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Monsoonal control on a delayed response of sedimentation to the 2008 Wenchuan earthquake

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Infrequent extreme events such as large earthquakes pose hazards and have lasting impacts on landscapes and biogeochemical cycles. Sediments provide valuable records of past events, but unambiguously identifying event deposits is challenging because of nonlinear sediment transport processes and poor age control. Here, we have been able to directly track the propagation of a tectonic signal into stratigraphy using reservoir sediments from before and after the 2008 Wenchuan earthquake. Cycles in magnetic susceptibility allow us to define a precise annual chronology and identify the timing and nature of the earthquake’s sedimentary record. The grain size and Rb/Sr ratio of the sediments responded immediately to the earthquake. However, the changes were muted until 2 years after the event, when intense monsoonal runoff drove accumulation of coarser grains and lower Rb/Sr sediments. The delayed response provides insight into how climatic and tectonic agents interact to control sediment transfer and depositional processes.

INTRODUCTION
Sedimentary archives contain valuable information about past climatic, tectonic, and human activities (1–6). Abrupt changes in sediment type, volume, and structure, as well as physical, paleontological, geochemical, and mineralogical records, have been used to identify extreme events in the past and to assess how often they occur (3–11). Sediment pulses that result from earthquake-triggered landslides have been used to reconstruct past events from lake deposits (12, 13), helping to constrain predictive tectonic models and evaluate the long-term effects of large earthquakes (14–16). However, inferences from sedimentary records are often based on the coincidence of sedimentary changes with indications (e.g., biological or geochemical) of an extreme event. The infrequency of these events means that direct observations are scarce, and the challenges in developing a precise sedimentary chronology at an annual time scale typically preclude direct age assignments for specific event layers (6, 10, 11, 14). These obstacles have inhibited full understanding of the depositional processes associated with sediment inputs triggered by extreme events and, particularly, how the event record might be modulated by climate. These interactions as manifest following individual events are also important for understanding the roles of tectonics in controlling erosion, sediment transfer, and landscape evolution (1, 17–19).

A unique opportunity to document the link between a large earthquake and its sedimentary signature is provided by continuously deposited and annually resolved sediments from the Zipingpu reservoir in Sichuan Province, China. The reservoir, behind a 156-m-high dam completed in September 2004, is fed by the Min Jiang River (with a drainage area of 22,664 km²) and is located downstream of the area affected by the 2008 moment magnitude (Mw) 7.9 Wenchuan earthquake (Fig. 1). This devastating earthquake occurred along the steep Longmen Shan mountain front at the eastern margin of the Tibetan Plateau and triggered more than 56,000 landslides in a region with limited landslide activity before the earthquake (20, 21). The total volume of earthquake-triggered landslides was estimated at ~2.8 km³ (21), with a mass (~7.4 Gt) up to four to seven times the total annual sediment export from the Himalayas (1 to 2 Gt) (22), using a density of landslide material of 2.65 g/cm³. The co- and postseismic landslides associated with the Wenchuan earthquake caused substantial changes to the rates of erosion and fluvial sediment transfer (23–25), as well as to geochemical fluxes (26) from the Longmen Shan. The Zipingpu reservoir is ideally located to record the delivery of earthquake-triggered landslide material and document the propagation of the signal from a major earthquake into a sedimentary archive.

Zipingpu reservoir core
In October 2016, a 10.89-m-long sediment core was retrieved from the central area of the Zipingpu reservoir with 100% recovery. The core reached the prereservoir riverbed, characterized by brown coarse sands and gravels. The reservoir sediments mainly consist of horizontally laminated grayish brown silt and clay. The cores were scanned for both magnetic susceptibility (MS) and elemental intensity using an Avaatech x-ray fluorescence (XRF) core scanner. Grain size and magnetic mineralogy were measured on sediment samples using a Malvern 2000 particle size analyzer and an MFKi-1A Kappabridge and vibrating sample magnetometer (VSM), respectively (see Materials and Methods).

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The sedimentary signature of the Wenchuan earthquake

Because the distinct cycles of MS and the high sedimentation rate (~74 cm/year) in the core allow precise and independent assignment of the earthquake timing within the sediment, we can directly document the depositional signature of the earthquake. Grain size of fluviolacustrine sediments is a sensitive indicator of changes in sediment transfer processes (3, 12, 27–30). The median grain size ($D_{50}$) in the Zipingpu core was relatively lower before the earthquake ($D_{50} = 9.2 \pm 0.6 \mu m$, January 2006 to May 2008), although $Q_w$ was moderately high in 2006 and 2007 (Fig. 3). Grain size shows an immediate change following the 2008 Wenchuan earthquake, with $D_{50}$ coarsening from 9.2 to 11.4 $\mu m$ (fig. S5). It is known that earthquake-triggered landslides mobilized regolith, loosened surficial material, and bedrock (31, 32), supplying coarser material to river channels (16, 33) where it was subsequently transported downstream (23, 34, 35). We thus attribute the increase in grain size at the earthquake boundary in the Zipingpu core to the delivery of this landslide material by the Min Jiang River. We also observe a drop in sedimentary Rb/Sr ratios, which likely results from a relative increase in Sr inputs (fig. S6) from fresh minerals (i.e., carbonates) by bedrock landslides (26). This immediate response is consistent with observations of changes in active fluvial sediment transport following coseismic landsliding (23, 34–36), here documented in the sediments deposited downstream. Grain size and elemental ratios do not show cycles linked to MS, indicating that the management of water level does not affect these sedimentary characteristics in the reservoir.

Delayed response of the sedimentary signal from the earthquake

Although we see a distinct sedimentary signal immediately after the Wenchuan earthquake, the most pronounced response in both grain size and Rb/Sr ratio appeared in 2010, 2 years after the earthquake (Fig. 3). In 2010, the $D_{50}$ sharply increased to a maximum of 24.2 $\mu m$, while Rb/Sr ratios dropped to their lowest values in the entire core of ~0.35. This delayed response likely reflects the discharge dynamics of the Min Jiang River; 2008 and 2009 had relatively lower peak $Q_w$ and thus lower fluvial transport capacity than other years (Fig. 3), inhibiting the transfer of earthquake-triggered landslides to the reservoir. The peak $Q_w$ in 2010 was much higher, with intense rainstorms that caused extensive debris flows (37), flooded Yingxiu town upstream of the reservoir, and resulted in >8000 resident evacuations (32). Both grain size and Rb/Sr ratios remained peaks but variable during 2010 and 2011. The delay of the sedimentary response in the reservoir highlights the importance of hydrological controls on sediment evacuation and downstream delivery following an earthquake, consistent with studies of suspended sediment evacuation from large landslides (38, 39).
concentrations and fluxes in rivers draining earthquake-affected regions (23, 34, 35).

Notably, annual reservoir sediment thickness has a statistically significant correlation ($r^2 = 0.62$) with total annual $Q_w$ (Fig. 4A), further supporting the control of monsoonal precipitation on sediment transfer in this setting. The sedimentation rate at the core site did not change systematically after the earthquake, despite changes in total fluvial sediment fluxes (fig. S7). These observations suggest that sedimentation rate at the core site, which is located at a relatively distal position within the reservoir, has been largely controlled by hydrodynamic conditions rather than upstream sediment supply. Observed changes in grain size and Rb/Sr provenance signatures, but not in sedimentation rate, suggest that sediment grain size and geochemistry may better record events than sediment thickness, at least for conditions similar to the core site studied here.

The relationship between intense runoff in the Min Jiang River and the fraction of coarse grains (>32 µm) in the reservoir sediment was altered by the earthquake (Fig. 4B). The coarse grain fraction increased with intense runoff ($r^2 = 0.71$) after the earthquake and was consistently higher than limited measurements made before the earthquake (Fig. 4B). This shift in particle size following the earthquake may indicate a change in sediment transfer regime for the >32-µm grains in the Min Jiang River, from “supply-limited” to “transport-limited” regimes (Fig. 4B) (38). Under the transport-limited regime, low $Q_w$ in 2009 resulted in limited transfer of coarse grains, whereas in 2010, high $Q_w$ facilitated enhanced sediment transport. The peak in transport capacity in 2010, reflected in the coarse grains in the reservoir core, is further supported by an eightfold increase in sediment yield in a Min Jiang tributary near the earthquake epicenter during that year (fig. S7).

After 2011, both grain size and Rb/Sr ratio returned gradually to pre-earthquake values over a time scale of ~5 to 6 years. However, much of the 2008 Wenchuan earthquake-triggered landslide debris remains visible on hillslopes and in river channels 10 years later (fig. S8). If runoff intensity reaches or exceeds 2010 levels in the future (Fig. 3), then this may create an additional sedimentary response in the reservoir. Quantifying the precise record that is left by time-varying runoff would provide important information for understanding longer-term sedimentary signatures at this location and other tectonically active mountain ranges, such as those observed in the several packages of coarser sediments that have accumulated over decades following earthquake events in New Zealand lake records (12).

**DISCUSSION**

Field data and modeling studies have revealed how sedimentation is regulated by climatic (1, 2, 18, 28) and tectonic forcings (5, 6, 12, 30, 39), but the interplay of these factors in creating the sedimentary signatures of an earthquake is typically difficult to observe and quantify directly (11, 12). Our well-dated sediment core with very high sedimentation rates, together with independent hydrometeorological data, enables us to identify the role of hydroclimatic forcing in the creation of a seismic record. The combination of these data in the observational record allows us to decode detailed annual depositional
processes associated with a single large earthquake event and, crucially, to assess the role of climate in sediment accumulation under postseismic conditions. Our results also provide modern context for other studies of event deposits, which typically lack the annual chronologic resolution needed to resolve the dynamics and evolution of a single event.

The Zipingpu core shows that the sedimentary signal of widespread inputs of landslide debris after an earthquake is likely regulated by runoff associated with the monsoonal climate. Even when a major earthquake has greatly perturbed the system and provided large amounts of landslide material to rivers (21, 31, 34, 35), the downstream signal recorded even in fairly proximal sedimentary deposits (such as the mountain-front reservoir studied here) may be muted if fluvial transport capacity is insufficient. This interplay of tectonic and climatic factors may have particular relevance for interpretation and correlation of event deposits between different locations (6, 10–14, 18, 19). For example, a major earthquake followed by a multiyear period of aridity and low fluvial transport capacity may be difficult to identify in sedimentary deposits and any record will be somewhat lagged, while an earthquake followed by intense rainfall in following years such as after the 1999 Mw 7.9 Chi-Chi earthquake (34, 35) could leave a more distinct and immediate signature.

Our results also show how the hydroclimatic control on sediment transport following an earthquake could generate the appearance of multiple “peaks” in a sedimentary record; for example, the muted change in grain size at the time of the Wenchuan earthquake is followed by a much more prominent peak a few years later, driven by intense rainfall (Fig. 3). In a paleo-archive, these multiple peaks might be mistakenly interpreted as reflecting two different earthquakes (such as a main shock/aftershock sequence or a sequence of earthquakes on adjacent fault segments), emphasizing the need to tease apart the hydroclimatic role in these records for robust interpretation.

Although hydrological filtering of an earthquake event is likely to affect sedimentary records (16, 19, 28, 29), it is notable that the seismic signal of the Wenchuan earthquake is propagated quickly and clearly in the sediment grain size and bulk elemental chemistry when evaluated in terms of the typical precision of available geochronological tools (Fig. 3). Efficient transfer of the earthquake signal into reservoir sediments is emphasized by the similar trends shown by suspended sediment yields in the Min Jiang (fig. S7) and the grain-size and geochemical records in the reservoir (Fig. 3). The identifiable fingerprint of the Wenchuan earthquake in fairly proximal mountain-front reservoir sediments shows that fine-grained sedimentary deposits are less susceptible to environmental signal shredding by the nonlinear
filters imposed by sediment transport, when compared to rates of bed load transport (16, 19, 28, 29, 40), which supports views from lacustrine records of landscape responses to large earthquakes (12).

The hydrological imprint of a large earthquake on the sedimentary record may also provide information on the sediment-related hazards that can persist for many years after the event, controlled largely by hydroclimatic conditions. Extensive storm-triggered debris flows and landslides had devastating effects in the years following the Wenchuan earthquake, particularly in 2010 (32, 37), and we find that their signature is (perhaps expectedly) recorded in the Zipingpu reservoir. If a characteristic fingerprint of these postseismic sediment pulses could be constrained from sedimentary archives, then this might shed new light on how long the associated hazards can persist (i.e., years, decades, or longer).

Our unique, well-dated sediment core in a man-made reservoir provides greater understanding of how erosion and sedimentation processes respond to an extreme event. Our results emphasize the importance of the interplay between a major earthquake and the prevailing monsoonal climate, highlighting the central role of run-off as an erosional agent in removing earthquake-triggered landslide material and in creating a depositional signal of the earthquake. The high-resolution Zipingpu record provides rare direct evidence that can inform the interpretation of palaeorecords and helps to illuminate the ways in which sedimentary archives reflect the complex interaction of tectonics and climate in controlling sediment transfer in tectonically active mountain ranges.

MATERIALS AND METHODS
Zipingpu reservoir and sediment core drilling

The Zipingpu reservoir is located at the Min Jiang River at the Longmen Shan mountain front, upstream of the Sichuan Basin (Fig. 1), with a water depth of 110 m at the highest water level and 57 m at the lowest water level in 2016. The entrance of the reservoir at the highest water level is ~2 km downstream from the epicenter of the 2008 Wenchuan earthquake (fig. S3). The reservoir forms an elongated “L” shape, with a maximum length of ~19 km and a width of ~2.1 km at its highest water level. The location of the reservoir means that it captures a significant portion of the landslide material associated with the 2008 Wenchuan earthquake. According to the records from the Zipingpu Reservoir Company, the Min Jiang River channel was intercepted on 15 June 2008 due to the influence of climate change on erosion rates.

For grain size analyses, a total of 648 samples were collected at 2-cm core intervals. The samples were pretreated by adding 10% H2O2 and 10% HCl to remove organic matter, carbonate, and iron oxides and were dispersed with NaPO3 in an ultrasonic bath before grain size measurement. The grain size distribution was measured by a Malvern 2000 laser diffraction instrument with 100 bins ranging from 0.02 to 2000 μm in the IEECAS. The analytical error of median grain size is better than ~2%, based on repeated measurements of samples.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/6/eaav7110/DC1

SUPPLEMENTARY MATERIALS AND METHODS: Magnetic mineralogy

Fig. S1. χ-T curves of representative samples.
Fig. S2. Hysteresis loops of representative samples from the Zipingpu sediment core.
Fig. S3. Seasonal water level difference of the Zipingpu reservoir.
Fig. S4. Difference in MS of topmost 60-cm sediments of cores A and B from the Zipingpu reservoir.
Fig. S5. Grain size distributions of the Zipingpu core sediments around the earthquake.
Fig. S6. Correlation of Rb/Sr ratio versus Sr content.
Fig. S7. Interannual variations of daily runoff (>3 mm/day; orange crosses), daily (gray dots), and annual (blue dots) suspended particulate material yield at the Guojia hydrological station on the Shouxi River before and after the Wenchuan earthquake.
Fig. S8. Remaining seismic landslides within the catchment after ten years since the earthquake.
Fig. S9. Difference in suspended sediment fluxes versus river water discharge (Qw) between two typical tributaries within the Min Jiang Basin during the period of 2006–2012.

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