Collaborative Research: Deciphering connections among land management, soil erosion, and sediment yield in large river basins

PI: Amanda Schmidt, Oberlin College
Co-PIs: Paul Bierman, University of Vermont
Dylan Rood, Earth Research Institute, University of California at Santa Barbara

Funded by: National Science Foundation, 2011

Directorate: Geosciences
Division: Earth Sciences (EAR)
Program: Hydrologic Sciences

Collaborative research: Deciphering connections among land management, soil erosion, and sediment yield in large river basins

Project Summary

Using a unique, and unusually complete, daily record of sediment yield from the major rivers of western China, along with a fluvial network analysis of meteoric and *in situ* ^{10}Be, ^{137}Cs, and ^{210}Pb, we will decipher the connections between land use, soil erosion, and sediment yield in 4 large rivers draining the Tibetan Plateau. Sediment yield data, measured daily for 44 stations in Yunnan and Tibet, each with up to 27 years of daily sediment concentration and discharge record, suggest that in these basins there is no systematic increase in sediment yield over time despite significant land clearance. Tracing sediment sources and sinks will allow us to understand why 30 years of extensive deforestation did not change sediment yield. Such work is critical for understanding the response of the landscape to land management decisions in high relief areas that support a growing number of the world's expanding population.

We propose to leverage the record of sediment yield in Yunnan and Tibet and known dates for major land use changes with isotopic measurements in detrital sediments at locations for which we have sediment yield data. We will use a nested and phased sampling approach where we first focus exclusively on three small sub-basins of the Mekong River with at least 20 years of daily data – one of which is in a region experiencing rapid climate change. Our second field season will be framed by results from the first. We tentatively expect to sample broadly at each of the sediment gauging stations. The *in situ* ^{10}Be samples will allow us to calculate basin-wide background erosion rates for each location – rates integrated over millennial time scales. The meteoric ^{10}Be samples will be a tracer for sediment mixing from heavily disturbed and less-disturbed regions. The meteoric ^{10}Be, in combination with sediment yields, will be used to calculate erosion indices for each basin, a measure of soil loss. Short-live nuclides, ^{137}Cs and ^{210}Pb, will suggest how much of the sediment in transport comes from deep gully/landslide erosion and how much comes from near surface sources. This project will provide background erosion rates against which to compare modern sediment yield data and will provide a robust means of identifying sub-basins that have been heavily disturbed and are losing soil, even if much of that soil is not making it into the river network. Geomorphic mapping, both in the field and through remote sensing, will determine where and how much eroded sediment is stored on the landscape as colluvium and in terraces.

Intellectual merit – Relying on a daily record of sediment yield, a chronology of government prescribed land-use changes, and new developments in isotope geochemistry, this will be the first study to rigorously and quantitatively approach the question, "How much sediment moves, where does it come from, and where does it go when land-use changes in heavily populated mountain areas". Such data have the potential to transform the way in which we understand both short- and long-term dynamics of sediment movement within and out of mountain ranges in response to disturbance. The team doing this research brings deep experience in isotope analysis and application, familiarity with fieldwork in China, and established scientific contacts within the study area.

Broader impact – This project will provide information about how land-use affects soil erosion and sediment yield at different spatial and temporal scales, critical data for implementing meaningful land-use policies in mountainous regions around the world. The Chinese government is building a series of dams in the study area, the source of fresh water for nearly 2 billion people. Understanding the time scales over which sediment moves off slopes, into channels, and downstream is critical for determining the life span of these and other dams in mountainous areas worldwide. This project will bring together an early career faculty member at an exceptional undergraduate institution, a senior researcher who directs a state-of-the art R-1 research facility and a scientist at a research facility in order to achieve maximum enrichment of both undergraduate science education and pedagogical training for the doctoral students. International exchanges are key to this project – a Chinese student will do science at UVM and Oberlin; Schmidt, the UVM PhD student, and Oberlin students will do field work in China with our Chinese collaborators.

Project Description

This proposal describes a systematic, multidisciplinary study of the relationship between land-use and fluvial sediment transport in a mountainous region of western China. In this region, a unique hydrological dataset provides a framework to relate sediment transport changes to land-use, in the context of rapid urbanization and climate change. We will use hydrological observations and isotopic measurements to estimate sediment transport over a variety of temporal and spatial scales, determine the sources and sinks of the sediment, and tie our findings to regional land-use history. In this proposal:

1) We will show that understanding the source and fate of sediment is important because it will allow us to unravel the effect of land-use on sediment transport in sensitive mountain regions undergoing population expansion, provide critical information for development and environmental conservation projects, and better allow us to use sediment flux measurements on a variety of time scales to estimate geological-time-scale rates of mass export from the landscape;
2) We describe the methods and datasets we will use and explain what information about sediment sources, transport and sinks we will gain from each of these methods; and,
3) We explain how we will use this information to achieve the overall goals.

The PI, Amanda Henck, changed her name to Amanda Schmidt as of fall 2010; therefore references to her work may appear under both last names.

1. Introduction

Rugged mountains and the rivers draining them are dynamic systems where erosion varies over time and space. Human impact can be significant. Land-use changes, such as clearing slopes for timber and farm land, rapidly mobilize hillslope sediment (Hooke, 1994; Bierman et al., 1997; Hooke, 2000). Some of this sediment moves directly to river channels, where it can cause rapid and massive aggradation (Reusser and Bierman, 2010), impair water quality, and prematurely fill reservoirs. However, much of this material is trapped on footslopes, in colluvial wedges, and in alluvial and debris fans (Costa, 1975; Trimble, 1977). Understanding how quickly steep hillslopes respond to land-use change and where the sediment they shed goes is not only scientifically important but also of great practical importance as Earth's exponentially growing population usurps increasingly marginal steeplands for food and timber production.

Sediment budgets (a quantitative means of reporting where sediment comes from, where it is stored, and where it goes) are a fundamental tool in the study of Earth surface processes (Dietrich et al., 1982). Yet, until recently, quantifying rates of sediment production, storage, and delivery to the channel from hillslopes were difficult, if not impossible, tasks that required specific, unique settings and techniques (i.e., Dietrich and Dunne, 1978). Suspended sediment data provides a means of measuring sediment yield over short time intervals (c.f., Judson and Ritter, 1964) and are often used to estimate long-term rates of mass loss (erosion) from drainage basins. Such data, however, are usually fragmentary in nature, e.g., grab samples collected at varying time intervals, and rely on assumptions of steady state. Furthermore, extrapolating short-term sediment yield data is uncertain and may be biased by irregular sampling, use of sediment rating curves, sediment storage in dams, and sediment generated from development/agriculture.

Over the past 20 years, isotopic analysis has opened new ways of quantifying the amount and source of sediment moving over the landscape and through fluvial systems. Measurements of *in situ* and meteoric ^{10}Be in fluvial sediments have been used to estimate rates of sediment supply (Brown et al., 1988; Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996), for sediment budgeting (Nichols et al., 2005), and to trace sediment sources (Clapp et al., 2001; Reusser and Bierman, 2010). Similarly, ^{137}Cs and ^{210}Pb have been measured in fluvial sediment to identify sediment sources (Walling and Woodward, 1992).

We propose to apply these well-tested isotopic analyses to understanding the effects of Chinese policy on sediment yield in the International Rivers of Yunnan and Tibet (IRYT). The IRYT are the rivers that drain the eastern and southern Tibetan Plateau. The region includes the Tsangpo, Salween, Mekong, and Red Rivers and lies between 20^{o} and 34^{o}N and 80^{o} and 105^{o}E at elevations ranging from 200 to over 6000 m; has mean annual rainfall between 180 and 1500 mm/yr; and mean local relief between 150 and 3000 m.

The IRYT are of particular interest because: 1) they contain part of the Three Parallel Rivers (TPR) UNESCO World Heritage Site, where proposals for dams along the Salween and Mekong Rivers (Feng and He, 2004; Magee, 2006) may result in the TPR being moved to the World Heritage Sites at Risk List (IUCN, 2006); 2) the Yangtze River has been extensively studied during planning for and construction of the Three Gorges Dam; and, 3) there is a long record (up to 27 years) of daily sediment yield measurements for 44 stations in the region (Figure 1).

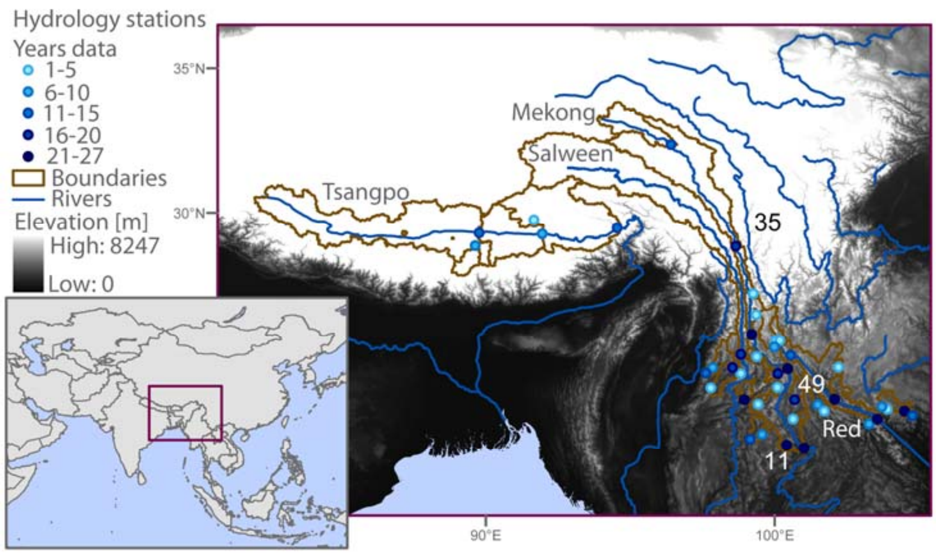

Figure 1: Location of stations in the dataset. The brown boundaries are the unique area sampled by each station. Stations we will focus on in the first field season are noted (11, 35, and 49).IRYT rivers are also labeled.

We propose to use these Chinese hydrology data as a framework on which to combine a variety of modern isotopic measurements and land-use-history observations into a coherent story about the effect of land-use changes in a region that is culturally, environmentally, and geologically important.

2. Justification of Research

Our proposed research approaches a fundamental issue in the hydrologic sciences: the movement of sediment in large river systems and the effect of land-use change on sediment budgets in mountainous terrain. Previous research in western China suggests that on large scales sediment yield does not correlate with land-use, population density, or geomorphic/climatic parameters such as mean local relief, monsoon rainfall, or mean annual rainfall (Henck et al., in press). We propose to determine why this lack of variability occurs. Specifically, we will use an exceptional and unique suspended sediment load dataset from four major Chinese rivers in conjunction with new isotopic data to address these questions:

1. Do mass fluxes estimated using sediment yield data and *in situ* ^{10}Be measurements differ, and if so, how and why do they differ?
2. Are mass and isotope fluxes out of basins in mountainous terrain related to specific land-use histories over the past 50 years?
3. Has climate change affected these fluxes?
4. Do specific areas of the landscape function as sources and sinks of sediment? If so, is the location of these areas related to land-use, underlying geology, or topography?

In addition to these fundamental issues in hydrologic sciences, broader impacts of our work include addressing methodological issues in the application of sediment isotopic tracers to river systems such as:

1. Can sediment fluxes and sources be more reliably determined by measuring multiple isotopic systems in each sediment sample (*in situ* ^{10}Be, meteoric ^{10}Be, and the short-lived radionuclides ^{137}Cs and ^{210}Pb)?
2. Given the monsoonal nature of precipitation and runoff in the region, do seasonal changes in erosion processes and sediment sources cause sediment deposited during the monsoon to have a different isotopic composition than sediment sampled from the channel during low flow?
3. What, if any, effect does grain size have on the concentration of meteoric ^{10}Be and short-lived isotopes in fluvial sediment?

3. Experimental Design

To answer the questions posed above, we will combine analysis of sediment yield data collected daily over periods of up to 27 years at 44 stations with isotope data for sediment collected at each station. We propose a three-pronged, phased approach where data from year one inform the sampling in year two.

1) During field season one and the following year, we will perform detailed analysis of two watersheds which are similar in topography, climate, and land-use but have extremely different calculated sediment yields. Our work will use remote sensing and Chinese land-use data (checked in the field) to determine land-use change over time, Chinese sediment data for modern sediment yields, and meteoric and *in situ* ^{10}Be, ^{137}Cs, and ^{210}Pb for sediment fingerprinting and long term denudation rate calculation. Samples will be collected from both the previous year's flood deposits and from the active channel to allow us to determine the different sources and sinks of sediment during the monsoon and non-monsoon seasons. We will also split some samples for analysis of grain size effects on the short-lived isotopes and meteoric ^{10}Be.

2) During field season one and the following year, we will focus on a small basin where climate (temperature) has changed rapidly in order help us to separate the relative effects of climate and land-use. We will perform detailed sampling for all isotopes as well as determine pre-settlement, paleo-erosion rates (from river terrace sediment) in this basin where county weather station data suggest that MAT is changing at a rate of 10^{o}C/100 yrs over the last 25 years (Haynes, 2010).

3) During field season two and the following year, Phase 2 of the project will include collection of samples for meteoric and *in situ* ^{10}Be and the short-lived isotopes at the sites of all Chinese gauging stations combined with land-use analysis based on remote sensing, Chinese government land-use data, and field checking of these data sources. The specific distribution of samples (in channel and previous year's flood deposits) will be determined by the results from year one.

Figure 2: From left to right: A basin heavily altered by human use, a typical distribution of land-use in the upper Salween watershed, and a relatively pristine section of the upper Mekong watershed.

4. Background – Study site

Environmental degradation is well documented in modern Chinese history (Figure 2). Three major Communist government policies, known as the "three great cuttings", are blamed for mass deforestation

Figure 3: *A reforestation project in Sichuan on former agricultural land.*

since 1949: 1) the Great Leap Forward (1958-1960), when widespread "backyard" steel furnaces induced extensive deforestation; 2) the "Grain as a Key Link" policy (1966-1976) to clear land for expanding cropland; and, 3) "Opening and Development" in the early 1980s when free markets opened and people could benefit financially from trees they cut and sold (Shapiro, 2001; Hyde et al., 2003). In response to concerns that upstream land-use was causing downstream flooding, a 1998 policy banned logging in western China and the 2003 Grain to Green and Sloping Land Conversion plans banned farming on slopes with angles greater than 20^o and mandated tree planting on these slopes (Trac et al., 2007) (Figure 3).

Figure 4: A widening channel draining 30 km^2 basin which was extensively logged during all three great cuttings.

Analysis of regional data leads to complicated conclusions regarding the impact of these logging events on erosion in western China. For example, up to 40% of forests in Sichuan were cut in modern times (Winkler, 1996) and this has been blamed for increased sediment load and subsequent flooding in the Yangtze Basin (Chen, 2000; Yin and Li, 2001; Yi, 2003). In contrast, a number of studies conclude that human activity and modern policies have not, on average, increased sediment yield in the Yangtze River (Lu and Higgitt, 1998; Higgitt and Lu, 1999; Lu and Higgitt, 1999; Lu et al., 2003a; 2003b) or have decreased sediment yield to the river (Xu, 2000; Chen et al., 2001a; Xu, 2005; Wang et al., 2007a; 2007b). On a finer scale, Higgitt and Lu (1996) use ^{137}Cs to show that although soil erosion was increasing in the Upper Yangtze watersheds over the period from the late 1940s to the late 1980s, sediment yield in rivers did not increase, suggesting that sediment is being stored and not leaving the basins. Other studies found sediment loads increased in mountainous tributaries and decreased in urban tributaries (Zhang, 1999; Zhang and Wen, 2002; 2004).

In a rural township in Sichuan, local slash and burn agricultural practices striped the hillslopes of vegetation and deposited sediment into the main river valley (Collins et al., 2011). When the watershed was then heavily logged during all three "great cuttings" (Trac et al., 2007), the single river channel set in a wooded floodplain was transformed into a widening channel actively eroding into hillslopes and undercutting roads and houses (Urgenson et al., 2010) (Figure 4).

5. Results of our preliminary research in the region

To date we have completed a study of trends in sediment yield data over the period of record and have measured *in situ* ^{10}Be in 6 detrital sediment samples from gauging station locations in the upper Salween, Mekong, and Tsangpo Rivers, and find little to no effect of land-use change on sediment yield (Henck et al., 2006a; 2007; 2009; in press).

Sediment yield data

We used daily mean total suspended sediment and discharge data compiled for 44 stations in the IRYT operated by the Ministry of Hydrology of the People's Republic of China from 1953 to 1987 (Ministry of Hydrology, 1962-1989); data after 1987 are not publicly available. The data are compiled in a database described by Henck at al. (2010a; http://depts.washington.edu/shuiwen).

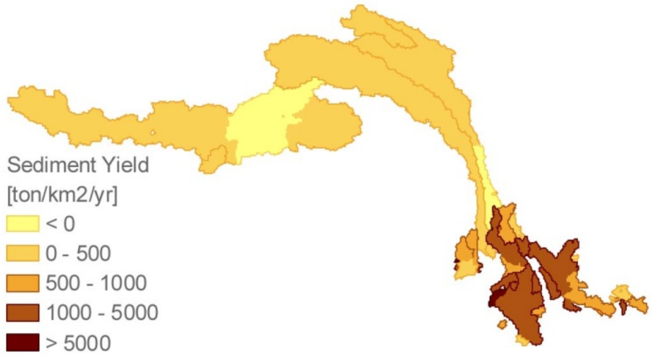

Figure 5: Mean annual sediment yield for unique area sampled by each station and averaged over all the years of data available for each station.

Using these data we calculated sediment yield (tonnes sediment/km^2*yr) for each of the stations, which individually have one to twenty-seven years of data available. For the seventeen stations with stations upstream of them in the same basin, we calculated the sediment yield for both the intermediate reaches between stations and the entire upstream area (Figure 5).

We find no systematic trends with time in sediment yield at any station. We find a weak correlation between sediment yield and both rainfall and fraction land under cultivation (from county-level Chinese data) (Figure 6).

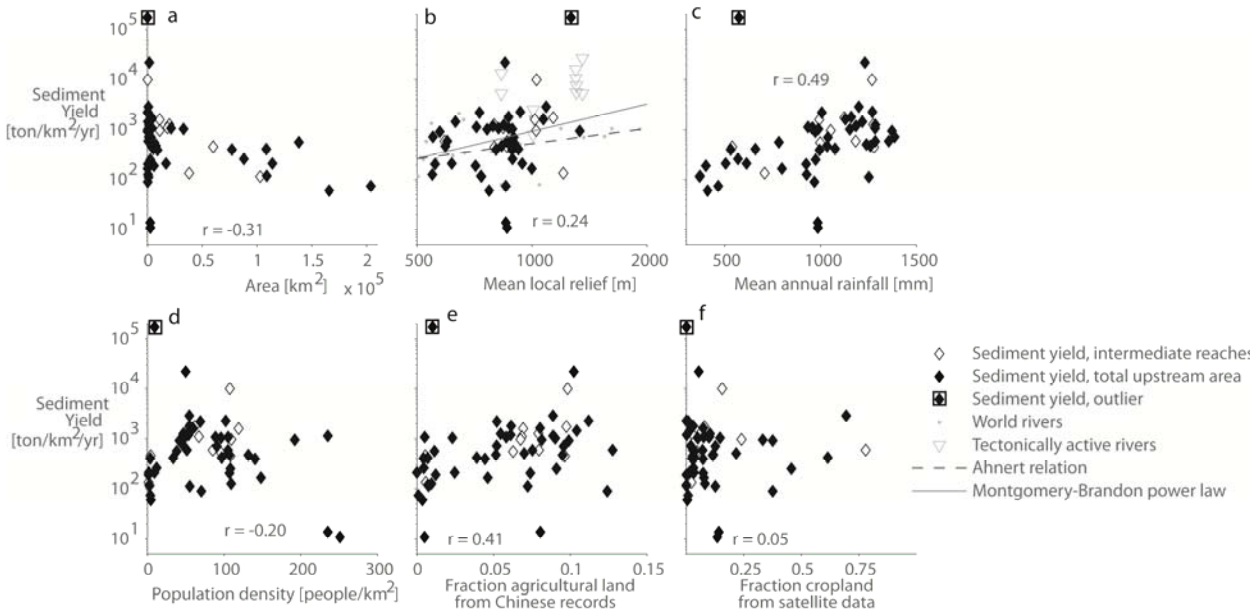

Figure 6: Variation in sediment yield decreases with increasing area (a), and there is no correlation between sediment yield and relief (b), a weak correlation between sediment yield and rainfall (c), no correlation with population density (d), a weak correlation with fraction of agricultural land from Chinese data (e), and no correlation with crop land from satellite land-cover data (f).

Erosion rates measured from in situ ^{10}*Be*

Using the measured concentration of *in situ* produced ^{10}Be, we estimated basin-scale erosion rates in 6 detrital sediment samples collected from the upper reaches of the Salween, Tsangpo, Yangtze, and Mekong Rivers at approximately the same location as four Chinese hydrology stations and find no systematic difference between the short- and long-term erosion rates (Figure 7).

6. Background – Tracing river sediment with isotopes

Streams and rivers move large amounts of sediment; yet, until recently, determining *where on the landscape river-borne sediment originated* and *how rapidly landscapes shed sediment over time* were both largely unanswerable questions. Now, by combining proven techniques in multiple isotopic systems, hydrologists have the data and analytical techniques to begin answering these questions.

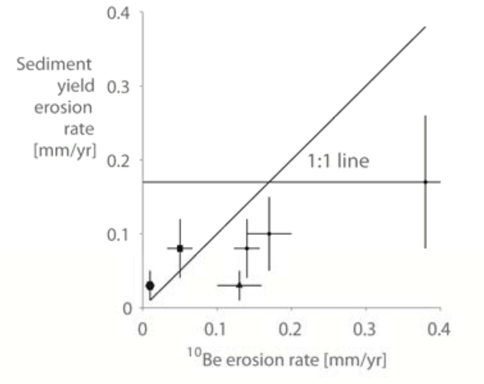

Figure 7: Erosion rates inferred from sediment yield data compared with those measured from in situ *^{10}Be in detrital sediments. Error bars are shown. We use reported errors for ^{10}Be data and estimate 50% errors on sediment yield data. Salween, Mekong, and Yangtze River ^{10}Be data are from Henck et al.(in revision), Tsangpo River ^{10}Be data are from Finnegan et al. (2008), and Yangtze River sediment yield erosion rates are calculated from Higgitt and Lu (1996).*

Measuring suspended sediment loads allows estimates of contemporary *sediment yield* – the rate at which sediment moves through river systems over a period of record. Initially, fragmentary sediment yield data (discrete samples of suspended sediment concentration convolved with discharge data) were used to estimate long-term rates of landscape change assuming a balance between *sediment generation* (erosion) and *sediment transport* (Dole and Stabler, 1909; Judson and Ritter, 1964). Soon, more detailed work showed the situation to be far more complex. First, much of the eroded sediment never made it into the fluvial network, at least over human time scales (Trimble, 1977). Second, the extrapolation of sediment discharge through the use of sediment rating curves was fraught with error because sedigraphs typically display significant hysteresis (Jansson, 2002). Third, there are, in some locations, effects of basin size on sediment yield – the sediment delivery ratio (Walling, 1983). Fourth, sediment is often delivered to river systems in pulses due to stochastic events such as landslides, which occur infrequently but greatly affect long-term erosion rates; short-term sediment yields often miss these events (Kirchner et al., 2001).

Enter isotopes. The ability to measure a variety of rare nuclides associated with river sediment has dramatically improved our understanding of sediment generation rates and large-scale, fluvial sediment transport over the past several decades. Specifically, three isotope systems have seen wide application monitoring sediment generation and tracing sediment as it moves into and through river systems.

1. **Meteoric ^{10}Be** (t1/2 = 1.38 My), produced in the atmosphere and delivered to Earth's surface in precipitation and dry-fall, sticks tenaciously to sediment (Valette-Silver et al., 1986b) and accumulates in soil A- and B-horizons. The concentration of meteoric ^{10}Be provides a means to determine whether soil production and soil loss are in balance (the *erosion index* of Brown et al., (1988)), estimate rates of landscape erosion over millennial time frames (Helz and Valette-Silver, 1992; Bierman et al., 2009), and, through the use of sediment cores in receiving bodies, detect erosion events tapping the meteoric ^{10}Be-enriched, soil horizons (Valette-Silver et al., 1986a). Meteoric ^{10}Be is also useful as a tracer of sediment sources provided a contrast in concentration exists between potential sources (Helz and Valette-Silver, 1992; Reusser and Bierman, 2010).
2. ***In situ* ^{10}Be** (t1/2 = 1.38 My), produced in rock and soil by the interaction of cosmic rays with atoms in mineral lattices, is found primarily within a meter or two of Earth's surface (Lal and Peters, 1967; Lal, 1988; 1991). The concentration of *in situ*-produced ^{10}Be in river sediment is inversely proportional to the average erosion rate of the basin (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). On the scale of hillslopes, *in situ* ^{10}Be concentrations are similar over the top several decimeters as soils tend to be well mixed by both physical and biological processes (Figure 8); *in situ* ^{10}Be concentrations decline exponentially over the next several meters as isotope-producing neutrons are attenuated. Over the past decade, over 1000 basin-scale erosion rates have been estimated using ^{10}Be concentrations measured in fluvially transported quartz (Bierman et al., 2001; von Blanckenburg, 2005; Portenga et al., in review). Similar to meteoric ^{10}Be, *in situ* ^{10}Be can also be used as a tracer of sediment source (Clapp et al., 2002).

3. **Short-lived radionuclides**, ^{137}Cs ($t_{1/2}$ = 30 y) and ^{210}Pb ($t_{1/2}$ = 22.2 y) are delivered to Earth's surface both in dry-fall and by precipitation. ^{137}Cs is an artificial radionuclide, produced and released primarily by the atmospheric testing of nuclear weapons in the late 1950s and early 1960s. ^{210}Pb is produced in the ^{238}U decay series and is thus present in all soils, its measured concentration "supported" in part by the decay of ^{226}Ra to ^{222}Rn and then to ^{210}Pb. "Unsupported" ^{210}Pb is delivered from the atmosphere where ^{222}Rn, having escaped as a gas from soil and rock, decays to solid ^{210}Pb and falls out. Because both ^{137}Cs and unsupported ^{210}Pb are short-lived and are deposited on Earth's surface, they accumulate primarily in near-surface soil (Walling and Woodward, 1992; Kaste et al., 2007). Sediment derived from deeper than a few decimeters (from gully erosion, landsliding, or river cut-bank failure) rarely contains measureable levels of either ^{137}Cs or unsupported ^{210}Pb (Wallbrink and Murray, 1993). Thus, ^{137}Cs and ^{210}Pb are excellent markers for the depth of soil erosion providing sediment to river networks as shown by Olley et al. (1993) and Whiting et al. (2001) and summarized by Walling and Woodward (1992) and Bierman et al. (1998).

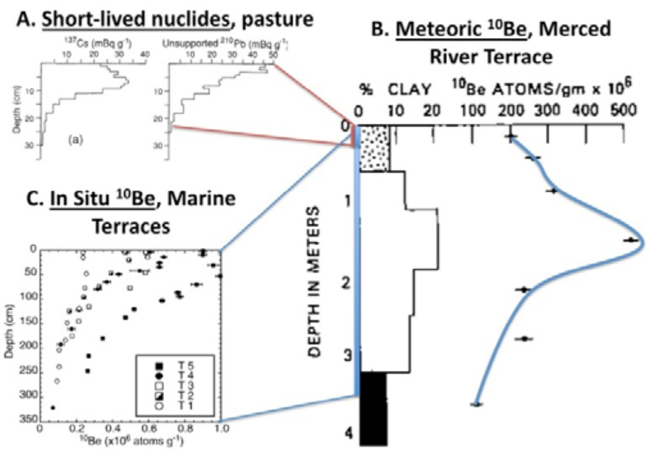

Figure 8: Compilation of "typical" depth profiles for three isotopic systems proposed in this research. A. ^{137}Cs and unsupported ^{210}Pb in English pastureland; penetration depth ≤ 30 cm, maximum activity 5 to 10 cm (Walling and Woodward, 1992). B. Meteoric ^{10}Be in Merced River terraces; penetration depth > 300 cm, maximum concentration 150 cm (Pavich et al., 1986). C. In situ *^{10}Be, Santa Cruz marine terraces; well mixed upper 50 cm, penetration depth ~200 cm, maximum concentration ~50 cm (Perg et al., 2001).*

Although the three isotopic systems described above have been employed repeatedly in isolation, to the best of our knowledge, they have not yet been applied to the same fluvial sediment samples in order to understand better, on a variety of temporal and spatial scales, the variability of erosion rates and sediment sources. Because each of these systems has different depth/concentration relationships (Figure 8), we hypothesize that different erosional processes (sediment sources) should result in identifiable relationships between measured isotope concentrations as illustrated schematically below (Table 1).

Table 1: Expected isotopic fingerprints for different catchment sediment sources

	Shallow Surface Erosion	**Deep Landsliding**	**Rills/Shallow Gullies**	**Bank failure of Holocene river terraces**
In situ *^{10}Be*	Unchanged (homogenized soil)	Low (parent material)	Unchanged (homogenized soil)	Unchanged (homogenized soil)
Meteoric ^{10}Be	High (A-horizon)	Low (parent material)	High (A-horizon)	Unchanged (homogenized soil)
^{137}Cs and ^{210}Pb	High (A-horizon)	Low (parent material)	Low (parent material)	Low (parent material)

We propose to combine measurements of meteoric ^{10}Be, *in situ* ^{10}Be, and short-lived nuclides (^{137}Cs and ^{210}Pb) in the same sediment samples. Alone, each isotope will provide specific, useful information: *in situ* ^{10}Be will allow calculation of millennial, basin-scale erosion rates, meteoric ^{10}Be will suggest the basin-scale magnitude of soil loss, ^{137}Cs and ^{210}Pb will suggest whether sediment is derived from surface or deeper erosion, and suspended sediment concentration will allow calculation of sediment yield; however, the real power of our approach is illustrated by Table 1. By examining multiple parameters together, we will be able to understand better how the fluvial system as a whole responds to outside forcing, both land-use and climate change. Multiple isotope systems, when teamed with the suspended sediment load data, reduce the degrees of freedom and thus will allow us to better constrain our interpretation.

7. Can multiple isotopic systems combined with extant sediment data and remote sensing potentially distinguish between human impact, biased land-use data, and climate change effects?

By measuring multiple isotopic systems throughout a pair of watersheds with known land-use history and current land-use (determined from remotely sensed data, Chinese records, and field checking of the previous two lines of evidence) during Phase 1, we will be able to isolate the fingerprints of sediments from different sources and then track those fingerprints as the sediment moves downstream throughout the system. The Chinese sediment records will enable us to calculate erosion indices (e.g., Brown et al., 1988) and thus further quantify levels of soil loss as well as the major sources and sinks of sediment in the Phase 1 watersheds. Once we understand the system for these smaller (10^3 km^2) watersheds, we can then apply our knowledge to the larger gauged watersheds (Phase 2).

Potential complicating factors – Although first principles analysis suggests that the combination of remote sensing, Chinese sediment data, and analysis of multiple isotopic systems will help us understand the sediment system, there are potential complications to this approach. Below we address these complications and explain why we believe they will not interfere with the proposed research.

A. Are the Chinese sediment data reliable? The Chinese Ministry of Hydrology operates numerous hydrologic gauging stations throughout the country. Each station is staffed by 12 hydrographers who measure cross-sections, discharge, and suspended sediment concentration daily. The suspended sediment concentration is measured using a Jakowski sampler and the 0.2-0.8 method (Ministry of Water Conservancy and Electric Power, 1962; 1975). Although the quality of these data has not been independently assessed, they have been used extensively in publications on Chinese erosion (Liu and Zhang, 1995; Higgitt and Lu, 1996; Lu and Higgitt, 1998; Wang and Wang, 1998; Higgitt and Lu, 1999; Lu and Higgitt, 1999; Zhang, 1999; Lu and Higgitt, 2000; Chen et al., 2001b; Higgitt and Lu, 2001; Lu and Higgitt, 2001; Yin and Li, 2001; Jing, 2002; Zhang and Wen, 2002; Lu et al., 2003a; 2003b; Yi, 2003; Li et al., 2004; Zhang and Wen, 2004; Lu and Siew, 2006; Wang et al., 2006; Wang et al., 2007a; 2007b; Yang et al., 2007; Chen et al., 2008; Hassan et al., 2008; Wang et al., 2009; Hassan et al., 2010).

B. Can the relative effects of climate change and land-use be distinguished? We recognize that disentangling these drivers will be difficult. Our task is made simpler for *in situ* ^{10}Be by repeated observations that climate change appears to have no significant effect on long-term, integrated erosion rates (Riebe et al., 2001; Portenga et al., in review). We will investigate the possibility of erosion rate changes over time by ^{14}C dating and sampling buried sediment from multiple river terraces; using the *in situ* ^{10}Be content of these dated and shielded sediments we will estimate paleo-erosion rates (e.g., Cox et al., 2009) over space and time. In Phase 1, we will focus our work in basin 35, where temperature is changing rapidly. By detailing paleo-erosion rates here, and considering the established timing of the land-use and climate change in this region, we will attempt to decipher the importance of human-induced and climatic change affecting this one watershed. In Phase 2, we will apply this knowledge to our sampling and interpretation approach in other regions.

C. Does the monsoon strength vary over time? Several lines of evidence indicate that varying monsoon strength probably has little effect on erosion rates although it may affect the source of sediments from the landscape. Previous research in the IRYT suggests that monsoon rainfall has little influence on basin wide sediment yield (Henck et al., in press) and detrital *in situ* ^{10}Be samples from around the world suggest that climate has little effect on basin-wide erosion rates (Riebe et al., 2001; Portenga et al., in review). Furthermore, the monsoon has varied 2-fold in strength on cycles of 35 years (Tan et al., 2009) over the millennial-scale time-period recorded by *in situ* ^{10}Be in detrital sediments. *In situ* ^{10}Be averages over the entire time when sediments were within 2 meters of the surface thus blurring the effect of these changes. Similar to the different sediment sources apparently tapped during glacial and inter-glacial periods in

Australia (Dosseto et al., 2006), we expect that monsoon and dry-season sediment sources may differ. To test for this, at all sample sites we will collect both in-channel sediments and flood deposits from the previous year. Using this information, we can understand the contemporary effects of the monsoon on sediment sourcing and extrapolate our findings to the effect of variations in monsoon strength.

D. Sediment in rivers is a mixture of different sources. We realize that sediment moving down the river system is a mixture of material derived from different sources; thus, our approach will be most effective if one sediment source or another dominates. However, examining how the three different isotope parameters and the sediment yield data cluster should identify similarities between regions as well as downstream trends in sediment sourcing and erosion.

E. The area may not be in steady state. The validity of the steady state assumption depends on the time and spatial scale of observation in dynamic mountain watersheds like those we propose to study. *In situ* ^{10}Be is well buffered due to deep penetration of cosmic radiation and bioturbation of the active zone (Jungers et al., 2009). The short-lived isotopes are less well buffered because of their shallow penetration depth and the buffering of meteoric ^{10}Be will depend on its depth penetration and the rapidity of pedogenic redistribution (Jungers et al., 2009). It is possible that a rapidly eroding, steady state landscape could have landslides sourcing deeper material. However, the more rapidly the landscape is eroding, and thus the more likely it is to have extensive landsliding, the less likely it is that the landslides will affect *in situ* ^{10}Be concentrations (Niemi et al., 2005). Thus, if the region is out of steady state we will see the signature of deeply sourced erosion most clearly in small basins and in short-lived isotopes (Table 1).

F. Are Chinese land-use data reliable? We recognize that there are cultural and political biases present in the land-use data. Thus, we will use the Chinese land-use data in conjunction with remotely sensed data and field checking of land-use. This way we will compile a complete picture of land-use in the watersheds we are studying and identify any systematic biases in the Chinese land-use data.

8. Proposed research and work plan

The goal of this work is to leverage detailed and extensive sediment yield measurements with *in situ* ^{10}Be-based, long-term erosion rate estimates and sediment fingerprinting provided by other isotope systems (^{137}Cs, ^{210}Pb, and meteoric ^{10}Be). Our approach is as follows. First we will complete analyses for a small number of samples already in our possession and conduct GIS-based land-use analysis and field planning for our first field season. During the first field season we will sample three basins with long sediment records – two for network analysis of isotopes, end-member basins, and grain-size effects and one for paleo-erosion rates in a region experiencing rapid climate change. During the following year we will process and analyze the samples and then conduct the GIS-based land-use analysis and field planning for the next field season. During the second field season, we will sample at the sites of all gauging stations.

<u>Winter 2011</u> – We will start the project by acquiring, installing, and testing the cryo-cycle for Schmidt's gamma counter. In addition, we will start isotopic measurements on the 45 samples already in Schmidt's possession from dissertation research, six of which are from sites near gauging stations (Figure 7). Processing samples from sites where we already have *in situ* ^{10}Be measurements will inform our 2012 field work. For example, combining these analyses with land-use analysis will enable us to start testing isotopic signatures from samples for watersheds with different land-use. These samples are from basins ranging in size from 2 to over 300,000 km^2, allowing us to test our procedures for basins spanning a large range of areas. These samples will also be processed by the PhD student at UVM for meteoric ^{10}Be and at Oberlin for short-lived isotopes. All these samples have already been analyzed for *in situ* ^{10}Be.

<u>Spring 2012</u> – Planning for fieldwork will begin with extensive remote sensing analysis to determine land-use/land cover for basins upstream of stations 11, 35, and 49. Stations 11 and 49 have a reported order of magnitude difference in sediment yield but are in similar climatic regions (southern Yunnan), in the same drainage basin (the Mekong River), have long records of data (≥20 years), are relatively small watersheds (<3000 km^2; this is on the small side of the watersheds with hydrology stations) and have

similar population densities, fraction agricultural land from Chinese data, mean local relief, basin relief ratio, drainage density, mean annual rainfall, and mean monsoon rainfall. We will use station 35 for analysis of climate effects on sediment yield. We chose station 35 because it is in a region with documented extreme climate change over the last 25 years (a rate of 10^{o}C/century; Haynes (2010)) and is a small watershed (200 km^2) with a long record of sediment data (18 yrs).

We will use this GIS-based analysis, done over the time period of the sediment yield data and beyond, to determine which small sub-basins are heavily disturbed and which are pristine and to locate and map large terraces and colluvial deposits within these two watersheds. We will work with the China Data Center online database (http://chinadataonline.org/) to determine when land was under cultivation or whether it was logged and allowed to regrow. Initially we will focus on the land-use data in the Eurasia Land Cover Characteristics Database v. 2.0 using the USGS classifications for land cover (USGS, 2008). In addition, to control for possible variations in geology across the watersheds, we will digitize a geologic map of the region already in Schmidt's possession. Digitally available geologic layers for the area (USGS, 2001) are not diagnostic of rock type and thus are not useful for our analysis.

We will work with Liang Chuan at Sichuan University to apply for research permits for hydrology sampling and to arrange travel logistics (see letter of commitment). The permits and visas will be processed through Sichuan University, building on a collaborative network Schmidt has established there.

Table 2: Sample collection plan for both field seasons.

Type of sample	*Number to collect (year one)*	*Number to collect (year two)*	*Total*
Samples at sediment yield stations – over bank deposits	3	41	44
Samples at sediment yield stations – channel deposits	3	41	44
Samples in end-member basins within basins 11 and 49; 10 pristine, 10 heavily disturbed	20	0	20
Samples at tributary junctions in basins 11 and 49 – over bank deposits	17	0	17
Samples at tributary junctions in basins 11 and 49 – channel deposits	17	0	17
Samples from datable fluvial terraces – sediment samples	10	0	10
Samples from channels adjacent to fluvial terraces – sediment samples	10	0	10
Samples from datable fluvial terraces (2/terrace) – radiocarbon samples	20	0	20
Total	**100**	**82**	**182**

June 2012 – Field work will be done prior to the onset of the summer monsoon so that we can move easily across the countryside. We will collect a total of 100 samples from 3 watersheds (Table 2). These samples will be from both active channel and overbank sediments deposited during the last annual monsoon flood at all three of the gauging stations (11, 35, and 49), as well as major tributary junctions, and end-member basins upstream of stations 11 and 49. In the watershed upstream of station 35 and in other areas where we find appropriate terraces that expose older sediments (along with ^{14}C-datable organic material) we will collect samples of sediment and organic material in the terraces and modern sediment in adjacent channels in order to estimate variability in the *in situ* ^{10}Be concentration over time. This approach (taken by Cox et al. (2009) in Madagascar) allows estimation of pre-settlement erosion rates from *in situ* ^{10}Be content. During our time in the field, we will also be field checking our remote sensed maps of historic terraces, land-use and colluvial deposits and measuring thicknesses of these deposits wherever possible to constrain volumes.

We will spend approximately one week in each of the watersheds in Yunnan. We will fly to Kunming and then travel by rented car with a driver. Schmidt has a Chinese driver's license and so can drive if needed in China. We will be accompanied by one of Liang's graduate students. We will stay in hotels in larger towns and cities, making day trips to collect samples.

Samples will be sent from Kunming to UVM by airmail and the end of field work, ensuring that samples arrive in the United States in a timely manner. Geologic materials are not restricted from leaving China, so we do not anticipate any customs delays for our samples.

Summer 2012 – When samples arrive from China, the PhD student will dry them and sieve them to specific grain sizes. Aliquots will be removed for gamma counting (^{137}Cs and ^{210}Pb) and meteoric ^{10}Be and powdered using UVM's SPEX mill. Samples for gamma counting will be mailed to Oberlin for analysis. While the samples are being prepared at UVM, the undergraduate students will compile field notes and revise the remote sensing analysis based on ground-truth data gathered during field work.

Samples for *in situ* ^{10}Be analysis will be treated using UVM's established laboratory protocols (http://uvm.edu/cosmolab) including multiple hot HCl etches to remove Fe and Al oxyhydroxides, repeated 1% HF/HNO_3 heated ultrasonic etches, density separation, and burning to remove organic material. During the summer, we will select a variety of samples (n=10) in which to measure any influence sediment grain size has on meteoric ^{10}Be, ^{137}Cs, and ^{210}Pb content. Samples will come from a variety of different landscape settings, including disturbed and undisturbed basins, large and small basins, and basins of different steepness as well as those with and without large mass movements.

Simultaneously, a PhD student from UCSB will be in residence at LLNL learning to run the AMS and reduce the data produced. The UCSB student will work with Rood to design AMS experiments aimed at developing a rapid analysis approach for high-ratio meteoric ^{10}Be samples that increases throughput and reduce cost of measuring meteoric ^{10}Be. This would reduce cost of analysis and thus increases the number of meteoric ^{10}Be samples that we can measure for this project. Experiments will be conducted on synthetic standard materials, then applied to real meteoric ^{10}Be samples processed in the UVM lab (IRYT samples either collected in June 2012 and archival samples from Schmidt's collection).

Table 3: Sample analysis plan following first field season.

Type of sample	*Number to collect*	*Grain size to analyze*	*In situ ^{10}Be*	*Meteoric ^{10}Be*	*^{137}Cs ^{210}Pb*	*^{14}C*
Channel sediments	20	Sand (250-850 µm)	20	20	20	0
Overbank sediments	20	Sand (250-850 µm)	20	20	20	0
Grain size dependence	N/A	Silt (63-250 µm) Sand (250-850 µm) Gravel (850-4000 µm)	0	30	30	0
End member land-uses	10 pristine 10 disturbed	Sand (250-850 µm)	20	20	20	0
Paleo-erosion samples – sediment from terraces and adjacent channels	20	Sand (250-850 µm)	20	20	20	0
Paleo-erosion samples – radiocarbon	20	N/A	0	0	0	20
		Total	**80**	**110**	**110**	**20**

Fall 2012/January 2013 – Working at UVM, the PhD student and Bierman will spend the fall processing *in situ* and meteoric ^{10}Be samples in the UVM cosmogenic laboratory, which is set up so that multiple batches of samples can be processed concurrently (http://uvm.edu/cosmolab). Refinement of our extraction techniques now allows one person to process either two batches of meteoric samples (15 samples and a blank) or a batch of *in situ* samples (11 samples and a blank) in a week or less, on average. Given the sample load this project will generate in the first field season (80 *in situ* and 110 meteoric samples, Table 3) it would take about 16 straight weeks of work to complete sample preparation. Accounting for other responsibilities and lab downtime for Fall GSA and AGU, we anticipate that all isotope extraction will be completed by February 2013. We will make our first AMS isotope measurements at LLNL during fall 2012. At least one batch of meteoric and one batch of *in situ* samples will be processed during January 2013 when Schmidt and the two undergraduate students visit UVM to participate in sample processing. During this time, ^{14}C samples will be processed and analyzed at LLNL. We plan to complete isotope analyses by the end of winter 2013.

Simultaneously, Schmidt and the undergraduate students will collect gamma spectroscopy data for one sample each day. The undergraduates will spend their January term, aside from their time at UVM, processing the gamma spectroscopy data and making measurements of the samples and grain size splits.

Winter/Spring 2013 – The UVM PhD student will spend spring semester 2013 in residence at Oberlin College. During that time Schmidt will mentor him/her. The student will learn to process, measure, and analyze gamma spectroscopy data for ^{137}Cs and ^{210}Pb while teaching the undergraduate students to analyze ^{10}Be data and conducting remote sensing analysis to plan for the second field season. The UVM PhD student will also teach at least one unit of Schmidt's Applied GIS class and work on an initial publication with Schmidt and the undergraduate students.

During this time we will analyze results from the first field season. We will consider the differences between basin-scale erosion rates estimated from *in situ* ^{10}Be and sediment yield data for stations 11 and 49. We will compare erosion rates calculated for in-channel and over-bank deposits derived from *in situ* ^{10}Be analyses for the major tributaries sampled upstream of stations 11 and 49. We will examine ^{137}Cs, , ^{210}Pb, and meteoric ^{10}Be data for the same samples to determine if the concentration of short-lived nuclides is related to any seasonal discordance in the *in situ* ^{10}Be concentration. This analysis will answer the question of whether sediment sources and apparent erosion rates are related to the time at which the sediment was transported. In other words, does sediment transported during the monsoon have a different isotopic signature (and thus a different source) than sediment transported during the dry season?

Using the methods of Brown et al. (1988), we will determine meteoric ^{10}Be erosion indices for each of the station locations and compare them to land-use classifications determined from remote sensing analysis and ground-truth data collected during the first field season. This will provide information related to the relative soil loss for each watershed and help to relate soil loss to land-use. It will also provide a test-of-concept for this process in conjunction with the Chinese sediment data.

We will estimate sources and sinks of sediment in the region from the meteoric ^{10}Be data using network analysis (Reusser and Bierman, 2010). This is an important supplement to erosion rate and erosion index data because heavily disturbed areas, those where deep erosion has mobilized meteoric ^{10}Be-poor sediment, will have an apparently low erosion index despite heavy disturbance. Identifying sources and sinks of sediment will provide an important control on erosion index calculations.

We will consider the short-lived nuclide data as binary tracers (fingerprints, ala Walling and Woodward (1992)) for sediment sourcing. Sediment sources by deep erosion (gullies, landslides) will have low concentrations of these nuclides whereas sediment sources from at or near the soil surface will have higher concentrations. By considering short-lived nuclide activity in concert with land-use parameters as well as with meteoric and *in situ* ^{10}Be concentration, we should be able to indentify confidently basins affected by deep-seated erosion or failure of once-stable stream banks from incision.

Finally, we will analyze meteoric ^{10}Be, ^{137}Cs, and ^{210}Pb measurements taken from different grain sizes to determine if there are any grain size dependencies in the concentration of these isotopes in sediments. To date there has been little analysis of such grain size dependencies in meteoric ^{10}Be (only Brown et al., 1988) and none for ^{137}Cs and ^{210}Pb. If there are grain size dependencies, it is important to understand them as these isotopes become increasing common for tracking of sources and sinks of sediments.

These analyses will frame our field work plan for 2013. Beyond refining our sampling plan based on our results, our planning for the second field season will be similar to that outlined for winter/spring 2012. However, logistics will require more planning as we will be traveling extensively in Yunnan and Tibet.

June 2013 – As with 2012, field work will be done prior to the onset of the summer monsoon. Although results from 2012 will inform our sampling strategy, we plan to collect samples from both active channel and overbank sediments the 41 gauging stations (Table 2, Figure 1). As in 2012, if we find dissected terraces that expose older sediment (along with ^{14}C-datable organic material), we will collect samples of both sediments and organic material to estimate the variability in *in situ* ^{10}Be concentration over time.

We will spend 3 weeks in Yunnan and 1 week in Tibet. Logistics in Yunnan are the same as outlined for the first field season. In Tibet, we will be accompanied by Liang's graduate students and contacts at the Ministry of Hydrology. We will be based in Lhasa and make day trips to the sample locations. Sample shipment to UVM will follow the same procedure as during June 2012.

Summer 2013 – As in summer 2012, the PhD student will dry, sieve, separate, and grind the samples prior to shipping samples for ^{137}Cs and ^{210}Pb to Oberlin where the undergraduate students will be consolidating field data. Our summer plan for 2013 will be similar to summer 2012.

Fall 2013 – Liang's graduate student who accompanied us for field work will be in residence at Oberlin and UVM (approximately six weeks in each location). He/she will learn to process samples and analyze results for all four isotopic systems we are using. In addition, Rood, Schmidt, Bierman, the undergraduate students, the UCSB and UVM PhD students, and the Chinese student will travel to either the Fall GSA or AGU to meet as a team and present preliminary results from the project.

Winter 2014 – We will complete isotope analysis and continue gamma spectroscopy measurements.

Spring/Summer 2014 – Data analysis and dissemination of our results will occupy the last year of project activities. Analysis will parallel that done in spring 2013 but this time for samples from all sediment gauging stations. In addition, for 17 of the stations, there are other stations upstream in the same basin. For these locations, we will calculate both the erosion rates for the entire upstream are as well as by difference for the intermediate reaches between stations. This will yield important information related to how sediment is sourced and transported over different time and length scales in the field area.

Fall 2014 – Schmidt, Bierman, Rood, the undergraduate students, and the UVM student will present their findings at either or both GSA and AGU fall meetings. Data dissemination and archiving will continue.

Personnel responsibilities – This project is a fully collaborative effort between Schmidt, Bierman, and Rood. To further collaborations and training experience for students, Oberlin students and Schmidt will travel to UVM and LLNL, the UVM student will travel to Oberlin and LLNL, and the Chinese graduate student will travel to UVM and Oberlin. Schmidt will mentor undergraduate students, lead field expeditions to China, complete short-lived isotope analyses, and mentor the PhD student and Chinese graduate student when they are in residence at Oberlin College. Bierman will mentor the PhD student as well as the Chinese graduate student and undergraduates when they are in residence at UVM. He will supervise the sample preparation, processing, and analysis of meteoric and *in situ* ^{10}Be samples. Rood will measure isotopic ratios in the meteoric and *in situ* ^{10}Be and ^{14}C samples at LLNL, performe necessary data reduction, and mentor a UCSB graduate student in AMS experiments at LLNL. Liang will complete in-country logistics for field work and advise the Chinese graduate student.

9. Data distribution and archiving

As Bierman's lab has done for the last 17 years, all samples will be archived in their secure, off-site storage facility and made freely available to the community. We will strive to publish our data as soon as possible in widely accessible journals, as all three collaborators have a record of doing. We will continue our established protocol of publishing on the lab web site (http://uvm.edu/cosmolab) information about the sample collection sites, site photos, and initial data reports. Schmidt will incorporate the results of the project into a case study for her *Soils and Society* class.

10. Results from prior NSF support

NSF Graduate Research Fellowship and NSF IGERT Multinational Collaborations on Challenges to the Environment Traineeship (Schmidt, graduate support)

PI Schmidt is a beginning investigator. She was supported in graduate school by an NSF Graduate Research Fellowship and an NSF IGERT Traineeship. Her research during these fellowships was based primarily in western China and focused on tectonic geomorphology and human-landscape interactions. She worked extensively with Chinese hydrology data, *in situ* ^{10}Be measurements of erosion rates in large watersheds in western China, and smaller-scale projects focusing on the effects of land-use changes on small watersheds in Sichuan. The IGERT program encouraged interdisciplinary, international, and inter-institutional work and she has thus published in a variety of disciplines (including archaeology, geology, environmental science, environmental engineering, and ecology). Her research has been collaborative with Chinese colleagues and included training opportunities for Chinese National Park staff and Sichuan University graduate students. Research supported by these two grants resulted in 8 abstracts (Dryer et al., 2005; Gaulke et al., 2005; Henck et al., 2006a; 2006b; Feathers et al., 2008; Taylor et al., 2008; Henck et al., 2009; Lu et al., 2010) and 9 papers (Trac et al., 2007; Gaulke et al., 2009; Henck et al., 2010a; 2010b; Urgenson et al., 2010; Henck et al., in press; Combs et al., in review; Feathers et al., in revision; Henck et al., in revision).

Collaborative Research: Detrital cosmochronology of the Greenland Ice Sheet (Bierman, ARC-0713956, 9/15/2007-8/14/2011, $273,052)

Bierman and his laboratory (http://uvm.edu/cosmolab) have been funded numerous times by NSF over the past 16 years; he has received funding from Hydrologic Sciences, Geomorphology and Land-use Dynamics, Geography, Polar Programs, and Arctic Sciences for research and graduate research training. Bierman has received support for equipment from Instrumentation and Facilities, and from DUE for the Director's Award for Teaching Scholars. Much of this work involves using *in situ* and meteoric ^{10}Be to quantify and trace sediment movement in the landscape – research which is directly applicable to this project. These awards have supported two dozen graduate students at the MS and PhD levels and resulted in nearly 50 publications and over 100 abstracts. Some recent publications (all student authored) relevant to this proposal include: Reusser and Bierman (2010), Graly et al. (2010), Pearce et al. (2010), Reusser et al. (2010), Jungers et al. (2009), Cox et al. (2009), Reusser and Bierman (2007), Reusser et al. (2006), Safran et al. (2005), Bierman et al. (2005), and Reusser et al. (2004).

EAR-PF: Geologic Age Constraints for Seismic Hazard Assessment of Critical National Infrastructure (Rood, 04/01/2010-03/31/2012, $170,000)

Rood is an expert in the application of accelerator mass spectrometry (AMS) to the measurement of ^{10}Be for isotopic studies in the Earth Sciences. He has performed AMS measurements at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory (LLNL) for 5 years (mentored by Dr. Robert Finkel), and currently directs the GeoCAMS program at LLNL. He is a promising early career scientist and has published extensively on research conducted at the LLNL GeoCams facility (i.e., Amidon et al., 2009; Amos et al., 2010; Behr et al., 2010; Reusser et al., 2010; Rood et al., 2010; Scherler et al., 2010; Rood et al., in press-b; in press-a; Young et al., in press; Borg et al., in review). Rood's recently begun NSF Fellowship has already resulted in a paper based on the research from the fellowship project (Balco et al., in review).

11. Intellectual merit

This project addresses both significant scientific questions in Hydrologic Sciences related to human-landscape interactions as well as methodological questions related to tracing sediment movement in fluvial systems using multiple isotopic systems. Our study is transformative because it integrates multiple techniques at different spatial and temporal scales to address erosion and sediment dynamics. The project is timely because it incorporates a unique daily record of sediment yield at 44 different sites over several decades, a well-documented chronology of government-prescribed land-use changes, and combines techniques in multi-isotope fluvial sediment geochemistry including measurement of meteoric ^{10}Be, ^{210}Pb, and ^{137}Cs in fluvial sediment (e.g., Walling and Woodward, 1992; Whiting et al., 2001; Reusser and Bierman, 2010). We will approach rigorously and quantitatively questions such as "How much sediment moves and where does it go when land-use changes in mountainous regions" in a region with previously collected sediment yield data to provide a framework for our isotopic analyses. The data we collect have the potential to transform the way we understand both short- and long-term dynamics of sediment movement in mountain ranges as they respond to disturbance. In addition to these specific hydrologic questions, this project will also advance isotope tracing and fingerprinting methodologies by providing the first seasonal variance data for *in situ* and meteoric ^{10}Be, ^{210}Pb and ^{137}Cs concentrations of sediments allowing us to identify seasonal differences in sediment sources in this monsoonal climate. We will also investigate grain-size dependencies in meteoric ^{10}Be, ^{137}Cs, and ^{210}Pb – something we have done for *in situ* ^{10}Be (Bierman et al., 2007) but so far, little data exist for the other isotope systems in sediments.

12. Broader impacts

This project has scientific and cultural broader impacts. As Earth's population continues to increase, people alter large tracts of land formerly considered too steep, marginal, or erodible to use. Understanding how land-use affects soil erosion and sediment yield at different spatial and temporal scales is critical for implementing meaningful land-use policies around the world. The IRYT is particularly important for understanding sediment sourcing because of the potential detrimental downstream impacts of sediment-laden water. The IRYT is the headwaters for rivers that supply water to nearly 2 billion people.

This project will provide information essential for determining the life span and operation of dams currently being planned for the project area. The project is timely; it cannot be done after the dams are built, cutting off the free flow of the rivers and the free movement of sediment. Previous dam building projects in China, such as the Sanmenxia Dam on the Yellow River, have quickly fallen out of operation because of poor knowledge of the sediment load in the river and the speed at which the reservoir filled.

In addition, this project has human resources broader impacts. It will bring together an early career faculty at a top undergraduate institution, a senior researcher directing a state-of-the-art lab at an R1 institution and an early career scientist at a world-class research facility. Through the combination of a teaching/mentoring residence at Oberlin, work in UVM research labs and visits to LLNL, the project will uniquely train a PhD student interested in positions that integrate teaching and research. The project will also support undergraduate students for research-intensive summer and academic year experiences. Undergraduates will experience field work in addition to processing and analyzing samples for ^{137}Cs, ^{210}Pb, as well as meteoric and *in situ* ^{10}Be. It also provides a unique training opportunity for a graduate student studying at a relatively isolated university in western China to gain exposure to research and teaching in the United States. Although China is rapidly developing, Western China lags behind in academic opportunities, leaving universities in western China with fewer resources than those in the east.

Beyond directly mentoring students, this project will be integrated in Schmidt's teaching. For example, one of the classes Schmidt teaches, *Soils and Society*, is an introduction for non-majors to basic soil science, hillslope geomorphology, and anthropogenic impacts to these systems. Schmidt will use the results of this project as a case-study unit for the class.

This project will facilitate important international collaborations. It will continue Schmidt's existing collaboration with Liang Chuan at Sichuan University and expand that collaboration to the University of Vermont and Oberlin College, enabling stronger connections for future projects.

References

Amidon, W. H., Rood, D. H., and Farley, K. A. (2009). Cosmogenic 3He and 21Ne production rates calibrated against 10Be in minerals from the Coso volcanic field. *Earth and Planetary Science Letters* **280,** 194-204. doi: 10.1016/j.epsl.2009.01.031

Amos, C. B., Kelson, K. I., Rood, D. H., Simpson, D. T., and Rose, R. S. (2010). Late Quaternary Slip-Rate on the Kern Canyon Fault at Soda Spring, Tulare County, California. *Lithosphere* **2,** 411-417. doi: 10.1130/L100.1

Balco, G., Rood, D. H., and Purvance, M. D. (in review). Exposure dating of percariously balanced rocks. *Quaternary Geochronology*

Behr, W. M., Rood, D. H., Fletcher, K. E., Guzman, N., Finkel, R., Hanks, T. C., Hudnut, K. W., Kendrick, K. J., Platt, J. P., Sharp, W. D., Weldon, R. J., and Yule, J. D. (2010). Uncertainties in slip rate estimates for the Mission Creek strand of the southern San Andreas fault at Biskra Palms Oasis, southern California. *Geological Society of America Bulletin* **112**(9-10)**,** 1360-1377. doi: 10.1130/B30020.1

Bierman, P. R., and Steig, E. (1996). Estimating rates of denudation and sediment transport using cosmogenic isotope abundances in sediment. *Earth Surface Processes and Landforms* **21,** 125-139

Bierman, P. R., Lini, A., Brown, S., Davis, P. T., and Zehfuss, P. (1997). Fans and pond sediments record concurrent episodes of hillslope erosion. *Geological Society of America Abstracts with Programs* **29**(7)**,** A-411

Bierman, P. R., Albrecht, A., Bothner, M., Brown, E., Bullen, T., Gray, L., and Turpin, L. (1998). Weathering, erosion and sedimentation. *In* "Isotope Tracers in Catchment Hydrology." (C. Kendall, and J. J. McDonnell, Eds.), pp. 647-678. Elsevier

Bierman, P. R., Clapp, E. M., Nichols, K. K., Gillespie, A. R., and Caffee, M. (2001). Using cosmogenic nuclide measurements in sediments to understand background rates of erosion and sediment transport,. *In* "Landscape Erosion and Evolution Modeling." (R. S. Harmon, and W. M. Doe, Eds.), pp. 89-116. Kluwer, New York

Bierman, P. R., Howe, J., Stanley-Mann, E., Peabody, M., Hilke, J., and Massey, C. A. (2005). Old images record landscape change through time. *GSA Today* **15**(4)**,** 4-10

Bierman, P. R., Nichols, K. K., Sullivan, C., Duxbury, J., and Matmon, A. (2007). Little influence of grain size on cosmogenic ^{10}Be concentration in river sediment. *Geological Society of America Abstracts with Programs* **39**(6)**,** 137

Bierman, P. R., Reusser, L., and Pavich, M. (2009). New ways of using an old isotopic system – meteoric 10-Be is back and ready to do geomorphology. *In* "European Geological Union." Geophysical Research Abstracts - EGU General Assembly 2009

Borg, J. L., Bierman, P. R., Dewoolkar, M. M., Rizzo, D. M., and Rood, D. H. (in review). Meteoric 10Be adhered to suspended sediment: transport dynamics in a large New England watershed. *Journal of Geophysical Research-Earth Surface*

Brown, E. T., Stallard, R. F., Larsen, M. C., Raisbeck, G. M., and Yiou, F. (1995). Denudation rates determined from the accumulation of in situ-produced 10Be in the luquillo experimental forest, Puerto Rico. *Earth and Planetary Science Letters* **129,** 193-202

Brown, L., Pavich, M., Hickman, R. E., Klein, J., and Middleton, R. (1988). Erosion of the eastern United States observed with ^{10}Be. *Earth Surface Processes and Landforms* **13,** 441-457

Chen, G. J. (2000). Major causes of soil erosion in the Upper Yangtze River valley and the control countermeasures (in Chinese). *Rural Eco2Environment* **16**(3)**,** 5-8

Chen, X. Q., Zong, Y. Q., Zhang, E. F., Xu, E. G., and Li, S. J. (2001a). Human impacts on the Changjiang (Yangtze) River basin, China, with special reference to the impacts on the dry season water discharges into the sea. *Geomorphology* **41**(2-3)**,** 111-123

Chen, X. Q., Yan, Y. X., Fu, R. S., Dou, X. P., and Zhang, E. F. (2008). Sediment transport from the Yangtze River, China, into the sea over the Post-Three Gorge Dam Period: a discussion. *Quaternary International* **186,** 55-64

Chen, Z., Li, J, Shen, H, Wang, Z. (2001b). Yangtze River of China: historical analysis of discharge variability and sediment flux. *Geomorphology* **41**(2-3)**,** 77-91

Clapp, E., Bierman, P. R., and Caffee, M. (2002). Using ^{10}Be and ^{26}Al to determine sediment generation rates and identify sediment source areas in an arid region drainage basin. *Geomorphology* **45**(1,2)**,** 89-104

Clapp, E. M., Bierman, P. R., Nichols, K. K., Pavich, M., and Caffee, M. (2001). Rates of sediment supply to arroyos from upland erosion determined using in situ produced cosmogenic ^{10}Be and ^{26}Al. *Quaternary Research* **55**(2)**,** 235-245

Collins, B. D., Schmidt, A. H., and Harrell, S. (2011). Soil erosion, fluvial processes, and land use history in a mountainous catchment in southwest Sichuan Province, China. *In* "Association of American Geographers." Seattle, WA

Combs, J. K., Freeburg, A., Henck, A. C., Jesperson, G., Robbins, A. S. T., Rogers, H. S., Sheldon, K. S., and Wheat, E. (in review). Interdisciplinary, inter-institutional, international graduate education: a new model for training future environmental leaders. *Bioscience*

Costa, J. E. (1975). Effects of agriculture on erosion and sedimentation in the Piedmont province, Maryland. *Geological Society of America Bulletin* **86,** 1281-1286

Cox, R., Bierman, P., Jungers, M. C., and Rakotondrazafy, A. F. M. (2009). Erosion rates and sediment sources in Madagascar inferred from ^{10}Be analysis of lavaka, slope, and river sediment *Journal of Geology* **117,** 363-376. doi: 10.1086/598945

Dietrich, W. E., and Dunne, T. (1978). Sediment budget for a small catchment in mountainous terrain. *Zeitschrift für Geomorphologie Supplement* **29,** 191-206

Dietrich, W. E., Dunne, T., Humphrey, N. F., and Reid, L. M. (1982). Construction of sediment budgets for drainage basins. *In* "Sediment Budgets and Sediment Routing in Forested Drainage Basins, General Technical Report PNW-141." (F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston, Eds.), pp. 5-23. USDA Forest Service

Dole, R. B., and Stabler, H. (1909). Denudation. *USGS Water Supply Paper* **234,** 78-93

Dosseto, A., Turner, S. P., and Douglas, G. B. (2006). Uranium-series isotopes in colloids and suspended sediments: Timescale for sediment production and transport in the Murray–Darling River system. *Earth and Planetary Science Letters* **246**(3-4)**,** 418-431

Dryer, D., Gaulke, L., Henck, A., Nguyen, T., and Wheat, E. (2005). Assessing the oxygen dead zone in the Hood Canal. *Graduate Student Research Symposium, University of Washington*

Feathers, J. K., Casson, M. A., and Henck, A. (2008). Application of pulsed OSL to fine-grained samples. *In* "12th International Conferences on Luminescence and Electron Spin Resonance Dating." Beijing, China

Feathers, J. K., Casson, M. A., Henck, A., and Chithambo, M. L. (in revision). Application of pulsed OSL to fine-grained samples. *Radiation Measurements*

Feng, J. K., and He, Y. H. (2004). Nu Jiang, Lancang Jiang, and Jinsha Jiang: Researches on the Exploitation of Hydropower Resources and the Protection of the Environment. Social Sciences Academic Press (China)

Finnegan, N. J., Hallet, B., Montgomery, D. R., Zeitler, P. K., Stone, J., Anders, A., and Liu, Y. (2008). Coupling of rock uplift and river incision in the Namche Barwa-Gyala Peri massif, Tibet. *Geological Society of America Bulletin* **120**(1-2)**,** 142-155. doi: 10.1130/B226224.1

Gaulke, L., Henck, A., Nguyen, T., and Frister, S. (2005). Three pedagogical internships focusing on the internationalization of science education. *IGERT meeting*

Gaulke, L., Xiao, W. Y., Scanlon, A., Henck, A., and Hinckley, T. M. (2009). Evaluation criteria for implementation of a sustainable sanitation and wastewater treatment system at Jiuzhaigou National Park, Sichuan Province, China. *Environmental Management* **45**(1)**,** 93-104. doi: 10.1007/s00267-009-9398-1

Graly, J. A., Bierman, P. R., Reusser, L. J., and Pavich, M. J. (2010). Meteoric 10Be in soil profiles – a global meta-analysis. *Geochimica et Cosmochimica Acta*. **74**(23), 6814-6829. doi: 10.1016/j.gca.2010.08.036

Granger, D. E., Kirchner, J. W., and Finkel, R. (1996). Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediments. *Journal of Geology* **104**(3)**,** 249-257

Hassan, M. A., Church, M., Xu, J. X., and Yan, Y. X. (2008). Spatial and temporal variation of sediment yield in the landscape: Example of Huanghe (Yellow River). *Geophysical Research Letters* **35**(6)**,** L06401

Hassan, M. A., Church, M., Yan, Y. X., and Slaymaker, O. (2010). Spatial and temporal variation of in-reach suspended sediment dynamics along the mainstem of Changjiang (Yangtze River), China. *Water Resources Research* **46**, W11551. doi: 10.1029/2010WR009228

Haynes, M. (2010). Rapid climate change in NW Yunnan (A. H. Schmidt, pers. comm.)

Helz, G. R., and Valette-Silver, N. (1992). Beryllium-10 in Chesapeake Bay sediments: an indicator of sediment provenance. *Estuarine, Coastal and Shelf Science* **34**, 459-469

Henck, A., Montgomery, D. R., Hallet, B., Liang, C., and Frister, S. (2006a). Patterns of Erosion in the Three Rivers Region, China. *Eos Transactions AGU*, **87**(36), Western Pacific Geophysics Meeting Supplement, Abstract H25A-03

Henck, A., Mulligan, M. D., Frister, S., Scanlon, A., Chen, R., Hinckley, T. M., and Harrell, S. (2006b). Taking environmental science out of the classroom and into Jiuzhaigou National Park, Sichuan, China. *Geological Society of America Abstracts with Programs* **38**(7)**,** 220

Henck, A., Stone, J. O., Montgomery, D. R., and Hallet, B. (2007). Patterns of erosion in the Three Rivers Area, Eastern Tibet. *Geological Society of America Abstracts with Programs* **39**(6)**,** 183

Henck, A., Montgomery, D. R., Huntington, K. W., and Liang, C. (2009). Cryptic legacy of Chinese Communist Party policies on sediment yield in SW China and SE Tibet. *Geological Society of America Abstracts with Programs* **41**(7)

Henck, A., Montgomery, D. R., Huntington, K. W., and Liang, C. (2010a). Monsoon control of effective discharge, Yunnan and Tibet. *Geology* **38**(11)**,** 975-978. doi: 10.1130/G31444.1

Henck, A., Taylor, J., Lu, H. L., Li, Y. X., Yang, Q. X., Grub, B. L., Breslow, S. J., Robbins, A., Elliott, A., Hinckley, T. M., Combs, J., Urgenson, L. S., Widder, S., Hu, X. X., Ma, Z. Y., Yuan, Y. W., Jian, D. J., Liao, X., and Tang, Y. (2010b). Hillslope terraces and swidden agriculture in northern Sichuan, China. *Quaternary Research* **73,** 201-207

Henck, A., Montgomery, D. R., Huntington, K. W., and Liang, C. (in press). The question of Communist land degradation: new evidence from local erosion and basin-wide sediment yield in SW China and SE Tibet. *Annals of the Association of American Geographers*

Henck, A., Huntington, K. W., Stone, J. O., Montgomery, D. R., and Hallet, B. (in revision). Spatial controls on erosion in the Three Rivers Region, southwest China. *Earth and Planetary Science Letters*

Higgitt, D. L., and Lu, X. (1996). Patterns of sediment yield in the Upper Yangtze basin, China. *Erosion and Sediment Yield: Global and Regional Perspectivites* **IAHS Pub. No. 236,** 205-214

Higgitt, D. L., and Lu, X. X. (1999). Challenges in relating land use to sediment yield in the Upper Yangtze. *Hydrobiologia* **410,** 269-277

Higgitt, D. L., and Lu, X. X. (2001). Sediment delivery to the three gorges: 1. Catchment controls. *Geomorphology* **41**(2-3)**,** 143-156

Hooke, R. L. (1994). On the efficacy of humans as geomorphic agents. *GSA Today* **4**(9)**,** 217,224-225

Hooke, R. L. (2000). On the history of humans as geomorphic agents. *Geology* **28**(9)**,** 843-846

Hyde, W. F., Belcher, B., and Xu, J. T. (2003). China's Forest: Global Lessons from Market Reforms. Resources for the Future, Washington, DC. 224 pp.

IUCN, W. C. U. (2006). A report of a joint reactive monitoring mission to the Three Parallel Rivers of Yunnan Protected Areas, China. *In* "Report to the UNESCO committee."

Jansson, M. B. (2002). Determining sediment source areas in a tropical river basin, Costa Rica. *Catena* **47,** 63-84

Jing, K. (2002). Sediment delivery ratio in the Upper Yangtze River (in Chinese). *Journal of Sediment Research* **1,** 53-59

Judson, S., and Ritter, D. (1964). Rates of regional denudation in the United States. *Journal of Geophysical Research* **69**(16)**,** 3395-3401

Jungers, M. C., Bierman, P. R., Matmon, A., Cox, R., Pavich, M., and Finkel, R. C. (2009). In Situ-produced vs. Meteoric 10Be in Hillslope Soils: One Isotope, Two Tracers, Different Stories. *In* "American Geophysical Union." San Francisco

Kaste, J. M., Heimsath, A. M., and Bostick, B. C. (2007). Short-term soil mixing quantified with fallout radionuclides. *Geology* **35**(3)**,** 243-246

Kirchner, J. W., Finkel, R. C., Riebe, C. S., Granger, D. E., Clayton, J. L., King, J. G., and Megahan, W. F. (2001). Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. *Geology* **29**(7)**,** 591-594

Lal, D., and Peters, B. (1967). Cosmic ray produced radioactivity on the earth. *In* "Handbuch der Physik." (K. Sitte, Ed.), pp. 551-612. Springer-Verlag, New York

Lal, D. (1988). In situ-produced cosmogenic isotopes in terrestrial rocks. *Annual Reviews of Earth and Planetary Science* **16,** 355-388

Lal, D. (1991). Cosmic ray labeling of erosion surfaces; in situ nuclide production rates and erosion models. *Earth and Planetary Science Letters* **104**(2-4)**,** 424-439

Li, L., Wang, Z. Y., Qin, N. S., and Ma, Y. C. (2004). Analysis of the relationship between runoff amount and its impacting factor in the upper Yangtze River (in Chinese). *Journal of Natural Resources* **19**(6)**,** 694-700

Liu, Y., and Zhang, P. (1995). Surface erosion in Upper Yangtze region and river sediment transport (in Chinese). *Journal of Yangtze River Scientific Research Institute* **12**(1)**,** 40-44

Lu, H. L., Henck, A., Taylor, J., and Li, Y. X. (2010). Archaeological research at a Han Dynasty settlement in Jiuzhaigou National Park, Sichuan. *In* "Society of American Archaeologists." St. Louis, MO

Lu, X. X., and Higgitt, D. L. (1998). Recent changes of sediment yield in the Upper Yangtze, China. *Environmental Management* **22**(5)**,** 697-709

Lu, X. X., and Higgitt, D. L. (1999). Sediment yield variability in the Upper Yangtze, China. *Earth Surface Processes and Landforms* **24**(12)**,** 1077-1093

Lu, X. X., and Higgitt, D. L. (2000). Estimating erosion rates on sloping agricultural land in the Yangtze Three Gorges, China, from caesium-137 measurements. *Catena* **39**(1)**,** 33-51

Lu, X. X., and Higgitt, D. L. (2001). Sediment delivery to the Three Gorges 2: Local response. *Geomorphology* **41**(2-3)**,** 157-169

Lu, X. X., Ashmore, P., and Wang, J. (2003a). Sediment yield mapping in a large river basin: the Upper Yangtze, China. *Environmental Modelling & Software* **18**(4)**,** 339-353

Lu, X. X., Ashmore, P., and Wang, J. F. (2003b). Seasonal water discharge and sediment load changes in the Upper Yangtze, China. *Mountain Research and Development* **23**(1)**,** 56-64

Lu, X. X., and Siew, R. Y. (2006). Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams. *Hydrology and Earth System Sciences* **10**(2)**,** 181-195

Magee, D. (2006). Powershed Politics: Hydropower and Interprovincial Relations under Great Western Development. *The China Quarterly* **185**, 23-41

Ministry of Hydrology, PRC (1962-1989). "Zangdian Guoji Heliu Shuiwen Ziliao (District 9 Region 2 1947-1987) (in Chinese)." Yunnansheng Shuiwen Zongzhan Geming Weiyuanhui Kanyin

Ministry of Water Conservancy and Electric Power, PRC (1962). "National Standards for Hydrological Survey (in Chinese)." China Industry Press, Beijing

Ministry of Water Conservancy and Electric Power, PRC (1975). "Handbook for Hydrological Survey (in Chinese)." Water Conservancy and Electric Power Press, Beijing

Nichols, K. K., Bierman, P. R., Caffee, M., Finkel, R., and Larsen, J. (2005). Cosmogenically enabled sediment budgeting. *Geology* **33**(2)**,** 133-136

Niemi, N. A., Oskin, M., Burbank, D. W., Heimsath, A. J. M., and Gabet, E. J. (2005). Effects of bedrock landslides on cosmogenically determined erosion rates. *Earth and Planetary Science Letters* **237**(3)**,** 480-498

Olley, J. M., Murray, A. S., Mackenzie, D. H., and Edwards, K. (1993). Identifying Sediment Sources in a Gullied Catchment Using Natural and Anthropogenic Radioactivity. *Water Resources Research* **29**(4)**,** 1037-1043

Pavich, M. J., Brown, L., Harden, J. W., Klein, J., and Middleton, R. (1986). 10Be distribution in soils from Merced River terraces, California. *Geochimica et Cosmochimica Acta* **50**(8)**,** 1727-1735

Pearce, A. R., Bierman, P. R., Druschel, G. K., Massey, C., Rizzo, D. M., Watzin, M. C., and Wemple, B. C. (2010). Pitfalls and successes of developing an interdisciplinary watershed field science course. *Journal of Geoscience Education* **58**(3)**,** 213-220

Perg, L. A., Anderson, R. S., and Finkel, R. C. (2001). Use of a new ^{10}Be and ^{26}Al inventory method to date marine terraces, Santa Cruz, California, USA. *Geology* **29**(10)**,** 879-882

Portenga, E. W., Bierman, P. R., and Reusser, L. J. (in review). Understanding earth's eroding surface with Be-10. *GSA Today*

Reusser, L. J., Bierman, P. R., Pavich, M. J., Zen, E.-a., Larsen, J., and Finkel, R. (2004). Rapid Late Pleistocene incision of Atlantic passive-margin river gorges. *Science* **305,** 499-502

Reusser, L. J., Bierman, P. R., Pavich, M., Larsen, J., and Finkel, R. (2006). An episode of rapid bedrock channel incision during the last glacial cycle, measured with ^{10}Be. *American Journal of Science* **306**(2)**,** 69-102. doi: 10.2475/ajs.306.2.69

Reusser, L. J., and Bierman, P. R. (2007). Accuracy assessment of LiDAR-derived DEMs of bedrock river channels: Holtwood Gorge, Susquehanna River. *Geophysical Research Letters* **34**(23) L23S06. doi: 10.1029/2007GL031329

Reusser, L. J., and Bierman, P. R. (2010). Using meteoric 10Be to track fluvial sand through the Waipaoa River basin, New Zealand. *Geology* **38**(1)**,** 47-50. doi: 10.1130/G30395.1

Reusser, L. J., Graly, J., Bierman, P., and Rood, D. (2010). Calibrating a long-term meteoric 10Be accumulation rate in soil. *Geophysical Research Letters* **37**, L19403. doi: 10.1029/2010GL044751

Riebe, C. S., Kirchner, J. W., Granger, D. E., and Finkel, R. C. (2001). Minimal climatic control on erosion rates in the Sierra Nevada, California. *Geology* **29**(5)**,** 447-450

Rood, D. H., Hall, S., Guilderson, T. P., Finkel, R. C., and Brown, T. A. (2010). Challenges and opportunities in high-precision Be-10 measurements at CAMS. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms* **268**(7-8)**,** 730-732. doi: 10.1016/j.nimb.2009.10.016

Rood, D. H., Burbank, D. W., and Finkel, R. C. (in press-a). Chronology of glaciations in the Sierra Nevada, California from 10Be surface exposure dating. *Quaternary Science Reviews*. doi: 10.1016/j.quascirev.2009.11.031

Rood, D. H., Burbank, D. W., and Finkel, R. C. (in press-b). Spatiotemporal patterns of fault slip rates across the central Sierra Nevada Frontal Fault Zone. *Earth and Planetary Science Letters*. doi: 10.1016/j.epsl.2010.11.006

Safran, E. B., Bierman, P. R., Aalto, R., Dunne, T., Whipple, K. X., and Caffee, M. (2005). Erosion rates driven by channel network incision in the Bolivian Andes. *Earth Surface Processes and Landforms* **30**(8)**,** 1007-1024

Scherler, D., Bookhagen, B., Strecker, M. R., Blanckenburg, F. v., and Rood, D. (2010). Timing and extent of late Quaternary glaciation in the western Himalaya constrained by 10Be moraine dating in Garhwal, India. *Quaternary Science Reviews* **29,** 815-831. doi: 10.1016/j.quascirev.2009.11.031

Shapiro, J. (2001). Mao's War Against Nature: Politics and the Environment in Revolutionary China. Cambridge University Press, Cambridge. 287 pp.

Tan, L. C., Cai, Y. J., Cheng, H., An, Z. S., and Edwards, R. L. (2009). Summer monsoon precipitation variations in central China over past 750 years derived from a high-resolution absolute-date stalagmite. *Palaeogeography Palaeoclimatology Palaeoecology* **280,** 432-439

Taylor, J., Henck, A., Li, Y. X., Lu, H. L., and Yang, Q. X. (2008). Interdisciplinary, international research at the Asano Archaeological Site, Jiuzhaigou National Park, Sichuan, China. *In* "Society of American Archaeologists." Vancouver, Canada

Trac, C. J., Harrell, S., Hinckley, T. M., and Henck, A. (2007). Reforestation programs in Southwest China: reported success, observed failure, and the reasons why. *Journal of Mountain Science* **4**(4)**,** 275 - 292

Trimble, S. W. (1977). The fallacy of stream equilibrium in contemporary denudation studies. *American Journal of Science* **277,** 876-887

Urgenson, L. S., Harrell, S., Hinckley, T. M., Hagmann, R. K., Grub, B. L., Henck, A., Chi, P. M., and Shepler, S. J. (2010). Social-ecological dynamics of a forested watershed in SW China. *Society and Ecology* **15**(4)**,** 2

USGS. (2001). Global GIS database: digital atlas of South Asia. *In* "Global GIS Database, Digital Data Series DDS-62-C." (J. P. Hearn, T. Hare, P. Schruben, D. Sherrill, C. LaMar, and P. Tsushima, Ed.). USGS

USGS. (2008). Eurasia land cover characteristics data base version 2.0. *In* "Global Land Cover Characterization." (USGS, Ed.)

Valette-Silver, J. N., Brown, L., Pavich, M. J., Klein, J., and Middleton, R. (1986a). Detection of erosion events using 10Be profiles; example of the impact of agriculture on soil erosion in the Chesapeake Bay area (U.S.A.). *Earth and Planetary Science Letters* **80**(1-2)**,** 82-90

Valette-Silver, J. N., Tera, F., Klein, J., and Middleton, R. (1986b). ^{10}Be in geothermal systems. *In* "Geothermal energy; a milestone year Transactions - Geothermal Resources Council 10 (1986)." (G. K. Crane, and chairperson, Eds.), pp. 161-166. Geothermal Resources Council, Davis, CA

von Blanckenburg, F. (2005). The control mechanisms of erosion and weathering at basin scale from cosmogenic nuclides in river sediment. *Earth and Planetary Science Letters* **237**(3-4)**,** 462-479

Wallbrink, P. J., and Murray, A. S. (1993). Use of fallout radionuclides as indicators of erosion processes. *Hydrological Processes* **7,** 297-304

Walling, D. E. (1983). The sediment delivery problem. *Journal of Hydrology* **65**(1-3)**,** 209-237

Walling, D. E., and Woodward, J. C. (1992). Use of radiometric fingerprints to derive information on suspended sediment sources. *Erosion and Sediment Transport Monitoring Programmes in River Basins* **210,** 153-163

Wang, J., Bai, S. B., Liu, P., Li, Y. Y., Gao, Z. R., Qu, G. X., and Cao, G. J. (2009). Channel sedimentation and erosion of the Jiangsu reach of the Yangtze River during the last 44 years. *Earth Surface Processes and Landforms* **34,** 1587-1593. doi: 10.1002/esp.1841

Wang, S. J., Hassan, M. A., and Xie, X. P. (2006). Relationship between suspended sediment load, channel geometry and land area increment in the Yellow River Delta. *Catena* **65**(3)**,** 302-314

Wang, Y. T., and Wang, Z. (1998). Upper Yangtze water resources administration and neglect (in Chinese). *Economic Change***,** 108-110

Wang, Z. Y., Huang, W. D., and Li, Y. T. (2007a). Sediment budget of the Yangtze River. *Journal of Sediment Research* **2,** 1-10

Wang, Z. Y., Li, Y. T., and He, Y. P. (2007b). Sediment budget of the Yangtze River. *Water Resources Research* **43,** 14

Whiting, P. J., Bonniwell, E. C., and Matisoff, G. (2001). Depth and areal extent of sheet and rill erosion based on radionuclides in soils and suspended sediment. *Geology* **29**(12)**,** 1131-1134

Winkler, D. (1996). Forests, forest economy and deforestation in the Tibetan Prefectures of west Sichuan. *Commonwealth Forest Review* **75,** 296-301

Xu, J. X. (2000). Runoff and sediment variations in the upper reaches of Changjiang River and its tributaries due to deforestation (in Chinese). *Shuili Xuebao* **1,** 72-80

Xu, J. X. (2005). Variation in grain size of suspended load in upper Changjiang River and its tributaries by human activities (in Chinese). *Journal of Sediment Research* **3,** 8-16

Yang, G. F., Chen, Z. Y., Yu, F. L., Wang, Z. H., Zhao, Y. W., and Wang, Z. Q. (2007). Sediment rating parameters and their implications: Yangtze River, China. *Geomorphology* **85**(3-4)**,** 166-175

Yi, Z. W. (2003). Upper Yangtze River sediments (in Chinese). *Sichuan Shuili* **5,** 29-32

Yin, H. F., and Li, C. G. (2001). Human impact on floods and flood disasters on the Yangtze River. *Geomorphology* **41**(2-3)**,** 105-109

Young, N. E., Briner, J. P., Steward, H. A. M., Axford, Y., Csatho, B., and Rood, D. H. (in press). The response of Jakobshavn Isbrae to Holocene climate change. *Geology*. doi: 10.1130/G31399.1

Zhang, X. B. (1999). Status and causes of sediment change in the Upper Yangtze River and sediment reduction measures **-** comparison of Jialing River with Jinsha River (in Chinese). *Soil Water Conservation in China* **2,** 22-24

Zhang, X. B., and Wen, A. B. (2002). Variations of sediment in upper stream of Yangtze River and its tributary (in Chinese). *Shuili Xuebao* **4,** 56-59

Zhang, X. B., and Wen, A. B. (2004). Current changes of sediment yields in the upper Yangtze River and its two biggest tributaries, China. *Global and Planetary Change* **41**(3-4)**,** 221-227