Eastern margin of Tibet supplies most sediment to the Yangtze River

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ABSTRACT

Zircon provenance studies of modern and ancient fluvial systems help reveal the relative contributions and importance of upstream sediment sources. A 2014 study of detrital zircon U-Pb age distributions from the Yangtze River (China) and its tributaries proposed a strong anthropogenic control on sediment flux. Those data, along with other data from the region, were reanalyzed using multiple detrital zircon U-Pb age distribution comparison techniques and a distribution-mixing model to construct an improved and quantitative view of provenance. The variability in the Yangtze River trunk stream U-Pb age distributions is evaluated with respect to trunk-to-trunk stream comparisons, trunk-to-tributary comparisons, and in mixture models that consider tributary and bedrock contributions, the latter using a comprehensive compilation of bedrock source terranes. Uniformity in the zircon age distribution of the Yangtze River trunk stream is established in the upper reaches, downstream of the first bend, and maintained by the left-bank tributaries to its outlet. Whether considering the bedrock source terranes or only the modern Yangtze River sediments, the major source of sediments contributing to Yangtze River is clearly the eastern edge of the Tibetan Plateau (e.g., Songpan Ganze complex, Longmenshan Range), where rock uplift rates are high. The purported increase in anthropogenic impact on sediment yield in the lowlands, at least as viewed through detrital zircon age distributions, is insignificant.

INTRODUCTION

The Yangtze River has headwaters in the Tibetan Plateau, and is the longest river in Asia and fourth longest river in the world. The Yangtze River traverses the eastern-two-thirds of China and integrates multiple large tributaries draining crustal terranes with characteristic detrital zircon U-Pb age signatures. Zircon U-Pb ages may help fingerprint the dominant sediment sources to the trunk stream of the Yangtze River and thus elucidate the spatial pattern of erosion across the catchment. Accurate constraints on the zircon contribution from different catchments enhance our understanding of catchment-wide erosional patterns and may help frame future studies on how the river’s course has evolved over time.

The expeditious and inexpensive acquisition of data made possible by laser ablation–inductively coupled plasma–mass spectrometry (e.g., Gehrels et al., 2008) has made zircon the mineral of choice for many modern and ancient provenance studies. In ancient settings, detrital zircon ages are routinely used to deduce drainage network reorganization and the timing of local and regional tectonic events (Gehrels et al., 2003, 2011; Darby and Gehrels, 2006; Hoang et al., 2009; Yan et al., 2012; Wang et al., 2013; He et al., 2013; L. Wang et al., 2014). At its simplest, erosion and rock uplift control the zircon contributions of progressively unroofed rock to fluvial sediments; thus, measured zircon ages should be traceable to a unique source. Studies have shown that variable zircon concentrations in source areas (Moeccher and Samson, 2006; Malùsà et al., 2013, 2015) can affect downstream age distributions, and U-Pb age distributions of detritus may differ significantly from its assumed source over very short distances (Bonich et al., 2013). The interpretation of U-Pb ages from larger river systems may be further complicated by spatial variability in erosion due to climate change, or large but irregular influxes of sediment, for example, from coseismic landslides (Gallen et al., 2015). However, despite some limitations, detrital zircon U-Pb ages have proven a valuable provenance tool in studies of basin evolution (Yan et al., 2012; Zheng et al., 2013; C. Wang et al., 2014), crustal evolution (Wang et al., 2010; Xu et al., 2014), and tectonic and erosional histories (e.g., Weislogel et al., 2010; Lang et al., 2013).

Much of the landscape traversed by the Yangtze River and its tributaries is tectonically inactive, with the exception of the eastern and southeastern margin of the Tibetan Plateau. Punctuated episodes of rapid river incision into the eastern and southeastern margins of the plateau reached localized rates of >300 m/m.y. (Clark et al., 2005; Ouimet et al., 2010), with an abrupt decrease ca. 7 Ma (McPhillips et al., 2016). The Yangtze River catchment, like much of China, is subject to moderate to intense agricultural activity (He et al., 2014). At values of 30 m/m.y., **Be-derived erosion rates in the main course of the upper Yangtze River (Jinsha River) are remarkably low, yet some small tributaries are rapidly eroding at 500 m/m.y.** (Henck et al., 2011). Immediately following large earthquakes, such as the 2008 Wenchuan earthquake, the mountain rivers of the eastern plateau margin become choked with material shed off the failed hillslopes (Parker et al., 2011). Active rock uplift decreases dramatically east of the plateau margin (Richardson et al., 2008), and variations in anthropogenic activity, principally from agriculture, likely become important agents of erosion (Wilkinson and McElroy, 2007). Previous work examining the detrital zircon U-Pb age distributions from the Yangtze River and its tributaries used here concluded that high zircon flux to the trunk stream is driven by tributaries characterized by high agricultural land use (He et al., 2014). We revisit these data through a...
more detailed analysis of the modern U-Pb age distributions, and include an extensive compilation of bedrock zircon data across the Yangtze River catchment (Figs. 1 and 2). Our attempt to resolve the provenance of zircon in the Yangtze River includes multiple visual representations of qualitative and quantitative zircon U-Pb age distribution comparisons and two mixing models that consider (1) the modern fluvial distributions and (2) potential bedrock sources within the modern drainage area to determine their relative contributions of zircon to the Yangtze River sedimentary budget. We combine multiple statistical approaches to describe the variance in the zircon U-Pb age signal of the Yangtze River with the goal of evaluating the distribution of ages in the context of erosional variability throughout the Yangtze River catchment. This study not only reinterprets the data of He et al. (2014), but also provides a framework for thorough analysis of detrital data sets for future studies.

DATA SETS

We reexamine the modern Yangtze River data set, which comprises 25 sand samples, with an average of 96 ages per sample spanning nearly the entire length of the river and its major tributaries, first reported by He et al. (2013) (Figs. 1 and 3). At the first bend (Shigu), we included age data from Kong et al. (2012) making the total number of zircon U-Pb ages at that location 182. As part of the He et al. (2013) study, samples were collected in 2008 and 2009 from channel deposits (mid-channel, lateral, and point bars) exposed at low river levels. They collected riverbed sand in multiple locations around each sampling site to sample a representative mixture at each locale.

The detrital zircon age data are coupled with the zircon age distributions of 35 potential bedrock sources compiled from the literature (Figs. 1 and 2). The major geologic provinces encompassed by the Yangtze River catchment and described by these 35 bedrock units include the Songpan Ganze complex, the eastern Qiangtang terrane, the Yidun terrane, the Sichuan Basin, the Yangtze craton, the Longmenshan, the Qinling-Dabieshan fold belt, the South China fold belt, and several smaller geologic provinces that also may contribute zircons (Figs. 1 and 2). The majority of the 35 bedrock U-Pb age distributions represent the combined zircon ages of multiple, genetically related samples (e.g., shared depositional, emplacement, or metamorphic histories). For example, sandstone samples with similar geographic extent, sedimentary facies, depositional age, and age distributions were combined to generate an average distribution for a particular suite of samples, simplifying the data set. However, great care was taken to not combine clearly dissimilar age distributions, for example, keeping the Songpan Ganze complex divided into the three depocenters (southwest, central, and northeast) identified by Weislogel et al. (2010). Unimodal bedrock units, particularly plutonic outcrops, were only combined when age distributions were statistically indistinguishable.

METHODS

We apply multiple conventional and new approaches of detrital zircon data analysis in our reexamination of the spatial distribution of provenance changes for the modern Yangtze River. Through robust analytical evaluation of the data set, we can better understand key characteristics of the Yangtze River sediment budget.

Kolmogorov-Smirnov Test, Likeness, and Cross-Plot R² values

The two-sample Kolmogorov-Smirnov test (K-S test) is one of the most widely utilized nonparametric statistical tests in detrital zircon geochronology (e.g., Press et al., 1987). The null hypothesis of the K-S test is that two sample distributions are derived from the same distribution, thus, a rejection implies that they are drawn from distinct distributions. The results of the K-S test are contingent on the K-S statistic, or sample effect size (K-S), which is the maximum difference between the empirical cumulative distribution functions for each sample. The K-S test is used to calculate the K-S test p-value to evaluate the null hypothesis. The K-S test provides a binary representation of whether any two distributions are statistically unique from one another (Table 1). The goal of this approach is to statistically test if downstream samples are derived from the same or different distributions than their upstream counterparts.

As the K-S test is both binary and weighted toward the center of age distributions, other comparison metrics are better suited to highlight differences between zircon age distributions. Likeness (Satkoski et al., 2013) and probability function cross-plot R² (CPR) values (Saylor et al., 2013) have been proposed as alternative quantitative metrics of comparison. The value of CPR and likeness is their sensitivity to both shapes of components within the distributions and the presence and absences of components. Likeness (Satkoski et al., 2013), or its inverse, percent area mismatch (Amidon et al., 2005), is a measure of the summed absolute subtracted difference at incremental age values between two probability curves, where greater dissimilarity between two probability curves results in larger calculated differences. As both probability curves are normalized to unity, the maximum summed difference is two, therefore, the difference is halved and subtracted from one, giving likeness values that vary from 0 to 1, with higher values indicating greater intersample similarity. Probability function cross-plots are generated by plotting the probabilities of two distributions against one another over a given range of ages (Saylor et al., 2013). The coefficient of determination (R² value), calculated from a linear fit to the plot, provides the CPR value. Similar to likeness, values range from 0 to 1, with 1 reflecting identical distributions.

Multidimensional Scaling

Multidimensional scaling (MDS) is a technique common in statistical analysis of data sets (e.g., Carroll and Arabie, 1980; Hayward and Smale, 1992; Smosna et al., 1999); however, it is relatively new in its application to detrital zircon U-Pb age data sets (Vermeesch, 2013; Vermeesch and Garzanti, 2015; Spencer and Kirkland, 2016). MDS in detrital zircon geochronology attempts to translate pairwise dissimilarities measured between sample age distributions (e.g., likeness, CPR, or K-S statistic) into Euclidian distances, generally into two-dimensional configurations (Vermeesch, 2013). In this construct, greater plotted distances between two samples, represented as points in MDS configurations, indicate increasing degrees of dissimilarity. MDS attempts to find the optimal spatial distribution of the sample points for the matrix of distances (e.g., translated dissimilarities). There are multiple evaluative loss functions for MDS, but the most common is stress (S) (Kruskal, 1964). Lower S values, generally <0.1, indicate a good fit of the translated dissimilarity configuration, while S > 0.2 indicates a poor fit. MDS can be applied to detrital data using either metric or nonmetric MDS. Metric MDS uses the absolute measures of the dissimilarities to solve for the configuration and stress value simultaneously (Vermeesch, 2013). Nonmetric MDS ranks the dissimilarities (i.e., ordinal data) and numerically (e.g., isotonic regression) finds the optimal configuration by minimizing the loss function (Vermeesch, 2013). Along with the stress value, a Shepard plot is a good tool for MDS evaluation (Vermeesch, 2013); here, the measured dissimilarities are plotted against the translated distances, and a better fit to either a linear (metric MDS) or some nonparametric monotonically increasing function (nonmetric MDS) indicates a better configuration.

For this study we use likeness as measure of dissimilarities, rather than K-S as originally applied by Vermeesch (2013), because likeness more accurately represents the dissimilarities between two distributions (Wissink, 2016). Here
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Figure 1. The Yangtze River catchment and sampling locations. Letters indicate trunk stream location of river sediment samples. Trunk samples: A—Tuotuohe; B—Shigu (First Bend of the Yangtze; note that sample contains data from both He et al., 2014 and Kong et al., 2012); C—Panzhihua-1; D—Panzhihua-2; E—Yibin; F—Chongqing; G—Fuliang; H—Yichang; I—Yueyang-1; J—Yueyang-2; K—Wuhan; L—Hukou; M—Datong; N—Nanjing; O—Changxing Island. Roman numerals indicate the tributary samples (from He et al., 2013, 2014). Tributary samples: I—Yalongjiang; II—Daduhe; III—Minjiang-1; IV—Minjiang-2; V—Jialingjiang; VI—Wujiang; VII—Yuanjiang; VIII—Xiangjiang; IX—Hanjiang; X—Qandian. Black filled circles indicate the approximate sampling locations of potential bedrock source zircon age components (for bedrock names and references, see supplementary material). Source sampling locations may represent geologically contiguous units with extents in and outside of the Yangtze River catchment.

Figure 2. Geologic terrane map for the Yangtze River catchment (modified from Burchfiel and Zhiliang, 2013; Heam et al., 2001). Terranes are colored if they are areally extensive in the Yangtze River catchment (bold black line). OB—Ordos Basin; SP—Shanxi Plateau; THB—Taikang Hefei Basin; SYSB—Subei–Yellow Sea Basin; LSB—Lanping Simao Basin; SB—Sichuan Basin; LMS-DS FB—Longmenshan–Dabieshan fold belt.
Figure 3. Probability density curves for each of the Yangtze River samples. On the right are the 15 trunk stream samples and the left are the 10 tributaries samples (locations in Fig. 1; Isl—-island). Groups and solid lines extending from the tributaries indicate approximate confluence of these tributaries to the trunk stream. N is the number of zircon grain ages per sample.
we use nonmetric MDS as it yields lower stress values than metric MDS, which yields stress values >0.2. Theoretically, MDS will highlight differences in the Yangtze trunk stream samples and identify which tributaries appear to be the most similar to trunk stream samples, if any. For example, if several tributaries account for the majority zircon in the trunk streams, these tributaries should surround and possibly cluster within the trunk stream samples that are downstream from the confluence of the tributaries. The remaining tributaries, which contribute minimal zircon to the trunk stream, should plot at greater distances from the trunk samples around the periphery, assuming they have distinct age distributions from the contributing tributaries. A dramatic shift in provenance following the incorporation of a specific tributary should become readily apparent, with an obvious downstream and upstream clustering of trunk stream samples and the downstream samples closer in configuration to the major contributing tributary. Should an upstream catchment dominate zircon supply, there would be little to no differentiation between upstream and downstream trunk samples.

Gaussian Component Breakdown

He et al. (2014) divided the Yangtze River data set into 6 age brackets based on visual assessment of the sample age distributions; their age intervals were 0–65 Ma, 100–300 Ma, 300–600 Ma, 600–1000 Ma, 1700–2000 Ma, and 2000–2700 Ma. However, closer inspection of both their detrital data set and bedrock source data suggests that these broad age brackets do not adequately represent distinct geologic emplacement events. Instead, we divide the data set into individual Gaussian components that more effectively describe the true trunk stream distributions. Here a component is, at its simplest, a normally distributed suite of ages around some mean value that represents some discrete geologic zircons-producing event. Our goal is to identify the variation in the Yangtze trunk stream samples in relation to its tributaries and associated bedrock sources; therefore, we isolate the major components associated with the trunk stream distributions, following an approach described in Wissink and Hoke (2015). The probability density curves of all trunk stream samples are summed and normalized to unity. From this summation, unique age components are identified using a deconvolution algorithm that fits a Gaussian curve to each of the largest (in integrated area) age modes, by minimizing the mean square error for each. The two standard deviations above and below the mean of each curve define an age component. Similarly to He et al. (2014), we calculate the proportions of zircon ages within the Yangtze River sediments for each defined component. This is achieved by integrating the probability density functions (PDFs) for each sample between the end points defined by each component. Using this approach, we identify the major components and their overall variance within trunk stream samples. We can use these component percentages to make components inferences that are more robust.

Mixing Model

We apply a mixing model of U-Pb age distributions modified from Lang et al. (2013) to assess whether changes in sediment source explain age distribution variations observed in the Yangtze River trunk stream detrital zircon data set. The Lang et al. (2013) mixing model determines the optimal mixing proportions of potential contributing sources to recreate the original distribution with no a priori knowledge of which sources to include. Source distributions, here represented by PDFs, are mixed at varying proportions over a range of possible combinations. These mixed PDFs are then quantitatively compared to the true sample. Mixtures are generated by multiplying the PDFs of each source distribution by some percentage contribution (because PDFs are normalized to unity) and summing each (summed proportions must equal 100%), resulting in the mixed PDF. An optimal mixing of sources corresponds to the mixture with the highest comparison metric (e.g., likeness, CPR, or K-S statistic) to the original sample comparison. We use likeness (Satkoski et al., 2013), because it best represents the overall shape of the distributions. We apply the mixing model to the detrital sediments of the Yangtze River using two separate constructs of source, bedrock and upstream modern sediments.

For the first model, sources are defined as any possible contributing lithologic unit, ranging from large sedimentary sequences to localized plutons. The contribution of a bedrock unit...
RESULTS

Results of K-S Test, Likeness, and CPR Values

The K-S test was used for each pairwise coupling of the Yangtze River trunk and tributary samples. The results are summarized in Table 1, where an F indicates a failure to reject the null hypothesis, meaning that, statistically, the samples are likely not derived from different distributions. Two-thirds of all Yangtze River trunk-to-trunk sample comparisons fail to reject the null hypothesis, indicating shared provenance with no obvious differentiation between the upper and lower reaches of the trunk stream samples. The trunk samples that appear to have the strongest differentiation, i.e., reject the null hypothesis most frequently, are at the first bend of the Yangtze River (Shigu; Fig. 1, sample B), and at Yibin (Fig. 1, sample E), suggesting a greater uniqueness (Figs. 2 and 3; Table 1); however, these samples still fail to reject the null hypothesis in 40% and 47% of all trunk-to-trunk comparisons, respectively. In contrast, only 18% of trunk-to-tributary comparisons fail to reject the null hypothesis, indicating far greater variability in provenance within the trunk stream compared to the tributary.

In practice, it is difficult to identify more than 10 unique sources with confidence, given random sampling uncertainties as well as large computational times. For the bedrock-source scenario, there are more than 30 possible contributing sources for trunk samples collected in the lower Yangtze River reaches. Therefore, we modify how the mixing algorithm is applied depending on the number of potential contributing sources. When fewer than 7 sources are identified as possible contributors, the mixing algorithm uses all combinations of source PDFs at 5% incremental changes. For 8–12 possible sources, the incremental changes are increased to 10% for computational efficiency. If the total number of possible contributing sources exceeds 12, we use a grid search technique that prioritizes those sources with the highest initial similarity metric values of source to sample comparisons (see Supplementary Material in the GSA Data Repository1) to determine the optimal mixture for each detrital sample. The grid search technique will be biased toward sources with initially higher similarities.

1GSA Data Repository Item 2016285, which includes four additional figures, one movie of a 3-D MDS visualization, an overview of the mixing model, and a list of references used for bedrock U/Pb ages, is available at www.geosociety.org/pubs/fl2016.htm, or on request from editing@geosociety.org.

Figure 4. Intersample likeness and probability function cross-plot R² (CPR) values. Results shown using the likeness comparison metric (left) and CPR values (right) for trunk-to-trunk, trunk-to-tributary (Trb.), and tributary-to-tributary intersample comparisons. N equals the number of comparisons per histogram. Higher values indicate higher similarity between pairwise comparisons. Note that the trunk-to-tributary comparisons are on average higher.
trunk-to-trunk CPR values of 0.26% ± 0.13%. The tributaries with the highest CPR and likeness values in trunk-to-tributary comparisons are the Daduhe, Minjiang, Yuanjiang, and Hanjiang tributaries, with no relationship between downstream incorporation and high values (see Supplementary Tables 1 and 2 in the Data Repository). Assuming a significant single shift in provenance, one would expect some bimodality in likeness values of the intertrunk comparisons driven by samples downstream exhibiting a positive increase in comparative likeness and decrease compared to the upstream samples. It is clear that there is no such step function present in the measures of similarity of downstream versus upstream samples. Trunk samples exhibit strong overall similarities, particularly at the confluence of the Yalongjiang at Panzhihua.

Results of MDS

The variability in the Yangtze River data set using MDS is summarized in Figure 5; the MDS configuration results in a strong clustering of trunk stream samples (filled circles) in the center of the MDS map. This clustering closely resembles the scatter seen when randomly sampling ~100 ages from a larger population of ages, highlighting their overall similarity while also lending no evidence of significant changes in provenance further downstream. This is not unexpected, given the results of the likeness test. The four trunk samples, nearest the mouth of the Yangtze River (Hukou, Datong, Nanjing, and Changxing Island), show no dramatic differentiation in MDS with samples collected from the upper reaches. The minimal geographic clustering of samples observed (i.e., minor upper versus lower trunk stream separation) is not unexpected, because proximity should lead to a certain degree of similarity. The nearest neighbor lines (samples with highest and second highest likeness values between them), however, hint at its limited significance. There is an apparent shift downstream of Shigu toward the Daduhe, Minjiang, and Yalongjiang tributaries, suggesting that the Jinsha portion (upper reaches) of the Yangtze may contribute less than the tributaries feeding off the east and southeast margins. The trunk samples furthest from the center include Tuotuohe, Shigu, Yueyang-2, and Yibin. Tuotuohe and Shigu represent the upper reaches and least integrated portion of the Yangtze River and thus possibly differing provenance or limited contributions to the river downstream of Panzhihua, mirroring the results of He et al. (2014), Zhang et al. (2014), and Vezzoli et al. (2016). Yibin and Yueyang are more closely linked to the Yalongjiang and Xiangjiang tributaries, respectively; both tributaries represent the immediately preceding large tributary for each of the respective trunk stream samples. The tributaries (unfilled circles) plot on the outer rim of the MDS map (Fig. 5), ringing the trunk samples. While this configuration may suggest that all tributaries are contributors in some fashion, the clustering of trunk stream samples demonstrates a lack of downstream differentiation. Of the 10 Yangtze River tributaries, those closest to the trunk sample cluster are the Minjiang, Daduhe, and Jialingjiang tributaries, all of which occupy the northwestern portion of the Yangtze River catchment, and correspond to tributaries identified by Vezzoli et al. (2016) as major sediment contributors.

Results of Gaussian Component Analysis

We identify 15 prominent components that define ~80% of the overall variance within the Yangtze River trunk stream distributions (Fig. 6A). However, just 6 describe 75% of the total variance. In decreasing order of proportional contribution and given in the format of $\mu \pm 2\sigma$, these 6 are 675–904 Ma, 1734–1974 Ma, 389–481 Ma, 199–225 Ma, 2417–2605 Ma, and 2342–2492 Ma. These ranges represent substantial revisions to those described by He et al. (2014) through visual assessment. Using the Gaussian components defined here, we calculate the proportions of each component in every Yangtze River sediment sample, individually, and the average proportion of each component for the trunk sediment samples. This average allows us to examine the deviation of each sample age distribution from the trunk stream mean value for each component (Fig. 6B). The mean value for each component is normalized to zero, and the deviation for each sample is given as a

Figure 5. Multidimensional scaling (MDS) plot of Yangtze River data. The nonmetric MDS plot (main) and Shepard plot (inset) for the translated configuration of dissimilarities (likeness) for the Yangtze River data set. Trunk stream samples are given as filled colors, with warmer colors (red-orange-yellow) indicating farther downstream sampling; tributary edge colors indicate downstream location. Solid and dashed lines indicate the closest neighbors and second closest neighbors in likeness, respectively. Greater interpoint distances indicate greater dissimilarity between samples. Inset: Shepard plot for the given data. Points represent the scatter plot of the measured dissimilarities (likeness values) versus the distances in MDS space. Because the MDS is nonmetric, the monotonic function that best translates the data (red line) is calculated numerically. Better fits plot closer along function line. A stress value of ~0.14 indicates a fair translation of the data (Kruskal, 1964) into MDS space.
Figure 6. Results of the Gaussian component analysis of the Yangtze River data set. (A) The black line indicates the summed curve of all trunk stream samples of the Yangtze River. The colored, dashed curves are the Gaussian components that best describe the overall variance of the data set. The range of each curve at ±2σ from the mean value is given in the legend in millions of years. (B) The deviations (in percentage points) in proportion of the seven components, which account for >75% of the overall variance of the Yangtze River, at each sampling location from the mean value (μ) of that component; μ is given as a percentage in the legend. Top of B is for trunk samples; bottom is for tributary samples. Vertical dashed lines indicate the confluence point of the tributaries. Note that the Daduhe and Minjiang tributaries share a confluence point, as do the Xiangjiang and Yuanjiang tributaries. FB—First Bend. (C) Model of deviation plot for synthetic unique components with proportions equivalent and color coordination to the seven components in B. Note the similarity in curve shapes to trunk samples of B. The shaded pink areas in B and C represent the approximate range of deviations seen in the synthetic distribution of C, overlain on the plots of B. This shows how the variability seen in the trunk stream samples of B is difficult to separate from random sampling.
percentage point difference between the mean value and the proportion within that sample. For example, if component one has a mean value of 20%, and the sample Z age distribution contains 25% component one, it would be represented as a +5 percentage point (pp) deviation for sample Z from the normalized 0 mean value. In Figure 6B, we plot the deviations of the 6 components described here as well as the Cenozoic component of 34–48 Ma to better match the components of He et al. (2014). The deviations for the remaining components can be seen in Supplementary Figure 3 in the Data Repository. A striking feature revealed in Figure 6B is the low deviation from the mean value for nearly all components for trunk stream distributions, generally within ±5 pp, throughout most of the fluvial system downstream of Shigu. The same cannot be said for the tributary component proportions, which differ widely, deviating 10–20 pp from the mean trunk values for the same components (Fig. 6B).

The establishment of the mean component values for the trunk stream appears to occur in the upper Yangtze River between Shigu, where component deviations are high (10–20 pp), and Panzhihua, where trunk stream proportions settle around the mean (Fig. 6B). Following Panzhihua, trunk stream proportions rarely deviate significantly from mean proportions (pink in Fig. 6B). There are clear spikes of certain components at trunk stream sites near Yibin (676–904 Ma) and Yueyang (389–481 Ma). Both increases occur after the incorporation of tributaries containing higher than average proportions of those specific age components (see tributaries Minjiang and Daduhe, and Xiangjiang). Nonetheless, they immediately return to proportions closer to the mean value by the next downstream trunk sample. The trunk samples with the greatest distance downstream from the incorporation of any major tributary are Yichang, Nanjing, and Changxing Island, and are likely the most homogenized. These samples have roughly equal proportions to Panzhihua; in other words, they show no greater deviations in mean values than would be expected from multiple random 100-age draws from a single distribution of ages with component proportions consistent with trunk stream averages (Figs. 6B, 6C; shaded area). The low deviation in values around the mean of the trunk samples (Fig. 6B), and the relatively high deviation for tributary samples (Fig. 6C) match well with the results of the K-S test and calculated dissimilarity values. The high deviations in values of tributary samples, and thus, the uniqueness of these age distributions, also suggests that any major flux of sediments from one or more tributaries should appear and persist downstream of its incorporation, depending on how sediment flux varies downstream.

We examine how much variance one can expect if a single distribution of ages containing seven unique components in proportions consistent with the trunk stream averages (Fig. 6B; μ values) is sampled randomly to create 100-age distributions. To do so, we create distribution of 100,000 ages composed of 7 components in proportions equal to the trunk stream averages of Figure 6B. This is done by assigning each component an age defined by the mean age of the Gaussian component. Because the averages of the 7 components sum only to 61%, the remaining ages of the distribution are randomly, uniformly distributed between 1 and 3000 Ma. This distribution of ages is then randomly sampled with replacement, to represent a nearly infinite source of ages, for 15 (number of trunk stream samples) 100-age samples. The proportions and deviations from mean values for each component in each sample are then calculated. The results of this model yield nearly indistinguishable curves from the majority of trunk stream samples found downstream of the First Bend of the Yangtze. The results of a single model run are given in Figure 6C. In multiple model runs, components with a mean value between 1% and 4% yield standard deviations generally of ±1.5–2.5 pp (1σ). 5–10% components have standard deviations of ±2–3 pp, and components with >10% yield standard deviations of ±2.5–5.5 pp (Fig. 6C). Therefore, the possible deviations of a single random sampling can be >10 pp, particularly for larger components, but <10 pp deviations are difficult to distinguish from random draws. Samples from Yibin and Yueyang-2, which show the largest and likely not randomly derived deviations, are easily associated with immediately upstream tributaries. The remaining trunk samples at and downstream of Panzhihua exhibit a striking resemblance to the simple model, suggesting shared provenance.

Results of Yangtze River Mixture Models

The results of the mixture model applied to the Yangtze River data set are described here and illustrated in Figure 7. The optimal mixtures of bedrock sources achieved likeness values of ranging from 57% to 75% when comparing the mixed distributions to the original sample distributions. Of these bedrock mixtures, the Yangtze River trunk samples, with the exception of Tuotuohe in the headwaters, yielded maximum average likeness of 67% ± 4%. Within the achievable 100-age resampled likeness of 72% ± 6% described by Satkoski et al. (2013). Tributaries also return similar averages of 67% ± 5.5% (see Supplementary Table 3). The bedrock source distribution data set consisted of a maximum of 35 possible source units; the results of the optimal mixtures excluded nine from any of the sample optimal mixtures. For geographic and geologic simplification, we can further reduce the number of geologically distinct bedrock units to 17 units that contribute in one or more optimal mixtures. The full 26-source mixture model can be found in the supplementary material in the Data Repository.

The units of the Songpan Ganze complex (SGC), the Triassic flysch deposits found near the headwaters and left-bank tributaries of the upper Yangtze River (Fig. 1 and I–IV, Fig. 7A) show a clear dominance in zircon supply to modern trunk stream sediments. Deposits related the southern depocenter of the SGC (Weislogel et al., 2010) make up the majority of contributing sediments from this complex (see Supplementary Table 3). Sediments from the Qando Basin, which shares a depositional history with the SGC (Shang and Weislogel, 2014), and the Jurassic sediments of Yunnan Provence (Su et al., 2014), are included in two-thirds of trunk optimal mixtures. These units each have likeness values exceeding 45% with the southeast depocenter of the SGC, and thus may be difficult for the mixing model to differentiate, although all are present in the northeastern margin of the Yangtze River catchment. By simply grouping sources derived from geologic terranes upstream of sample Panzhihua-2, optimal trunk mixtures are composed of 65%–100% of these bedrock units, averaging ~85% for the 15 trunk stream distributions. Together this grouping constitutes <20% of the overall area of the Yangtze River catchment.

Two volcanic units associated with the Longmenshan Range and South China block both share Neoproterozoic emplacement ages and make clear contributions to the trunk stream samples; these units, in dark red and pink, respectively, in Figure 7 are essentially unimodal and share a 33% likeness. While less likely to affect the final mixture output of <12 sources, these units may be difficult for the grid-search mixture model to differentiate. Following the incorporation of the Ganjiang and Yuanjiang Rivers, which both have very high South China block components, we observe an increase in South China–derived units in the mixture model at the apparent expense of Longmenshan units. The similarity between Longmenshan and South China block Neoproterozoic zircon make it difficult for this simple mixture model construct to differentiate between them. Neoproterozoic ages account for ~5%–25% of the overall composition of our mixtures. Other minor contributors include Cenozoic volcanics, the Laji and Dabieshan mountain ranges, and sediments from the Sichuan Basin.

The second mixture model using major tributaries and upstream trunk samples as sources for the downstream trunk distributions (Fig. 7B;
Supplementary Table 4) yields optimal mixtures with far stronger trunk stream contributions than tributary contributions. There are 12 trunk stream samples that contain at least one major tributary within their catchment, 8 of which are best described by mixtures that contain >70% trunk stream zircon (red outlined wedges of pie charts; see Fig. 7). These require minimal contributions from tributaries to push the mixing model toward higher optimal metric values. The remaining samples, those near Yibin, Fuliang, Yichang, and Wuhan range from 30% to 55% trunk stream contributions. Yibin, due to its high Neoproterozoic concentrations, favors the incorporation of the Yalongjiang. It is interesting that this is despite the obvious lack of strong Neoproterozoic age proportions at Panzhihua-2 immediately following the incorporation of the Yalongjiang (Fig. 7B). Fuliang and Yichang have elevated incorporation of the Wujiang tributary grains in the mixing model (Fig. 7B). This is notable, given that the Wujiang River only accounts for ~8% of the total catchment area at the sample locations. Figure 7 shows that these two samples both have slightly higher than average Paleoproterozoic age zircons and may be why Wujiang, which shares this characteristic, is favored in the model. Samples at both Yibin and Yueyang-2 mirror the results shown in Figure 7, where higher than average concentrations...
of particular age modes of the most immediately incorporated tributaries lead the mixture model to include higher than expected tributary concentrations.

**DISCUSSION**

Statistical and quantitative analysis is critical to our understanding of large detrital data sets. By applying rigorous quantitative techniques to the Yangtze River data set, we are able to reevaluate and expand upon the work of He et al. (2014). Each analysis of zircon ages explored here demonstrates that the zircon U-Pb age distribution of the Yangtze River is established early in its upper reaches near the sampling location of Panzhihua-2 and is, on average, statistically invariant downstream. Proportions of identified significant age components downstream of the first bend, with the exception of samples from Yibin and Yueyang-2, are consistent with the sampling of a single distribution of ages (Fig. 6). This at least partially refutes the claim of He et al. (2014), who argued that the tributaries of the Hanjiang, Xiangjiang, and Jialingjiang, and the trunk between Panzhihua and Yibin, constitute the largest contributions of sediment to the Yangtze. The conclusion of He et al. (2014) relied heavily on a coarse grouping of zircon age components and just eight bedrock units to characterize the structural blocks of the Yangtze River catchment, a total that we have greatly expanded upon and refined here. Our more robust bedrock data set, Gaussian component analysis, and multiple techniques to analyze zircon age distributions argue for the more tectonically active and steeper topographic regions of the Yangtze River catchment to dominate the sediment budget of the modern river.

**Measures of Similarity and Deviations**

The K-S test demonstrates a consistent, seemingly shared provenance for the vast majority of the trunk stream samples along the length of the Yangtze River. This argument is at least bolstered by the rejection of the K-S test null hypothesis in most trunk-to-tributary comparisons, demonstrating that no one tributary dominates the fluvial system, but rather it is the left-bank tributaries that supply the most zircon. The K-S test, likeness, CPR, and component deviations from the mean trunk values all point toward a uniform character of the detrital zircon component downstream of Panzhihua. The few trunk samples that exhibit large variations in components occur immediately downstream of specific tributaries or within zones of known higher concentrations (Fig. 6B). It is plausible to assume that the upward spike in zircon contributions is indicative of higher than average erosion or zircon fertility from these tributaries. However, following these jumps in contribution from the nearest upstream tributary, the high signal is consistently lost at the next downstream trunk sample (Fig. 6B). For the remaining samples, the deviations from mean trunk stream values are essentially impossible to distinguish from the noise of random sampling (Fig. 6C). The uniformity of the remaining trunk samples suggests either poor homogenization of the tributary sediments in the trunk or remobilization of stored sediments. If we assume that concentration spikes are indicative of drainage dominance, as He et al. (2014) argued, then one could assume that reworked sediments from terraces could add an additional flux of sediment that renormalizes the zircon age signal. However, this supposition requires the sediment of the river terraces, and thus total sediment flux, be dominated by sediment from the upper reaches, supporting our initial claim. This also requires that the rate of remobilization would need to exceed the sediment flux of the tributaries. However, if we assume that the spikes in concentration represent poor homogenization, much like sampling dye concentrations right near the point of input, then the total remobilized sediment does not need to exceed tributary flux, making poor homogenization seem most likely. Looking specifically between Yibin and Chongqing, there is a 24% increase in total catchment area; 70% of the increase is from the addition of the Jialingjiang trunk stream. Using the component concentrations at Yibin, Chongqing, and the Jialingjiang, and assuming equal fertility (Vezzoli et al., 2016), a simple mass balance calculation determines that over an order of magnitude greater sediment flux from the Jialingjiang catchment is required to compensate for the component proportions at Chongqing. This is inconsistent with erosion rates estimates of these catchments (Chappell et al., 2006; Kong et al., 2011), and supports the notion that the spike in zircon concentration at Yibin and subsequent decrease to mean values at Chongqing is due to poor homogenization at Yibin and homogenization at Chongqing. This is not to suggest that flux from the Jialingjiang does not also help bring components back to mean trunk values, but a ten-fold increase in sediment load is unrealistic. Sample selection effects are further highlighted by comparing the data of He et al. (2014) to the data of Yang et al. (2012), looking specifically at Yalongjiang. In He et al. (2014), the sample from the Yalongjiang has Neoproterozoic ages proportions >70%, while Neoproterozoic ages only account for 40% in the Yalongjiang sample from Yang et al. (2012). This difference is well outside the range of random sampling error and cannot be attributed to higher erosion rates or sediment flux as they are sampling the same catchment. Therefore, it is likely more related to variation in the homogenization of the samples at the specific sample location. We note, as did Vezzoli et al. (2016), that the data from the Yalongjiang tributary in Yang et al. (2012) match much more closely the component proportions at Panzhihua-2 and downstream sediments, indicating that it may hold more significance than is initially apparent due to its disproportionately high Neoproterozoic concentrations. We therefore believe that the samples at Yibin and Yueyang-2 likely reflect poor homogenization of the sediment downstream of a major confluence point or source with disproportionately high component concentrations causing a spike in sample concentrations.

The issue of poor homogenization is recognized as a pitfall in detrital studies. If a sample in modern fluvial systems can potentially be so easily biased by a nearby contributor and does not necessarily reflect the true upstream integration, it becomes difficult to say whether preserved ancient sediments are not susceptible to the same problem. Future tests may focus on the variation in trunk stream components between the confluence of two major tributaries rather than immediately before and after major confluence points, as is more common.

**MDS Discussion**

MDS analysis also supports the notion of a shared derivation of zircon at and downstream of Panzhihua. Within MDS space, the progressive incorporation and dominance of zircon ages from downstream tributaries would result in a drift in zircon ages across MDS space. Instead, we observe the majority of trunk stream samples clustering together in MDS space centered on the Panzhihua trunk stream samples, suggesting little deviation in zircon age downstream of those sampling localities (Fig. 5). Unfortunately, because MDS is projecting an N-dimensional set of data into two or three dimensions, the true projection of the relationship between samples can be difficult to interpret. The low variability in dissimilarities between samples also leads to the poor projection into two dimensions (Fig. 5) and three dimensions (see supplementary material), as a maximum of three samples of equal dissimilarity in two dimensions, or four samples in three dimensions can be perfectly configured; any more leads to distortion of the configuration. MDS configurations are not sensitive to the geographic relationships between samples (i.e., upstream versus downstream), only of the best ordination for the measure of dissimilarity, so caution must be taken when analyzing scatter in MDS plots. We argue that the overall striking clustering of both upper and lower reaches of the...
Yangtze sediment highlights the minimal variation in age distributions and thus provenance moving downstream.

**Mixture Model Discussion**

Our mixture models, both of bedrock mixtures and upstream tributary mixtures, further support our supposition of a quickly established and maintained zircon age distribution for the Yangtze. In the bedrock model we find that high concentrations of eastern Tibetan Plateau bedrock units yield the highest likeness values of any mixture model, reaching likenesses near the proposed threshold of 72% ± 6% established by Satkoski et al. (2013). Although we do not test all possible mixtures for samples containing 12 or more possible contributing sources, nor can we guarantee that similar age distributions are not substituted at the expense of the correct source (e.g., South China block versus Longmenshan Neoproterozoic ages), the corroborating results of the bedrock mixture model with the previously described methods suggest a high confidence in the overall results of the bedrock-mixing model and interpretations. The U-Pb age distribution of the Yangtze River is arguably fixed after the river traverses the upper reaches of the Yangtze, which largely sources the SGC and the Longmenshan. The Longmenshan zircon, or more specifically Neoproterozoic zircon, is commonly found in the Longmenshan mountain range and surrounding regions of the upper reaches of the Yangtze River, at and downstream of Panzhihua, and the Yangtangjiang, Minjiang, Daduhe, and Jialingjiang tributaries. Therefore, the high exhumation rates at the eastern margin of the Tibetan Plateau (Kirby et al. 2012; Densmore et al. 2007; Wang et al., 2012) likely provide much of the Yangtze’s overall sediment load. This is consistent with well-documented large sediment flux to valleys (Park et al., 2011) after large earthquakes. Such consistent, far-traveled, geochemical signals that traverse thousands of kilometers of lowlands are not unique to the Yangtze, as is evidenced by data from the Amazon River (e.g., Dobson et al., 2001; Wittmann et al., 2011). It is important that our results are consistent with those with other detrital studies of the Yangtze that focus on nonzircon systems. Zhang et al. (2014) characterized Pb isotopic composition of potassium feldspar and demonstrated that erosion of the Longmenshan and neighboring regions is the important sediment supplier to the middle-lower Yangtze. The high-resolution petrographic and heavy mineral analysis of Vezzoli et al. (2016) found that left-bank tributaries draining the topographic front of the Longmenshan and Qinling mountains, believed to be a major source of sediment to the SGC (Weislogel et al., 2010), are the principle contributors to sediment reaching the East China Sea. Both studies noted that the higher contributions of these tributaries and regions correlate well with slope steepness, precipitation, stream power, and tectonic hazard (Zhang et al., 2014; Vezzoli et al., 2016). Vezzoli et al. (2016) found that the Hanjiang is a relatively significant contributor, contributing >20% of the sediment load, and gave less weight to the Yangtangjiang tributary. The Hanjiang being a major contributor downstream does not necessarily conflict with our interpretations, as its overall zircon characteristics share key ages with the other left-bank tributaries. The contribution of the Hanjiang would likely blend with the U-Pb ages signal seen upstream.

The results of the fluvial sediment-mixing model (Fig. 7B) are consistent with the previously established results that the sediment of the trunk stream and left-bank tributaries dominates the U-Pb age signal of trunk samples. The majority of trunk stream samples downstream of Panzhihua are best described by mixtures of almost exclusively trunk stream sediments. Notable exceptions, such as samples near Yibin and Yuyeyang-2, can be attributed to high proportions of particular components linked closely to recently incorporated tributaries that do not maintain consistently high proportions downstream.

**Tectonic vs Anthropogenic Driven Erosion**

Based on our analysis, the interpretation of enhanced erosion within the Hanjiang, Jialingjiang, and Xiangjiang catchments due to anthropogenic activity proposed by He et al. (2014) cannot be substantiated. Anthropogenic activity clearly plays a significant role in the overall movement of sediment on Earth (Wilkinson and McElroy, 2007), and future studies may focus on examining the zircon U-Pb age characteristic of mobilized soil. However, in no analysis performed here is there evidence that these tributaries contribute disproportionately to the overall trunk stream catchment, while it appears the right-bank tributaries of the southern catchment do not dominate the sediment flux. Vezzoli et al. (2016) argued that the mischaracterization of He et al. (2014) may be in part due to higher zircon fertility of the right-bank tributaries. We do not refute the Vezzoli et al. (2016) suggestion that fertility might play a role in the Yangtze River’s downstream evolution, and support the supposition that mineral fertility can possibly impart a bias to a single mineralogical characterization of provenance (e.g., Malusà et al., 2015). However, we argue that the mischaracterization in He et al. (2014) is the result of only considering broad age ranges, using over generalized bedrock age distributions, and giving a disproportionate weight to U-Pb changes in individual samples rather than to the overall characteristics of U-Pb ages of the Yangtze. The notable increase in contributions associated with Neoproterozoic zircon related to the South China block in our mixing model is the one outlier in our results. However, the contributions of the South China block never exceed 20% in optimal mixtures, averaging ∼11%, which closely resembles the 6%–10% areal proportions of the Xiangjiang and Jialingjiang tributaries that source the South China block. Without more data to distinguish Longmenshan from South China block Neoproterozoic ages, it is difficult to determine whether these Neoproterozoic zircons are correctly grouped with the South China block units or merely incorrect substitutions of their western Longmenshan counterpart. Vezzoli et al. (2016) estimated that right-bank zircon concentrations are an order of magnitude higher than those of the left-bank tributaries. One would expect that a shift in zircon provenance driven by the right-bank anthropogenic input should therefore be amplified, an amplification we do not see.

Our analysis of provenance is limited exclusively to U-Pb zircon ages and could potentially be refined with a second layer of data, such as cooling ages (e.g., Reiners et al., 2005), εHf (e.g., Andersen et al., 2011), or using Th/U ratios (e.g., L. Wang et al., 2014). Other limitations endemic to nearly all regional- and continental-scale detrital zircon provenance include potentially incomplete descriptions of zircon ages from source terranes, because these are typically complex and strikingly different. The Wujiang mixture (see Supplementary Fig. 3) is predominantly derived from the Sichuan Basin despite its relatively minor areal contribution to the Wujiang catchment. The Yuanjiang catchment does not contain the Sichuan Basin and results in a very different mixture despite the shared South China block catchment. This implies either that the Sichuan Basin is much more fertile in zircon or has considerably higher erosion rates.

**Conclusions**

We reinterpret the Yangtze River detrital zircon data of He et al. (2014) and conclude that the upper Yangtze, more specifically the trunk stream area between the first bend and Panzhihua and the Yangtangjiang, Daduhe, and Jialingjiang tributaries, is the major source of zircon, and therefore sediment, to the Yangtze River. He et al. (2014) interpreted the Yangtze River detrital zircon data to represent an increase in erosion rates in three tributaries of the Yangtze, the Hanjiang, Xiangjiang, and Jialingjiang, and the trunk stream between Panzhihua-2 and Yibin related to Holocene human disturbance.
and high specific stream power. We argue that the tectonics of the left-bank tributaries, and not anthropogenic influences, control sediment flux to the Yangtze, consistent with K-feldspar data and petrographic and heavy mineral analyses of Zhang et al. (2014) and Vezzoli et al. (2016), respectively. Our interpretation is based on and supported by the results of K-S test, likeness and CPR analysis, Gaussian component analysis, and mixing models of bedrock and fluvial distributions. The U-Pb age distributions of trunk samples are established ~400 km downstream of the first bend of the Yangtze River at Panzhihua (Fig. 1) and maintained throughout the rest of the river. Mixtures models indicate that trunk stream samples are best described by high percentages of the Songpan Ganze complex and the Longmen-shan (Neo-)proterozoic zircon. The Yangjiang, Minjiang, Daduhe, and Jialingjiang tributaries help establish, and Hanjiang may help maintain, this signal for the remainder of the catchment, although from just detrital zircon U-Pb ages it is difficult to find conclusive evidence of the Hanjiang tributary influence. Inter-sample K-S tests and dissimilarity measures establish a clear high degree of similarity between trunk-to-trunk sample comparisons, a fact further supported in the study of the distributions. If specific downstream tributaries contribute disproportionate zircon fluxes to the main stream, particularly the right-bank tributaries with their order of magnitude higher zircon concentrations (Vezzoli et al., 2016), there would be some quantifiable measure seen in one more of the systematic approaches of detrital analysis performed here. However, there is no evidence of significant variation within the overall trunk stream sample distributions downstream of Panzhihua that cannot be explained by poor homogenization of recently incorporated tributaries. We demonstrate how rigorous analytical and statistical analysis of detrital zircon data leads to robust interpretation of zircon provenance. As data sets continue to grow, and detrital provenance analysis proves increasingly complex, quantitative analysis remains the best tool to characterize sedimentary pathways. The comprehensive approach presented here can be used as a framework for future detrital zircon provenance system because it integrates multiple quantitative comparison techniques.

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