UNDERSTANDING MODERN LANDSCAPE BEHAVIOR THROUGH ANALYSIS OF COSMOGENIC ^{10}BE AND SHORT-LIVED ISOTOPES IN FLUVIAL SEDIMENT

A Progress Report Presented

by

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I. Introduction

Humans have become one of the most effective geomorphic agents on the planet, altering 54% of the total land area on Earth, with agriculture and forestry accounting for 47% of that alteration (Hooke, 2012). By some estimates, humans move more earth materials annually than any other geomorphic process, including mountain building (Hooke, 1994). Through agriculture, forestry, urbanization and development, and mineral extraction, humans disturb and redistribute massive quantities of sediment that, undisturbed by humans, would otherwise be subject to significantly slower and more diffuse geomorphic processes. Sediment newly mobilized by humans on the surface quickly enters river systems or short-term colluvial storage (e.g. Trimble, 1977) and can directly impact society's ability to produce food, source drinking water, and build communities, as well as degrade the health of natural ecosystems (Foley et al., 2005; Fürst et al., 2013).

Characterizing the difference between background erosion rates prior to human modification and current erosion rates is critical to understanding the magnitude and types of impacts humans have on the landscape. Background rates of erosion occurring on the 1,000 to 100,000 year time scale provide a benchmark from which to more accurately understand the relative influence of human activity. My research seeks to use modern sediment-associated isotopic methods, up to 23 years of daily sediment yield data, and remotely sensed land-use information to characterize background rates of erosion, modern erosion rates and patterns, and the effect of land-use on erosion. My field area is within the Mekong River system, Yunnan province, SW China (Figure 1), and my field sites are three drainage basins (200, 1000, and 2000 km^2 in area).

Each isotope that I am using integrates a unique period of time, allowing me to address background and modern erosion rates (Figure 2). Beryllium-10 is a rare isotope widely used to determine background erosion rates (*in situ*) and soil loss rates (meteoric), and cesium-137 and unsupported lead-210 (collectively referred to as short-lived isotopes) have been widely used to assess shallow soil erosion in the past ~50-200 years (Figure 3).[*]

II. Research Questions

I am addressing four geologically and societally relevant questions (Table 1): (1) Where on the landscape is the sediment found in rivers coming from? For example, do certain sub-basins contribute proportionately more sediment than others, and if so, can I determine why? (2) How did the rate of erosion change from background, pre-human conditions to modern times? Are modern erosion rates similar, higher, or lower than background rates? (3) What are the primary types of erosion currently occurring? Do specific types of erosion, such as landslides or gullying, dominate certain basins and if so, is erosion type related to current land-use? (4) How efficiently is sediment exported from upland basins to main-stem trunk streams? Do we see changes in erosion rates from background to modern reflected in the daily sediment yield record?

III. Work Completed to date

III-i. Field Work

After extensive GIS planning in spring 2013, I traveled to Yunnan province, SW China with collaborators from UVM, Oberlin College, and Sichuan University to conduct fieldwork. We collected a total of 78 discrete samples between May 21, 2013 and June 13, 2013 at field sites throughout the three basins. Samples were collected from active channel deposits, terraces, and soil pits (Table 2). At some active channel sample sites we found abandoned fluvial terraces

[*] For a more detailed description of the properties of each isotope that make it useful for studying erosion please refer to my thesis proposal.

containing buried wood and charcoal. In these instances we collected buried wood or charcoal to determine deposition age through ^{14}C dating and sediment from the same horizon to calculate a "paleo" background erosion rate using *in situ* ^{10}Be.

We sampled at locations as close to the sites chosen during planning as possible. Occasionally, however, we were forced to move or eliminate sample locations if we were unable to access the pre-selected site or if conditions in the stream channel were un-representative of the landscape (e.g. the channel was full of sewage or made solely of concrete). Each sample site was documented with written notes regarding channel characteristics, surrounding geomorphic features, and land-use. Each site was photographed and has GPS coordinates to accurately locate it (Figure 4).

Soil pit locations, which were not defined during the planning phase, were selected after we had spent several days in the basin. This allowed us to estimate, to the best of our abilities, what type of landscape was least disturbed, thereby providing the most informative soil pit sample. Soils were highly variable, and detailed notes, photographs, and graphic logs were generated at each site. Samples for ^{137}Cs and unsupported ^{210}Pb were collected at 5-cm increments to a depth of 30-cm, and meteoric ^{10}Be samples were collected at 30-cm increments to the maximum depth of the pit (at least 60 cm).

All field notes, photographs, and sample locations have been compiled and sorted based on sample ID. Back-up copies of field notes and photos were generated in the field in case of equipment failure.

III-ii. Laboratory work

Prior to fieldwork in spring 2013, I learned the laboratory procedure for extracting meteoric ^{10}Be while processing archived samples for a preliminary data set of 35 samples. Upon returning from fieldwork in June, I began preparing quartz from 2013 samples for *in situ* ^{10}Be measurement at UVM; quartz purification is now complete. In September 2013, I was trained and then began extracting beryllium from *in situ* samples and as of November 18, 2013 fifty samples have been extracted. The remaining twenty will be complete by December 20, 2013.

In October 2013, I traveled to Glasgow, Scotland to learn the method for measuring ^{10}Be with Dylan Rood at the Scottish Universities Environmental Research Centre's (SUERC) accelerator mass spectrometer facility. While there, I helped to complete 20 of 133 total ^{10}Be measurements. Oberlin College undergraduates working with Amanda Schmidt have measured 28 of 65 ^{137}Cs and unsupported ^{210}Pb samples and have completed analyses for one of the watersheds.

III-iii. Presentation of research

I joined 8,000 geologists at the annual national Geological Society of America meeting in Denver, CO in October to present my research to-date and the approach I intend to take to distinguish modern, human-associated erosion from background erosion. I presented my work in poster form in the special session *Quaternary Geology and Geomorphology: Past, present, and future* (Neilson et al., 2013).

IV. Preliminary data and results

I have begun to address my research questions, both generally through field observations made during fieldwork and specifically through isotopic analysis of archived samples from the Yangtze, Mekong, and Salween rivers in the Three Rivers Region, adjacent and to the north of the sites visited in 2013.

IV-i. Field observations

In my field area, all three basins were under intensive and variable land-use; the dominant land-use was generally agriculture or forestry. Crops were cultivated on slopes up to 30 degrees; the method of cultivation varied from terraces to fall line parallel rows with no means of retaining soil. Many stream channels were sediment-choked, particularly in small upland basins, and main-trunk streams were very turbid (Figure 5). We saw few, if any, undisturbed areas in any of the basins, including forested areas, which generally appeared to consist of young trees, suggesting wide-spread logging in the recent past followed by reforestation. All field observations seem to indicate that the rate of modern erosion is high, and that areas with certain types of agriculture (i.e. not terraced) are likely to contribute proportionately more sediment than those with terraces or forest.

IV-ii. Preliminary data

In order to refine my skills in the laboratory and with data analysis, I have been working with data from drainage basins adjacent to my field area. Preliminary data from the adjacent Three Rivers Region, consisting of meteoric ^{10}Be samples prepared in spring 2013 at UVM, ^{137}Cs and unsupported ^{210}Pb measured at Amanda Schmidt's laboratory in Ohio, and published *in situ* ^{10}Be values (Henck et al., 2011) provide some insight into how erosion is changing over time, as well potential sources of error to address in our data from 2013.

Meteoric ^{10}Be concentration and long-term *in situ* ^{10}Be erosion rates were used to calculate erosion indices for each basin sampled (Equation 1). Erosion indices describe the ratio of meteoric ^{10}Be being exported from a basin to the ^{10}Be atmospheric delivery rate and were used by Brown et al. (1988) to characterize erosion in the Appalachian piedmont and elsewhere. Given that it is unlikely for a landscape to remain in equilibrium over the entire 1.38 My half-life of ^{10}Be, the erosion index gives a sense of the current state of a basin. If erosion rates are in equilibrium with soil production and weathering, ^{10}Be deposited on the landscape will neither accumulate in the regolith nor be depleted through erosion and the erosion index will be near 1. An erosion index of less than 1 indicates a current state of dis-equilibrium where erosion does not keep pace with the rate of soil production and weathering, while an erosion index of greater than 1 indicates a current state of dis-equilibrium where erosion outpaces soil production and weathering (Brown et al., 1988). There are, however, several complicating assumptions that are made when calculating an erosion index.

Equation 1.

$$\boldsymbol{Erosion\ Index} = \frac{\boldsymbol{Meteoric}\ ^{10}\mathbf{Be}\ \boldsymbol{leaving\ basin}}{\boldsymbol{Meteoric}\ ^{10}\mathbf{Be}\ \boldsymbol{delivery}} = \frac{\boldsymbol{Sed.Yield} * {}^{10}\mathbf{Be}\ \boldsymbol{Conc.in\ Sed.}}{\boldsymbol{Meteoric}\ ^{10}\mathbf{Be}\ \boldsymbol{Delivery} * \boldsymbol{Basin\ Area}}$$

In Brown et al.'s application of erosion indices, average annual sediment yield was estimated using sediment yield measured over a discrete time period. In my application, I use sediment yield derived from *in situ* ^{10}Be erosion rate, a long-term value reflecting millennial scale erosion. Using long-term sediment yields in conjunction with modern meteoric ^{10}Be concentrations, which may be different then the long-term average, has the potential to skew my results. Meteoric ^{10}Be delivery rate is another potential complicating factor. In my application, I estimate delivery rate based on analysis of global datasets from Graly et al. (2011) scaled using published mean annual rainfall for each basin (Henck et al., 2011). While Graly et al. find significant global trends in delivery rate, there is still substantial variability between individual locations. The final complicating issue is that of sample grain size. If ^{10}Be adsorption is not consistent across grain sizes, measuring the concentration within a single grain size fraction will not be representative of all ^{10}Be leaving the basin on sediment. To account for this, Brown et al. evaluated adsorption on five grain sizes ranging from 2 mm to <0.250 mm and determined that, while a slight difference in adsorption existed, the overall impact was negligible.

IV-iii. Results

The majority of erosion indices (88%, n=35) were below 1, with a mean of 0.58 and median of 0.55. Meteoric ^{10}Be concentrations ranged from 0.34 to 7.6 × 10^7 atoms/g (mean 2.0 × 10^7 atoms/g, median 1.5 × 10^7 atoms/g); lower than most fluvial sediment measurements made by researchers elsewhere in the world (Graly et al., 2010). Unsupported ^{210}Pb was only present in one sample, and three samples contained measurable ^{137}Cs (Figure 6). The samples containing measureable levels of short-lived isotopes had relatively low concentrations close to the detection limit of the instrument, as determined by counting statistics-derived error.

IV-iv. Interpretation

The short-lived isotopes, erosion indices and meteoric ^{10}Be appear to show differing accounts of erosion in the short versus long term. Low erosion indices, at face value, suggest relatively slow erosion and thus accumulation of meteoric ^{10}Be on the landscape in the long-term. Low concentrations of meteoric ^{10}Be relative to other studies suggest that river sediment is being derived from a landscape that is depleted in ^{10}Be. The absence of short-lived isotopes in almost all samples, and the low concentration in the few that contain measurable isotopes, indicate that the top 10 to 20 cm of the soil profile that contains the majority of the unsupported ^{210}Pb and ^{137}Cs has experienced significant erosion within the past ~50-200 years.

In order to understand the apparently conflicting results of the erosion indices and short-lived isotopes, I consider sources of uncertainty. For this archived data set, there is little sediment yield data available; however, I do have modern sediment yield data for the basins sampled in 2013 and will compare these yields and the erosion indices resulting from them to the *in situ* ^{10}Be-based erosion indices. Delivery rates of meteoric ^{10}Be are difficult to constrain, however, and will remain a potentially significant source of uncertainty. My meteoric ^{10}Be measurements were done on medium sand size sediment (0.250 - 0.850 mm) to ensure that I track the same sediment size as *in situ* ^{10}Be. Isotopes adhered to the outside of sediment grains, however, differ fundamentally from *in situ* ^{10}Be, in that they tend exhibit preference for smaller sediment grains with proportionately more surface area for sorption (Brown et al., 1988; He and Walling, 1996). Our measurements could be missing some of the total meteoric and short-lived inventories if the preference for smaller grains is strong.

While Brown et al. found relatively little variation in the grain sizes they tested, analysis of grain size dependency in short-lived isotopes from laboratory and empirical data show a significant increase in ^{137}Cs and ^{210}Pb sorption as grain size decreases, particularly in grains less than 0.250 mm (He and Walling, 1996). In order to maintain consistency in our analysis and reduce potential error across all three sediment-adhered isotopes, I will characterize the grain size dependency of meteoric ^{10}Be and short-lived isotopes in our samples during winter 2014.

V. Work remaining

As I complete lab work this winter and my data sets move toward completion I will begin modeling background erosion rates, estimating drainage network sediment mixing, and completing land-use classification. I will work with an undergraduate student of Amanda Schmidt's at Oberlin College to conduct a grain size experiment in January and February 2014 to determine the relative preferences of meteoric ^{10}Be, ^{137}Cs, and ^{210}Pb for 0.850 - 0.250, 0.250 – 0.125, 0.125 – 0.063, and <0.063 mm size fractions. In May 2014 I will travel to Oberlin to learn the method for measuring short-lived isotopes with Amanda Schmidt. Lee Corbett and an undergraduate from Oberlin College will process and measure ^{14}C at the University of California Irvine in winter 2014. Jenny Bower, a student at Oberlin College, will complete soil pit analysis in summer 2014.

VI. Time line for completion of work

Spring 2013

- Process archived meteoric ^{10}Be samples- *Completed*
- Select candidate sample sites- *Completed*
- Conduct preliminary remote sensing work- *Completed*
- Conduct Fieldwork- *Completed*

June-July 2013

- Sample inventory, send splits to Oberlin for gamma counting- *Completed*
- Quartz extraction- *Completed*

Fall 2013

- Be extraction of *in situ* samples at UVM- *In progress (complete 12/20/13)*
- Travel to SUERC to learn AMS methods, measure samples, and for research group meeting- *Completed*
- Travel to national GSA meeting to present preliminary data- *Completed*
- Present progress report

Winter 2013-2014

- Shatterbox 65 samples and extract meteoric ^{10}Be, including grain size experiment
- Meteoric and remaining *in situ* ^{10}Be samples measured at SUERC
- Begin data reduction
- Begin literature review

Spring 2014

- Begin statistical analysis of completed data set in CE 369 with Donna Rizzo
- Complete remote sensing work
- Complete Literature review and begin Methods and Results sections
- Begin working on paper for publication
- Travel to Oberlin to learn ^{137}Cs and ^{210}Pb radionuclide method and discuss results with Amanda Schmidt (and prepare paper for publication)

Summer 2014

- Complete Methods, Results, and write Discussion
- Submit paper for publication

Fall 2014

- Submit thesis
- Defend thesis and graduate

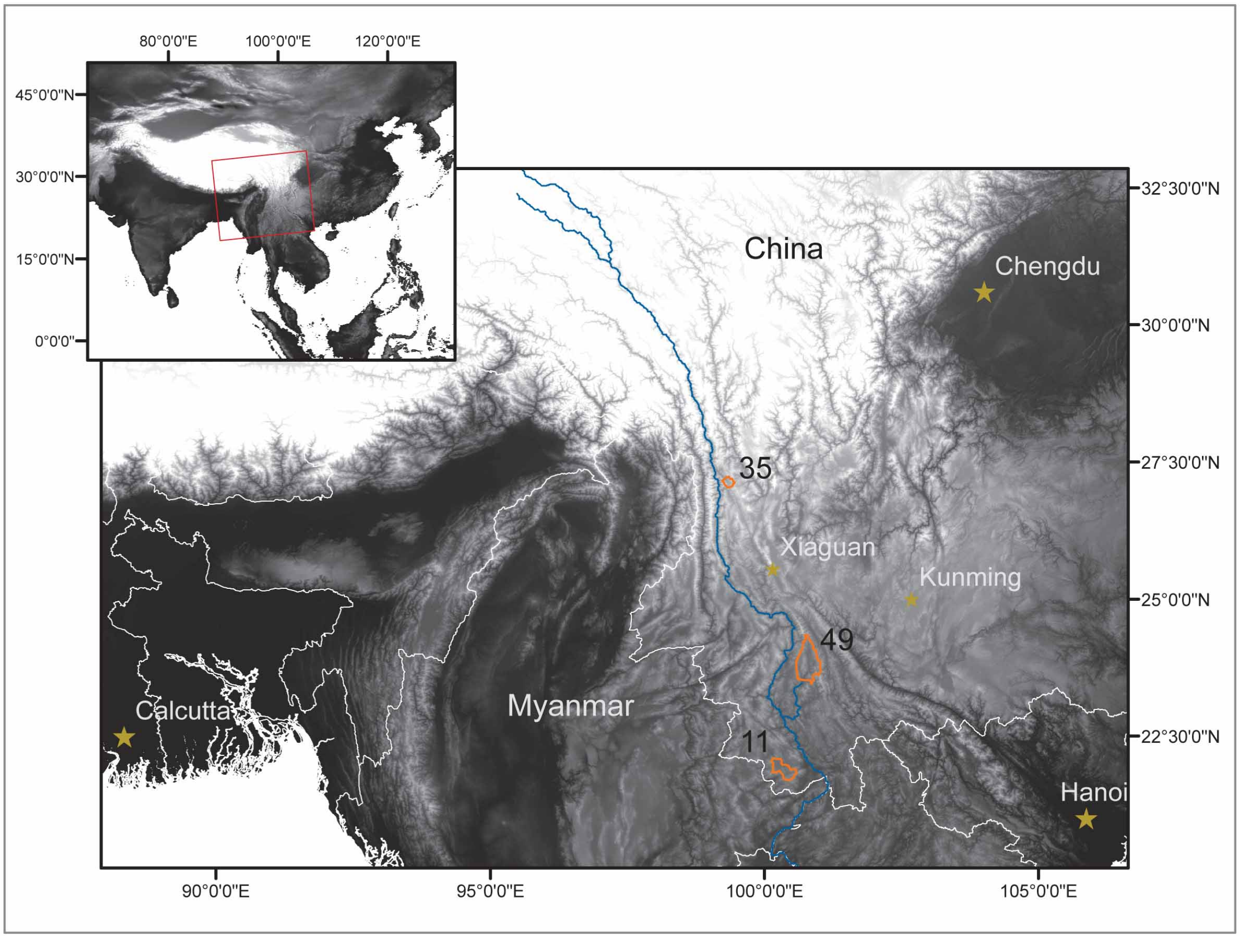


Figure 1. Map of Asia and regional map of study area showing the basins I sampled in orange (labeled 11, 35, and 49) and the Mekong River in blue.

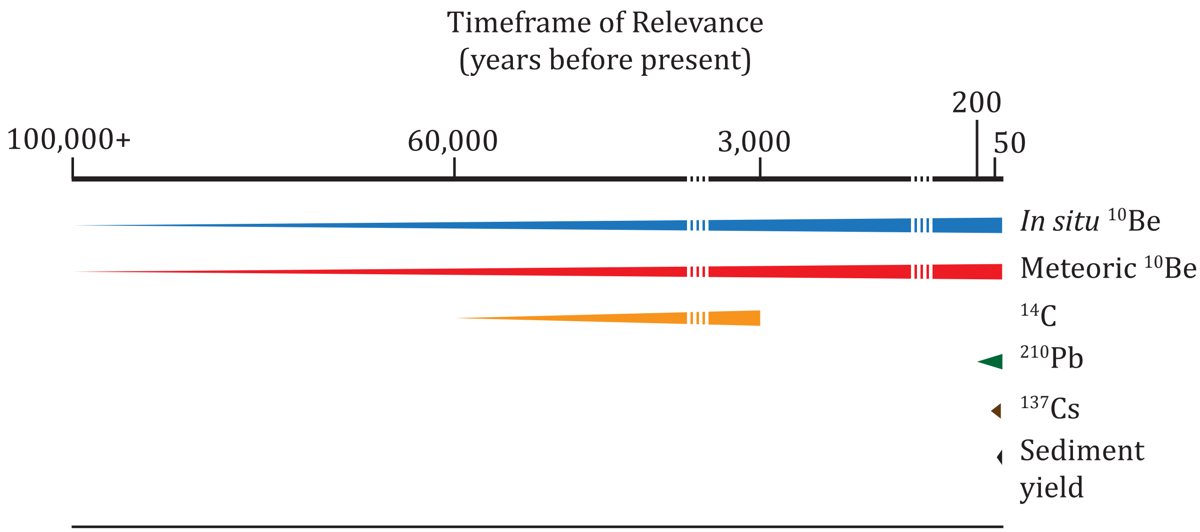


Figure 2. A general schematic showing the period of relevance for each isotopic system and sediment yield. Generally, the useful time period is defined by the half-life of the isotope and the sensitivity of instrument used; however, in the case of ^{10}Be the erosion rate controls the older end of the age range. Areas with higher erosion will shorten the time period of relevance compared to areas of slow erosion. The controlling factor for ^{137}Cs is not half-life, but rather depositional properties. Caesium-137 is the result of atmospheric nuclear weapons testing, and as such was only delivered to the landscape globally in the middle of the 20th century when atmospheric weapons testing was occurring.

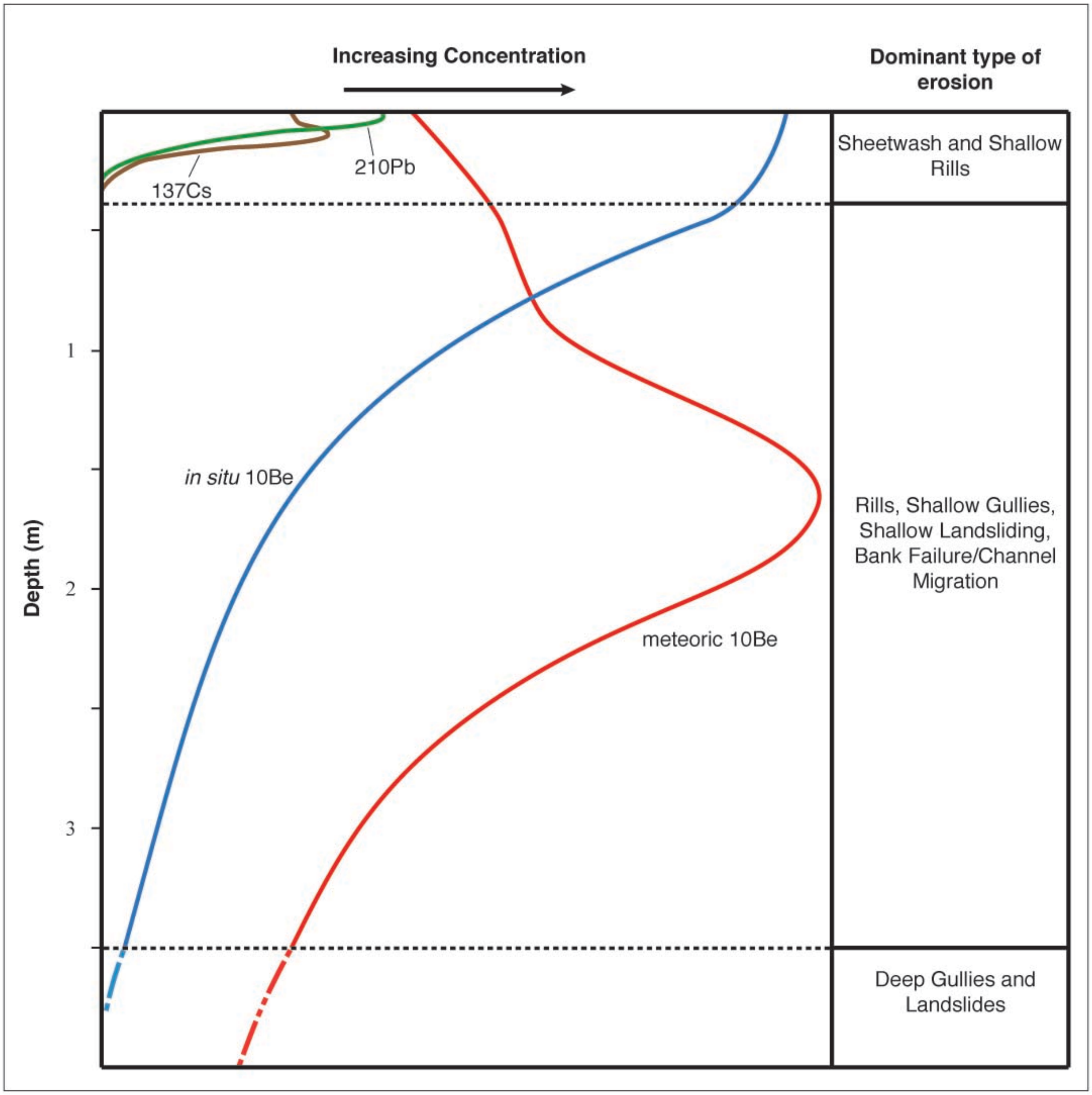


Figure 3. A conceptual plot of isotope concentration vs. depth (modified from (Pavich et al., 1986; Perg et al., 2001; Walling and Woodward, 1992) and active depth of different erosional processes. Suites of erosional processes can be inferred based on relative concentrations of each isotope in a sample (e.g. high levels of ^{137}Cs and ^{210}Pb indicate surface and shallow (<30cm) erosion). Isotope concentration (X-axis scale) is not standardized (e.g. the concentration of meteoric ^{10}Be at a given depth cannot be compared to the concentration of *in situ* ^{10}Be or ^{137}Cs at that depth)

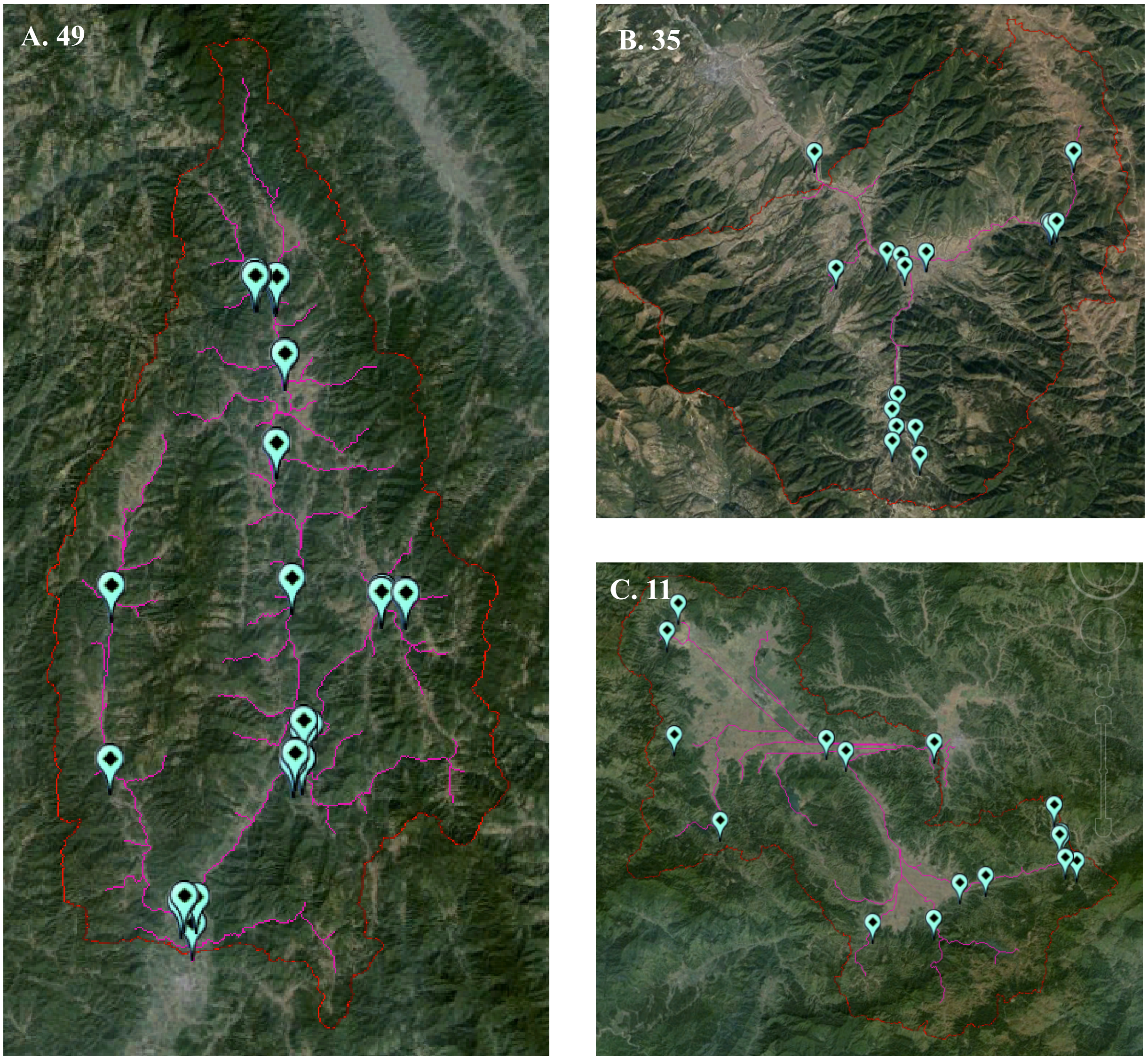
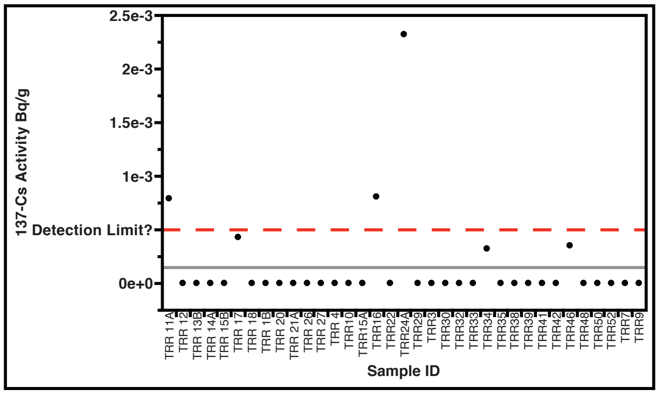


Figure 4. Satellite imagery with sample site locations in each basin. Blue balloons represent sample sites, pink lines show stream channels as modeled from digital elevation models, and the watershed boundary, also derived from digital elevation models, is shown in red. Scale is not consistent between images; A. 49 represents a ~2000 km^2 basin, B. 35 a ~200 km^2 basin, and C. 11 a ~1000 km^2 basin.

Figure 5. Photos taken during the spring 2013 field season. (A) A typical upland basin scene in heavily terraced area. Flooded terraces are built where hydraulic gradient is sufficient to provide water, and hillslopes are cleared, often up to the ridge crest, for various other crop types. (B) A typical upland basin with a sediment laden stream channel and a small agricultural field situated on a steep slope directly above the stream. (C) The outlet of a 2000 km^2 basin with active gravel mining on the point bar and river channel, agricultural fields on the terrace treads and risers, and very turbid water. This photo was taken prior to the monsoon at what is assumed to be near base-flow.

^{137}Cs concentration by sample



^{210}Pb concentration by sample

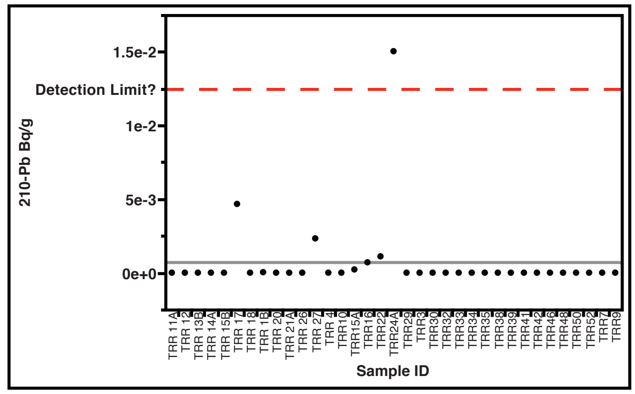


Figure 6. Plots showing concentration of ^{137}Cs and unsupported ^{210}Pb in archived samples from the Three Rivers Region. Detection limit is estimated based on counting-statistics derived error; all measurements below the detection limit line have errors too great to be considered "real" values. We are currently working to determine a more robust detection limit for the instrument.

Table 1. Data sets used to address specific research question

	1. Where is the sediment coming from?	2. How does erosion rate change over time?	3. What type of erosion is occurring in modern times?	4. How efficiently is sediment moved through rivers?
Meteoric ^{10}Be	X	X	X	X
In situ ^{10}Be	X	X	X	X
^{137}Cs and ^{210}Pb	X	X	X	X
^{14}C		X		
Sediment Yield		X		X
Land-use data	X		X	

Table 2. Analytical data that will be used in the thesis

	In situ ^{10}Be	Meteoric ^{10}Be	^{137}Cs and ^{210}Pb	Radiocarbon	**Total**
Active Channel†	58	58	58	0	174
Terrace‡	10	0	0	12	22
Soil Pit§	0	7	7	0	14
Total	68	65	65	12	210

† Active channel samples were collected from sediment in current channel deposits within rivers.

‡ Terrace samples were collected from abandoned fluvial terraces found adjacent to active channel deposits

§ Soil pits were dug in locations as close to "pristine" as possible to a depth of at least 60 cm.

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