Residence Times of Sediments in Large Rivers Quantified Using a Cosmogenic Nuclides Based Transport Model and Implications for Buffering of Continental Weathering Signals

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Abstract

The weathering of continental surfaces and the transport of sediments via rivers into the oceans is an integral part of the dynamic processes that shape the Earth's surface. To understand how tectonic and climatic forcings control regional rates of weathering, we must be able to identify their effects on sedimentary archives over geologic timescales. Cosmogenic nuclides are a valuable tool to study rates of surface processes and have long been applied in fluvial systems to quantify basin-wide erosion rates. However, in large rivers, continual processes of erosion and deposition during sediment transport make it difficult to constrain how long sediments spend within the fluvial system. In this study, we examine the role of rivers in transmitting and buffering perturbations to the continental erosional signal by constraining the timescales of fluvial transport in large rivers across the world. We apply a stochastic numerical model based on measurements of cosmogenic nuclides concentrations and calculate sediment residence times of 10ˆ4-10ˆ5 years in large rivers. These timescales are equal to or longer than climatic cycles, entailing that changes to rates of weathering brought on by climatic variations are buffered during transport in large rivers and are not manifested in the sedimentary record.

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Residence Times of Sediments in Large Rivers Quantified Using a Cosmogenic Nuclides Based Transport Model and Implications for Buffering of Continental Weathering Signals

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Key Points

- We constructed a numerical model that simulates sediment transport dynamics in large-scale fluvial systems using cosmogenic nuclides
- Examining data from four large rives across the world, we constrain sediment residence time in large rivers
- The concluded 10^4-10^5 yr timescales of sediment transport in large rivers entail buffering of climate-induced weathering signals

Abstract

The weathering of continental surfaces and the transport of sediments via rivers into the oceans is an integral part of the dynamic processes that shape the Earth's surface. To understand how tectonic and climatic forcings control regional rates of weathering, we must be able to identify their effects on sedimentary archives over geologic timescales. Cosmogenic nuclides are a valuable tool to study rates of surface processes and have long been applied in fluvial systems to quantify basin-wide erosion rates. However, in large rivers, continual processes of erosion and deposition during sediment transport make it difficult to constrain how long sediments spend within the fluvial system. In this study, we examine the role of rivers in transmitting and buffering perturbations to the continental erosional signal by constraining the timescales of fluvial transport in large rivers across the world. We apply a stochastic numerical model based on measurements of cosmogenic nuclides concentrations and calculate sediment residence times of 10^4-10^5 years in large rivers. These timescales are equal to or longer than climatic cycles, entailing that changes to rates of weathering brought on by climatic variations are buffered during transport in large rivers and are not manifested in the sedimentary record.

Plain Language Summary

Large rivers are the most effective agent for transporting sediment from the weathering continents into the oceans, with the world's biggest rivers draining nearly half of the continental surface. In this work, we calculate the time sediment spends in large rivers between weathering and deposition in four large rivers across the world. We do this by simulating the processes of sediment erosion and deposition in rivers and applying this model to new and existing data. The results of this model show that the time it takes for sand to be eroded from the source rock and transported down the river is tens to hundreds of thousands of years. These extended timescales mean that sediment transport in large rivers buffers the effect of climatic fluctuations on weathering rates. This finding can explain how seemingly contradictory evidence points to mountains eroding faster as the world cooled over the past ~40 million years, while products of erosion measured at the oceans show no significant changes during these times.

1. Introduction

The dynamic processes that shape the surface of our planet are governed by climate and tectonics, with temperature and precipitation dictating rates of weathering and rock uplift controlling erosion rates (e.g., DiBiase & Whipple, 2011; Perron, 2017). However, the influence of climate variability on denudation rates and erosion over geological timescales has been the subject of an ongoing debate. On one side, weathering rates in mountainous source regions show acceleration with the cooling climate during the Pliocene and Pleistocene (Herman et al., 2013; Peizhen et al., 2001). Conversely, records from sedimentary basins indicate that rates of sediment input into the oceans have remained stable throughout the late-Cenozoic (von Blanckenburg et al., 2015; Willenbring & von Blanckenburg, 2010). In this work, we examine sediment transport of the sand-sized fraction in four large rivers worldwide. We show how short-term ($<10^5$ yr) variations to the weathering signal at the source, such as ones brought on by climatic changes, are buffered by fluvial dynamics in large rivers and are therefore not preserved in the sedimentary record.

Transport of sediment in rivers is crucial for relating variations in long-term continental weathering rates to sedimentary archives that record climatic and tectonic events and the dynamic processes shaping the Earth's surface over geologic timescales (Armitage et al., 2011; Romans et al., 2016). Rivers are the most effective transport systems on the Earth's surface, with the world's largest rivers (with annual sediment discharge greater than ~15 megatons) draining nearly 50% of the Earth's continental surface (Milliman & Meade, 1983). To understand how the weathering signal is transferred from continental denudation to sedimentary basins, we need to consider the route that sediment takes within the fluvial transport system.

An idealized fluvial system can be divided into three parts (Schumm, 1977); the uppermost is the 'production zone', where slopes are steep, and weathering and erosion rates are high (Roering et al., 1999). Sediment is then transported downstream through the 'transport zone', an uninterrupted conduit for sediment, and is finally deposited in the sedimentary sink, the 'deposition zone' (Fig. 1). This simplified scheme is not applicable for large natural rivers, where deposition occurs intermittently during transport at the lower relief section of the 'transport zone'. In large-scale fluvial systems (with basins larger than ~$5 \cdot 10^5$ km^2), the transport zone is characterized by meandering and braiding streams, where processes such as channel bank erosion and accretion, and fluvial avulsion cause sediment to be temporarily stored in channel-bars and floodplains during transport downstream (Fig. 1; Hajek & Wolinsky, 2012; Mason & Mohrig, 2019). Continuous cycles of deposition and remobilization that occur stochastically within the transport zone have been shown to delay, buffer, and shred the weathering signal as it propagates through the fluvial system (Jerolmack & Paola, 2010; Romans et al., 2016). Constraining the timescales of sediment transport in large rivers allows a better understanding of which past environmental conditions can be reconstructed from the stratigraphic record and how (Meade, 1994; Sadler, 1981).

However, quantifying the timescales of fluvial transport in large rivers is not straightforward since the residence times of sediment, i.e., the timespan between weathering from the source until sediment accumulates in the sedimentary basin is protracted by complex fluvial dynamics of intermittent deposition and temporary burial in the transport zone (Dunne et al., 1998; Lauer & Parker, 2008; Pizzuto, 1987). The many fluvial processes acting concurrently (i.e., sediment deposition and erosion at fluvial bars, floodplains, and riverbeds) make it extensively challenging to compute these processes reliably using a physical-based model alone (Straub et al., 2020). Geochemical dating methods, such as radiocarbon ages of terrestrial organic carbon, support the premise that inland riverine systems are more than passive pipes. Dating organic matter from rivers shows longer that fluvial transport processes influence the storage of organic matter in surface deposits for timescales reaching up to millennia. These timespans indicate that sediment is transported through a series of short transport events and long pauses (e.g., Clark et al., 2013; Martin et al., 2013; Torres et al., 2017, 2020). Similarly, the timescales of weathering and transport of fine-grained clastic sediment (<63 m) measured using U-series isotopes, range from 10^3 to 10^4 yr with large variability between the sampled large rivers (Dosseto et al., 2008; Granet et al., 2010; Vigier et al., 2001). Similar storage intervals for very fine sediment were also evaluated using meteoric ^{10}Be in the alluvial lowland rivers, the lower Amazon basin, and Rio Bermejo in Argentina (Repasch et al., 2020; Wittmann et al., 2018).

Although numerous previous studies were conducted to constrain sediment transport rates and evaluate their effects on natural processes, quantifying the residence time in large rivers systems remains a challenging task. Correspondingly, applying different geochemical proxies and dating methods to quantify residence times is similarly challenging due to the stochastic transport and continuous mixing and recycling of sediments (Carretier et al., 2020). Here we offer a profound data-based evaluation of the fluvial processes that control sediment residence times. We present a stochastic numerical model simulating fluvial transport dynamics based on a compilation of cosmogenic nuclide data from four large rivers across the world. Our modeling approach acknowledges the complex randomness of transport processes exhibited in multiple burial and erosion cycles. It combines it with measurement-based exposure times using cosmogenic ^{10}Be and ^{26}Al in quartz sands. This combined approach yields better constraints on the residence time of the sand-sized fraction in large rivers, enabling us to assess the implications of fluvial transport of the sand-sized fraction transport on the buffering of continental weathering signal and the preservation of changes to environmental conditions in sedimentary archives.

1. Methods

(a) Modeling approach

The many different modeling approaches to evaluate sediment transport in rivers reflect the diverse fluvial processes that operate over a range of timescales (e.g., Carretier et al., 2020; Li et al., 2018; Pizzuto, 2020; Pizzuto et al., 2017; Straub et al., 2020). To overcome complexities arising from the different individual processes leading to sediment storage in large rivers, we constrain timescales of fluvial transport of silicate sand in large rivers using a probabilistic numerical model that computes sediment residence times based on measurements of cosmogenic ^{26}Al and ^{10}Be in modern fluvial sand. These analyses constrain a permissible family of transport times for each of the examined rivers, allowing for a quantifiable timescale for sediment transport within these rivers. To account for sediment mixing and continuous erosion, transport, and re-deposition, the model stochastically determines burial depth and time intervals (Table 1), allowing for a multitude of erosional processes varying temporally, regardless of spatial scale. Using these parameters, we calculate the production and decay of cosmogenic ^{10}Be and ^{26}Al at each time interval, dependent on the sediment burial depths. Hence, a decrease in burial depth can represent erosion from the top or dispersal and re-deposition, resulting in higher cosmogenic nuclides' production rates. Similarly, an increase in burial depth can represent deposition on top or re-deposition at a new deeper depth (and slower production rates).

This modeling approach allows us to simulate the cosmogenic nuclide concentrations produced during transport and compare them to measured concentrations from multiple sampling sites along a downstream transect from four large rivers worldwide. We examine cosmogenic ^{10}Be and ^{26}Al concentrations measured in sand-sized (125-850 m) quartz samples from transects along the lower basin of the Colorado River (Table 2), the Amazon lowlands (Wittmann et al., 2011), the Branco River, a tributary of the Amazon (Wittmann et al., 2011), and the Po River (Wittmann et al., 2016). Combining cosmogenic nuclide measurements with the modeled changes to burial depths and durations enables us to observe the effects of the different fluvial processes on sediment residence times without needing to account for spatial variations in erosional and depositional patterns or making additional assumptions regarding the various sediment transport mechanisms controlling transport in large rivers.

1. Applying cosmogenic ^{10}Be and ^{26}Al to quantify residence time

Terrestrial in-situ cosmogenic nuclides, produced within minerals at or near the surface by secondary cosmic-ray interactions, are widely applied to study surface processes by dating the exposure of surfaces and sediments, quantifying basin-wide erosion rates, and evaluating burial and deposition times (Dunai, 2010; Gosse & Phillips, 2001). Here, we examine changes to ^{10}Be and ^{26}Al concentrations measured in quartz grains produced during transport in large rivers. Generally, the total measured cosmogenic nuclide concentration in any quartz grain is the result of accumulation during bedrock erosion and downslope transport (the inherited component), and the nuclides produced during alluvial transport at varying rates depending on burial depth and duration during intermittent storage (the transport component). The inherited component depends on the rate of erosion, which can also change with time.

To account for production during erosion at the source, we assume that the ratio of ^{26}Al to ^{10}Be is consistent with production at the surface ($^{26}Al/^{10}Be$ = 6.75 in quartz, Balco et al., 2008). This assumption is reasonable even when considering the effect of slow rates of bedrock erosion on the initial $^{26}Al/^{10}Be$ ratio. In all of the source regions of the presented rivers, bedrock erosion rates are not slow and are estimated to range between 40-1350 mm/kyr (Champagnac et al., 2007; Matmon et al., 2012; Safran et al., 2005).

The other component contributing to the concentration of cosmogenic nuclides is the 'transport component', produced over multiple deposition and erosion cycles during fluvial transport and storage within the fluvial system. To account for this component, we determined the concentration of each of the measured radioactive nuclides (N) for each model time-step (i) by the production and decay rates, which can be expressed by (Dunai, 2010; Lal, 1991):

1. $N_i = N_{i-1}e^{-\lambda t_i} + \frac{P_{\text{total}}}{\lambda}\left(1 - e^{-\lambda t_i}\right),$

where N_{i-1} is the inherited concentration of the cosmogenic nuclide from the previous step, is the decay constant in yr^{-1} (with half-lives of 0.708±0.017 and 1.387±0.012 Myr for ^{26}Al and ^{10}Be, respectively, Granger, 2006), P_{total} is the production rate for both spalleogenic and muonic production at a subsurface depth z, and t is the time interval for which the sediment was buried at a depth z. For both nuclides, spalleogenic and muonic production decreases exponentially with depth (z) and can be described by:

1. $P\left(z_i\right) = P_{\text{sp}}e^{\frac{-\rho z_i}{\Lambda_{\text{sp}}}} + P_{\text{mu}}e^{\frac{-\rho z_i}{\Lambda_{\text{mu}}}},$

where is the density of the sediment (2200 $kg \cdot m^{-3}$ for quartz sand) and Λ is the attenuation length in $kg \cdot m^{-2}$ ($1.6 \cdot 10^3$ for neutron spallation [sp] and $1.5 \cdot 10^4$ for muons [mu], Balco, 2017). Production (P) is calculated for the mean latitude and elevation (Dunai, 2000) in the sampling region (Table 2). Due to the extensive nature of these fluvial systems, they cover several degrees of latitude and longitude. However, when examining possible changes in the

Amazon, Po, and Colorado rivers, these variations are negligible in the total production rate calculations.

1. Stochastic simulations

For each of the presented rivers, the initial ^{10}Be concentration (N_0) is drawn from a uniform random distribution with a maximum value equal to the lowest concentration of ^{10}Be (including uncertainty) measured in the analyzed samples, allowing us to account for erosion rates at the source. While it is likely that some of the measured ^{10}Be was produced during transport, this conservative estimation accounts for varying (slower) rates of erosion at the source as well as exposure prior to temporary deposition in the sampling location. The significance of this assumption to the model results is that calculated residence times are minimum times. Due to the complexity of sediment transport dynamics in the low relief section of the transport zone and continuous mixing, we can presume that sediment exposure time does not necessarily increase downstream. Therefore, we use the highest measured value of ^{10}Be in each river without accounting for its relative distance from the source. Based on the ^{10}Be concentration, we calculate ^{26}Al concentration given a surface production ratio in quartz (~6.75).

Burial time intervals are generated randomly using an exponential distribution so that recently deposited sediment is more likely to be eroded (Lauer & Parker, 2008; Lauer & Willenbring, 2010; Malmon et al., 2003), while burial depths are randomly chosen from a uniform distribution. These distribution types were chosen to better represent the cycle of deposition, burial, and erosion (Lauer & Parker, 2008; Lauer & Willenbring, 2010; Malmon et al., 2003; Pizzuto et al., 2017). We have chosen to use an exponential distribution to determine the burial times interval. While Torres et al. (2017) found that a Pareto distribution better describes the burial time intervals, their results suggest an exponential distribution is the next best choice. Exponential distributions are well suited for the type of model constructed here because they only depend on one parameter (µ) and allow for calibration when using small data samples.

As most previous works evaluate sediment transport times of 10^4-10^6 years (e.g., Blöthe & Korup, 2013; Carretier et al., 2020; Fülöp et al., 2020; Repasch et al., 2020), we run the model for a maximal time of 10^6 years and a maximum of 10^6 time-steps. At each model time-step, we calculate the concentrations of ^{26}Al and ^{10}Be based on nuclide-specific production at the determined burial depth and radioactive decay.

The modeled concentrations of ^{10}Be and ^{26}Al were calculated iteratively for each sampling site at each of the four examined rivers. The simulation stopped when the modeled concentrations of both nuclides were simultaneously equal to the measured concentrations within natural analytical uncertainty (see an example from the Colorado River in the Supplemental Material). If the measured value was reached, the simulation was considered "successful". For each successful run, the minimal and maximal modeled times until agreement was reached (corresponding to minimal and maximal cosmogenic measurements uncertainties) were saved. The residence time for each successful run is defined as the median between the two end results with the range as its uncertainty (see an example from the Amazon River in the Supplemental Material).

1. Sensitivity analyses and model calibration

The sensitivity of the model results to the number of simulations was tested based on one example (in the range of 1 to $10 \cdot 10^5$ simulations). The result showed that 1000 simulations were enough to reach a value within the measurement uncertainty (Fig. 2). Therefore, the model was run for each of the samples 1000 times. In each of the 1000 runs, the calculation can be considered as if it is a single grain of sand. Each of these grains has its own stochastic history with random burial depths and time intervals spent at each depth. Therefore, when examining the simulation results at a specific site, we take a thousand different grains, each with its own different history. The result is obtained from the distribution of the grains within each site.

The model was calibrated separately for each river for the parameters of the depth range of 0-50 m and time-span of 0-5000 years. The model parameters for each river were determined based on the burial and time intervals that produced the highest number of successful runs considering all the samples at each river (see figs. S3-S6 in the Supplemental Material). This way, while success rates can be lower for a specific sample at a river, the model parameters can represent the fluvial process at this specific river. Since the parameters of the random distributions are unknown, the model was calibrated so that its success rate (the ratio of successful to total runs) was maximized for all the samples together within each river, thus resulting in more universal parameters. Furthermore, since each simulation produced a different residence time, calibration using the success rate promised that the results were as reliable as in such a stochastic framework.

1. **Results**

We ran the model for 1000 runs generating 1000 stochastic samples for each of the sampling sites. Residence time for each of the rivers is presented as the range of medians from each of the samples along the river (Fig 3). The success rate was calculated for each sample as the ratio of runs yielding the measured cosmogenic nuclides' concentrations (within uncertainty) out of all model runs. The overall success rate at each river is a simple mean of all samples, with unsuccessful samples counted as 0%. At the Amazon River, four out of the five sampling sites analyzed reached the measured ^{10}Be and ^{26}Al concentrations within analytical uncertainty, except for site Ir0.4c. While both Ir0.4c and Ir0.4b were sampled at the confluence with Rio Iriri, 0.4 km from the left bank (Wittmann et al., 2011), sample Ir0.4c shows higher ^{10}Be and ^{26}Al concentrations compared to the rest of the Amazon samples. These concentrations are likely the result of natural variability in large rivers caused by stochastic transport and complex mixing dynamics. Similarly, at the Branco River, four out of the five sampling locations showed results except for Br5b sampled at the exact location as Br5c but separated for a different grain-size fraction (250-500 µm and 500-800 µm, accordingly). All three sites at the Po River and only four out of the six sites at the Lower Colorado River reached the measured ^{10}Be and ^{26}Al concentrations.

The median residence times at the different rivers vary and appear to agree with the basin size and length of the rivers. The longest median residence times were reached at the Amazon River ranging ~300-600 kyr (Fig 3), with overall similar results between the different sampling locations, except for site Par0.9a that showed shorter minimal residence times ranging from 0 years (i.e., faster than ~1000 years) and median of ~300 kyr. The Branco and Colorado rivers show similar ranges of median residence times of ~200-250 kyr and the Branco Rivers and 200-400 at the Colorado River with the exception of site PD that shows a median residence time of ~800 kyr. The minimal residence time medians were found for the Po River and range between ~20 and 35 kyr. The shorter sediment residence times in the Po River could be attributed to its smaller drainage basin and overall shorter length and proximity to the source region.

Overall, for all rivers, the high degree of freedom of the model, the relatively small range of residence times for each river together with high model success rates (65%), versus the large deviation of inter-river residence times, strengthen the validity of the model results. Additionally, the calculated ranges agree with previous evaluations of inorganic sediment storage from Himalayan Rivers (Blöthe and Korup, 2013) and, to some degree, with lag-times from the Murray-Darling basin in Australia (Fülöp et al., 2020). These results lead us to ascertain that overall residence times of ~10^4-10^5 yr reached by our model are indeed a reliable quantification.

1. Discussion

(a) Model viability

A recent analysis of cosmogenic nuclides from over 50 large rivers shows that in 65% of the examined rivers, ^{26}Al/^{10}Be ratios are within the uncertainty of the surface-production-rate ratio. In contrast, for the other 35%, ratios were significantly lower (Wittmann et al., 2020). However, since the periodic and prolonged burial of sediment at shallow depths frequently occurs within the low relief section of the transport zone, ^{26}Al/^{10}Be ratio by itself cannot resolve the actual residence time of the sediment. Thus, sediment residence times in large rivers cannot be directly evaluated using measured concentrations based on a single cosmogenic nuclide nor the calculated ^{26}Al/^{10}Be burial ages separately. Both the concentrations and their ratio must be considered simultaneously. Because nuclide production rates at or near the surface are much faster than decay rates, the overall ^{26}Al and ^{10}Be concentrations increase with residence time during shallow burial while their ^{26}Al/^{10}Be ratio will show little change. Our model shows that even small variations in the ^{26}Al/^{10}Be ratio may represent long residence times of sediments within rivers at shallow burial depths (Table 1). Our model simulates sediment transport and storage in the low relief section of the transport zone of large rivers by accounting for stochastic intermittent erosion and deposition at shallow depths and brief time intervals. Using two separate cosmogenic nuclides with different production rates and decay rates, the model can account for production with varying sediment cover and sedimentary processes, resulting in longer timescales that are more representative than simple exposure age calculations. Constraining model simulations of sediment transport dynamics with measured concentrations of cosmogenic nuclides produces a realistic determination of residence times of silicate sand in large rivers.

A potential source for variations in the cosmogenic nuclide production rates that needs to be considered are changes to the intensity and orientation of the Earth's geomagnetic field over 10^3-10^4 yr timescales (Pigati & Lifton, 2004). These changes may affect the calculated residence time in the model. For three out of the four studied fluvial systems, timescales of sediment transport are one to two orders of magnitude longer, so these variations are averaged during transport. This is not the case for the Po River, where transport is at the 10^4 yr timescale (Table 1). Yet, considering the geographical location of the Po River, changes in production rates of ^{10}Be resulting from changes in the geomagnetic field over time are smaller than 5% (Pigati & Lifton, 2004).

We, therefore, propose that the presented model provides an accurate and more realistic "age" for the sediment than the more common exposure or burial age applications of cosmogenic nuclides. We use this calculated "age" to quantify the residence time of sand-sized quartz sediment transported by large rivers.

1. Geologic implications

The timescales of sediment transport in large rivers dictate how upstream perturbations to continental weathering are communicated downstream. To distinguish signal perturbations at the outlet of a river, the intrinsic response time of the river, recorded in sediment residence times, must be significantly shorter in comparison to the perturbations themselves. Otherwise, transport in the fluvial systems will buffer the signal by the time it reaches the outlet of the river (Straub et al., 2020). Therefore, we must consider the timescales of fluvial transport compared to environmental forcings that control weathering rates. Climatic cycles, such as glacial-interglacial periods, Milankovitch cycles, and other shorter climatic oscillations, trigger large changes in temperature and precipitation that affect weathering rates (Lupker et al., 2013). However, these variations operate over timescales ranging from decades to tens of thousands of years (Abe-Ouchi et al., 2013; Fig. 5). The timescales of fluvial transport calculated here are 10^4-10^5 yr, within the same range or longer compared to climatic variations.

Prolonged sediment residence times, together with complex sedimentary dynamics in large rivers (Gärtner et al., 2020), lead to downstream signal attenuation. The implication of which is the dampening of the signal of climatic cycles (as well as uncommon short-term, $<10^5$ yr, tectonic events) on rates of weathering recorded in sedimentary archives. Conversely, as tectonic forcings primarily operate over timescales that are longer by at least an order of magnitude compared to rates of fluvial transport (Nance & Murphy, 2013), the difference in timescales entails that variations to weathering rates brought on by tectonic events will mostly be preserved in the sedimentary record.

1. **Conclusions**

The intrinsic response time of rivers manifested as sediment residence times cannot be measured directly and was previously mostly calculated from a mass balance (sediment budget) perspective. Using a stochastic model, constrained with cosmogenic nuclide data, we simulate sediment transport dynamics and produce reliable residence times for sand-sized sediment in large rivers. Results from four large rivers across the world constrain the residence time of sand in large-scale fluvial systems to 10^4-10^5 years. These prolonged sediment transport times, brought on by temporary storage of sediments within the fluvial system, lead to buffering of the perturbations in the continental weathering signal with timescales $<10^5$ yr. This observation denotes that variations to weathering rates caused by climatic cycles will be buffered by fluvial transport, reconciling the apparent conflict between variations in denudation rates at the source (Herman et al., 2013; Peizhen et al., 2001) and stability of the weathering signal preserved by sedimentary archives (von Blanckenburg et al., 2015; Willenbring & von Blanckenburg, 2010). The presented outcomes further illustrate the importance of rivers for deciphering how the different forces that impact landscape evolution are recorded in sedimentary archives and call for further examination on how climate-induced weathering signals can be implicitly deduced from sedimentary archives.

Acknowledgments, Samples, and Data

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Cosmogenic nuclide data analyzed in this study are available in the referenced published literature for the Po River (Wittmann et al., 2016) and Amazon and Branco rivers (Wittmann et al., 2011). Cosmogenic nuclide data for the lower Colorado River are available in SI Table S1.

All the codes used in this study have been described in published work and are available in the public domain. The sediment residence time model was accomplished using the MATLAB® software and is available in the Supplementary Matterial.

References

Abe-Ouchi, A., Saito, F., Kawamura, K., Raymo, M. E., Okuno, J., Takahashi, K., & Blatter, H. (2013). Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume. *Nature*, *500*(7461), 190–193. https://doi.org/10.1038/nature12374Armitage, J. J., Duller, R. A., Whittaker, A. C., & Allen, P. A. (2011). Transformation of tectonic and climatic signals from source to sedimentary archive. *Nature Geoscience*, *4*(4), 231–235.Balco, G. (2017). Production rate calculations for cosmic-ray-muon-produced 10 Be and 26 Al benchmarked against geological calibration data. *Quaternary Geochronology*, *39*, 150–173. https://doi.org/10.1016/j.quageo.2017.02.001Balco, G., Stone, J. O., Lifton, N. A., & Dunai, T. J. (2008). A complete and easily accessible means of calculating surface exposure ages or erosion rates from 10Be and 26Al measurements. *Quaternary Geochronology*, *3*(3), 174–195. https://doi.org/10.1016/j.quageo.2007.12.001von Blanckenburg, F., Bouchez, J., Ibarra, D. E., & Maher, K. (2015). Stable runoff and weathering fluxes into the oceans over Quaternary climate cycles. *Nature Geoscience*, *8*(7), 538–542. https://doi.org/10.1038/ngeo2452Blöthe, J. H., & Korup, O. (2013). Millennial lag times in the Himalayan sediment routing system. *Earth and Planetary Science Letters*, *382*, 38–46. https://doi.org/10.1016/j.epsl.2013.08.044Carretier, S., Guerit, L., Harries, R., Regard, V., Maffre, P., & Bonnet, S. (2020). The distribution of sediment residence times at the foot of mountains and its implications for proxies recorded in sedimentary basins. *Earth and Planetary Science Letters*, *546*, 116448. https://doi.org/10.1016/j.epsl.2020.116448Champagnac, J. D., Molnar, P., Anderson, R. S., Sue, C., & Delacou, B. (2007). Quaternary erosion-induced isostatic rebound in the western Alps. *Geology*, *35*(3), 195. https://doi.org/10.1130/G23053A.1Clark, K. E., Hilton, R. G., West, A. J., Malhi, Y., Gröcke, D. R., Bryant, C. L., et al. (2013). New views on "old" carbon in the Amazon River: Insight from the source of organic carbon eroded from the Peruvian Andes. *Geochemistry, Geophysics, Geosystems*, *14*(5), 1644–1659. https://doi.org/10.1002/ggge.20122Clift, P. D., & Giosan, L. (2014). Sediment fluxes and buffering in the post-glacial Indus Basin. *Basin Research*, *26*(3), 369–386.DiBiase, R. A., & Whipple, K. X. (2011). The influence of erosion thresholds and runoff variability on the relationships among topography, climate, and erosion rate. *Journal of Geophysical Research*, *116*(F4), F04036. https://doi.org/10.1029/2011JF002095Dosseto, A., Bourdon, B., & Turner, S. P. (2008). Uranium-series isotopes in river materials: Insights into the timescales of erosion and sediment transport. *Earth and Planetary Science Letters*, *265*(1–2), 1–17. https://doi.org/10.1016/j.epsl.2007.10.023Dunai, T. J. (2000). Scaling factors for production rates of in situ produced cosmogenic nuclides: a critical reevaluation. *Earth and Planetary Science Letters*, *176*(1), 157–169. https://doi.org/10.1016/S0012-821X(99)00310-6Dunai, T. J. (2010). *Cosmogenic Nuclides: Principles, Concepts and Applications in the Earth Surface Sciences*. (Intergovernmental Panel on Climate Change, Ed.). Cambridge: Cambridge University Press.Dunne, T., Mertes, L. A. K., Meade, R. H., Richey, J. E., & Forsberg, B. R. (1998). Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil. *Bulletin of the Geological Society of America*, *110*(4), 450–467. https://doi.org/10.1130/0016-7606(1998)110<0450:EOSBTF>2.3.CO;2Foreman, B. Z., & Straub, K. M. (2017). Autogenic geomorphic processes determine the resolution and fidelity of terrestrial paleoclimate records. *Science Advances*, *3*(9), e1700683.Fülöp, R. H., Codilean, A. T., Wilcken, K. M., Cohen, T. J., Fink, D., Smith, A. M., et al. (2020). Million-year lag times in a post-orogenic sediment conveyor. *Science Advances*, *6*(25), eaaz8845. https://doi.org/10.1126/sciadv.aaz8845Gärtner, A., Merchel, S., Niedermann, S., Braucher, R., Steier, P., Rugel, G., et al. (2020). Nature Does the Averaging—In-Situ Produced 10Be, 21Ne, and 26Al in a Very Young River Terrace. *Geosciences*, *10*(6), 237. https://doi.org/10.3390/geosciences10060237Gosse, J. C., & Phillips, F. M. (2001). Terrestrial in situ cosmogenic nuclides:theory and application. *Quaternary Science Reviews*, *20*, 1475–1560. https://doi.org/10.1016/S0277-3791(00)00171-2Granet, M., Chabaux, F., Stille, P., Dosseto, A., France-Lanord, C., & Blaes, E. (2010). U-series disequilibria in suspended river sediments and implication for sediment transfer time in alluvial plains: The case of the Himalayan rivers. *Geochimica et Cosmochimica Acta*, *74*(10), 2851–2865. https://doi.org/10.1016/j.gca.2010.02.016Granger, D. E. (2006). A review of burial dating methods using 26Al and 10Be. In A. M. Alonso-Zarza & L. H. Tanner (Eds.), *Special Paper 415: In Situ-Produced Cosmogenic Nuclides and Quantification of Geological Processes* (Vol. 415, pp. 1–16). Boulder, CO: Geological Society of America. https://doi.org/10.1130/2006.2415(01)Hajek, E. A., & Wolinsky, M. A. (2012). Simplified process modeling of river avulsion and alluvial architecture: Connecting models and field data. *Sedimentary Geology*, *257–260*, 1–30. https://doi.org/10.1016/j.sedgeo.2011.09.005Herman, F., Seward, D., Valla, P. G., Carter, A., Kohn, B., Willett, S. D., & Ehlers, T. A. (2013). Worldwide acceleration of mountain erosion under a cooling climate. *Nature*, *504*(7480), 423–426. https://doi.org/10.1038/nature12877Jerolmack, D. J., & Paola, C. (2010). Shredding of environmental signals by sediment transport. *Geophysical Research Letters*, *37*(19).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. https://doi.org/10.1016/0012-821X(91)90220-CLauer, J. W., & Parker, G. (2008). Modeling framework for sediment deposition, storage, and evacuation in the floodplain of a meandering river: Theory. *Water Resources Research*, *44*(4), W04425. https://doi.org/10.1029/2006WR005528Lauer, J. W., & Willenbring, J. (2010). Steady state reach-scale theory for radioactive tracer concentration in a simple channel/floodplain system. *Journal of Geophysical Research*, *115*(F4), F04018. https://doi.org/10.1029/2009JF001480Li, Q., Gasparini, N. M., & Straub, K. M. (2018). Some signals are not the same as they appear: How do erosional landscapes transform tectonic history into sediment flux records? *Geology*, *46*(5), 407–410. https://doi.org/10.1130/G40026.1Lupker, M., France-Lanord, C., Galy, V., Lavé, J., & Kudrass, H. (2013). Increasing chemical weathering in the Himalayan system since the Last Glacial Maximum. *Earth and Planetary Science Letters*, *365*, 243–252. https://doi.org/10.1016/j.epsl.2013.01.038Malmon, D. V., Dunne, T., & Reneau, S. L. (2003). Stochastic Theory of Particle Trajectories through Alluvial Valley Floors. *The Journal of Geology*, *111*(5), 525–542. https://doi.org/10.1086/376764Martin, E. E., Ingalls, A. E., Richey, J. E., Keil, R. G., Santos, G. M., Truxal, L. T., et al.

(2013). Age of riverine carbon suggests rapid export of terrestrial primary production in tropics. *Geophysical Research Letters*, *40*(21), 5687–5691. https://doi.org/10.1002/2013GL057450Mason, J., & Mohrig, D. (2019). Differential bank migration and the maintenance of channel width in meandering river bends. *Geology*, *47*(12), 1136–1140. https://doi.org/10.1130/G46651.1Matmon, A., Stock, G. M., Granger, D. E., & Howard, K. A. (2012). Dating of Pliocene Colorado River sediments: Implications for cosmogenic burial dating and the evolution of the lower Colorado River. *Geological Society of America Bulletin*, *124*(3–4), 626–640. https://doi.org/10.1130/B30453.1Meade, R. H. (1994). Suspended sediments of the modern Amazon and Orinoco rivers. *Quaternary International*, *21*, 29–39. https://doi.org/10.1016/1040-6182(94)90019-1Milliman, J. D., & Meade, R. H. (1983). World-Wide Delivery of River Sediment to the Oceans. *The Journal of Geology*, *91*(1), 1–21. https://doi.org/10.1086/628741Nance, R. D., & Murphy, J. B. (2013). Origins of the supercontinent cycle. *Geoscience Frontiers*, *4*(4), 439–448.Peizhen, Z., Molnar, P., & Downs, W. R. (2001). Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates. *Nature*, *410*(6831), 891–897.Perron, J. T. (2017). Climate and the Pace of Erosional Landscape Evolution. *Annual Review of Earth and Planetary Sciences*, *45*(1), 561–591. https://doi.org/10.1146/annurev-earth-060614-105405Pigati, J. S., & Lifton, N. A. (2004). Geomagnetic effects on time-integrated cosmogenic nuclide production with emphasis on in situ 14C and 10Be. *Earth and Planetary Science Letters*, *226*(1–2), 193–205. https://doi.org/10.1016/j.epsl.2004.07.031Pizzuto, J. (1987). Sediment diffusion during overbank flows. *Sedimentology*, *34*(2), 301–317.Pizzuto, J. (2020). Suspended sediment and contaminant routing with alluvial storage: New theory and applications. *Geomorphology*, *352*, 106983.Pizzuto, J., Keeler, J., Skalak, K., & Karwan, D. (2017). Storage filters upland suspended sediment signals delivered from watersheds. *Geology*, *45*(2), 151–154.Repasch, M., Wittmann, H., Scheingross, J. S., Sachse, D., Szupiany, R., Orfeo, O., et al. (2020). Sediment Transit Time and Floodplain Storage Dynamics in Alluvial Rivers Revealed by Meteoric 10 Be. *Journal of Geophysical Research: Earth Surface*, *125*(7). https://doi.org/10.1029/2019JF005419Roering, J. J., Kirchner, J. W., & Dietrich, W. E. (1999). Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology. *Water Resources Research*, *35*(3), 853–870.Romans, B. W., Castelltort, S., Covault, J. A., Fildani, A., & Walsh, J. P. (2016). Environmental signal propagation in sedimentary systems across timescales. *Earth-Science Reviews*, *153*, 7–29. https://doi.org/10.1016/j.earscirev.2015.07.012Sadler, P. M. (1981). Sediment accumulation rates and the completeness of stratigraphic sections. *The Journal of Geology*, *89*(5), 569–584.Safran, E. B., Bierman, P. R., Aalto, R., Dunne, T., Whipple, K. X., & Caffee, M. (2005). Erosion rates driven by channel network incision in the Bolivian Andes. *Earth Surface Processes and Landforms*, *30*(8), 1007–1024. https://doi.org/10.1002/esp.1259Schumm, S. A. (1977). *The Fluvial System*. New: John Wiley and Sons.Straub, K. M., Duller, R. A., Foreman, B. Z., & Hajek, E. A. (2020). Buffered, Incomplete, and Shredded: The Challenges of Reading an Imperfect Stratigraphic Record. *Journal of Geophysical Research: Earth Surface*, *125*(3). https://doi.org/10.1029/2019JF005079Torres, M. A., Limaye, A. B., Ganti, V., Lamb, M. P., West, A. J., & Fischer, W. W. (2017). Model predictions of long-lived storage of organic carbon in river deposits. *Earth Surface Dynamics*, *5*(4), 711–730.Torres, M. A., Kemeny, P. C., Lamb, M. P., Cole, T. L., & Fischer, W. W. (2020). Long-term storage and age-biased export of fluvial organic carbon: field evidence from West Iceland. *Geochemistry, Geophysics, Geosystems.*Vigier, N., Bourdon, B., Turner, S., & Allègre, C. J. (2001). Erosion timescales derived from U-decay series measurements in rivers. *Earth and Planetary Science Letters*, *193*(3–4), 549–563. https://doi.org/10.1016/S0012-821X(01)00510-6Willenbring, J. K., & von Blanckenburg, F. (2010). Long-term stability of global erosion rates and weathering during late-Cenozoic cooling. *Nature*, *465*, 211–214. Retrieved from https://doi.org/10.1038/nature09044Wittmann, H., von Blanckenburg, F., Maurice, L., Guyot, J. L., Filizola, N., & Kubik, P. W. (2011). Sediment production and delivery in the Amazon River basin quantified by in situ-produced cosmogenic nuclides and recent river loads. *Geological Society of America Bulletin*, *123*(5–6), 934–950. https://doi.org/10.1130/B30317.1Wittmann, H., Malusà, M. G., Resentini, A., Garzanti, E., & Niedermann, S. (2016). The cosmogenic record of mountain erosion transmitted across a foreland basin: Source-to-sink analysis of in situ 10 Be, 26 Al and 21 Ne in sediment of the Po river catchment. *Earth and Planetary Science Letters*, *452*, 258–271. https://doi.org/10.1016/j.epsl.2016.07.017Wittmann, H., Oelze, M., Roig, H., & von Blanckenburg, F. (2018). Are seasonal variations in river-floodplain sediment exchange in the lower Amazon River basin resolvable through meteoric cosmogenic 10Be to stable 9Be ratios? *Geomorphology*, *322*, 148–158. https://doi.org/10.1016/j.geomorph.2018.08.045Wittmann, H., Oelze, M., Gaillardet, J., Garzanti, E., & von Blanckenburg, F. (2020). A global rate of denudation from cosmogenic nuclides in the Earth's largest rivers. *Earth-Science Reviews*, *204*, 1–17. https://doi.org/10.1016/j.earscirev.2020.103147**Figure and Table Captions**

Figure 1. Schematic diagram of sediment transport in large-scale fluvial systems. Sediment is mostly produced in the mountainous region upstream (the Production Zone) and is transported to the depositional basin (Deposition Zone). As sediments reach the downstream low-relief section of the transport zone, they are intermittently deposited at floodplains and channel bars for varying periods and depths represented here by shades of brown. Storage in a specific point in space occurs until erosional processes remobilize and transport the sediment further downstream. These continuous erosional and depositional cycles lead to a complex storage framework of sediment within the fluvial system and make it difficult to quantify the transport time of sediments in rivers. The graph on the bottom left shows changes in sediment flux as a function of time (after Straub et al., 2020). The perturbation in sediment flux due to climate-induced increase in weathering rates at the production zone (red) is buffered when the signal reaches the deposition zone (blue) because of the

residence times of sediment in the low-relief section of the transport zone.

Figure 2. Sensitivity of the model to number of runs. Probability of the maximal calculated residence time from 1-10^5 model runs for sample CRWB (Colorado River) with burial depth 20 m and burial time 100 years. The spread of residence time of 1000 runs (purple) is smaller than the natural analytical uncertainty and therefore allows for a reliable calculation of residence times.

Figure 3. Boxplots of calculated residence times from the four examined rivers. Each box presents all calculated residence times for 1000 runs, with a maximum of 10^6 steps, and maximal run time of 10^6 yr (see specific river parameters in Table 1). The central red mark is the median, and the bottom and top blue edges of the box indicate 25^{th} and 75^{th} percentiles, respectively. The dashed whiskers extend to the most extreme data points which are not considered outliers (the presented dataset does not contain outliers).

Figure 4. Residence time of sand-sized silicate sediments in large rivers. (A) Box plot of calculated residence times and percentage of successful runs for each sample in the Branco River. See supplementary information for detailed residence times of all other rivers examined in this study (SI Table S1). (B) Map of the corresponding sampling stations along the Branco River. (C) Map showing the locations of the rivers analyzed in this work and the model results. Sediment residence time is presented as the range of medians (RM) calculated for each of the samples in a specific river. n - number of samples analyzed, and SI is the averaged success rate from all stations.

Figure 5. A comparison of timescales of fluvial transport and major tectonic and climatic variations. Timescales of fluvial transport represent sediment residence times in large rivers reported here as well as published lag times and sediment storage (Blöthe & Korup, 2013; Clift & Giosan, 2014; Fülöp et al., 2020) from large rivers across the globe. Climatic cycles are after Foreman and Straub (2017). ENSO stands for El Niño–Southern Oscillation, and NAO stands for North Atlantic Oscillation. Tectonic cycles are after Meade (1994). The timescales of fluvial transport are longer or similar to climatic variations and mostly shorter compared to tectonic variations, implying that climatic variations and short-term tectonic events will be buffered by the fluvial transport system and will not be preserved in the sedimentary record.

Table 1. Model Variables and Data

Table 2. Analytical Results of Terrestrial Cosmogenic Nuclides ^{10}Be and ^{26}Al Geochronology