Signatures of mountain building: Detrital zircon U/Pb ages from northeastern Tibet

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ABSTRACT

Although detrital zircon has proven to be a powerful tool for determining provenance, past work has focused primarily on delimiting regional source terranes. Here we explore the limits of spatial resolution and stratigraphic sensitivity of detrital zircon in ascertaining provenance, and we demonstrate its ability to detect source changes for terranes separated by only a few tens of kilometers. For such an analysis to succeed for a given mountain, discrete intrarange source terranes must have unique U/Pb zircon age signatures and sediments eroded from the range must have well-defined depositional ages. Here we use ~1400 single-grain U/Pb zircon ages from northeastern Tibet to identify and analyze an area that satisfies these conditions. This analysis shows that the edges of intermontane basins are stratigraphically sensitive to discrete, punctuated changes in local source terranes. By tracking eroding rock units chronologically through the stratigraphic record, this sensitivity permits the detection of the differential rock uplift and progressive erosion that began ca. 8 Ma in the Laji Shan, a 10–25-km-wide range in northeastern Tibet with a unique U/Pb age signature.

Keywords: detrital zircon, Tibet, provenance, unroofing, Miocene, U/Pb.

INTRODUCTION

Single-grain U/Pb dating of detrital zircons is a potent tool for provenance studies because it can fingerprint source areas with distinctive zircon age populations (Gehrels et al., 1995; Amidon et al., 2005a, 2005b). Provenance is determined by linking a population of similarly aged zircons in a given sedimentary sample to a specific source terrane and its corresponding paleogeographic location. Changes in provenance become apparent when superposed strata have different detrital zircon age distributions.

Detrital zircon analysis of a stratigraphic succession becomes a powerful tool for unraveling unroofing histories when discrete source areas have distinctive U/Pb age signatures and the age of the sedimentary succession from which samples are collected is well defined. Until now, however, the potential for detrital zircon analyses to discern provenance changes at the resolution of an individual mountain range has remained largely unexplored. Most detrital zircon provenance studies have been regional in nature, with source terranes commonly separated by hundreds to thousands of kilometers (Gehrels et al., 1995; DeCelles et al., 1998; DeGraaff-Surpless et al., 2003; Weislogel et al., 2006).

Here we demonstrate the ability of U/Pb detrital zircon provenance to discern the differential uplift and erosion of an individual ~10–25-km-wide mountain range in northeastern Tibet (Qinghai Province, China) within a precise 2 m.y. interval. We first use >700 single-grain U/Pb zircon ages from modern stream samples to characterize discrete local source terranes (see GSA Data Repository Table DR1[1]). To track the unroofing of the newly emergent range, we then exploit ~700 U/Pb zircon ages from magnetostratigraphically dated Miocene–Pliocene strata deposited in nearby basins. These data record both the emergence of a new range and the change in its detrital-age signature as rocks erode from it during continuing deformation.

GEOLOGIC SETTING

The timing and nature of broad surface uplift of the Tibetan Plateau to its present average elevation, >4000 m, remains uncertain. Different lines of evidence support competing models for synchronous uplift of the entire plateau, pulsed plateau uplift, and incremental outward and upward plateau growth (Molnar et al., 1993; Tapponnier et al., 2001; Rowley and Currie, 2006). Even within any given sector of the plateau, there is controversy over whether the entire region rose together or whether the growth of individual ranges and ponding of intervening rivers led to incremental expansion and upward plateau growth.

The northeastern margin of the Tibetan Plateau is a broad, eastward-sloping topographic ramp (Clark and Royden, 2000) punctuated by individual mountain ranges, an area some refer to as Pliocene–Quaternary Tibet (Tapponnier et al., 2001). However, Miocene cooling ages from these ranges and the onset of increased sediment accumulation in nearby basins cluster near 10 Ma (Fig. 1A) and are attributed to accelerated rates of erosion, although the exact timing is poorly resolved (Molnar, 2005).

Our provenance case study examines the Laji Shan, a particularly prominent range in northeastern Tibet that partitions Neogene fills in the Guide (Fang et al., 2005) and Xunhua Basins from the Linxia (Fang et al., 2003) and Xining (Horton et al., 2004) Basins (Fig. 1B). Guide and Linxia magnetostratigraphy and detrital apatite fission-track data suggest rock uplift of nearby ranges accelerated at 5–8 Ma and ca. 14 Ma. With this knowledge, we collected a suite of detrital zircon ages to test whether intermontane basins are stratigraphically sensitive to punctuated changes in discrete local source terranes.

METHODS

To identify the age signature of distinct rock units (source terranes) within the Laji Shan and West Qinling, we collected ~5 kg of medium-coarse sand from 9 catchments, each of which drains a few discrete lithologic units that were expected to yield zircons (Fig. 1B). We sampled along the range front to avoid contamination by recycled zircon populations from recently eroded Neogene strata.

To investigate the unroofing of these Laji Shan and West Qinling source terranes into adjacent basins, we collected seven Miocene–Pliocene sandstones from adjacent basins. Our interpretations are based primarily on the late Miocene–Pliocene Guide Basin, which has a very well established 1.8–11.5 Ma magnetostratigraphic succession (correlated with mammalian fossils) overlying a more uncertain 16–21 Ma magnetostratigraphy.

We collected samples from the Laji Shan range front wherever possible because these are more likely to contain locally derived sediment and therefore record growth of the nearby range. To preclude potential biasing of the zircon distribution by a poorly mixed depositional

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[1] GSA Data Repository item 2007053, Table DR1 (ICP-MS: single-grain U/Pb zircon ages) is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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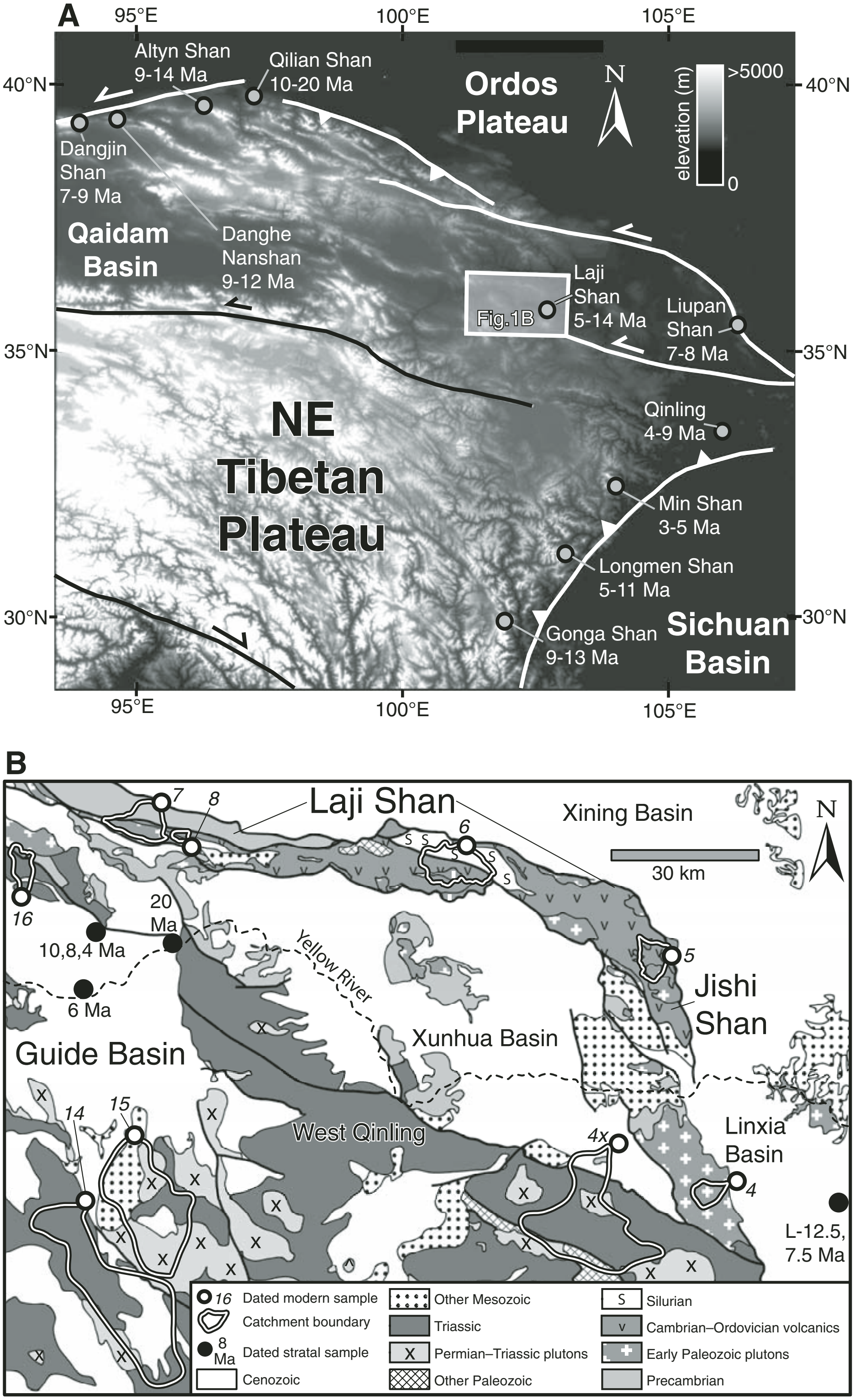

Figure 1. A: Northeastern Tibetan Plateau with ages of rock uplift and erosion from bounding ranges indicating late Miocene range growth; exact timing is poorly resolved (Molnar, 2005). Data include apatite fission-track cooling histories from Laji Shan (Zheng et al., 2003), Liupan Shan (Zheng et al., 2006), Qinling (Enkelmann et al., 2006), Dangjin Shan (Wan et al., 2001), Qilian Shan (George et al., 2001), and Qilian and Altyn Shan (Jolivet et al., 2001), and (U-Th)/He histories from Longmen and Min Shan (Kirby et al., 2002) and from gorges near Gonga Shan (Clark et al., 2005). Several basins exhibit increased sediment-accumulation rates and grain size around this same time: Danghe Nanshan (Wang et al., 2003), Altyn Shan (Sun et al., 2005) and Guide (ca. 8 Ma: Fang et al., 2005) and Linxia Basins (ca. 6 Ma: Fang et al., 2003) adjacent to Laji Shan. B: Laji Shan–West Qinling study area; source terranes and sampling locations are shown (modified from Qinghai Geology Bureau, 1989).

environment (DeGraaff-Surpless et al., 2003), each sample comprises several subsamples collected a few meters apart within the same stratum or catchment.

The U/Pb ages were determined using a laser-ablation multicollector inductively coupled plasma–mass spectrometer at the University of Arizona operated at the specifications of Gehrels et al. (2003). Analyses generally have 2%–4% uncertainty (2σ). Analyses with ≥30% discordance or ≥5% reverse discordance were excluded. We determined ~95 ages per sample unless, during the analysis, the age distribution indicated a single population, in which case ~50 ages were measured. All analytical results are in the GSA Data Repository (see footnote 1).

DETRITAL ZIRCON RESULTS—SOURCE TERRANES AND PROVENANCE

Catchments draining the modern Laji Shan (Fig. 1B) exhibit two unique zircon age populations (ca. 450 Ma and 500–1000 Ma; Fig. 2A), both of which can be tied to a discrete source terrane within the modern range. The 450 Ma population is the greatest contributor to modern Laji Shan–derived zircons, representing >80% of 4 of 6 samples. These ages come from a source terrane of early Paleozoic plutons and volcanics (*Pp & Cv*, Fig. 2) that crop out along the modern Laji Shan crest. The 500–1000 Ma population is also distinctive, constituting 20% of sample 6, and characterizes recycled zircons from Silurian strata (*S*, Fig. 2) present in the Laji Shan. Ordovician–Silurian strata from the western Nan Shan also show a similar population (Gehrels et al., 2003). Both the ca. 450 Ma and 500–1000 Ma populations are locally unique to the Laji Shan; populations of similar age and proportion have not been identified in the West Qinling.

Catchments draining the modern West Qinling (Fig. 1B) are characterized by a unique ca. 250 Ma zircon population that constitutes >50% of 2 of 3 samples and is derived from a source terrane of Permian–Triassic plutons (*Tp*, Fig. 2B); such a population has not been identified in the Laji Shan. Catchments in both the Laji Shan (samples 6 and 16) and West Qinling (samples 14 and 15) exhibit sizable populations older than 1500 Ma. This population may largely comprise recycled zircons from Triassic Songpan-Ganzi metasediments (subdivided elsewhere: Kroner et al., 1993; Weislogel et al., 2006). Assigning this population to a unique source area is ambiguous because Triassic metasediments crop out in both the Laji Shan and West Qinling. Triassic outcrops define a significantly larger area in the West Qinling, however, such that we believe that the bulk of the older than 1500 Ma population is likely to come from here.

In the context of these contrasting source areas, the timing of emergence of the Laji Shan as an important source area can be delineated by comparing the U/Pb age distributions in strata from the northern edge of the Guide Basin. To determine the combination of source terranes that best defines the age distribution of each stratum, we developed a sediment-mixing model modified from Amidon et al. (2005a, 2005b) to include our four primary source terranes. For the range of possible combinations, we modeled synthetic age distributions by mixing the source terranes and by iteratively calculating which synthetic age distribution gave the minimum mismatch to the real age distribution for a given stratum. The Kolmogorov-Smirnov test returned high P values (>.96) for the best fit samples, indicating that the real and synthetic age distributions are nearly identical. Therefore, our model can reasonably be employed to decompose a real stratal age distribution into its source terrane components (Fig. 3).

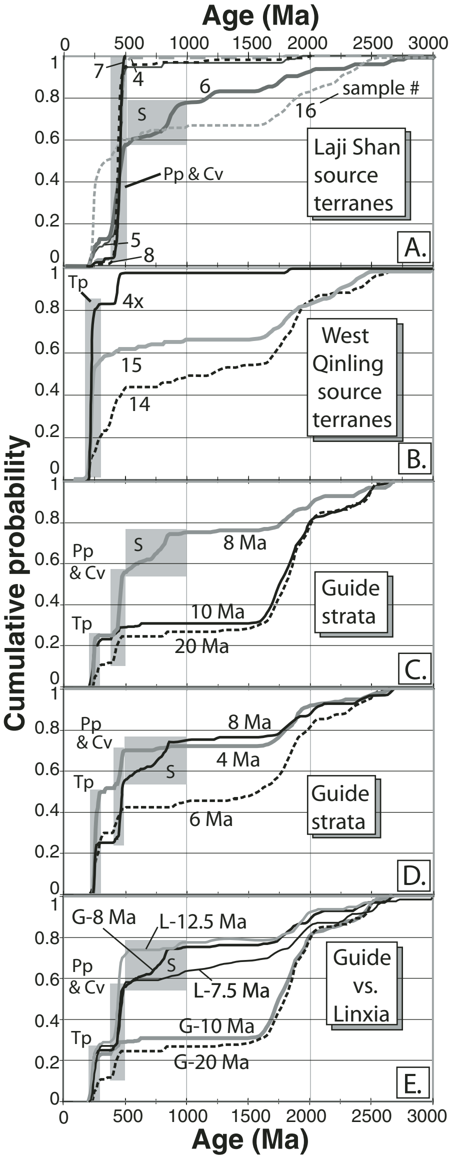

Figure 2. Detrital zircon cumulative probability distributions of samples shown in Figure 1B. A: Modern Laji Shan zircons show unique ca. 450 Ma (Pp & Cv) and 500–1000 Ma (S) populations. B: Modern West Qinling zircons show unique ca. 250 Ma population (Tp). C: Zircons from 8–20 Ma Guide range-front strata show dramatic provenance change at 8 Ma with strengthening of Laji Shan–derived Pp & Cv and S populations, indicating growth of this range. D: Zircons from 4–8 Ma Guide strata show that basin-center 6 Ma strata are less sensitive to source changes than strata located closer to range front. E: zircons from 7.5–12.5 Ma Linxia basin-center strata indicate that stratigraphic sensitivity to record local uplift diminishes toward basin center.

Age distributions from 20 Ma and 10 Ma strata (Figs. 2C and 3) are almost identical; >70% of the ages derive from sources older than 1500 Ma and the remainder from sources younger than 500 Ma. A dramatic provenance change at 8 Ma (Figs. 2C and 3) is highlighted by two significant additions of Laji Shan–derived sources: the ca. 450 Ma *Pp & Cv* population (32% of the total) and the 500–1000 Ma *S* population (18%). These diagnostic populations are otherwise absent or subdued in the 10 Ma and 20 Ma strata, with *Pp & Cv* composing <14% (450 Ma) and *S* composing <2% (500–1000 Ma) of these older age distributions. The abrupt introduction of these zircon populations at 8 Ma indicates that the Paleozoic and Silurian source terranes in the Laji Shan began actively eroding at 8 Ma, and the Laji Shan underwent uplift at this time.

In addition to recording an influx of new sediment sources, detrital zircons in Guide Basin strata also record the disappearance of discrete Laji Shan source units as they eroded from the newly emergent range. The 500–1000 Ma S zircon population derived from Silurian strata is a significant proportion only in the 8 Ma Guide stratum (Figs. 2C, 2D, and 3), where it constitutes 18% of the distribution. This distinctive zircon population is otherwise absent in strata deposited both before and after 8 Ma, thus showing that Silurian-derived sediment underwent punctuated deposition into the Guide Basin. Furthermore, Silurian strata are present today only in the central Laji Shan, >45 km to the east of the Guide Basin. The disappearance of *S* due to shifting or capture of drainage networks is unlikely because Guide strata show consistently southward paleocurrents throughout the succession. Deeper structural levels are currently exposed in the Laji Shan near Guide, indicating that the Silurian strata were once more widespread in the range, but have since been unroofed from west to east over the past 8 m.y.

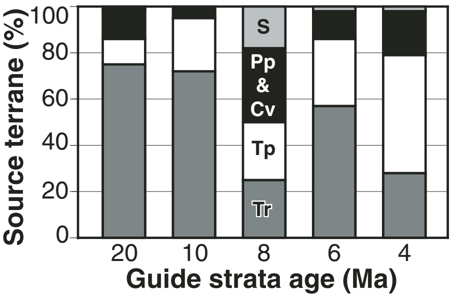

Figure 3. Source terrain mixtures that best define Guide strata as determined from our four-component sediment-mixing model, run with a smoothing window of 80 Ma. Abbreviations as in Figure 2. Note that S and Pp & Cv are derived from Laji Shan sources (to north), whereas Tp and perhaps Tr are from West Qinling sources (to south).

Although depositional systems at range-front locations along the edges of intermontane basins may be stratigraphically sensitive to discrete, punctuated changes in local source terranes, our detrital zircon data indicate that this sensitivity diminishes toward the center of a basin. Whereas the range-front 8 Ma stratum is dominated by Laji Shan–derived zircons, the basin-center 6 Ma stratum has more than twice as many West Qinling zircons as Laji Shan zircons (Figs. 2D and 3). The 6 Ma stratum also has twice as many older than 1500 Ma zircons in comparison to the range-front 4 Ma and 8 Ma Guide strata that bracket it chronologically. Thus, the 6 Ma zircon distribution appears to be dominated by zircons from the south and east as opposed to zircons shed off the newly emergent Laji Shan to the north. Also, the parity of the zircon distributions for the basin-center 12.5 Ma and 7.5 Ma Linxia strata (Fig. 2E) lends credence to the notion that the sensitivity of strata to record local uplift diminishes toward the basin center.

CONCLUSION

The emergence of the Laji Shan as an actively eroding terrane at 8 Ma adds to a growing body of evidence (Fig. 1A) for accelerated erosion and/or deformation along the northern and eastern margins of the Tibetan Plateau during the late Miocene, significantly earlier than Pliocene–Quaternary models (Tapponnier et al., 2001). In particular, synchronous uplift of the Laji Shan and Liupan Shan (Zheng et al., 2006), two discrete ranges in northeastern Tibet separated by >300 km, indicates initiation of deformation ca. 8 Ma over a broad region. Although competing models of plateau expansion gain support from the large Pliocene–Holocene increase in mass accumulation rates in the Qaidam Basin (Metivier et al., 1998), they ignore the role of climate-induced increases in sedimentation rates worldwide (Zhang et al., 2001; Molnar, 2004). Alternatively, perhaps late Miocene deformation of northeastern Tibet was limited to the present margins of the plateau, where the Qaidam block collides with the stable backstop of north

China, and subsequent Pliocene–Quaternary deformation has stepped inward toward the more central portion of the plateau.

In contrast to earlier regional studies, we demonstrate that detrital zircon sediment tracers can detect provenance changes on spatial scales of tens of kilometers. We use the late Miocene emergence and erosion of the Laji Shan in northeastern Tibet as a case study. The ability to discern hinterland erosion at the scale of an individual range is predicated on local source terranes with distinct U/Pb ages and well-dated stratigraphic successions. Our spatially focused detrital zircon age data set shows that depositional systems at the edges of intermontane basins are stratigraphically sensitive to discrete, punctuated changes in local source terranes. By tracking the sedimentary record of rock units with distinctive age signatures as they are unroofed from a mountain range, this sensitivity permits the detection of differential uplift of discrete ranges with unique U/Pb age distributions.

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