Multisystem dating of modern river detritus from Tajikistan and China: Implications for crustal evolution and exhumation of the Pamir

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ABSTRACT

The Pamir is the western continuation of Tibet and the site of some of the highest mountains on Earth, yet comparatively little is known about its crustal and tectonic evolution and erosional history. Both Tibet and the Pamir are characterized by similar terranes and sutures that can be correlated along strike, although the details of such correlations remain controversial. The erosional history of the Pamir with respect to Tibet is significantly different as well: Most of Tibet has been characterized by internal drainage and low erosion rates since the early Cenozoic; in contrast, the Pamir is externally drained and topographically more rugged, and it has a strongly asymmetric drainage pattern. Here, we report 700 new U-Pb and Lu-Hf isotope determinations and >300 \(^{40}\)Ar/\(^{39}\)Ar ages from detrital minerals derived from rivers in China draining the northeastern Pamir and >1000 apatite fission-track (AFT) ages from 12 rivers in Tajikistan and China draining the northeastern, central, and southern Pamir. U-Pb ages from rivers draining the northeastern Pamir are Mesozoic to Proterozoic and show affinity with the Songpan-Ganzi terrane of northern Tibet, whereas rivers draining the central and southern Pamir are mainly Mesozoic and show some affinity with the Qiangtang terrane of central Tibet. The \(t_{1/2}\) values are juvenile, between 15 and ~40, for the northeastern Pamir and juvenile to moderately evolved, between 10 and ~40, for the central and southern Pamir. Detrital mica \(^{40}\)Ar/\(^{39}\)Ar ages for the northeastern Pamir (eastern drainages) are generally older than ages from the central and southern Pamir (western drainages), indicating younger or lower-magnitude exhumation of the northeastern Pamir compared to the central and southern Pamir. AFT data show strong Miocene–Pliocene signals at the orogen scale, indicating rapid erosion at the regional scale. Despite localized exhumation of the Mustagh-Ata and Kongur-Shan domes, average erosion rates for the northeastern Pamir are up to one order of magnitude lower than erosion rates recorded by the central and southern Pamir. Deeper exhumation of the central and southern Pamir is associated with tectonic exhumation of central Pamir domes. Deeper exhumation coincides with western and asymmetric drainages and with higher precipitation today, suggesting an orographic effect on exhumation. A younging-southward trend of cooling ages may reflect tectonic processes. Overall, cooling ages derived from the Pamir are younger than ages recorded in Tibet, indicating younger and higher magnitudes of erosion in the Pamir.

INTRODUCTION

The Pamir Mountains form the western prolongation of the Tibetan-Himalayan collisional orogenic system (Fig. 1), which is the locus of Earth’s highest mountains and largest continental plateau. Although both Tibet and the Pamir are characterized by similar rocks and tectonostratigraphic architecture (Şengör, 1984; Dewey et al., 1988; Burtman and Molnar, 1993; Schwab et al., 2004; Robinson et al., 2007, 2012; Robinson, 2009), current debate exists about the exact correlation of terranes and sutures along strike (Schwab et al., 2004; Robinson et al., 2007, 2012; Robinson, 2009). Current models suggest northward displacement of the Pamir with respect to Tibet but differ in the magnitude of offset along the Karakorum fault as well in the width of individual geologic terranes across the orogenic system and in the degree of correlation (Fig. 2). In particular, early work by Tapponnier et al. (1981) and the more recent correlation of Schwab et al. (2004) call for a large magnitude of slip (~250 km), whereas others (Searle, 1996; Robinson et al., 2004; Robinson, 2009) suggest a much smaller offset (~150 km).

Tibet and the Pamir are strikingly different in terms of morphology and exhumation history. Tibet is largely characterized by internal drainage, high elevation, relatively low internal relief (Fielding et al., 1994), and limited erosion since the early Cenozoic (Rowley and Currie, 2006; DeCelles et al., 2007a, 2007b; Rohrmann et al., 2012). Cenozoic exhumation is localized around Miocene rifts (Kapp and Guynn, 2004) and the southeastern externally drained margin of the plateau (Clark et al., 2005) and on the frontal (southern) flank of the Himalaya (Thiede and Ehlers, 2013). Because of the aridity, glaciers are for the most part restricted to the crests of mountain ranges north of the Himalaya (Owen, 2009), and glacial erosion has not significantly affected landscape morphology. The Pamir, in contrast, is mostly externally drained, has high topographic relief (>2–3 km), and contains widely exposed high-grade metamorphic domes that have been exhumed since early Miocene time (Fig. 1; Schwab et al., 2004; Schmidt et al., 2011; Lukens et al., 2012). A striking feature of the Pamir is the asymmetry in morphology.
Figure 1. (A) Inset map showing political borders. (B) Simplified geologic map of the Pamir, showing lithologic units and main sutures, compiled after Bershaw et al. (2012), Lukens et al. (2012), Robinson et al. (2007), and Teraoka and Okumura (2007).
Figure 2. Simplified tectonic map of the Indo-Asian collision zone showing major active structures and suture zones (after Burtman and Molnar, 1993; Yin and Harrison, 2000). (A) Terrane correlations after Schwab et al. (2004); (B) terrane correlations after Robinson et al. (2004); (C) terrane correlations after Robinson (2009) and Robinson et al. (2012). Abbreviations: MPT—Main Pamir thrust; IYS—Indus-Yarlung suture; BNS—Bangong-Nujiang suture; JS—Jinsha suture; AKMS—Aygimash-Kunlun-Muztagh suture; RPS—Rushan-Pshart Suture; TS—Tanymas Suture. Terranes of western Indo-Asian collision zone are: A—Northern Pamir; B—Central Pamir; C—Southern Pamir–Karakorum–Hindu Kush; D—Kohistan arc.

The regional geology of the Pamir is dominated by the exhumation of the Pamir to a depth of at least 200 km (Schneider et al., 2013), including the Fedchenko glacier in Tajikistan. Precipitation drops off dramatically eastward across the Pamir to less than 10 cm/yr by the midpoint of the range. Glaciers and permanent snow cover correspondingly decline (Fuchs et al., 2013). Eastern drainages are much less dissected and are dominated by the structural basin in the hanging wall of the Kunghur extensional system (Robinson et al., 2004). A wealth of thermochronological, geochronological, and structural data exists from Tibet (e.g., Copeland et al., 1995; Ratschbacher et al., 1996; Murphy et al., 1997; Kapp et al., 2007; Jolivet et al., 2001; Kirby et al., 2002; Rohrmann et al., 2012), whereas only sparse data exist for the Pamir (e.g., Amidon and Hynek, 2010; Robinson et al., 2012; Sobel et al., 2013; Stübner et al., 2013a, 2013b; Thiede et al., 2013), leaving the exhumation and tectonic history of this part of the orogenic system largely unresolved. Here, we apply geochronology, thermochronology, and Hf isotope geochemistry to modern river sand grains in order to determine the timing of crustal evolution and the timing and pattern of exhumation of the Pamir. The rivers sampled for this study drain not only metamorphic domes but also Paleozoic–Mesozoic and older rocks (Fig. 1); therefore, the ages presented here represent the timing of regional tectonic and erosional processes. We also discuss the role that climate-enhanced erosion may play in explaining the geomorphic and erosional differences between the Pamir and Tibet.

GEOLOGICAL SETTING OF THE PAMIR

The Pamir Mountains occupy a roughly 120,000 km² region extending ~360 km north from the Hindu Kush Mountains to the Alai River valley and the Main Pamir thrust system (Fig. 1), a group of south-dipping thrust faults along which crust of the Tarim Basin and Tajik depression has been underthrust beneath the Pamir to a depth of at least 200 km (Schneider et al., 2013). The Pamir is bounded by major strike-slip faults on its eastern and western flanks, and it is composed internally of three or four large crustal blocks (or terranes) that accreted onto Eurasia from Paleozoic to early Cenozoic time (Burtman and Molnar, 1993). The regional geology of the Pamir is dominated and climate from west to east (Fig. 3). The west side of the range receives up to 60 cm/yr in rainfall, dominantly delivered by the midlatitude westerlies during the spring (Aizen et al., 2001). Rivers are deeply incised, and the drainage divide is displaced far to the east within the range. The western Pamir hosts some of the largest glaciers outside of the polar regions and the Himalaya and Karakoram (Fuchs et al., 2013), including the Fedchenko glacier in Tajikistan. Precipitation drops off dramatically eastward across the Pamir to less than 10 cm/yr by the midpoint of the range. Glaciers and permanent snow cover correspondingly decline (Fuchs et al., 2013). Eastern drainages are much less dissected and are dominated by the structural basin in the hanging wall of the Kunghur extensional system (Robinson et al., 2004).
Figure 3. (A) Digital elevation model (DEM) and shaded relief map of the Pamir on Shuttle Radar Topography Mission (SRTM) base (http://www2.jpl.nasa.gov/srtm/). Sample locations and upstream drainage areas are marked with stars and shaded regions, respectively. Major structures are indicated with black lines and standard structural symbols. Location of swath profile (Fig. 3C) is indicated by black rectangle. (B) Topographic map of the Pamir with drainages and precipitation, showing winter (December-January-February) average, long-term mean (1948-2007) rainfall data shown on shaded relief SRTM base. Precipitation data are from the Precipitation Reconstruction Over Land data set (Chen et al., 2002) with a spatial resolution of 0.5° x 0.5°. Location of the metamorphic domes is indicated by black outlines with labels. Note that the location of the Sares dome is from Schmidt et al. (2011) and differs from the location in Schwab et al. (2004). Watersheds (gray) and sample sites (stars) are indicated. (C) Swath profile and precipitation data for box shown in A and B. Gray shaded region indicates maximum and minimum elevation, and black line indicates mean. Drainage divide, pushed far to the east, is indicated. Relief is higher on the western side of the Pamir. Precipitation data show a strong decrease from west to east. (D) Cumulative hypsometric curves for western (cool colors) and eastern (warm colors) drainages. Note lower curves for less-incised eastern drainages. (E) Hypsometric curves (same colors as D). Note plateau-like shape of eastern drainages and sharper peaks of western drainages. Colors in D and E are from drainages in A. SS—Shyok Suture.
by five domal structures (Fig. 3) developed in medium- to high-grade metamorphic rocks that yield pressure-temperature-time estimates consistent with exhumation from midcrustal depths, mostly during the Miocene (Schmidt et al., 2011; Stüber et al., 2013b).

The Pamir terranes are referred to as the Northern, Central, and Southern Pamir (Fig. 1) and have been correlated in different ways to terranes in Tibet (e.g., Schwab et al., 2004; Robinson et al., 2007, 2012; Robinson, 2009). Different correlation models (Fig. 2) have been discussed in detail by Schwab et al. (2004) and Robinson et al. (2004, 2012). The Schwab et al. (2004) correlation model is based on geological structures and geochemistry of magmatotic belts in the Pamir-Tibet orogen. This study correlates the Karakul granites, which are found in parts of the Northern Pamir terrane, to the Songpan-Ganzi terrane in Tibet. This correlation is supported by a continuous chain of ca. 200 Ma plutons with similar geochemical signatures that wraps around the Pamir from the Karakul Basin into the Mazar region of western Kunlun (Schwab et al., 2004). In the Central Pamir terrane, the presence of mid-Triassic granitoids similar to those observed in the Qiangtang block led the same authors to propose a correlation between these terranes. Schwab et al. (2004) also documented a long-lasting Cretaceous magmatic history of intrusions in the Southern Pamir terrane. U-Pb geochronology of xenoliths in this region yielded clusters of ages at 84–57 Ma, 170–146 Ma, 465–412 Ma, 890 Ma, and 1400 Ma, with the youngest zircon age at 56.7 ± 5.4 Ma (Duca et al., 2003). These ages correlate with magmatic activity of the Tirich Mir–Karakoram–Gangdese arc, which was active in the northernmost part of the Southern Pamir and Hindu Kush–Lhasa block and includes suites of granite and granodiorites that yield crystallization ages of ca. 1624 Ma, 902 Ma, 417 Ma, 355 Ma, and 196 Ma (Schwab et al., 2004). The proposed correlation of the Northern Pamir terrane to Songpan-Ganzi, the Central Pamir terrane to Qiangtang, and the Southern Pamir terrane to Lhasa by Schwab et al. (2004) implies a displacement of ~250 km along the Karakorum fault (Fig. 2A).

The correlation model proposed by Robinson et al. (2004) (Fig. 2B) suggests a smaller offset along the Karakorum fault of <200 km (120–150 km—Searle, 1996; Searle et al., 1998; 60–70 km—Murphy et al., 2000). This model correlates the Tanymsas suture south of the Northern Pamir to the Ayimaqin-Kunlun-Muztagh suture, suggesting a correlation between the Northern Pamir terrane and the Kunlun-Qaidam terrane in Tibet. Similarly, by correlating these suture zones, the Central Pamir terrane is matched to the Songpan-Ganzi, the Southern Pamir terrane is matched to the Qiangtang, and the Kohistan arc is correlated to the Lhasa terrane (Searle, 1996; Searle et al., 1998; Murphy et al., 2000). Yin and Harrison (2000) considered the Lhasa terrane and Kohistan arc to be a continuous magmatic arc.

The correlation model of Robinson et al. (2004) (Fig. 2C) is a slight modification of the Robinson et al. (2004) model and is based on remote mapping of the Late Triassic–Early Jurassic Aghil Formation, which implies 149–167 km of offset along the northern and southern portions of the Karakorum fault. This study suggests a correlation between the Bangong-Nujiang and Shyok sutures, consistent with the interpreted maximum offsets of the Miocene Baltoro granodiorite (40–150 km). Further analysis of the Aghil Formation shows that the antiforms in both the Central Pamir and Qiangtang are not offset by the Karakorum fault. This model correlates the Northern Pamir with Songpan-Ganzi, the Southern Pamir with Qiangtang, and the Kohistan arc with Lhasa. This model also suggests that the Central Pamir is a crustal fragment with no equivalent in Tibet (Burtman and Molnar, 1993; Robinson, 2009). Burtman (2010) interpreted the Central Pamir to be a partially rifted portion of the Southern Pamir–Qiangtang terrane. More recent geochronological data from the northeastern Pamir support correlation of the Northern Pamir with the Songpan-Ganzi terrane (Robinson et al., 2012). Despite differences between correlation models, all agree that Pamir terranes have been offset northward relative to their Tibetan counterparts by slip along the Karakoram strike-slip fault (Burtman and Molnar, 1993; Lacassin et al., 2004; Schwab et al., 2004; Robinson, 2009; Peltzer and Tapponnier, 1988).

**DETrital APPROACH TO RESOLVING TECTONICS AND EROSION**

Geochronology and thermochronology applied to detrital minerals provide information on the timing of crystallization, cooling, and exhumation of the river catchment areas and thus on regional tectonic and erosional processes (e.g., Hodges et al., 2005; Carrapa, 2010). In particular, U-Pb geochronology combined with Lu-Hf geochemistry applied to zircons provides information on crystallization age and crustal evolution (e.g., Patchett et al., 1982; Griffith et al., 2000; Dickinson and Gehrels, 2009). The ⁴⁰Ar/³⁹Ar thermochronometry method applied to white mica and apatite fission-track (AFT) thermochronometry document the time of mineral crystallization and cooling through the ~350–80 °C temperature window (McDougall and Harrison, 1999; Gleadow and Duddy, 1981; Green et al., 1986), which corresponds to ~12–2.5 km of crust removal (assuming a conservative 30 °C/km paleogeothermal gradient). Erosion and normal faulting (tectonic exhumation) are responsible for cooling and exhumation of Earth’s crust (England and Molnar, 1990). High relief, precipitation, and active deformation can enhance exhumation (Ring et al., 1999).

Detrital thermochronology is particularly useful in areas where sampling in situ rocks is challenged by high relief and the paucity of roads, such as in the Pamir. In this study, we let nature do the job of sampling the orogenic system by utilizing rivers. We collected 12 samples of medium-grained sand from major rivers draining catchments within the Northern, Central, and Southern Pamir terranes (Figs. 1 and 3); of these, nine samples yielded mica, and 11 yielded apatites. We present data from four river samples from the Central and Southern Pamir (western drainages), one from the interior of the Pamir (TJK4) of Tajikistan, and seven river samples from the northeastern Pamir of China. The Tajik Pamir samples were previously analyzed for zircon U-Pb and ⁴⁰Ar/³⁹Ar geochronology and thermochronology (Lukens et al., 2012). Lu-Hf geochemistry and AFT thermochronology are here applied to all samples; U-Pb geochronology and ⁴⁰Ar/³⁹Ar thermochronometry are applied to the northeastern Pamir samples.

The Tajik river samples were collected from the Vanj, Yazgulem, Bartang, Gunt, and Murghab Rivers and drain a larger area than the Chinese rivers, including mainly the Central and Southern Pamir and only part of the Northern Pamir (Fig. 3). Drainage areas of the Tajik rivers include Paleozoic sedimentary and basement rocks, Mesozoic and Cenozoic magmatic rocks, and large metamorphic domes (Vlasov et al., 1991; Burtman and Molnar, 1993). The samples from the northeastern Pamir were collected from the Kalate and Gez Rivers and tributaries of the Tashkorgan River that flow eastward, debouching into the Tarim Basin (Fig. 3). The Chinese rivers drain the northeastern Pamir, which is dominated by Triassic and Jurassic sedimentary and metamorphic rocks (Fig. 1; Robinson et al., 2007). Out of the seven samples we collected from the northeastern Pamir, four (1071-1, 1071-2, 1071-4, 1071-6) come from the footwall of the Kongur Shan normal fault, whereas the other three (1071-3, 1071-5, 1071-7) come from the hanging wall. Together, the sampled rivers drain a land surface area, representing roughly 90% of the Pamir; the data provide the first regional-scale assessment of exhumation ages for almost the entire range.
**U-Pb and Lu-Hf Geochronology Methods and Results**

Zircon U-Pb and Hf geochronology was conducted by laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron Center (Gehrels et al., 2006, 2008; Cecil et al., 2011; Gehrels and Pecha, 2014). For details on analytical procedure, we refer the reader to the GSA Data Repository1 and https://sites.google.com/a/laserchron.org/laserchron/. For zircon U-Pb data from the Tajik rivers, see Lukens et al. (2012).

In total, 700 zircons from all seven samples from the northeastern Pamir were analyzed. Out of the 700 grains, 605 were included in the data reduction processes (Table DR1 [see footnote 1]). The excluded grains include those with high 206Pb/238U error (>20%), high 204Pb (>100 cps [counts per second]), and grains that produced analyses that were >20% discordant or >5% reverse discordant. Selected zircons were analyzed for Lu/Hf geochemistry, with an average of 20 grains analyzed per sample.

Samples 1071-1, 1071-2, 1071-3, 1071-4, and 1071-5 from the Gez and Tashkorgan Rivers show mainly Permian–Triassic zircon U-Pb ages (ca. 200–300 Ma; Fig. 4). A minor component at 400–500 Ma is present in most samples. Sample 1071-6, and to a lesser extent sample 1071-1, contains a component at ca. 80 Ma. Sample 1071-4 contains a small Miocene (ca. 16 Ma) component. Zircons from the Tajik rivers draining the Central and Southern Pamir terranes produced Proterozoic through Cenozoic U-Pb ages, exhibiting affinity with Asian rocks. These data were presented by Lukens et al. (2012) and will be further discussed in this paper.

The Hf isotopic data from the zircon grains exhibit widely variable $\varepsilon_{\text{Hf}}$ values (Table DR2 [see footnote 1]), ranging from +15 to −40 (Figs. 5A and 5B). A few highly juvenile values (within 5 epsilon units of the depleted mantle array) are present for grains between 300 and 900 Ma. The Hf isotopic data from the zircon grains show a range of values from juvenile to intermediate (near chondrite uniform reservoir [CHUR]).

**U-Pb and Lu-Hf Data Interpretation**

We interpret the zircon U-Pb ages from the northeastern Pamir to dominantly reflect Trias-

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Figure 4. Age probability plots for U-Pb geochronology. (A) Crystallization ages for northeastern Pamir samples. (B) Comparison of crystallization ages between northeastern and western Pamir. (C) Comparison of crystallization ages between Pamir and Tibet terranes. Shaded dark-green and red box highlight the similarities between the corresponding signals from the different terranes (Gehrels et al., 2011; Weislogel et al., 2006).

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**Notes**

1 GSA Data Repository Item 2014332, Analytical details and data tables, is available at www.geosociety.org/pubs/fl2014.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
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Early Paleozoic ages (ca. 400–500 Ma) may be associated with sources from the northern and southern Kunlun magmatic belts as suggested by Schwab et al. (2004). Samples 1071-5 and 1071-7, which were collected close to the village of Oytag and the easternmost section of the Tashkorgan River, record a different signal mainly characterized by early Paleozoic ages (ca. 400–600 Ma). Samples 1071-6, and to a lesser extent sample 1071-1, could be derived from Cretaceous plutons (Jiang et al., 2014).

In general, the zircon U-Pb ages from rivers draining the northeastern Pamir differ from the zircon U-Pb ages of rivers draining the central and southern Pamir (Fig. 4); western Pamir Rivers contain stronger 300 and 500 Ma components.

40Ar/39Ar and AFT Thermochronology

The 40Ar/39Ar analyses of white mica from the northeastern Pamir samples were conducted at the U.S. Geological Survey Laboratory in Denver. Samples were irradiated for 10 MWH (Megawatt per hour) in the central thimble position of the Denver USGS TRIGA reactor with cadmium shielding. Sandine from the Fish Canyon Tuff was used as the neutron influence monitor with a reference age of 28.20 ± 0.8 Ma (Kuiper et al., 2008). For more details, see Table DR3 (see footnote 1). For 40Ar/39Ar analyses of Tajik rivers draining the central and southern Pamir, we refer the reader to Lukens et al. (2012). AFT analyses were conducted at the University of Arizona following procedures described in Table DR4 (see footnote 1). In total, 330 white micas were analyzed by 40Ar/39Ar thermochronology from the northeastern Pamir rivers, and 1154 grains from the 12 samples draining both the northeastern and central and southern Pamir were analyzed for AFT thermochronology.
The \(^{40}\text{Ar}/^{39}\text{Ar}\) single-grain ages range from ca. 350 Ma to ca. 8 Ma (Fig. 6A). AFT age density distributions and detrital populations (calculated using DensityPlotter and Binomfit; Brandon, 2002; Vermeesch, 2012) are mainly late Cenozoic, but with a tail of early Cenozoic ages (Fig. 6B); the youngest AFT population is ca. 6 Ma (Fig. 7; Tables DR4 and DR5 [see footnote 1]). Samples from the Vanj (TJK-8), Yazgulem (TJK-7), Gunt (TJK-5), Bartang (TJK-6), and Murghab (TJK-4) Rivers in Tajikistan, draining mostly the central and some of southern Pamir, including the Yazgulen, Sares, Muskol, and Shakhda metamorphic domes, have prominent \(^{40}\text{Ar}/^{39}\text{Ar}\) age components at ca. 18 Ma and ca. 25 Ma (Luken et al., 2012) and late Miocene AFT ages (Fig. 6), with youngest AFT populations between ca. 8 Ma and ca. 13 Ma (Fig. 7). Samples from the Kalate River (1071-4) and tributaries of the Gez (1071-1, 1071-2) and Tashkorghan (1071-3, 1071-7, 1071-6) Rivers, draining the northeastern Pamir, including the Kongur Shan and Mustagh Ata domes (Fig. 3), have prominent \(^{40}\text{Ar}/^{39}\text{Ar}\) age components at ca. 80 Ma, 100 Ma, and between ca. 150 Ma and 200 Ma (Fig. 6) and early to late Cenozoic AFT ages; the youngest AFT age populations are between ca. 6 Ma and 22 Ma (Fig. 7; Table DR5 [see footnote 1]).

\(^{40}\text{Ar}/^{39}\text{Ar}\) and AFT Data Interpretation

Overall, the \(^{40}\text{Ar}/^{39}\text{Ar}\) ages from rivers draining the northeastern Pamir are older than \(^{40}\text{Ar}/^{39}\text{Ar}\) ages from rivers draining the central and southern Pamir, indicating older exhumation for the northeastern Pamir. Alternatively, this pattern could indicate that exhumation in the northeastern Pamir has been insufficient to expose rocks recording Cenozoic \(^{40}\text{Ar}/^{39}\text{Ar}\) ages. Higher-magnitude exhumation of the western Pamir is supported by Miocene syn-orogenic deposits >6 km thick preserved in the Tajik depression (Nikolaev, 2002), indicating rapid erosion of the Pamir at this time.

Detrital AFT ages of ca. 22–24 Ma are consistent with initiation of exhumation of the northeastern Pamir, possibly as the result of southward-directed subduction or underthrusting of Asia (Aminud and Hynke, 2010; Sobel et al., 2013). The presence of sparse late Miocene \(^{40}\text{Ar}/^{39}\text{Ar}\) and AFT ages (between ca. 6 and ca. 9 Ma) in the northeastern Pamir coincides with the timing of tectonic exhumation of the Kongur Shan detachment system as recorded by regional in situ thermochronological and structural data (Robinson et al., 2004, 2007; Sobel et al., 2011, 2013; Thiede et al., 2013; Cao et al., 2013a) and supported by detrital zircon fission-track ages from the Gez River (Cao et al., 2013b). Older Cenozoic thermochronological ages in the northeastern Pamir have been interpreted to be the result of an early phase of subduction erosion along the Trans-Alai intracratonic suture (Sobel et al., 2013).

The new AFT ages from western Pamir range from early to late Cenozoic. In particular, ages from the Bartang River draining the southern Pamir, including the Shakhdara dome, show a significant late Cenozoic component (ca. 8–13 Ma; Fig. 6) that is consistent with ages recorded in basement rocks of the Shakhdara dome (Stübner et al., 2013b), suggesting that late-stage exhumation of the dome occurred during the late Miocene. The same signal is present in the Gunt and Yazgulem River samples, indicating regional exhumation of the Northern, Central, and Southern Pamir terranes during the Cenozoic.

Hypsometric Analysis

Hypsometry, hypsometric integral, and cumulative hypsometry were calculated using Shuttle Radar Topography Mission (SRTM) 90 m digital elevation data (bin size 100 m) for four drainages in the central and southern Pamir representing the upstream drainage areas for samples TJK-8, TJK-7, TJK-6, and TJK-5, and three drainages in the northeastern Pamir representing upstream drainage areas for samples 1071-4, 1071-1, 1071-2, 1071-3, 1071-7, and 1071-6 (Fig. 3).

Hypsometric integrals for the western drainages are, from north to south, 0.46 (corresponding to TJK-8), 0.51 (TJK-7), 0.49 (TJK-6), and 0.57 (TJK-5), with an average of 0.51 ± 0.4. Cumulative hypsometric curves are S-shaped (Fig. 3D), and hypsometry displays a prominent peak at around 4200 m (Fig. 3E).

The two smaller, northern drainages are more asymmetric, with longer tails at low elevations. Hypsometric integrals for the eastern drainages are lower. From north to south, values are 0.49 (corresponding to 1071-4), 0.42 (1071-1, 1071-2), and 0.45 (1071-7), with an average of 0.45 ± 0.04. Curves are S-shaped but plot slightly lower than the western cumulative hypsometries (Fig. 3D). The hypsometry displays a broad plateau from ~3500 to 5000 m for the southern two drainages. The plateau in the eastern drainage hypsometry could reflect gradual erosion of the depositional basin in the hanging wall of the Kongur extensional system at an elevation of 3500–4500 m. Higher hypsometric integrals in the western drainages are consistent with evidence for more intense fluvial erosion on that side of the range, which includes higher precipitation, higher relief, and the position of the divide well east of the midpoint of the range (Fig. 3).

DISCUSSION

Terrane Correlation and Crustal Evolution

The zircon U-Pb data from modern fluvial sediments in rivers draining the Pamir document an Asian crustal provenance. Compiled ages yield three main zircon U-Pb age components in the Pamir (Fig. 4). The youngest age group contains Cenozoic and Cretaceous populations younger than 100 Ma and constitutes more than 50% of the age spectra. The other two major age components are the Permian–Triassic (ca. 200–300 Ma) and Paleozoic (ca. 400–600 Ma), which together represent less than 50% of the entire age spectra. A striking regional difference is the higher proportion of younger grains in central and southern Pamir (western drainages) compared with northeastern Pamir rivers (Fig. 4). The younger (<100 Ma) detrital zircon U-Pb ages from rivers draining the central and southern Pamir are consistent with Cenozoic intrusions in the central Pamir domes (Schwab et al., 2004). Therefore, we interpret the younger than 100 Ma detrital ages to mostly represent sources from these domes and deep exhumation.

Schwab et al. (2004) correlated the central Pamir to the Qiangtang block in Tibet. Detrital U-Pb ages from our river samples support this interpretation (Fig. 4). However, apart from the small but significant presence of Paleozoic signals (ca. 400–600 Ma) in all the samples draining the central and southern Pamir (western drainages), all samples are dominated by grains younger than 100 Ma, suggesting an affinity with Gangdese arc rocks of the Lhasa terrane in Tibet (Ji et al., 2009). In contrast, zircon U-Pb ages from the northeastern Pamir are mostly older than 100 Ma and show affinity with the Kunlun and Songpan-Ganzi arc rocks (Robinson et al., 2012). We note that sample 1071-6 (located in northeastern Pamir) contains a large group of 80–100 Ma grains. We attribute this to the fact that this sample comes from a river draining part of the Southern Pamir terrane. Figure 4 illustrates the similarity of detrital patterns between the Northern Pamir terrane (including sample TJK-8 from Luken et al., 2012) and Songpan-Ganzi with two distinctive peaks at ca. 200 Ma and ca. 550 Ma. Gehrels et al. (2011) reported 212–537 Ma ages from the Songpan-Ganzi complex with peaks at ca. 264 Ma and 440 Ma, 720–850 Ma ages with age peaks at 770 and 793 Ma, 1730–2100 Ma ages with an age peak at 1870 Ma, and 2360–2630 ages with an age peak at 2515 Ma.

Based on the U-Pb zircon analyses of rivers draining the Northern Pamir terrane, we make the following interpretations: (1) The strong 200–300 Ma age component coincides with
Figure 6. Kernel density distributions curves of detrital $^{40}$Ar/$^{39}$Ar and apatite fission-track (AFT) ages (calculated using DensityPlotter; Vermeesch, 2012). $^{40}$Ar/$^{39}$Ar ages for the western Pamir drainages are from Lukens et al. (2012).
the Triassic magmatism recorded in the Kunlun are in the Karakul-Mazar Songpan-Ganzi terrane (Schwab et al., 2004). This implies that samples with these ages (1071-1, 1071-2, 1071-3, 1071-4, 1071-6) have affinity with the Permian–Triassic Karakul-Mazar terrane. (2) The early Paleozoic ages (ca. 400–600 Ma) represent a source from the northern and southern Kunlun magmatic belts, as suggested by Schwab et al. (2004).

Negative εHf values (as low as −42) in grains between ca. 180 Ma and ca. 700 Ma are present in samples derived from northeastern Pamir, with higher proportions in the central and southern Pamir, with significantly higher in the central and southern Pamir, with higher proportions in the central and southern Pamir, with significantly higher in the central and southern Pamir. Samples were both derived from granitic intrusions. The southern sample (1071-6) is from a river that drains a Miocene granite that has yielded biotite 40Ar/39Ar ages as young as 11.45 ± 0.3 Ma (Robinson et al., 2007), and could explain the presence of late Miocene 40Ar/39Ar ages. The northern sample (1071-1) taps into an undated intrusion mapped as Triassic–Early Jurassic (Robinson et al., 2007). Our data suggest the true age may be younger. Interestingly, both samples are also located on the drainage divide between the western and eastern Pamir.

Exhumation History

Cenozoic 40Ar/39Ar ages are widespread in samples from central and southern Pamir (western drainages), whereas northeastern Pamir is mainly characterized by Mesozoic ages (Fig. 6). For example, the main 40Ar/39Ar age populations comprising 63% of the ages from the Gunt River (Fig. 6; Table DR5 [see footnote 1]), which is the largest drainage in the western Pamir derived mostly from the Shakdara dome, is 15.7 Ma. The main 40Ar/39Ar age population consisting of 76% of the ages from the Tashkorgan River tributaries, derived mainly from the Kongur-Shan and Mustagh Ata domes, is 78.6 Ma (Fig. 6; Table DR5 [see footnote 1]), and the main 40Ar/39Ar age populations made of 61% and 42% of the ages from two tributaries of the Gz River are 172.4 Ma and 98.7 Ma, respectively (Table DR5 [see footnote 1]). Although the bulk of 40Ar/39Ar ages are mainly pre-Cenozoic in the northeastern Pamir (Fig. 6), two samples (1071-6, 1071-1) exhibit 40Ar/39Ar youngest population ages of 10.7 ± 0.2 Ma and 14.5 ± 0.2 Ma, consistent with in situ thermochronological ages (Thiede et al., 2013). These samples were both derived from granitic intrusions. The southern sample (1071-6) is from a river that drains a Miocene granite that has yielded biotite 40Ar/39Ar ages as young as 11.45 ± 0.3 Ma (Robinson et al., 2007), and could explain the presence of late Miocene 40Ar/39Ar ages. The northern sample (1071-1) taps into an undated intrusion mapped as Triassic–Early Jurassic (Robinson et al., 2007). Our data suggest the true age may be younger. Interestingly, both samples are also located on the drainage divide between the western and eastern Pamir.

Excluding these two anomalous samples, the bulk of the 40Ar/39Ar age spectra are pre-Cenozoic. Although some young (ca. 2–5 Ma) 40Ar/39Ar ages have been recorded in the Kongur Shan gneiss dome (Robinson et al., 2004) and reflect localized tectonic exhumation, our data indicate that regional exhumation rates are significantly higher in the central and southern Pamir, which is the western and wetter side of the range compared to the northeastern Pamir.

AFT ages for the central, southern and northeastern Pamir are mid- to late Cenozoic, indicating similar average rates of short-term exhumation (0.4 mm/yr; Table DR5 [see footnote 1]). Late Cenozoic AFT ages (ca. 6 Ma) in samples 1071-2 and 1071-3 from the northeastern Pamir, both of which tap into the footwall of the Kongur Shan extensional system, likely reflect localized rapid exhumation associated with movement along this young fault system. Modeling of thermochronologic data indicates exhumation of the Kongur Shan dome in the footwall of the fault system at rates of 1.5–4 mm/yr since the late Miocene (Robinson et al., 2010; Thiede et al., 2013).

Assuming a conservative paleogeothermal gradient of 30 °C/km, and closure temperatures for white mica 40Ar/39Ar of ~350–425 °C (for phengite—McDougall and Harrison, 1999; for muscovite—Harrison et al., 2009), we obtain average Cenozoic exhumation rates between 0.4...
and 0.2 mm/yr for the northeastern Pamir and between 0.6 and 1.3 mm/yr for the central and southern Pamir (Table DR5 [see footnote 1]). For a lower paleogeothermal gradient, average exhumation rates would be higher. The highest exhumation rates are recorded by the Murghab and Gunt Rivers (2.4 mm/yr and 2 mm/yr). The high exhumation rates recorded by the Murghab River, which drains a small area, may reflect exhumation of the Muskol dome and/or localized exhumation associated with movement along the Karakorum fault (Amidon and Hynek, 2010). Exhumation rates between 0.6 and 2 mm/yr recorded by the Gunt River detritus are interpreted here to reflect exhumation of the Shakdara dome and are consistent with rates recorded by in situ thermochronology (Stübben et al., 2013b). Although the similarity between our detrital Cenozoic cooling ages and the cooling ages of the metamorphic domes supports this interpretation, the fact that the sampled rivers also drain rocks other than the domes (Fig. 1) allows for the possibility that the grains with Cenozoic ages may be derived from Mesozoic–Paleozoic and older rocks. If this is the case, it would suggest that Cenozoic exhumation is orogen-wide rather than limited to the domes, and it would be consistent with erosion controlled by climate, rather than localized tectonic exhumation.

The different magnitude of exhumation of the central and southern Pamir (western drainages) versus northeastern Pamir is consistent with our geomorphic data, which indicate greater erosion on the western side of the range (Fig. 3). Western drainages exhibit higher hypsometric curves and hypsometric integrals, and relief is higher on the western side of the range (Fig. 3).

Figure 7 presents the younger than 50 Ma \(^{40}\text{Ar}/^{39}\text{Ar}\) ages and youngest \(^{40}\text{Ar}/^{39}\text{Ar}\) and AFT populations. The most recent exhumation signals from rivers draining the central and southern Pamir domes occurred mainly between ca. 19 Ma and ca. 8 Ma, and exhumation signals from the rivers draining the Kongur Shan and Mustagh Ata domes are between ca. 15 and ca. 6 Ma. The data also suggest a possible southward-younging trend of the youngest detrital \(^{40}\text{Ar}/^{39}\text{Ar}\) ages and youngest detrital AFT population ages for the central and southern Pamir. Although this signal may be an artifact of sample size and or statistical treatment of the data, the fact that both \(^{40}\text{Ar}/^{39}\text{Ar}\) and AFT youngest components show the same trend, which is consistent with documented cooling ages of metamorphic domes that also young to the south (Schmidt et al., 2011), suggests that our trend is geologically meaningful. We speculate that southward younging of exhumation of the Pamir may be related to tectonic processes.

For example, northward subduction and underthrusting of India under Asia has contributed to Cenozoic crustal thickening and east-west extension in Tibet (DeCelles et al., 2002; Sunnell et al., 2013) and most likely in the Pamir. If this is correct, the present-day location of the Indian slab under the Hindu Kush (Negredo et al., 2007) requires southward slab rollback following underthrusting, as proposed for Tibet during the Oligocene–Miocene (DeCelles et al., 2011). Southward slab rollback of India and asthenospheric upwelling, accompanied by upper-plate extension, could explain the southward-younging of thermochronological ages.

DISCUSSION AND CONCLUSIONS

Although both the Pamir and Tibet are composed of rocks with similar affinity, the exhumation history of the two regions appears to be significantly different. Overall, zircon U-Pb ages from modern river detritus derived from the central and southern Pamir are most similar to zircon U-Pb ages recorded in the Qiangtang terrane of central Tibet; U-Pb ages from modern rivers draining the northern Pamir are most similar to zircon U-Pb ages recorded in the Karakul-Mazar terrane (Fig. 1C), correlated to the Triassic Songpan-Ganzi terrane of northern Tibet, and Kunlun magmatic belt. Detrital zircon \(t_{ex}\) values in the Pamir river sands are consistent with \(t_{ex}\) values reported for Songpan-Ganzi, Qiangtang, and Lhasa terranes in Tibet.

Thermochronological ages from the Pamir record younger (mid-late Miocene), and on average much faster, exhumation than that recorded in Tibet. Lower magnitudes of exhumation in Tibet are supported by the surficial geology, which is characterized by widespread exposures of young volcanic and Mesozoic sedimentary rocks (Chung et al., 2005), indicating a shallow level of erosion. Outside of late Miocene rifts and marginal areas (Clark et al., 2005), low-temperature thermochronological ages are almost exclusively pre-Oligocene (Hetzel et al., 2011; Rohrmann et al., 2012; Duvall et al., 2012). Together, these observations indicate that most of the Tibetan Plateau has been internally drained and did not experience significant exhumation during the Cenozoic. This is consistent with increased aridification of large parts of the Tibetan Plateau during the Eocene–Oligocene (Dupont-Nivet et al., 2007) and with high elevations since at least the late Oligocene (Rowley and Currie, 2006; DeCelles et al., 2007b; Quade et al., 2011). In contrast, numerous early Miocene detrital thermochronological ages derived from the Pamir interior presented in this study indicate that most of the Pamir was undergoing extensive exhumation during the Cenozoic at much higher rates than those observed in Tibet. We hypothesize that greater precipitation on the upwind, western Pamir led to greater long-term exation, relief production, and migration of the drainage divide progressively toward the east. Alternatively, asymmetric exhumation may be related to asymmetric tectonics. However, based on the correlation between the locus of deep exhumation and higher precipitation (Fig. 3) in the Pamir, we favor climate as the controlling factor on regional exhumation by deep dissection of the western flank of the orogen. This is supported by the highly asymmetric Pamir drainage divide positioned near the eastern flank of the range and by the fact that major rivers generally drain westward (Fig. 1). Reanalysis data (Fig. 3) show that precipitation comes from the west and is most intense during the early spring. This precipitation is concentrated on the western side of the Pamir, which forms an orographic barrier to eastward moisture transport. We suggest that relatively intense precipitation on the windward side of the Pamir has been a major factor since at least the early Miocene in controlling bedrock exhumation and eastward retreat of the orogenic drainage divide. We also suggest that exhumation of the Pamir domes was facilitated by erosion and should be considered in tectonic models (Stübben et al., 2013a). A trend of southward-younging cooling ages between ca. 18 and ca. 6 Ma is observed throughout the Pamir and can be explained by southward migration of exhumation as a result of southward rollback of the subducting Indian slab under Asia. Overall, the magnitude of Cenozoic regional exhumation in the Pamir is greater than that observed in Tibet.

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