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Efficacy of in situ and meteoric ^{10}Be mixing in fluvial sediment collected from small catchments in China

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ABSTRACT

Using measurements of *in situ* and meteoric ^{10}Be in fluvial sand to measure erosion rates, quantify soil loss, and trace sediment sources and sinks relies on the assumption that such sediment is well-mixed and representative of the upstream area. We test this assumption at 13 river junctions in three tributary watersheds (200–2500 km^2) to the Mekong River, Yunnan, China, where human alteration of the landscape is significant and widespread.

We find that two of the three watersheds mix well for *in situ* ^{10}Be and none mix well for meteoric ^{10}Be when considering the concentration of ^{10}Be at the outlet compared to the area-weighted mean of headwater samples. We also assessed mixing at 13 river junctions by comparing the erosion rate-weighted isotopic concentration of sediment taken from tributaries upstream of a junction to the concentration in a sample taken downstream of the junction. With this metric, mixing is generally poor for both *in situ* and meteoric ^{10}Be but is better for *in situ* ^{10}Be than for meteoric ^{10}Be ($p < 0.05$). This is likely because *in situ* ^{10}Be is measured in quartz, which is resilient to physical and chemical breakdown in river systems whereas meteoric ^{10}Be is measured in grain coatings which can abrade and dissolve.

Basins eroding faster (> 100 mm/kyr) tend to mix better than slowly eroding basins. We find no evidence that agricultural land use in sampled basins affects sediment mixing downstream. Mixing improves with increased basin area (particularly > 200 km^2), increased sampling distance downstream from an upstream junction (> 500 m), and increased difference in size between tributaries (one tributary > 3 times larger than the other). The most important factor affecting mixing efficacy for both *in situ* and meteoric ^{10}Be is the fraction of the basin area contributing to the downstream sample that does not contribute to the upstream samples. Junctions with > 2% of the basin area unsampled by upstream samples tend not to mix as well. Our data suggest specific sampling location strategies (such as amalgamation) likely to improve the outcome of fluvial network analysis using cosmogenic nuclides.

1. Introduction

Understanding the source and volume of sediment moving across the landscape, and the role of humans in sediment generation and transport, are fundamental issues in Earth science (NRC, 2012). To that end, isotopic measurements of in situ and meteoric ^{10}Be have been used repeatedly to quantify sediment generation and transport processes. For example, *in situ* ^{10}Be (^{10}Be$_i$), which forms in and is preferentially measured in quartz grains, is used to quantify basin-average erosion rates over 10^2–10^5 year timescales (e.g., Bierman and Steig, 1996; Brown et al., 1998; Brown et al., 1995; Granger et al., 1996; Harel et al., 2016; Hewawasam et al., 2003; Portenga and Bierman, 2011; Reusser et al., 2015; Vanacker et al., 2007).

Meteoric ^{10}Be (^{10}Be$_m$), which forms in the atmosphere, is delivered to sediment by precipitation and dryfall and is incorporated in grain-coatings. ^{10}Be$_m$ has been used to measure local soil transport rates (Jungers et al., 2009), basin-average erosion indices (a measure of soil loss) (Brown et al., 1988), trace sediment sources and sinks (Belmont

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et al., 2014; Reusser and Bierman, 2010), and, more recently, to estimate basin-average erosion and weathering rates (Rahaman et al., 2017; Wittmann and von Blanckenburg, 2016; Wittmann et al., 2007). Underlying all such calculations with both $^{10}Be_i$ and $^{10}Be_m$ is the assumption that the sediment in rivers is well-mixed and representative of the entire upstream area (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996) without overrepresentation of some basin subregions (Carretier et al., 2015b; Safran et al., 2005).

^{10}Be derived erosion rates only represent an average of the entire contributing area if the sediment flux from contributing sub-basins is proportional to the long-term rate at which sediment is shed from the landscape in each basin (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996; von Blanckenburg et al., 2012). Sampling upstream and downstream of a junction allows testing of this assumption (Stone et al., 2006). For basins ranging in area from 10^0 to 10^6 km^2, prior work using $^{10}Be_i$ has found that the area-weighted mean erosion rate of tributary catchments converges on the erosion rate calculated from the $^{10}Be_i$ concentration in sediment at the basin outlet, suggesting that sediment is well-mixed (e.g., Bierman et al., 2005; Clapp et al., 2002; Matmon et al., 2003b; Portenga et al., 2015; Wittmann and von Blanckenburg, 2016; Wittmann et al., 2009). Conversely, poorly mixed sediment was identified at junctions in smaller (< 1–30 km^2) basins and generally attributed to insufficient sample collection distance downstream of the junction, stochastic sediment supply from tributaries (e.g., localized differences in precipitation or mass-wasting), and small catchment size (Binnie et al., 2006; Savi et al., 2014). In contrast, $^{10}Be_m$ mixing has not been tested, although Reusser and Bierman (2010) showed that $^{10}Be_m$ concentration increased downstream as sediment from less disturbed basins entered the system, suggesting that tributary sediment is mixing into the main stem channel sediment.

Sediment mixing is potentially affected by the location of sample sites (hereafter, termed *unmixed* above a junction and *mixed* below a junction), stochastic events, and human influence. Basin area contributing to the mixed sample can affect mixing because larger basins tend to have erosion rates that converge on the full basin average rate as determined from smaller subbasins (e.g., Clapp et al., 2002). The distance that the mixed sample was collected below the tributary junction can affect the apparent efficacy of mixing because too short a distance may limit the ability of the river to homogenize sediment from the tributaries (Binnie et al., 2006; Savi et al., 2014). The ratio of the larger upstream tributary area to the smaller upstream tributary area can affect mixing because relatively small tributaries entering relatively large rivers do not significantly increase channel sediment load (Benda et al., 2004), thus making it likely that sediment from tributaries that are more different in size will at least appear to be well mixed.

Different erosional processes determine the grain size of sediment leaving the watershed (Brown et al., 1995; Sosa Gonzalez et al., 2016), potentially resulting in a bias in mixing efficacy when only a specific grain size is sampled (Aguilar et al., 2014; Carretier et al., 2015a). The area contributing to the mixed sample, but not to the two unmixed samples (hereafter, termed *residual area*), could affect the modeled isotopic concentration of the mixed sample because sediment from this area is not measured in unmixed samples and this residual area may be eroding at a different rate than sampled upstream basins (Portenga et al., 2015).

Stochastic events, such as debris flows, can generate waves of sediment that take time to move down the fluvial system and overwhelm other sediment as they move through (Gran and Czuba, 2017; Miller and Benda, 2000; Sutherland et al., 2002). This would, in turn, affect sediment mixing because sampled sediment would predominantly come from the sediment wave (Kober et al., 2012; Savi et al., 2014) and might not reflect the long-term behavior (and isotopic character) of the entire upstream catchment.

Human activity can affect mixing in various ways. Difference in upstream agricultural land use between two basins could increase modern sediment yield relative to the long-term sediment generation rate (e.g., Covault et al., 2013; Regard et al., 2016; Reusser et al., 2015; Von Blanckenburg et al., 2004) and thus invalidate mixing model calculations. Conversely, dams will typically reduce the sediment yield from the dammed tributary (Syvitski et al., 2005; Walter and Merritts, 2008) similarly invalidating calculations based on isotopically determined erosion rates. Dams immediately upstream of sampling sites have been found to increase apparent erosion rates derived from $^{10}Be_i$ at sample sites because sediment is mostly sourced from areas between the dam and the sample collection site (Reusser et al., 2017).

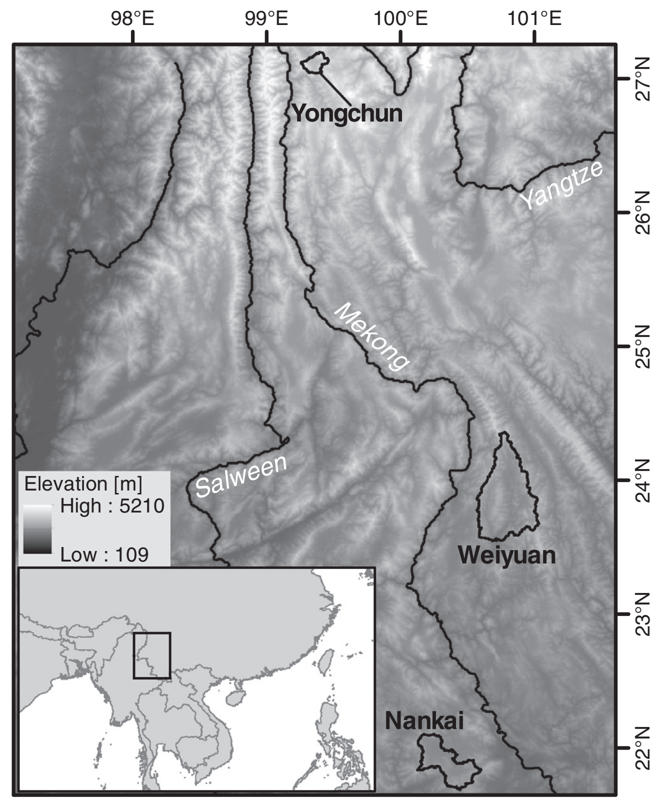

Fig. 1. Study location showing sampled basins, major regional rivers, and elevation (NASA LP-DAAC, 2012). Inset shows the region of interest within Southeast Asia.

Here, we test for thorough sediment mixing by measuring both $^{10}Be_m$ and $^{10}Be_i$ in three tributary watersheds to the Mekong River: the Yongchun (198 km^2), Weiyuan (2508 km^2), and Nankai (1006 km^2) (Fig. 1). We chose the Yongchun, Weiyuan, and Nankai Rivers based on the range in basin area, the gradient in agricultural land use, and the relative elevation of the basins. In this way, we are able to test if efficacy of mixing depends on human induced land-use change, topographic characteristics, or sampling site location (Fig. 2).

2. Field sites

The Yongchun watershed is a small (198 km^2), steep (mean slope = 19°), high-elevation watershed situated on the southeastern margin of the Tibetan plateau. In 2012, a large (~30 m tall) dam was completed in the southern arm of the Yongchun, and we observed numerous small diversion and check dams as well as out-of- and in-channel gravel mining operations. Land use in the basin consists primarily of forest, cultivated land on unterraced hillslopes, shrubland, and grassland. Although the rivers in the Yongchun watershed are relatively small, valley bottom rivers flow through Quaternary alluvium and are often braided. Headwater channels are steep with exposed bedrock. Wide-spread gravel mining has disturbed many rivers.

The Weiyuan basin is the largest of the three basins (2508 km^2) and lower in elevation than the Yongchun. Steep slopes (mean slope = 19°) generally prevail throughout the basin with gentle slopes limited to