thoroughly washed in DI water to remove organics and fines then subjected to a 6 N HCl etch in a heated ultrasonic bath to remove oxide coatings from sediment grains. Subsequently, aliquots of between 40 and 60 g of dried sediment were placed in 1 liter HDPE nalgene bottles with a 1% HF, 1% HNO_3 solution and placed on heated rollers for three 24 hour etches to dissolve all minerals except quartz. Following acid etching, the remaining impurities were removed by density separation using LST.

Between 0.3 and 0.5 g of each quartz sample was dissolved in HF, dried, redissolved in 1.2 N HCl, and tested for purity on an ICP (inductively coupled plasma). If sufficiently clean, the entire sample will be dissolved in HF after the addition of ^{9}Be carrier, and run through cation and anion exchange columns to isolate the Be. The Beryllium will then be precipitated as a hydroxide, and burned to produce beryllium oxide (Bierman and others, 2002). Each sample will then be mixed with Nb power and packed into targets for measurement on the Lawrence Livermore National Laboratory (LLNL) accelerator mass spectrometer.

<u>Completed and Proposed Data Processing and Interpretation:</u>

<u>Erosion Rate Modeling and Tests of Underlying Assumptions:</u> Upon the successful measurement of ^{10}Be by accelerator mass spectrometry, the nuclide concentrations for each sample will be modeled as 1) rates of sediment generation and 2) rates of erosion for drainage basin areas upstream of the sample collection points. These calculations will be accomplished with models first presented by Lal (1991) for exposure and erosion at discrete points on a landscape, and subsequently adapted for aerially averaged drainage basin estimates (e.g. Bierman and Steig, 1996, Brown and others, 1995, Granger, Kirchner, and Finkel, 1996).

For sediment generation rates m (g cm^{-2} yr^{-1}):

$$m = \Lambda\left(\frac{P_o}{N_{norm}}\right) \qquad (1)$$

For landscape erosion rates E (cm yr^{-1}):

$$E = \frac{\Lambda}{\rho}\left(\frac{P_o}{N_{norm}}\right) \qquad (2)$$

Where P_o is the surface production rate for ^{10}Be (5.17 atoms g^{-1} of quartz yr^{-1}) (Clark, Bierman, and Larsen, 1995), ρ is the density for rock (2.7 g cm^{-3}), and Λ is the absorption mean free path for nucleons (165 g cm^{-2}, equivalent to a penetration depth of ~60 cm in rock). Where N is the actual concentration of ^{10}Be measured in a sample (atoms gram^{-1}of quartz), N_{norm} is the concentration of ^{10}Be scaled for basin hypsometry (elevation distribution) and basin latitude. The time frame over which these models integrate mass loss, and in turn erosion, is a function of how quickly a given landscape is eroding, expressed as $t = (\Lambda/\rho)/E$ (Granger, Kirchner, and Finkel, 1996), where t is the integration time, and all other variables are the same as above. Stated another way, the integration time frame is equivalent to time required to erode the penetration depth Λ of cosmic ray neutrons (~60 cm in rock).

These models hinge on a number of key assumptions: first, that the sediment collected from an active channel is well mixed. Second, that the sediment has not been shielded from cosmic ray dosing for substantial periods of time (100's of kyrs), such as in alluvial terraces or buried floodplain deposits, or in landscapes recently covered by glaciers. Third, that the landscape in question is in relative "isotopic steady-state" such that the reservoir of ^{10}Be across the landscape is stable over the time frame of measurement. Forth, that concentrations of ^{10}Be reflect the full cosmic ray dosing history from exhumation on hillslopes to transport through fluvial networks, an assumption violated in regions subject to recent and rapid erosion of greater than several meters of rock and soil such as in recently glaciated landscapes. Fifth, that the time span represented by erosion rates (t, usually thousands to tens of thousands of years) is substantially less than the half-life of ^{10}Be (1,500,000 years), a non-issue in all but the most stable and slowly eroding environments such as parts of Australia (Bierman and Caffee, 2002a).

In most instances, samples collected for my dissertation adhere to these assumptions. All samples are from unglaciated regions, not subject to substantial reworking of buried old sedimentary deposits. Where sample basins are large enough (hundreds to thousands of km^2) to drain several lithologies each of which may erode at different rates, or may contribute disproportionately more or less quartz to downstream points, there is the potential to violate the first assumption. This scenario pertains mostly to larger basins in the Southern Appalachians and New Zealand, and while it has been demonstrated that this modeling still provides reliable long-term estimates for erosion within basins of considerable size (Schaller and others, 2001), these assumptions will be tested. In order to determine if channel sediments are thoroughly mixed as they are transported downstream, and if tributary basin contribute sediment in proportion to their size and model erosion rate, I will generate mixing models. In the case of the confluence of two tributary streams, samples collected from the streams just above the confluence reflect long-term erosion of the tributary basins individually, while one sample collected below the confluence should reflect the aerially averaged erosion rate of both basins. Where E is the combined erosion rate weighted by area, and e_1 and e_2 are the erosion rates for the tributary basins of area a_1 and a_2:

$$E = \frac{e_1 a_1 + e_2 a_2}{a_1 + a_2} \qquad (3)$$

If sediments are not thoroughly and proportionately mixed, the expected combined erosion rate (*E*) and the actual measured erosion rate will disagree. In several large basins where we collected numerous tributary samples, this approach will provide a means by which to determine how well sediment is mixed on its journey from headwater basins to the sea.

GIS Analysis: Over the past year, I have honed my skills with Geographic Information Systems (primarily Arc products) in order to model more accurately long-term erosion rates and summarize sampled drainage basins based on a number of physical parameters. Using various hydrologic geoprocessesing tools with stream and elevation data for each field area, I have accurately delineated the drainage basins that contribute sediment to all sample site locations. To streamline many of these time-consuming and repetitive processes, I built a number of models using ArcGIS Model Builder designed to extract data from the large stored datasets required for hydrologic modeling, subdivide large basins into their constituent tributary basins, and summarize each sub-basin (mean elevation, total relief, mean slope, predominant rock type, physiographic province, landcover, landuse, etc.). Where I have already collected the majority of samples (Pacific West Coast and New Zealand), these models provide an efficient way to summarize each sample basin. In addition, results from the models, in tandem with other spatial data types will aid in the selection of potential sample sites as I continue to develop sampling strategies for the southern Appalachians project. As an end result, GIS analysis will provide an efficient method for generating consistent summary statistics that will be directly comparable across all three regions of study.

Because the flux of cosmic radiation varies considerably as a function of latitude and elevation around the globe (with highest production rates at high latitudes and high elevations, and lowest at sea level along the equator), accurately understanding the distribution of latitude and elevation across a sampled drainage basin is critical when modeling erosion rates from ^{10}Be concentrations. Again using Model Builder, I constructed a model that quickly subdivides sampled basins into elevation bins, and generates output tables that can be fed directly into erosion rate calculations. Where drainage basins are small, latitudinal variations in ^{10}Be production rates are negligible and can be ignored. However, if sample basins are large enough to cover several degrees of latitude, as is the case for the southern Appalachian basins, variations in production rate must be incorporate into erosion rate modeling. I will construct a similar model with Model Builder to accomplish this task.

Comparing short- and long-term erosion rates: Implications for resource management: The comparison of short-term erosion rates altered by human landuse practices to background millennial-scale erosion rates affords researchers and planners the opportunity to assess both levels of landscape disturbance, as well as the quality or completeness of individual sediment yield records. I have compiled sediment yield data from all three study regions. Records are often difficult to find and/or attain, so the process is ongoing, but I present what appear to be fairly representative samples (Figure 7, Table 2) from each of the sites. In addition, I present all ^{10}Be long-term erosion rate data available in each of area for direct comparison. In some instances, short- and long-term estimates are from the same stream; in others, long-term estimates are from studies conducted nearby (Table 2). Considering all the data, erosion rates increase as expected across the three regions, with the slowest rates of sediment generation and erosion occurring along the passive Atlantic Margin, and the fastest occurring along the East Cape of New Zealand's North Island. While we have no natural long-term rates to put the exceptionally high short-term rates from New Zealand in context, sediment yield data alone suggest that the North Island is currently supplying sediment at rates nearly two orders of magnitude faster than the Appalachian Mountains.

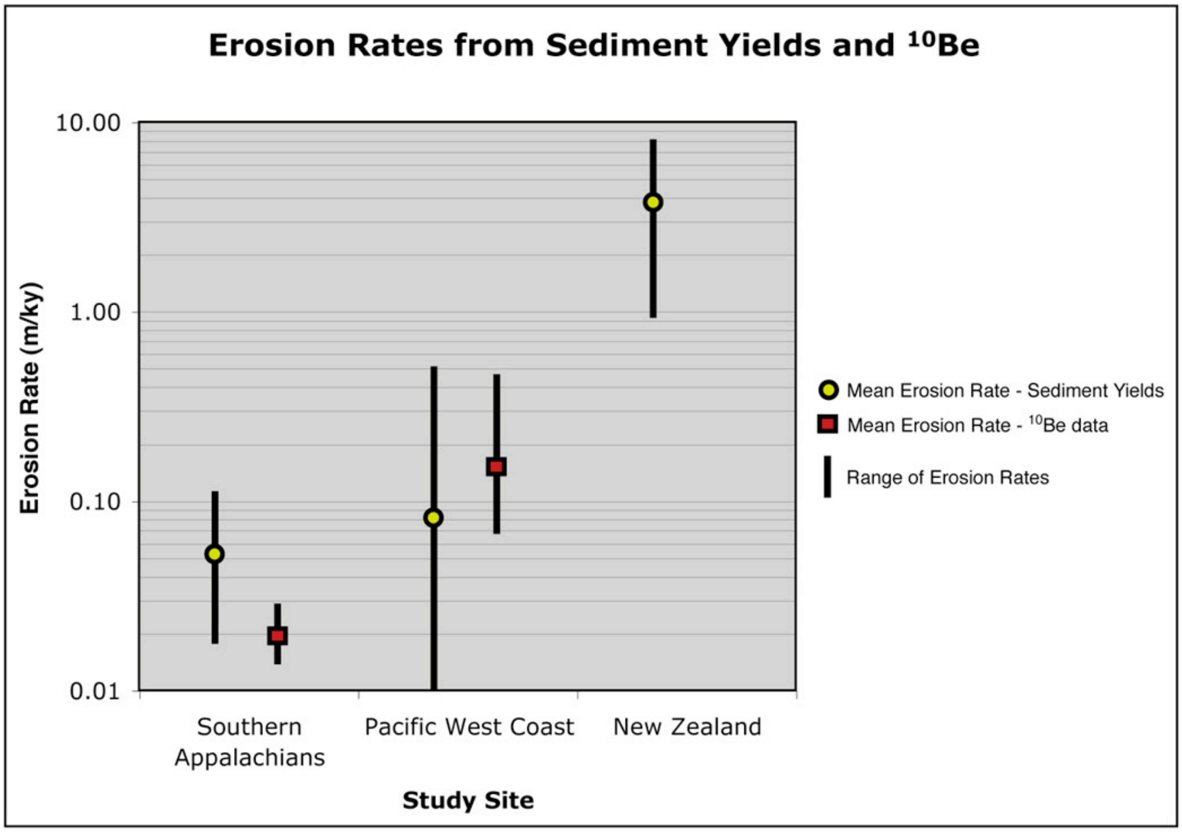

FIGURE 7: Compilation of short- and long-term erosion rates from the three study sites calculated with sediment yield data and ^{10}Be measurements, respectively. Refer to Table 2 for sources of data used in the average values for both short and long-term rates. Circles and squares represent mean values for each, while black bars represent the full range between maximum and minimum values.

Based upon the data presented here, several different relationships between short- and long-term erosion rates are apparent on opposite coasts of the United States. The uncertainties associated with these amalgamated rates are great, limiting discussion to that of general trends. Along the stable Atlantic Coast, modern-day erosion outpaces long-term estimates by more than two fold, where as along the active North Pacific Coast, long-term rates appear slightly higher, and much less variable than short-term rates. In the southern Appalachians, Trimble (1977) presented these short-term estimates as lower limits of human induced erosion rates. Long-term rates of sediment generation for the Appalachians are from the Susquehanna Basin in the northeastern U.S. (Reuter, 2005), and the Great Smoky Mountains in the southern Appalachians (Matmon and others, 2003a), both of which have considerably higher slopes than the southern Piedmont region of the Appalachians (Figure 4). If the relationship between slope and natural long-term erosion rates observed by Matmon and Reuter holds in the Piedmont, erosion rates measured in this study should be lower than the average of 0.02 m/ky. Trimble's assertion that short-term rates of erosion from sediment yield data (0.053

m/ky) in the southern Piedmont reflect a mere 6% of the total amount of amount of material eroded during peak agriculture substantially widens the gap between natural and human-induced erosion (Trimble, 1977). Supporting this claim, short-term sediment yield derived erosion rates from Piedmont basins subjected to heavy agricultural use in the middle Atlantic (~0.035 m/ky, n=6) were shown to be elevated over natural rates of erosion by more than two fold (~.01 m/ky, n=19) (Reuter, 2005). In the southern Piedmont, where no such long-term rates exist, ^{10}Be measurements will provide a wealth of information regarding the natural pace of erosion, and the ability to assess more effectively the level agricultural disturbance in this region.

Not unexpectedly, along the actively rising North Pacific Coast, erosion naturally proceeds ~10 times faster than in the Appalachians over the long-term. While long- and short-term rates along the heavily logged slopes of the humid coastal ranges appear to agree fairly well (Figure 7), sediment yields, rates of bedrock lowering, and erosion of hillslopes have been shown to vary considerably both temporally and spatially throughout the coastal ranges (Brenda, 1990, Ferrier, Kirchner, and Finkel, 2005, Reneau and Dietrich, 1991, Reneau and others, 1989). In some regions, the erosional effects of clearcutting are clearly apparent in records of sediment yield; in others, rates of short-term erosion from sediment yield data and rates of hillslope lowering in logged and unlogged basins are the same (Reneau and Dietrich, 1991). The delivery of sediment from steep hillslopes is episodic and such sediment is often stored in shallow valley bottoms confounding erosion rates calculated from the flux of sediment exiting a basin over short time intervals. Assessing landscape disturbance, or anticipating the erosional effects of proposed logging or development is extremely difficult with these short-term data. Our long-term ^{10}Be erosion rate estimates will provide a picture of background erosion along the North Pacific Coast, against which the completeness of short-term erosion rates can be measured.

In New Zealand, where no long-term estimates for erosion exist, our ^{10}Be measurements will provide the first glimpse of the natural behavior of this dynamic landscape prior to European settlement and land-clearance. Rarely have cosmogenic techniques been employed in such a rapidly eroding and transient environment. Results from the Waipaoa Basin will hopefully encourage new applications of cosmogenic isotopes for understanding complex spatial and temporal patterns of erosion in tectonically active regions severely impacted by human-landscape interactions.

Table 2:

short- and long-rates of erosion in the three study sites

Southern Appalachain Catchments:

Catchment/ Region	Upstream Area Above Station (km^2)	Annual Sediment Yield ($t/(km^2*yr)$)	Inferred Erosion Rate (m/ky)	^{10}Be Erosion Rate (m/ky)
* Chattahoochee	9195		0.057	
*Ocmulgee	5862		0.057	
*Oconee	7586		0.049	
* Savannah	19446		0.049	
* Saluda	6501		0.057	
* Wateree	13131		0.070	
* Pee Dee	17793		0.026	
* Neuse	2652		0.018	
* Dan	7071		0.106	
* Roanoke	7710		0.048	
† Susquehanna (60 basins)	~5			0.016 ± 0.01
† Susquehanna (28 basins)	15 - 62000			0.014 ± 0.004
∞ Great Smokey Mtns (27 basins)	1-330			0.027 ± 0.004
Average	**9695**		**0.054**	**0.019**
Std (1 sigma)			**0.024**	**0.007**

* Data from Trimble, 1977. † Data from Reuter, 2005. ∞ Data From Matmon 2003.

West Coast Transect

Catchment (from Reneau and Deitrich, 1991)	State	Upstream Area Above Station (km^2)	Annual Sediment Yield ($t/(km^2*yr)$)	Inferred Erosion Rate (m/ky)	^{10}Be Erosion Rate (m/ky)
*Ω Alsea River - Needle Branch	OR	0.7	53	0.018	
* Alsea River - ??	OR	??	146	0.049	
*Ω Alsea River - Flynn Creek	OR	2.0	98	0.033	
*Ω Alsea River - Deer Creek	OR	3.0	97	0.033	
* Alsea River - ??	OR	??	157	0.053	
* Umpqua River - Copper Creek	OR	11.4	179	0.060	
* Umpqua River - Sutherlin Creek	OR	23.3	174	0.058	
* Umpqua River - Olalla Creek	OR	158.0	95	0.032	
* Yaquina River	OR	655.0	129	0.043	
* Alsea River	OR	865.0	187	0.063	
* Siuslaw River	OR	1523.0	125	0.042	
† Caspar Creek - North Fork	CA	not listed	119	0.044	0.107 ± 0.02
† Caspar Creek - South Fork	CA	not listed	125	0.046	0.068 ± 0.013
† Caspar Creek - Carlson	CA	not listed	27	0.010	0.101 ± 0.019
† Caspar Creek - Eagle	CA	not listed	99	0.037	0.072 ± 0.014
† Caspar Creek - Henningson	CA	not listed	45	0.017	0.103 ± 0.02
† Caspar Creek - Iverson	CA	not listed	12	0.004	0.080 ± 0.017
† Redwook Creek - at Orick	CA	not listed	1304	0.483	0.438 ± 0.088
† Redwook Creek - Coyote Creek	CA	not listed	1112	0.412	0.184 ± 0.04
† Redwook Creek - Little Lost Man	CA	not listed	103	0.038	0.138 ± 0.028
† Redwook Creek - Panther Creek	CA	not listed	383	0.142	0.225 ± 0.044
¥ Drift Creek	OR	180.0			0.136 ± 0.043
Δ Coos	OR				0.117 ± 0.029
∞ Average of 19 Streams	CA and OR				0.205 ± 0.181
Average				**0.082**	**0.152**
Std (1 sigma)				**0.125**	**0.099**

* Data from Reneau and Deitrich, 1991. † Data from Ferrier, 2005. ¥ Data from Bierman et al, 2001.
Δ data from Heimsath et al, 2001. ∞ Data from Gandezsek, 2005.
Oregon Streams denoted as (*Ω) are from unlogged catchments

New Zealand - North Island:

Catchment	Upstream Area Above Station (km^2)	Annual Sediment Yield ($t/(km^2*yr)$)	Inferred Erosion Rate (m/ky)
* Waipaoa	2150	6750	2.50
* Waiapu	1378	20520	7.60
* Motu	1393	2530	0.94
Average	1640	9933	**3.68**
Std (1 sigma)			**3.48**

* Data from Hicks etal. 2000

Time Line:

Spring 2005: (RA Support)

- Courses: GEOL 351 Surface Processes and Quaternary Geology Seminar.
- Research for New Zealand Project (Waipaoa River Basin).
- Field logistics for New Zealand field Season.
- Field Work in New Zealand (late February to early April).
- Quartz purification of Colorado Front Range samples.
- Begin sample processing of Waipaoa Samples.
- Research, and field logistics for West Coast Transect sample collection.

Summer 2005:

- West Coast Transect (Oregon, southern Washington and, northern California) sample collection (June).
- Continue research.
- Quartz purification of West Coast Transect Samples.

Fall 2005: (GTA support)

- TA and course development of GEOG 151 –Geomorphology with Dr. Bierman
- Courses: CE 369 Geostatistics, NR 343 Grad. GIS, and GEOL 371 Communicating what we know about science.
- Continue research.
- Begin developing GIS strategies for sample basin delineation and summarization, and data interpretation.
- Continue quartz purification of West Coast Transect Samples.

Spring, 2006: (GTA support)

- TA GEOG 051 – Geotechniques with Dr. Dupigny-Giroux.
- Courses: CE 295 Engineering Water Resources, NR 285 GIS Practicum, GEOL 296 Cosmogenics Seminar.
- Continue research.
- Design GIS sample selection methods for Southern Appalachians field season (fall 2006).
- Quartz purification of Waipaoa Modern River samples.
- First committee meeting.

Summer 2006:

- Continue Research.
- Continue quartz purification of Waipaoa samples
- Begin ^{36}Cl preparation and processing of modern river basin Waipaoa samples.
- Begin sampling strategy for Southern Appalachian Project.
- Continue GIS summarization of all samples collected to date.
- Begin writing Ph.D. proposal.

Fall 2006: (RA support)

- Finish writing proposal.

- Finish Southern Appalachians planning.
- Present at the GSA Annual Meeting in Philadelphia, PA: Timing, Rates, and Volumes of Bedrock Channel Incision Measured with ^{10}Be, GPS and LiDAR: Holtwood Gorge, PA.
- Conduct Southern Appalachians field work (probably early December).
- Begin ^{10}Be extraction from New Zealand Samples.

Spring 2007: (GTA support)

- TA GEOG 002 – World Natural Environments with Dr. Wemple.
- Schedule and deliver Proposal Seminar to the Rubenstein School and Geology Department (February).
- Purify quartz from Southern Appalachian samples
- Schedule and take my Comprehensive Exams.
- Continue ^{10}Be extraction from New Zealand Samples.
- Continue ^{36}Cl extraction from New Zealand Samples.
- Measure West Coast Transect and New Zealand samples at LLNL.
- Continue research and begin working with West Coast Transect data.

Summer 2007:

- Continue research and data analysis.
- Finish quartz purification of Southern Appalachian and any other samples.
- Present at the INQUA Congress 2007 meeting in Cairns, Australia: Preliminary results from Waipaoa River Basin, North Island New Zealand.
- Field check all samples in New Zealand, and collect additional samples as needed.
- Prepare for teaching in Fall of 2007.

Fall 2007: (RA Support)

- Teach, or co-teach a Fluvial Geomorphology Class in Geology.
- Fulfill cross-cultural experience by co-leading an NR06 discussion group
- Present at GSA 2007 annual meeting in Denver, CO.
- Continue data analysis of New Zealand and West Coast Transect Samples
- Measure Southern Appalachian Samples at LLNL.
- Begin writing papers and dissertation.

Spring 2008: (RA support)

- Finish writing papers and dissertation.
- Defend dissertation.

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