Mesozoic evolution of the eastern Pamir

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ABSTRACT

We present field and analytical results from the Tashkurgan and Waqia valleys in the southeastern Pamir that shed new light on the tectonic evolution and terrane architecture of the region. Field mapping of metasedimentary and igneous units along the Tashkurgan and Waqia valleys in the Southeast Pamir, integrated with metamorphic petrology, garnet-biotite thermometry, and zircon U/Pb isotopic analysis, help identify major structures and terrane boundaries in the region, as well as compare structural units across the Miocene Muztaghata gneiss dome. South of the Muztaghata dome, the gently northwest-plunging synformal Torbashi thrust klippe juxtaposes amphibolite facies Triassic Karakul–Mazar terrane schist and gneiss structurally above (1) greenschist facies Triassic Karakul–Mazar terrane metasedimentary rock in the north, and (2) lower-amphibolite facies schist in the south that are interpreted to be Gondwanan-derived crust (Central or South Pamir terrane). Farther south, the Rouluke thrust fault imbricates the Gondwanan crust, placing early Paleozoic schists over Permian marble and slate. Exposure of the Torbashi thrust sheet terminates in the southeast, and with it the surface exposure of the Triassic Karakul–Mazar terrane, leaving the Paleozoic Kunlun terrane juxtaposed directly against Gondwanan terrane crust. Based on lithologic and isotopic similarities of units north and south of the Muztaghata gneiss dome, we document the existence of a regionally extensive thrust nappe that stretched across the northern and eastern Pamir, prior to being cut by Miocene exhumation of the Muztaghata dome. The thrust nappe links the Torbashi thrust in the southeast Pamir with the Tanymas thrust in the northern Pamir, and documents regionally extensive exposure of lithologically continuous units across the northeast Pamir. While timing of emplacement of the Torbashi thrust klippe and displacement on the Rouluke fault to the south is not well constrained, we interpret shortening to be Cretaceous in age based on previously published cooling ages. However, a component of Cenozoic shortening cannot be ruled out.

A key observation from our mapping results is that the surface exposures of the Karakul–Mazar–Songpan Ganzi terrane are not continuous between western Tibet and the Pamir, which indicates tectonic and/or erosional removal, likely sometime in the Mesozoic. Furthermore, our documentation of the Jinsha suture in the southeast Pamir on the eastern side of the Karakoram fault shows deflections of terranes across the Himalayan-Tibetan orogen were not primarily accommodated along discrete, large displacement faults (>400 km) faults. Instead, oroclinal bending of the northern Pamir, and dextral shear along the Pamir margins, may be largely responsible for the northward deflection of terranes.

INTRODUCTION

The Cenozoic Himalayan-Tibetan orogen is considered one of the type examples for understanding lithospheric deformation processes associated with continent-continent collision zones. One of the most pronounced aspects of the orogen is the strong northward deflection of topography and tectonic terranes at the western end of the orogen in the Pamir-Karakoram region (Fig. 1). However, it is unclear whether this deflection has been a result of distributed deformation, or displacement on discreet structures, notably the Karakoram fault, largely due to uncertainties in terrane boundary locations near to and west of the Karakoram fault. This has led to significantly different interpretations of how strain has been accommodated in the Cenozoic at the western end of the Himalayan-Tibetan orogen (Burri and Molnar, 1993; Yin and Harrison, 2000; Lacassin et al., 2004; Schwab et al., 2004; Robinson et al., 2012). Estimates for the total right-lateral slip across the Karakoram fault range from ~160 to >500 km based on correlations of geologic units and interpreted sutures across the fault (Valli et al., 2007, 2008; Robinson, 2009b). A related challenge in understanding the evolution of the Himalayan-Tibetan orogen has been separating the effects of the Cenozoic collision between India and Asia from the protracted Mesozoic tectonic history consisting of the accretion of several discrete terranes to the southern margin of Asia.

Geologic age and lithologic correlations are generally not well defined for the northern and eastern Pamir. Older regional maps depict a wide range of age assignments that are not laterally continuous or easily correlated across the region, mostly due to the high metamorphic grade of the rocks and resulting lack of available biostratigraphic data (Yin and Bian, 1995; Strecke et al., 1995; Sobel and Dumitru, 1997; Schwab et al., 2004;
Figure 1. Regional map showing major structures and sutures in the western Tibetan orogen with proposed terrane boundary correlations. Note the North Pamir consists of Karakul-Mazar and Kunlun terranes. The region bound by a red dashed line and question marks highlights an area of previously uncertain correlation of terranes in the region. Inset map shows the location relative to the major structures in the Himalayan-Tibetan orogen. MPT—Main Pamir thrust; TS—Tanymas Suture; RPZ—Rushan-Pshart Zone; W—Wakhan-Tirich Boundary Zone; SS—Shyok Suture; IYS—Indus-Yalu Suture; JS—Jinsha Suture; KS—Kunlun Suture; SAR—Sarez Dome; MUS—Muskol Dome; SA—Shakhdara Dome; SH—Shatput Dome; MUZ—Muztaghata Dome.

Terranes
- Kunlun Terrane
- Karakul-Mazar/Hoh-Xil/Songpan Ganze
- Qiangtang Equivalent Terranes
- Kohistan/Ladakh

Other Map Elements
- Cenozoic Gneiss Domes
- Regional Thrust Fault Zone
- Regional Strike-Slip Fault Zone
- Area of previously uncertain Terrane boundary relationships
Robinson et al., 2007). Recent detrital zircon studies in the northern Pamir have shed significant light on the matter, demonstrating that many of the units in the region are Triassic rather than Proterozoic to Paleozoic, and are therefore part of the Karakul-Mazar terrane, equivalent to the Songpan-Ganzi terrane to the east (Zhang et al., 2007; Yang et al., 2010; Robinson et al., 2012; Schwab et al., 2004). Further, detrital zircon and whole rock Nd isotopic analyses provide evidence for correlating units of the northern Pamir terranes with the eastern portions of the Pamir across the Muztaghata gneiss dome (Robinson et al., 2012). However, recent studies of ages of intrusive igneous rocks have suggested that much of the eastern Pamir is part of a continuous Cambrian terrane, the Bulunkuole Group, which collided with Tarim basin in the early Paleozoic (Zhang et al., 2018a, 2018b). While progress has been made in understanding the correlatives relationships among units in the northern and eastern Pamir, several questions remain, including the following. (1) What is the structural and tectonic setting of the southeastern Pamir east of the Karakoram fault, and how does it compare with other portions of the Pamir? (2) How do metasedimentary rocks in the southeast Pamir correlate with metasedimentary rocks in the northern Pamir? (3) Where is the boundary between Gondwana crustal fragments and the Paleozoic–early Mesozoic southern boundary of Asia (i.e., the Tanymas-Jinsha suture), in the eastern Pamir? Addressing these questions is crucial for better understanding the tectonic history of the Pamir region and the greater Himalayan-Tibetan orogen.

We present results from detailed field mapping, integrated with petrologic and geochronologic data, which provide new insights into the structural relationships and distribution of rock units in the southeast Pamir south of the Cenozoic Muztaghata gneiss dome. Our results show that the northeastern Pamir consists of two distinct structural/lithologic domains. (1) To the north, Triassic amphibolite facies schist and gneiss intruded by Late Triassic–Early Jurassic granite lie structurally above the Triassic amphibolite facies schist and gneiss. These rocks constitute portions of the Triassic Karakul-Mazar terrane, which is imbricated during later Cretaceous to Eocene shortening. (2) To the South, early Paleozoic gneiss of the gneiss dome lies structurally above low-grade Permian marbles and slate. These rocks constitute Gondwana crust of the Central or southern Pamir that we interpret to have been imbricated along SW-vergent thrusts, likely during the Cretaceous. Further, our results correlate portions of the Karakul-Mazar terrane across the northern and eastern Pamir which have been cut by the Miocene Muztaghata gneiss dome, suggesting the presence of a regionally extensive (i.e., 100s of km) thrust sheet across the northern Pamir, which accommodated significant Cretaceous shortening.

**Regional Geology**

**Tectonic Setting**

The Pamir form an arcuate region of elevated topography at the northwestern corner of the India-Eurasia collision zone (Fig. 1), bound to the north by the Tien Shan and Alai Basin, to the west by the Tajik Basin, to the east by the Tarim Basin, and to the south by the Karakoram Mountains. Significant crustal thickening during the Cenozoic, as revealed by Oligocene-Miocene prograde metamorphism recorded in Miocene gneiss domes across the region, has resulted in a present-day crustal thickness of ~70 ± 10 km (Negredo et al., 2007; Mechie et al., 2011; Schmidt et al., 2011; Mechie et al., 2012; Sippel et al., 2013, Stübner et al., 2013a, 2013b; Stearns et al., 2015; Rutte et al., 2017a; Hacker et al., 2017).

The Himalayan-Tibetan orogen consists of a series of distinct terranes accreted to the southern margin of Asia prior to the Cenozoic India-Asia collision (Yin and Harrison, 2000). In Tibet, the Jinsha suture separates terranes of Asian affinity from accreted terranes derived from Gondwana. Pamir terranes are generally assumed to be correlative with terranes in Tibet (e.g., Schwab et al., 2004; Angiolini et al., 2013; Robinson et al., 2012), although the correlation of terranes across the Karakoram fault is still debated (Tapponnier et al., 1981; Burtman and Molnar, 1993; Lacassin et al., 2004; Schwab et al., 2004; Valli et al., 2007, 2008; Robinson et al., 2012; Angiolini et al., 2013).

Terranes in the Pamir include, from north to south, the Paleozoic Kunlun and Permian-Triassic Karakul-Mazar terranes (often grouped together as the North Pamir), the Central and southern Pamir, and the Karakoram terrane (Fig. 1). The Paleozoic Kunlun terrane is a Cretaceous thrust and the Karakoram terrane (Fig. 1). The Permian-Triassic Karakul-Mazar terrane, correlative with the Songpan-Ganzi–Hoh Xil terrane of Tibet (Schwab et al., 2004; Robinson et al., 2012; Xiao et al., 2002a), is exposed throughout the northern Pamir, but thins to the west (Schwab et al., 2004). The eastern continuation of the terrane toward the Western Kunlun is unclear. This terrane is bounded to the south by the north-dipping Tanymas-Tobrami thrust faults, which form the boundary between Asian affinity terranes to the north and Gondwana affinity terranes to the south. The Gondwana Central Pamir terrane is exposed between the Tanymas thrust fault and the Rushan-Phshart fault zone, and has been interpreted to be equivalent to the Qinngang terrane of Tibet (Burtman and Molnar, 1993; Lacassin et al., 2004; Schwab et al., 2004; Robinson, 2015) or a distinct terrane (Robinson et al., 2009, 2012). The south Pamir and Karakoram terranes to the south are separated by the Bakan-Tirich Bounday Zone, with both terranes interpreted to be equivalent to the Qinngang terrane to the east (Robinson et al., 2012; Angiolini et al., 2013; Zanchi et al., 2000; Zanchi and Gaetani, 2011).

During the Cenozoic India-Asia collision, the Pamir has been interpreted to have been translated northward ~300 km via the Main Pamir thrust since ca. 25–16 Ma (Burtman and Molnar, 1993; Sobel and Dumitru, 1997), although several recent studies suggest more limited displacement (Chapman et al., 2017; Chen et al., 2018). Displacement was possibly due to rollback of the Alai slab in the north and west, and accommodated in the east by the right-slip Kashgar Youcheng Transfer System (Cowgill, 2010; Sobel et al., 2013) or driven by the arrival and underthrusting of Indian lithosphere (Kufner et al., 2016; Liao et al., 2017). While Pamir indentation during the Cenozoic resulted in northward deflection of terranes and suture relative to positions in Tibet (Fig. 1), it is unclear the extent to which these deflections have been accommodated by displacement on discrete structures (i.e., the Karakoram fault) or distributed deformation between Tibet and the Pamir-Karakoram region.

**Cenozoic Gneiss Domes**

Several Cenozoic gneiss domes crop out throughout the Pamir including the Shakhdara–Alichur domes in the southern Pamir, and the Sarez, Muskol, Shatput, and Muztaghata domes in the Central Pamir. The gneiss domes consist of Paleozoic to Mesozoic granulite to upper amphibolite facies metamorphic rocks intruded by Cretaceous and Miocene igneous rocks (Schwab et al., 2004; Robinson et al., 2004, 2007; Smit et al., 2014; Stübner et al., 2013a, 2013b; Rutte et al., 2017a; Hacker et al., 2017). These domes experienced prograde metamorphism during north-south contraction in the Eocene to early Miocene, followed by later extension and exhumation (Robinson et al., 2004, 2007; Schmidt et al. 2011; Stübner et al., 2013b; Stearns et al., 2013; Rutte et al., 2017a). Metamorphic conditions in exposed cores of the Central Pamir domes are estimated to be 650–800 °C and 0.7–1.1 GPa (Robinson et al., 2007; Schmidt et al., 2011; Cao et al., 2013; Smit et al., 2014; Hacker et al., 2017). Metamorphism began at or before 37 Ma in the southern Pamir and spread northward to the Central Pamir until ca. 27 Ma (Smit et al., 2014). Exhumation and
doming as the result of extension began at ca. 21 Ma (Stühner et al., 2013b; Rutte et al., 2017a) and ended in the Central Pamir gneiss domes in the late middle Miocene (Robinson et al., 2007; Schmidt et al., 2011; Smit et al., 2014; Rutte et al., 2017a), and in the Shakhdara gneiss dome in the southern Pamir by 2 Ma (Stühner et al., 2013a, 2013b).

REGIONAL STRUCTURES

Mesozoic Structures

Tanymas Thrust Fault

The Triassic Tanymas thrust fault strikes approximately east-west and dips to the north forming the boundary between the Karakul-Mazar terrane and the Central Pamir (Figs. 1, 2). Slip data long the fault trace yield top-to-the-south thrusting accompanied by dextral slip in the Paleo-Muztaghata Gneiss Dome (Rutte et al., 2017b). Along the central and eastern portion of the Tanymas thrust fault, the hanging wall consists of high-grade Triassic metasedimentary rocks intruded by Triassic granitoids (Schwab et al., 2004; Robinson et al., 2004, 2012; Rutte et al., 2017b). The footwall of the Tanymas thrust consists of siliciclastic and carbonate metasedimentary rocks of latest Proterozoic to Cretaceous age; units that are part of the Tuzguny-Terezi and Zartoskhol thrust sheets (Schwab et al., 2004; Rutte et al., 2017a). South of the Tuzguny-Terezi and Zartoskhol thrust sheets in the Central Pamir are an antiformal stack of thrust fault blocks with the Central Pamir gneiss domes exposed in the core (Rutte et al., 2017b). Structural analysis of fault blocks in the footwall of the Tanymas thrust indicates Cenozoic shortening was at least 80 km (Burtman and Molnar, 1993) to >95 km (Rutte et al., 2017b) in the Central Pamir. The Tanymas thrust fault is cut by the North Muskol shear zone (NMSZ) at its eastern end. The NMSZ is the northern boundary of the Shapat and Muztaghata gneiss domes.

Baoziya Thrust Fault

The Baoziya thrust fault in the northeast Pamir is exposed in the hanging wall of the Kongur Shan Extensional System, northwest of the Muztaghata gneiss dome (Figs. 1, 2). The fault strikes approximately north-south with a moderate west-tip. Shear sense indicators show a top-to-the-south shear sense (Pan, 1992; Robinson et al., 2004), with the current west-dipping geometry interpreted to be a result of rotation of the structure during subsequent regional deformation. The Baoziya thrust fault juxtaposes Triassic amphibolite facies metasedimentary rocks of the Karakul Mazar terrane in the hanging wall against greenschist facies calcareous quartzite, slate, and marble in the footwall, which are also interpreted to be part of the Triassic Karakul-Mazar terrane (Robinson et al., 2004, 2012).

Torbashi Thrust Fault

The Torbashi thrust fault is located south of the Muztaghata gneiss dome (Figs. 2, 3). Identification of the Torbashi thrust fault in the field is based on amphibolite facies schist and gneiss structurally overlying greenschist facies phyllite, marble, and quartzite (Robinson et al., 2007). The thrust has been previously mapped as a synformal klippe, with a northwest-trending fold axis and a top-to-the west to southwest sense of shear. Biotite cooling ages of the hanging wall rocks suggest the age of the thrust is Late Cretaceous (Robinson et al., 2007).

Cenozoic Structures

Muztaghata Gneiss Dome

The Muztaghata gneiss dome is the easternmost of a series of Miocene domes that crop out along the Central Pamir (Fig. 2; Robinson et al., 2007; Schmidt et al., 2011; Cao et al., 2013; Smit et al., 2014). The core of the Muztaghata dome consists of Triassic orthogneiss and schist (Trgn) (Figs. 2, 3), the latter of which have detrital zircon signatures that are interpreted to be equivalent with the Karakul-Mazar terrane (Robinson et al., 2012). In the southern portion of the Muztaghata dome, the Kexi-Liqi thrust fault separates Triassic rocks in the footwall from early Paleozoic rocks (Pz1) in the hanging wall (e.g., the Shen-Shi klippe of Rutte et al., 2017a). The Paleozoic rocks have detrital zircon signatures indicating a Gondwanan affinity with the Kexi-Liqi fault interpreted to represent the Paleo-Tethys suture zone (Yang et al., 2010; Robinson et al., 2012). Schist and gneiss in the Muztaghata dome record an Early Jurassic metamorphic event, overprinted by late Oligocene–early Miocene upper-amphibolite to granulite facies conditions (0.9–1.0 GPa, 700 °C–750 °C), with rapid cooling and exhumation in the middle to late Miocene (Robinson et al., 2007; Cao et al., 2013; Cai et al., 2017). The Muztaghata dome is bounded by the North Muskol shear zone on its northern margin, the Shen-Ti fault on its southern margin, and the Kuke fault on its eastern margin (Robinson et al., 2007; Sobel et al., 2011; Rutte et al., 2017b). The Shen-Ti fault generally strikes east-west, parallel with the axis of the dome. The fault separates migmatitic schist and quartzofeldspathic gneiss of the Muztaghata dome in the footwall (Trgn and Pz1) from greenschist facies metasedimentary rocks in the hanging wall (Trmgs). Ductile shear sense indicators south of Muztaghata show top-to-the-south sense of the hanging wall (Robinson et al., 2007). The southern trace of the Shen-Ti fault connects with the Waqia fault (Imrecke, 2013) to the southeast, where it juxtaposes Ordovician meta-chert (OCh) and Paleozoic granite in the footwall (Pz1) against Neogene sediments (Cz) with ~1 km thickness in the hanging wall (Imrecke, 2013).

The north-striking Kuke fault bounds the eastern margin of the Muztaghata dome, and forms a sub-vertical shear zone at its southern end (Sobel et al., 2011; Xinjiang Bureau of Geology and Mineral Resources, 1993). The steep fault dip and thermochronology data in the Muztaghata antiform suggest rotation of the fault to the present vertical orientation from a shallower orientation during its evolution from 12 to 6 Ma (Sobel et al., 2011). The Kuke fault trace is truncated by the Shen-Ti-Waqia fault at a high angle in the south (Robinson et al., 2007; Sobel et al., 2011). In the north, the Kuke fault is interpreted to link with the Ghez fault, which juxtaposes Kunlun terrane structurally above Karakul-Mazar terrane along the eastern Kongur Shan gneiss dome (Robinson et al., 2012).

Kongur Shan Extensional System

The prominent Kongur Shan Extensional System is an active 250-km-long north-south–striking system of normal faults that accommodate east-west extension along the eastern margin of the Pamir (Fig. 2; Brunel et al., 1994; Arnaud et al., 1993; Robinson et al., 2004). A minimum of 34 km east-west extension is recorded in the area of Kongur Shan initiating at ca. 7–8 Ma (Robinson et al., 2004, 2010). Offset across the Kongur Shan Extensional System decreases toward the south, with ~8 km of east-west extension near the anticlinal axis of Muztaghata initiating at 6–5 Ma, documenting south directed propagation of the system (Robinson et al., 2007; Robinson, 2010; Cao et al., 2013). South of Muztaghata, extension is transferred to the east-dipping Tashkurgan fault in the western portion of the study area (Robinson et al., 2007).

GEOLOGIC MAPPING

Structural field mapping was conducted in the Tashkurgan and Waqia valleys at 1:100,000 scale using ASTER images as map bases (Fig. 3). In the following sections, we describe the lithological and structural characteristics along north-to-south transects in the Tashkurgan and Waqia valleys.
Figure 2. Generalized geologic map of the eastern Pamir region noting the location of major Mesozoic and Cenozoic structures. Small circles and triangles (blue—other authors; red—this study) denote the location associated radiometric ages for detrital and igneous zircon samples cited within the manuscript. A–A' corresponds to Figure 9 of this study. BT—Baoziya thrust fault; GF—Ghez fault; KF—Kuke fault; KLF—Kexi-Liqi fault; KSES—Kongur Shan Extensional System; KKF—Karakoram fault; NMSZ—North Muskol shear zone; RF—Rouluke fault; STF—Shen-Ti fault; TaT—Tanymas thrust fault; TT—Torbashi thrust fault; WF—Waqia fault. Map modified from Cao et al. (2013), Cowgill (2010), Robinson et al. (2007, 2012), and Robinson (2015). Letters: a—Zhang et al. (2007); b—Yang et al. (2010); c—Bershaw et al. 2012; d—Ji et al. (2011); e—Robinson et al. (2012); f—Robinson et al. (2004).
Figure 3. Geologic map of northern (A) and southern (B) sections of the study area in the southeast Pamir. Note the orientation of the north arrows. Inset: stereonet plots of pole-to-foliation measurements in the mapped areas arranged from north to south. Black squares on stereonets are the beta axis. For mapping purposes, we designate the Shen-Ti fault northwest of its intersection with the Kuke fault and the Wapaa fault southeast of the intersection with the Kuke fault. The complete map can be found as Figure DR8 in the GSA Data Repository. Stereonets were generated using OGS Stereonet (Cardozo and Allmendinger, 2013). Contour interval: 200 m. (Continued on following page.)
Lithologic and Structural Observations in the Tashkurgan Valley

The northernmost section of the Tashkurgan valley is bound to the north by the south-dipping Shen-Ti fault, which forms the southern boundary of the Miocene Muztaghata gneiss dome (Figs. 2, 3). The Shen-Ti fault separates upper amphibolite facies (garnet + kyanite + K-feldspar) migmatitic schist and gneiss of the Muztaghata dome in the footwall from greenschist facies phyllite, quartzite, marble, and minor garnet-biotite schist (biotite + garnet + chlorite ± white mica) in the hanging wall (Fig. 4A). Garnets in hanging wall schist are subidioblastic and show strain shadows indicating deformation after peak metamorphism (Fig. 5A). Coexisting garnet and chlorite suggest maximum temperatures of 400–500 °C (Spear, 1995; Figs. 5A, 5B). Foliations in both the hanging wall and footwall strike northeast to northwest and dip moderately to the south (Fig. 3).

Immediately south of the Shen-Ti fault along the Tashkurgan river, low metamorphic grade schists are structurally overlain by high-grade schist, migmatite, andgneiss intruded by undeformed to weakly foliated granite (Trsch1, Fig. 3) along the Torbashi thrust fault (Robinson et al., 2007). Hanging wall peak metamorphic mineral assemblages include sillimanite + garnet + biotite ± K-feldspar (Figs. 5C, 5D) indicating upper amphibolite facies metamorphism (Yang et al., 2010). Sillimanite regularly occurs as fibrolite, garnets are subidioblastic, ranging from 1 to 5 mm in size, and quartz-rich lithologies show grain-boundary migration recrystallization deformation fabrics (GSA Data Repository Fig. DR1a, DR1b). Amphibolite facies metamorphic conditions are consistent throughout Trsch1 (Figs. 4B, 4G, 4H). Along the northern portion of the hanging wall of the Torbashi thrust fault, foliations strike west to northwest, and dip moderately to the south. Further south, foliations change to dipping moderately to steeply to the north-northeast defining a broad syncline that plunges gently to the northwest (calculated fold hinge t305°/p25°; Fig. 3). Shear sense indicators including outcrop scale asymmetric folds (axis: t/p~295°/30°, axial plane s/d~128°/75°NE), S-C mylonitic fabrics, and asymmetric porphyroclasts show top-to-the-south–southwest sense of shear, with generally south-trending mineral lineations (Figs. 4A, 4H).

Farther south near the town of Gedeben (Fig. 3), metamorphic grade decreases over a short distance indicating a significant geologic contact. To the north, rocks are amphibolite-facies (Trsch1), whereas to the south rocks are greenschist facies micaceous quartzite, marble, and schist (Pz2, Fig. 3) intruded by a large granitic sill. Peak metamorphic assemblages south of the contact are biotite + garnet (Figs. 5E, 5F, 5G). Quartz deformation consists of bulging and sub-grain rotation (SGR) deformation in deformed granites and the microlithons in quartz rich lithologies (Figs. DR1e–DR1e), indicating peak temperatures of at least ~450–500 °C (Stipp et al., 2002). Foliations south of the contact continue to strike northwest and dip northeast (Fig. 3). The consistent orientation of foliations above and below the contact and juxtaposition of high metamorphic grade rocks above low metamorphic grade suggests the contact is a thrust fault, which we interpret as the southern trace of the Torbashi thrust fault. The general trend of metamorphic fabrics can be distinguished in satellite imagery, which indicates the fault trace continues to the southeast. We note that our observations significantly shift the southern trace of the Torbashi thrust fault to ~20 km north of its previously interpreted position (compare to Robinson et al., 2007).

Continuing south, biotite-garnet schist and quartzite with northeast dipping foliations (Pz2) structurally overlie low metamorphic grade schlate and marble with north-dipping foliations (Pz3) (Fig. 3). Top-to-the-southwest shear sense is recorded in S-C fabrics and γ-type porphyroblasts near the contact in Pz2, and tension gashes in the structurally lower Pz2 (Fig. 4C). Lithologic relationships indicate this contact is a north-dipping thrust fault, which we name the Rouluke fault. The western continuation of the Rouluke fault is truncated by the younger Tashkurgan normal fault while the eastern continuation of the fault is unclear.

Rocks in the footwall of the Rouluke fault consist of slate, phyllite, quartzite, and marble (Pz3) (Figs. 3, 5H, 5I). The marble is granoblastic and shows Type II twins (tabular and thick twins) indicating maximum metamorphic temperatures of 150–250 °C (Fig. 5I; Groshong, 1988; Burkhard, 1993; Ferrill et al., 2004). Visible strain of quartz grains is limited to the presence of linearly oriented inclusions, which exhibit no evidence of dynamic recrystallization (e.g., bulging) or dislocation creep. Peak metamorphic mineral assemblages are limited to post-tectonic biotite. One sample, a biotite-and calcite-bearing quartzite (D1–7–15–10–4) has biotite growth across weakly defined foliation boundaries. Foliation consisting of slaty cleavage generally strikes northwest and dips northeast (Fig. 4F). Weak continuous foliation and cataclastic microtextures are present in the silicate-rich samples. As previously indicated, tension gashes in slate show top-to-the-southwest sense of shear.

Lithologic and Structural Observations in the Waqia Valley

The northernmost section of the Waqia valley is bound to the north and northeast by the eastward trace of the south-dipping Shen-Ti fault (Figs. 2, 3), which connects with the southeast dipping Waqia normal fault bounding the northeastern side of the Waqia valley along the southern trace (Figs. 2, 3). Rocks south and west of the Shen-Ti and Waqia faults consist of schist, phyllite, quartzite, and marble, similar to the Tashkurgan valley (Trsch1, Fig. 3). Peak metamorphic mineral assemblages consist of biotite + garnet + chlorite ± white mica (Figs. 5A, 5B). In biotite schist samples, quartz displays bulging and sub-grain rotation deformation along grain boundaries of quartz-rich microlithons. Foliations in Trsch1 generally strike east-west along and near the Tashkurgan River, but change to a northeast strike parallel to the trend of the Waqia valley (Fig. 3), and generally dip southwest, although several map-scale upright folds are present in the unit. Shear-sense indicators (S-C fabrics and asymmetric boudins) along the Tashkurgan valley show top to the south shear-sense (Robinson et al., 2007). Farther south in the Waqia valley mineral elongation lineations in Trsch1 are oriented northeast with top-to-the-south sense of shear recorded by asymmetric kink folds in phyllite (Fig. 5B). A notable characteristic of Trsch1 is the absence of igneous intrusions, although a meta-rhyolite layer is present along the Tashkurgan River (age of 228 ± 2 Ma: Zhang et al., 2007).

The Torbashi thrust fault strikes east-west along the northern end of the Tashkurgan valley before changing to a southeast strike along the northern end of the Waqia valley (Fig. 3). Continuing to the south, the fault trace strikes parallel to the axis of the Waqia valley through most of the valley (Fig. 3); the fault contact is generally buried beneath Neogene and Quaternary sedimentary rock and sediment (Figs. 3, 4E). Field evidence of the approximate location of the contact is indicated by significantly different metamorphic grades on either side of the valley (Trsch1 versus Trsch2 in Fig. 3) and radiometric ages obtained from samples discussed in subsequent sections. On the northeast side of the Waqia valley, metasedimentary rocks consist of greenschist facies phyllite, described above, while along the southwest side of the valley, metasedimentary rocks consist of upper amphibolite facies schist and gneiss (Figs. 5G, 5H). As along the Tashkurgan valley, high-grade schists and gneisses contain garnet + biotite + sillimanite indicating upper amphibolite peak metamorphic conditions (>700 °C) (Fig. 5D; Robinson et al., 2007; Yang et al., 2010; this study). Sillimanite displays a fibrolite habit (Fig. 5D), which suggests a lower
Figure 4. Views of rocks and structures within the study area (locations can be found in Fig. 3). (A) S-C fabrics within Tr_{sh1} showing top-to-southwest sense of shear (Torbashi fault hanging wall). (B) Foliation in the quartz-rich phyllite (s101/d63SW) of Tr_{sh2} (northern Torbashi fault footwall). (C) En-echelon tension gashes within slate of Pz_{3} showing top-to-the-southwest sense of shear (Rouluke fault footwall). (D) Carboniferous granite intrusions within Pz_{aq} (northeastern Torbashi fault footwall). (E) Looking southwest at the contact between Tr_{sh1} and Pz_{aq}. The Torbashi thrust is buried beneath Quaternary sediments. (F) Paleozoic slates (Pz_{3}) dipping moderately toward the northeast (Rouluke fault hanging wall). (G) Garnet-sillimanite-biotite schist of the hanging-wall of the Torbashi thrust. (H) Garnet-biotite migmatitic schist, axial planes are of isoclinal folds are parallel to regional foliation (Torbashi fault hanging wall).
Figure 5. Photomicrographs of metamorphic rocks from the Tashkurgan and Waqia valley study areas. Locations of samples are shown in Figure 3. Green-schist facies pelitic schist containing a garnet σ-porphyroclast with a quartz strain shadow (A) and kink-bands in quartz-rich phyllite (B) of Tr$_{\text{muc}}$. (C and D) Garnet-sillimanite-biotite schist of Tr$_{\text{muc}}$. (E) Quartz-rich garnet-biotite schist with quartz ribbons displaying undulose extinction from the footwall of the Torbashi thrust (Pz$_{2}$). (F and G) Garnet-biotite schist in the hanging wall of the Rouluke thrust in Pz$_{2}$. (H and I) Quartz-rich slate and marble of Pz$_{2}$. 

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pressure growth of sillimanite from muscovite, less than or equal to 0.65 GPa, which is consistent with a reasonable 35 °C/km geothermal gradient. Grain boundary migration deformation fabrics present in quartz-rich microclithons are overprinted by bulging fabrics in places. The hanging wall of the Torbashi thrust is intruded by multiple granitic sills and dikes, most of which are pervasively sheared.

An exposure of high-grade schist lies structurally above the greenschist facies Trs_2 along the eastern margin of the valley in the immediate hanging wall of the Waqia normal fault (Figs. 2, 3). The metamorphic rocks are identical to the high-grade rocks of the Torbashi fault hanging wall, and are interpreted as part of the Torbashi thrust hanging wall (Trs_m).

Further south, small exposures of quartzofeldspathic gneiss, amphibolite, and quartzite intruded by undeformed to weakly foliated granite are present (Pz_m). However, the contact with the greenschist facies rocks to the north is buried under Neogene and Quaternary sediments (Fig. 3).

At the southern end of the Waqia valley the southern exposure of the Torbashi thrust fault trace continues southeast from the Tashkurgan valley. The footwall of the thrust consists of similar greenschist facies schists and quartzites with northeast-dipping foliations as observed in the Tashkurgan valley. At the southern end of the Waqia valley, the exposed width of the hanging wall of the Torbashi fault tapers to the southeast where we interpret it to end. The map pattern of the Torbashi fault hanging wall therefore defines a gently northwest-plunging synformal klippe whose exposure terminates to the southeast.

**GARNET-BIOTITE THERMOMETRY**

**Methods**

To quantify peak metamorphic temperatures, and possible gradients, along the southwestern footwall of the Torbashi thrust fault, two samples were analyzed using the garnet-biotite Fe-Mg exchange thermometer. Electron Microprobe analyses were conducted at the Texas A&M University microprobe facility using a 1 µm spot size with a 15 kV accelerating voltage, a 20 nA beam current, and a 30 second counting time for each element. Activities of garnet and biotite end-members and equilibrium Clapeyron slopes were calculated using the programs AX and Thermocalc 2.7 (Powell et al., 1998). Electron microprobe traverses were used to identify zoning patterns in garnets and interpret the temperature results.

Average activities of matrix biotite end-members (phlogopite and annite) were used because (1) there was little variation in matrix biotite analyses (Table DR2), (2) using the highest and lowest biotite activities resulted in temperature differences of <40 °C, and (3) biotite activity variations did not correlate with distance from garnet grains. Pyrope activities (a_{mg}) are not interpreted for compositional variation due to the low values in the analysis (Table DR2). Temperatures are reported based on a pressure of 0.4 GPa, based on reasonable geothermal gradient of 30 °C/km (Spear, 1995).

**RESULTS**

**AR-940-09**

Sample 940-09, a quartz-rich garnet-biotite schist (Fig. 5G), was collected from the northern hanging wall of the Roulouk fault (Figs. 3, 5G). The primary metamorphic mineral assemblage is garnet + biotite + quartz. Garnets are subidioblastic to xenoblastic and appear to be late syn-tectonic to post-tectonic, evidenced by consistent foliation internal and external to garnet grains and the lack of strain shadows.

Electron microprobe transects were completed across three garnet grains in AR 940-09. Garnet transect 1 shows weak zoning in Mn with increasing concentrations toward the center (inversely related to Ca) while Fe and Mg# is invariable across the garnet grain (Fig. 6A). Garnet transect 2 shows similar weak zoning (Fig. 6B), with a decrease in Mn within <500 µm from the rims, and no clear zoning in Fe, Ca, and Mg#. Garnet transect 3 shows no evidence of consistent compositional zoning (Fig. 6C). Garnet-biotite thermometer results from the garnet rim analyses from transect 1 yield a temperature of ~560 °C, which we interpret to represent the peak metamorphic temperature of this sample.

**Summary of Results**

Peak temperatures in the footwall of the Torbashi thrust fault are significantly lower (upper greenschist to lower amphibolite facies) than peak temperatures indicated by metamorphic assemblages in its hanging wall (upper amphibolite to granulite facies; Yang et al., 2010), consistent with our mapped location of the southern trace of the Torbashi fault. The garnet-biotite thermometry results from the lithologies between the Torbashi and Roulouk faults shows a gradient in peak metamorphic temperatures from lower amphibolite to upper greenschist facies from north to south. Temperatures in the northern samples are slightly higher than would be expected given the quartz deformation fabrics (i.e., Stipp et al., 2002), suggesting that peak metamorphic temperatures post-dated deformation, consistent with the syn- to post-tectonic garnet inclusion patterns of AR-940-09.

**U-Pb GEOCHRONOLOGY**

**Methods**

Zircon grains from igneous and metasedimentary rock samples were separated using conventional techniques, mounted in epoxy, and polished to expose grain interiors. U-Pb analyses were performed at the University of Houston using a Varian 810 quadrupole inductively coupled plasma-mass spectrometer (ICP-MS). Laser ablation analyses were performed with a Cetac LSX-213 laser with a 50–20 nm beam diameter at 15 Hz and a Photon Machines Analyte 193 excimer laser with a 20 µm beam diameter at 10 Hz. Isotope abundances of 201Hg, 202Hg, 204(Hg + Pb), 206Pb, 207Pb, 232Th, and 238U were measured. On-peak backgrounds were measured for 20 s with the laser off prior to each 20 s of sample ablation. The first two seconds of sample and standard ablation are not included in the measured sample data to avoid surficial contamination. Instrumental fractionations of U/Pb and 206Pb/207Pb during analysis were calibrated by analyzing fragments of zircon standard Plesovice (all age uncertainties are expressed as 2σ) in between 5 consecutive unknown analyses following methods outlined in Shaulis et al. (2010). Analyses of zircon standard FC5z (1096.2 ± 1 Ma) or Peiex (564 ± 4 Ma) (Shaulis et al., 2010) were conducted after every 10 unknown analyses to monitor
the calibration. Analyses were not corrected for common Pb because the 3HePb signal after 204Hg background subtraction was below instrument detection. Age probability plots were created using Isoplot 4.1 (Ludwig, 2009). Detrital zircon probability plots exclude isotopic ratios with a discordance of >30% and < −5%. Ages >1.0 Ga are reported as 206Pb/207Pb ages and zircon ages <1.0 Ga are reported as 206Pb/238U ages. Maximum depositional ages are reported as the calculation of the weighted mean age of the youngest three overlapping zircon ages in the sample. Igneous ages are reported from the calculation of 206Pb/238U ages using the Isoplot TuffZirc age extractor (Ludwig, 2009).

RESULTS

Igneous Rocks

Sample AR-9-10-03-4
Sample AR-9-10-03-4 is from a weakly mylonitic granite that intrudes upper green schist to lower amphibolite facies schist (Pzaq) in the southern footwall of the Torbashi thrust fault along the eastern Tashkurgan valley (Figs. 2, 3). The granite forms an ~1-km-thick sill, sub-parallel to the regional foliation and continues to the southeast for at least 5 km. Thirty zircons were analyzed, which yielded 24 concordant analyses. The concordant analyses yield an Early Ordovician TuffZirc age of 479.0 ± 14.2/2.9 Ma from a coherent group of 20 grains (Fig. 7A).

Sample DI-7-25-10-17
Sample DI-7-25-10-17 is from a biotite hornblende granite (Pzaq) that lies in the southeastern footwall of the Torbashi thrust fault in the Waqia valley (Figs. 2, 3). 30 zircons were analyzed, with 13 yielding concordant analyses. Zircon grains from this sample were relatively U-poor (average of ~60 ppm). The concordant analyses have a spread in age from 303 to 334 Ma, and yields a Carboniferous weighted mean age of 315.9 ± 6.0 Ma from a coherent group of 10 analyses (Fig. 7B).

Sample AR-9-10-03-7
Sample AR-9-10-03-7 is from a garnet-bearing, weakly to non-foliated biotite granite sill that intrudes upper amphibolite facies schist and gneiss (TRsch1) in the hanging wall of the Torbashi thrust fault in the Tashkurgan...
45 zircons were analyzed, with 14 yielding concordant analyses. The concordant analyses have a spread in ages from 188 to 220 Ma, and yields an Early Jurassic TuffZirc age of 197.6 +3.3/–4.8 Ma from a coherent group of 11 analyses (Fig. 7C).

**Sample AR-4-28-00-11a**

Sample AR-4-28-00-11a is a garnet-biotite quartzofeldspathic orthogneiss from the hanging wall of the Torbashi thrust fault in the Waqia valley (Figs. 2, 3). 106 zircons were analyzed yielding 56 concordant ages. The sample yields a Late Triassic TuffZirc age of 205.6 +3.3/–4.8 Ma from a coherent group of 49 analyses (Fig. 7D). Zircons in this sample have a similar spread in ages to sample AR-9-10-03-7 of 187–239 Ma, although with an earlier peak at ~206 Ma (Fig. 7).

**Metasedimentary Rocks**

**Sample AR-6-26-00-7**

Sample AR-6-26-00-7 is a dark gray phyllite from the footwall of the Rouluke thrust fault in the southern Tashkurgan valley (Fig. 2). 164 zircons were analyzed yielding 92 concordant analyses. The three youngest
zircons overlapping in age yield an Early Devonian maximum depositional age of 413 ± 17 Ma (Fig. 8). Prominent Precambrian age peaks are 590–716, 730–1040, and 1690–1880 Ma with smaller peaks at 2050–2140 and 2340–2470 Ma. Phanerozoic ages range from ~405 to 480 Ma with maximum of 424 and 452 Ma. A Devonian maximum depositional age is typical of many late Paleozoic deposits in Tibet (e.g., Gehrels et al., 2011), and the previously published Permian age for the phyllite is likely correct (e.g., Yin and Bian, 1995).

**Sample AR-4-28-00-7**

Sample AR-4-28-00-7 is a quartz-rich phyllite from the northern footwall of the Torbashi thrust fault (Figs. 2, 3). 120 zircons were analyzed with 79 yielding concordant results. The youngest zircons with overlapping ages yield a Late Triassic weighted mean maximum depositional age of 212 ± 3 Ma (Fig. 8). Significant Precambrian age populations occur at 610–650, 690–780, 890–980, 1230–1390, and 1590–1650 Ma. Significant Phanerozoic age populations occur at ca. 211, ca. 295, ca. 325, and 390–520 Ma.

**Sample AR-4-27-00-9**

Sample AR-4-27-00-9 is a chlorite-bearing quartz-rich schist from the footwall of the Baoziya thrust fault north of Muztaghata (Fig. 2). 136 zircons were analyzed with 73 yielding concordant ages. Conservative analysis of the maximum depositional age using the three youngest zircons overlapping in age yields a Permian maximum depositional age of 268 ± 11 Ma (Fig. 8). However, two concordant grains in this sample with 218 ± 5.4 and 234 ± 6.2 Ma ages suggest the sample may be Late Triassic. Significant Proterozoic age populations occur at ca. 790, ca. 1600–2100, and ca. 2500 Ma. Significant Phanerozoic age populations occur at ca. 270, ca. 335, and ca. 410 Ma.

**Summary of Results**

Rocks in the hanging wall of the Torbashi thrust yield Late Triassic to Early Jurassic ages based on: (1) crystallization age of igneous rocks (AR-9-10-03-7 is 197.6 ±3/4 Ma and AR-4-28-00-11a is 205.6 ±3/4 Ma), and (2) a Late Triassic maximum depositional age of 228 Ma for the intruded metasedimentary rocks (Yang et al., 2010). Our results support previous interpretations that the hanging wall of the Torbashi thrust are part of the Karakul-Mazar terrane (Robinson et al., 2012). These igneous ages are some of the younger ages within the Karakul Mazar terrane, but are consistent with magmatism associated with the closure of the Paleo-Tethys Ocean.

Farther south near the town of Gedeben in the southern Tashkurgan valley, zircon U-Pb ages are different than those in the north. The crosscutting Early Ordovician granite (AR-9-10-3-4) indicates that the southern footwall metasedimentary rocks of the Torbashi thrust fault are early Paleozoic (Fig. 3), consistent with recently published Cambrian ages from gabbros and meta-rhyolites within the formation (Zhang et al., 2018a; 2018b) where the lithologies are part of the previously named Bulunkuole Group. This age is common in sediments from Gondwanan terranes in the Tibetan plateau, and we therefore interpret the block to be Gondwanan in origin, although others have interpreted these lithologies as part of the Western Kunlun Orogenic Belt (e.g., Zhang et al., 2018a). Detrital zircon results from Permian phyllites south of the Rouluke fault (AR-6-26-00-7) also yield a typical Gondwanan signature, as compared with detrital zircon results from Central Pamir metasedimentary rocks and the Qiangtang terrane (Figs. 2, 9, and 10C; Robinson et al., 2012; Gehrels et al., 2011; Rutte et al., 2017b).

Carboniferous granite intrudes gneisses to the east of the Torbashi klippe in the southern Waqia valley. This age is characteristic of the Carboniferous–Early Permian arc magmatism that is prevalent in the Western Pamir.

**Figure 8. U/Pb cumulative probability diagrams for samples collected within the southeastern Pamir. Sample ages and locations are shown on Figures 2 and 3.**
Figure 9. Geologic cross section of A–A’ on Figure 2. Faults are color coded to show relationships across the Pamir: blue—Baoziya/Torbashi thrust fault (Robinson et al., 2004, 2007); yellow—Shen-Ti fault/North Muskol shear zone (Robinson et al., 2007; Rutte et al., 2017b); red—Kongur Shan fault (Robinson et al., 2007); maroon—Rouluke fault (this study). Age of deformation is from associated literature. Thin section and field photo locations from Figure 3 are projected onto the cross section.
We compared the two samples using a Kolmogorov-Smirnov test, which yielded a P-value of 0.539 (Fig. 10A). As P-values greater than 0.05 are (Xiao et al., 2002a, 2002b).

**DISCUSSION**

**Tectonic Terrane Boundaries and Structural Relationships in Tashkurgan and Waqia Valleys**

Geologic structures, zircon geochemistry, and metamorphic petrology yield key information regarding the architecture, structural relationships, and deformation history of the southeastern Pamir. In the study area of the Tashkurgan and Waqia valleys, the rocks can be divided into three groups based on age, degree of metamorphism, and interpreted tectonic affinity. Metamorphic and igneous rocks in the study area are separated by major fault systems in the study area.

The first group of rocks lies along the northern section of the study area south of the Shen-Ti fault and Muztaghata dome and consists of two separate Triassic metasedimentary units separated by the Torbashi thrust fault: (1) a lower greenschist facies unit in the Torbashi thrust footwall, Trsh2, with a Late Triassic maximum depositional age (ca. 212 Ma, Fig. 8) and a pronounced lack of intrusive igneous bodies; and (2) and an structurally higher upper amphibolite facies unit in the Torbashi thrust hanging wall, Trsh1, with a Triassic maximum depositional age (Yang et al., 2010; Zhang et al., 2007) intruded by Late Triassic–Early Jurassic igneous rocks (Fig. 8). Our zircon results, integrated with previous work, indicate these units are part of the late Permian–Triassic Karakul-Mazar terrane that formed as part of an arc-crenulation complex system along the southern margin of Asia during subduction of the Paleo-Tethys Ocean (Schwab et al., 2004, Robinson et al., 2012; Xiao et al., 2002a), equivalent to the Songpan Ganzi–Hoh Xi terrane of Tibet (Fig. 10B). The Torbashi thrust between the two units suggests imbrication of the terrane, with previous thermochronology results from the hanging wall of the Torbashi thrust fault supporting a poorly defined Cretaceous age for exhumation and juxtaposition (Robinson et al., 2007). We interpret the Torbashi fault to have originally dipped north, but was subsequently rotated to a southward dip during Miocene exhumation of the Muztaghata dome (Robinson et al., 2007; Sobel et al., 2011) resulting in folding of the hanging wall of the Torbashi fault into a northwest plunging synform, the Torbashi klippe (Figs. 3, 9). Robinson et al. (2007) previously interpreted the southern contact of the Torbashi thrust in the location of the Rouluke fault: (1) a lower greenschist facies unit in the Torbashi thrust footwall, Trsh2, with a Late Triassic maximum depositional age (ca. 212 Ma, Fig. 8) and a pronounced lack of intrusive igneous bodies; and (2) and an structurally higher upper amphibolite facies unit in the Torbashi thrust hanging wall, Trsh1, with a Triassic maximum depositional age (Yang et al., 2010; Zhang et al., 2007) intruded by Late Triassic–Early Jurassic igneous rocks (Fig. 8). Our zircon results, integrated with previous work, indicate these units are part of the late Permian–Triassic Karakul-Mazar terrane that formed as part of an arc-crenulation complex system along the southern margin of Asia during subduction of the Paleo-Tethys Ocean (Schwab et al., 2004, Robinson et al., 2012; Xiao et al., 2002a), equivalent to the Songpan Ganzi–Hoh Xi terrane of Tibet (Fig. 10B). The Torbashi thrust between the two units suggests imbrication of the terrane, with previous thermochronology results from the hanging wall of the Torbashi thrust fault suggesting a poorly defined Cretaceous age for exhumation and juxtaposition (Robinson et al., 2007). We interpret the Torbashi fault to have originally dipped north, but was subsequently rotated to a southward dip during Miocene exhumation of the Muztaghata dome (Robinson et al., 2007; Sobel et al., 2011) resulting in folding of the hanging wall of the Torbashi fault into a northwest plunging synform, the Torbashi klippe (Figs. 3, 9). Robinson et al. (2007) previously interpreted the southern contact of the Torbashi thrust in the location of the Rouluke fault in this study. However, lithologic relationships (Figs. 3–5) and results from zircon U-Pb analyses (Figs. 2, 7, 8) show that the Rouluke fault is an independent structure from the Torbashi fault (Fig. 9).

The second group of rocks consists of low metamorphic grade rocks (Pz2) that are intruded by Late Carboniferous granite in the southeastern section of the Waqia valley in the footwall of the Torbashi thrust fault (Figs. 7, 8). Based on the age of the intrusive body (ca. 316 Ma, Fig. 7B), we interpret this unit to be part of the South Kunlun terrane, which records a significant period of Late Carboniferous–Permian arc magmatism. Unfortunately, the boundary between the Karakul-Mazar terrane and Kunlun terrane is covered by Neogene to Quaternary basin fill (Fig. 3), so we could not determine if the contact is depositional or tectonic (Fig. 3). However, both units are clearly in fault contact with the overlying Torbashi klippe.

The third group of rocks in the Tashkurgan and Waqia valleys is exposed south-southwest of the southern trace of the Torbashi fault, and consists of two main units: (1) upper-greenschist facies metamorphic...
rocks (Pz2) intruded by an Early Ordovician granite and Cambrian gabbros (Zhang et al., 2018b) in the hanging wall of the Rouluke fault, which are part of the Cambrian Bulunkuole group (Zhang et al., 2018a), and (2) late Paleozoic (Carboniferous-Permian) limestone and slate in the footwall of the Rouluke fault that yield detrital zircon ages typical of Late Paleozoic Gondwana derived stratigraphy (Gehrels et al., 2011; Robinson et al., 2012). Detrital zircon ages from the slates are consistent with those in the Qiangtang terrane in northern Tibet and in Central Pamir terrane rocks along the western portion of the Muztaghata gneiss dome (Robinson et al., 2012; Rutte et al., 2017a; Fig. 1), while late Proterozoic–Cambrian metamorphic rocks have been identified in the core of the Central Pamir gneiss domes (Rutte et al., 2017a), which are likely equivalent to the Bulunkuole group. Based on the above results, we interpret these units south of the Torbashi thrust fault to be Gondwanan terranes equivalent to the Central or southern Pamir to the west, and the Qiangtang terrane to the east.

The Tyanmas suture of the Pamir, equivalent with the Jinsha suture of Tibet, lies between lithologies of Karakul-Mazar Terrain and the Central/southern Pamir terranes in the study area (Rutte et al., 2017b). In the Wajia valley, the suture is buried beneath Neogene sedimentary rocks (N1) (Fig. 3) where it is cut on the eastern end by the younger Wajia fault and is defined by the Torbashi fault to the west (Fig. 3). Southeast of the Torbashi klippe, our mapping and zircon geochronology suggest that there is no exposure of the Karakul-Mazar terrane, and that in this region the Kunlun and Central/southern Pamir terranes are directly juxtaposed across the Paleo-Tethyan suture zone (the Tyanmas suture of the Pamir and Jinsha suture of Tibet). The observation that the Karakul-Mazar terrane tapers out is consistent with regional geologic maps that show Triassic Songpan Ganzi-Hoh Xi terrane terminating in NW Tibet near the southeastern syntaxis of the Pamir Salient, and is not continuously exposed between northwestern Tibet and the Pamir (Fig. 11) (e.g., Yin and Bian, 1992; Xiao et al., 2002a, 2002b, 2005). This is similar to the situation on the western side of the Pamir, where the Karakul-Mazar terrane pinches out between the northern Pamir and Central Pamir near the border with Afghanistan (Schwab et al., 2004). We propose two possibilities for the absence of the Karakul-Mazar-Songpan Ganzi-Hoh Xi in this region: (1) the Karakul-Mazar-Songpan Ganzi-Hoh Xi has been tectonically removed via uplift along thrust faults and erosion; or (2) the Karakul-Mazar and Songpan Ganzi–Hoh Xi are two distinct terranes within the orogen. Although we cannot rule out the latter scenario, we prefer the interpretation that the Karakul-Mazar-Songpan Ganzi-Hoh Xi was tectonically removed, which is consistent with results from Cao et al. (2015), who documented significant Mesozoic exhumation of the West Kunlun Shan from detrital zircon fission track analyses from the Tarim basin. We suggest that in the West Kunlun Shan, the Karakul-Mazar-Songpan Ganzi-Hoh Xi terrane was tectonically and erosionally removed during documented Cretaceous shortening (Robinson et al., 2004; Cao et al., 2015). This is consistent with metamorphic grade of the Karakul-Mazar terrane generally increasing to the east in the Pamir where deeper structural levels should be exposed (Robinson et al., 2004), with the Torbashi klippe preserving the highest grade portions of the terrane. Finally, our results show that this fundamental terrane boundary is located farther north than previously interpreted (Robinson et al., 2012; Lacassin et al., 2004), showing there is no deflection of terranes between the Pamir and Tibet along a discreet fault, and that large-scale (>400 km) offsets along the Karakoram fault are not feasible (Valli et al., 2008).

**Implications for the Cambrian Bulunkuole Group**

Recently published work has suggested that much of the eastern Pamir consists of a structurally contiguous late Proterozoic–Cambrian terrane, the Bulunkuole Group, which is interpreted to have accreted to the southern margin of Tarim in the early Paleozoic and be part of the South Kunlun terrane of the Western Kunlun Orogenic Belt (Zhang et al., 2018a). Several key observations show that this is not the case. (1) The core of the Kungr Shan and Muztaghata gneiss domes are composed almost entirely of Triassic orthogneiss and granitic bodies, with no documented exposures of Cambrian or older lithologies except along the western portion of the Muztaghata gneiss dome (Robinson et al., 2012). (2) Cambrian igneous rocks are only found south of the Torbashi klippe, and in the western Muztaghata gneiss dome where they are continuous with late Proterozoic–early Paleozoic lithologies in the core of the Shatput gneiss dome (Zhang et al., 2018a, 2018b; Rutte et al., 2017a). (3) As documented in this study and previous work (Zhang et al., 2007; Yang et al., 2010), the Torbashi klippe and its northern footwall are Triassic in age, and are continuous with the Karakul-Mazar terrane of the northern Pamir.

Based on these observations, we suggest that the Bulunkuole Group is exposed in a relatively narrow structural block in the southeast Pamir, located between the Torbashi and Rouluke thrust faults (Pz2; Figs. 2, 3). Further, while we agree with the interpretation that the Bulunkuole Group likely records early Paleozoic subduction and collision between Tarim and Gondwana (Zhang et al., 2018a; Metcalfe, 2013), we suggest that it remained part of Gondwana during subsequent Devonian rifting. The Bulunkuole Group is therefore interpreted as part of the Qiangtang equivalent terranes of the Pamir, which collided with Asia during the Late Triassic closure of the Paleo-Tethys along the Tyanmas-Jinsha suture.

**Correlating Units across the NE Pamir**

We have identified several characteristics of the geologic units in the northern and southeastern Pamir on either side of the Late Cenozoic Muztaghata dome that suggest the presence of regionally correlative rock units and a regionally extensive thrust nappe in the northern Pamir (Fig. 9).

To the south and north of the Muztaghata dome, the hanging wall and footwall rocks of the Torbashi and Baoziya thrust faults, respectively, share similar lithologic and geochemical characteristics. As reported above, south of the Muztaghata gneiss dome the hanging wall of the Torbashi thrust fault (Trsch2) consists of Triassic upper amphibolite facies pelitic schist and quartzite intruded by Late Triassic–Early Jurassic granite (Figs. 2, 3, 7D) structurally overlying Triassic greenschist facies marble, phyllite, and quartzite. Similarly, north of the Muztaghata gneiss dome, the hanging wall of the Baoziya thrust consists of Triassic amphibolite facies pelitic schist and quartzite intruded by Late Triassic granite, structurally overlying Triassic greenschist facies marble, phyllite, schist, and quartzite (Figs. 2, 3). The footwalls of the Torbashi and Baoziya thrust faults have similar εNd and Sr isotope values (Robinson et al., 2012). Further, maximum depositional ages for the hanging walls of both thrusts are comparable (Triassic in age), with similar detrital age populations (Fig. 10A) (Robinson et al., 2012; Yang et al., 2010; Zhang et al., 2007), and their detrital zircon age populations between the footwalls of the Torbashi and Baoziya thrust faults (Trsch2) are statistically indistinguishable indicating the protoliths were part of the same sedimentary basin (Figs. 10A, 10B).

The lithologic and isotopic similarities between the hanging wall and footwall rocks of the Baoziya and Torbashi faults indicate that these units and thrust fault separating them were contiguous across the eastern margin of the Pamir. The hanging wall was part of a regionally continuous thrust nappe across the northern Pamir. This thrust sheet emplaced higher-grade portions (T2sch2) of the Karakul-Mazar terrane over lower-grade portions (T1sch2), as well as the Central Pamir terrane to the south (Fig. 9). Robinson et al. (2007) reported muscovite and biotite cooling ages (105–125 Ma) in the Torbashi thrust hanging wall, which have been interpreted to...
record exhumation during thrust displacement. These results indicate the once-continuous Baoziya-Torbashi thrust likely records Cretaceous retroarc shortening, which has been previously documented in the northeastern Pamir and South Pamir terrane (Robinson et al., 2012; Angiolini et al., 2013; Robinson, 2015; Chapman et al., 2018). The thrust fault, and the hanging wall and footwall lithologies, were then crosscut in the Miocene by the Muztaghata gneiss dome (Robinson et al., 2007; Thiede et al., 2013). As a final note, our results document a more coherent, and laterally continuous, series of lithologic units across the northern and eastern margin of the Pamir than previously recognized.

REGIONAL INTERPRETATIONS AND IMPLICATIONS

Pamir Terrane Structure

The three-dimensional structural architecture between terranes in the northern Pamir and southeastern Pamir is complex, most notably the observation that the terranes are tectonically interleaved (Fig. 9). The Kexi-Liqi fault is the oldest structure, juxtaposing Pz1 lithologies above Triassic lithologies during closure of the Paleo-Tethys. Next, the south-directed Baoziya-Torbashi thrust emplaced Triassic lithologies above
Gondwanan Paleozoic lithologies, with the south directed Rouluke fault imbricating the Gondwanan terranes likely active at this time. These structures were then cross-cut in the Miocene by the Shen-Ti fault and North Muskol shear zone during tectonic exhumation of the Muztaghata gneiss dome (Robinson et al., 2007; Rutte et al., 2017a), and then subsequently cross-cut again by the late Miocene to recent Kongur Shan normal fault (Robinson et al., 2007). This study documents that in both the northern Pamir and southeastern Pamir, Triassic lithologies of the Karakul-Mazar terrane are structurally emplaced above Gondwanan terranes (Central and southern Pamir) with the Torbashi thrust an along-strike equivalent to the Tanymas thrust (Figs. 2, 9).

Our results in the Waqia valley add another aspect of complexity as we document that the Karakul-Mazar terrane has been completely removed either structurally or erosionally in the southeast portion of the study area, with the Western Kunlun terrane in direct contact with Gondwanan terranes (Fig. 1). However, the polarity of this contact is currently not known, although relationships within the Muztaghata dome suggest the possibility of a south-dipping contact. Finally, our documentation of the location of the Paleo-Tethys suture, and the lack of documented strike-slip faults east of the Karakoram fault, shows that detachment of terranes between the Western Kunlun and Pamir was not primarily accommodated along discrete, large displacement faults. Instead, our results suggest that Cenozoic northward displacement of terranes was accommodated by oroclinal bending of the northern Pamir/Kunlun terranes and dextral shear along the Pamir margins. We note, however, that recent results indicating limited Cenozoic northward displacement of the Pamir suggest the northward deflection of terranes may be an inherited feature (Chapman et al., 2017; Chen et al., 2018).

Model for the Southeastern Pamir

Here, we propose an updated tectonic model for the evolution of the southeastern Pamir. North-directed subduction of the Paleo-Tethys Ocean beneath the Karakul-Mazar terrane in the late Triassic produced subduction-related magmatism and built an arc-accumulatory complex, the Karakul-Mazar terrane (Fig. 11A; Schwab et al., 2004; Robinson et al., 2012). During this time, drainages sourced north of the magmatic arc provided sediment from the southern margin of Asia, i.e., Kunlun terrane, as well as the active arc, evidenced by the occurrence of Paleozoic and Precambrian zircon age populations (Yang et al., 2010; Robinson et al., 2012). During subduction, the Karakul-Mazar terrane experienced high-grade metamorphism and intrusion of igneous bodies lasting into the earliest Jurassic, similar to what has been documented in the western Pamir in the Kurgovat metamorphic complex (Figs. 11A, 11B) (Robinson et al., 2004; Schmidt et al., 2011; this study). Initial closure of the Paleo-Tethys Ocean resulted in the Central Pamir/Qiangtang terrane being thrust over the Karakul-Mazar terrane (Figs. 9, 11A, 11B) (Robinson et al., 2012).

Retroarc shortening related to subduction of the Neo-Tethys Ocean during the Cretaceous is interpreted to have resulted in development of the Tanymas-Baoziya-Torbashi thrust as a regionally extensive thrust nappe. This period of deformation resulted in imbrication of the Karakul-Mazar terrane and emplaced it above the Central Pamir to the south (Fig. 11C) (Robinson et al., 2007, 2012; Rutte et al., 2017b). Cooling ages in the hanging wall from Robinson et al. (2007) suggest shortening occurred at ca. 120–100 Ma. This slightly pre-dates documented Cretaceous shortening. Therefore, our results indicate that the Torbashi thrust fault is correlative to the Tanymas thrust fault of the Central Pamir, and that both may have been active in the Early Cretaceous. These results suggest (1) that lithologic units are more contiguous across the northern Pamir than previously recognized; and (2) the presence of a regionally extensive thrust nappe, continuous across much of the northern Pamir and into the southeastern Pamir, which juxtaposed Karakul-Mazar terrane above Gondwanan terranes during Early Cretaceous retroarc shortening.

CONCLUSIONS

Geologic mapping integrated with metamorphic petrology and igneous and detrital zircon geochronology, document the presence of several discrete thrust sheets in the region south of the Muztaghata gneiss dome. The Torbashi thrust sheet, made up of upper amphibolite facies Karakul-Mazar terrane, is folded into a broad gently northwest-plunging syncline, and overlies greenschist facies Karakul-Mazar terrane in the north, and Gondwanan terrane crust (Central or southern Pamir) to the south. We document the southern contact of the Torbashi thrust (which represents the local equivalent of the Jinsha suture zone) as farther north than previously proposed. Further south, Gondwanan crust is imbricated by the south-southwest–vergent Rouluke thrust fault, which places upper greenschist facies Cambrian rocks of the Bulunkule group over sub-greenschist facies Permian slate and marble.

Along the southern end of the Waqia valley, the northern and southern traces of the Torbashi thrust connect and the Kunlun terrane crust is juxtaposed directly against Gondwanan crust. This shows that exposure of the Karakul-Mazar terrane are not contiguous with the Songpan Ganzi-Hoh Xil terrane of northern Tibet. We suggest this discontinuity is the result of structural and erosional removal the terrace in the Western Kunlun and southeastern Pamir, possibly during the Cretaceous. Further, our documented position of the Jinsha suture shows that deflections of northern terranes in the Pamir have not been accommodated by displacement on discreet, high-slip faults, and oroclinal bending within the eastern northern Pamir may account for northward deflection of terranes.

Lithologic similarities and concordant isotopic and detrital zircon age signatures that the footwall and hanging wall of the Baoziya and Torbashi thrusts are directly correlative and represent a once-continuous structural-lithologic package, which was subsequently cut by the Mio-cene Muztaghata gneiss dome. Furthermore, our results indicate that the Torbashi thrust fault is correlative to the Tanymas thrust fault of the northern Pamir, and that both may have been active in the Early Cretaceous. These results suggest (1) that lithologic units are more contiguous across the northern Pamir than previously recognized; and (2) the presence of a regionally extensive thrust nappe, continuous across much of the northern Pamir and into the southeastern Pamir, which juxtaposed Karakul-Mazar terrane above Gondwanan terranes during Early Cretaceous retroarc shortening.

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