Cretaceous shortening and exhumation history of the South Pamir terrane

James B. Chapman1,*, Alexander C. Robinson2, Barbara Carrapa1, Dustin Villarreal1, James Worthington1, Peter G. DeCelles1, Paul Kapp1, Mustafo Gadoev3, Ilhomjon Oimahmadov3, and George Gehrels1

1DEPARTMENT OF GEOSCIENCES, UNIVERSITY OF ARIZONA, TUCSON, ARIZONA 85721, USA
2DEPARTMENT OF EARTH AND ATMOSPHERIC SCIENCES, UNIVERSITY OF HOUSTON, HOUSTON, TEXAS 77204, USA
3INSTITUTE OF GEOLOGY, EARTHQUAKE ENGINEERING AND SEISMOLOGY, TAJIK ACADEMY OF SCIENCES, DUSHANBE, TAJIKISTAN

ABSTRACT

Despite Miocene extension and exhumation of middle to lower crust in a series of gneiss domes and interpreted Cenozoic delamination of the lower crust, the crust in the modern Pamir Mountains is among the thickest in the world. Cenozoic shortening, crustal thickening, and prograde metamorphism in the Pamir have been associated with India-Asia collision. However, new mapping in the South Pamir terrane indicates relatively minor, distributed shortening since the Jurassic, which occurs in a thrust belt overprinted by late Cenozoic transpression. The thrust belt connects with the Rushan-Pshart suture zone, a Mesozoic terrane boundary. New detrital zircon U-Pb and detrital zircon fission track ages of synorogenic clastic rocks exposed in the footwall of thrust faults in the South Pamir thrust belt provide maximum deposition ages (76–112 Ma), which are interpreted to document Cretaceous shortening prior to India-Asia collision. Furthermore, zircon (U-Th)/He and apatite (U-Th)/He data from the South Pamir terrane generally record cooling ages of ca. 102–44 Ma, suggesting limited Cenozoic exhumation. These results (1) are consistent with widespread Cretaceous deformation throughout the Pamir-Tibet orogen with limited Cenozoic upper crustal shortening in the South Pamir terrane, (2) together with previous studies, allow for the possibility that the upper crust of the Pamir orogen was characterized by net extension during the Cenozoic rather than net shortening, and (3) are consistent with models that relate Cenozoic crustal thickening to the insertion of Indian lower crust beneath the Pamir. Lower crustal thickening of the South Pamir terrane is difficult to reconcile with the progradem metamorphic history of gneiss domes in the South Pamir terrane and may require a relatively shallow (<15–20 km) shear zone separating lower crustal contraction from upper crustal extension.

1. INTRODUCTION

The Pamir Mountains form a high-elevation orogenic plateau and high-relief mountain range that is equivalent and contiguous with the Tibetan plateau to the east. Similar to the Tibetan plateau, the modern thickness of continental crust in the Pamir is ~70 km (Mechie et al., 2012; Schneider et al., 2013). Unlike the Tibetan plateau, the Pamir Mountains contain widespread exposures (~30% of the surface area) of middle to lower crust within a series of extensional gneiss domes (Robinson et al., 2004, 2007; Schmidt et al., 2011; Stübner et al., 2013a; Stearns et al., 2013, 2015; Rutte et al., 2017a) (Fig. 1). The middle to lower crust exposures in the Pamir gneiss domes record chiefly Eocene to Oligocene ages that have been interpreted to represent prograde metamorphism associated with crustal thickening in response to India-Asia collision (Robinson et al., 2007; Schmidt et al., 2011; Stearns et al., 2013, 2015; Smit et al., 2014; Hacker et al., 2017; Rutte et al., 2017a). Previous studies have suggested at least 300 km of Cenozoic internal shortening in the Pamir (Burtman and Molnar, 1993). However, both the timing and magnitude of this interpreted shortening may be incorrect. For example, the Shakhdara-Alichur gneiss dome was previously interpreted as a basement-involved thrust nappe (Shvol’man, 1978; Burtman and Molnar, 1993), but subsequent analysis has shown that it is extensional in origin (Stübner et al., 2013a). Aside from the mechanisms involved in the formation of the gneiss domes, the ages of the contractional structures within the Pamir are poorly constrained. Robinson (2015) hypothesized that many of these structures may be of Cretaceous age and that Pamir crust was in part thickened prior to India-Asia collision, during Mesozoic Cordilleran (i.e., Andean-style) orogenesis and accretion of Gondwanan terranes. There is evidence along strike in Tibet for precollisional (Mesozoic) crustal shortening and thickening in a retroarc position (Allègre et al., 1984; Murphy et al., 1997; Kapp et al., 2005, 2007a, 2007b; Raterman et al., 2014), which may provide a template for understanding the Mesozoic tectonic evolution of the Pamir. Key to understanding the mechanisms involved in crustal thickening and orogenic growth in the Pamir is establishing the timing and magnitude of upper-crustal shortening.

This study investigates the Mesozoic to recent geological history of the South Pamir terrane, the largest of several accreted terranes that comprise the modern Pamir (Burtman and Molnar, 1993; Schwab et al., 2004) (Fig. 1). The South Pamir terrane hosts the Karakoram and South Pamir batholiths, which are remnants of a Cretaceous continental arc associated with northward subduction of oceanic lithosphere (Debon et al., 1987; Crawford and Searle, 1992; Schwab et al., 2004; Ravikant et al., 2009; Aminov et al., 2017) (Fig. 2). The South Pamir terrane also hosts
the Shakhdara-Alichur extensional gneiss dome, the largest gneiss dome in the Pamir and one of the largest in the world (Stübner et al., 2013a) (Fig. 1). As a result, lower crustal deformation in the Shakhdara-Alichur gneiss dome can be compared directly to upper crustal deformation in the hanging wall of the gneiss dome. We conducted geological mapping and integrated stratigraphic, geochronological, thermochronological, and structural analyses to assess the geological evolution of the South Pamir terrane and its role in the growth of the Pamir orogen. The results provide new insight into the timing of upper crustal shortening and thickening in the region with implications for (1) mechanisms for crustal thickening in Cordilleran-style and continental collisional orogens, (2) the extent of coupling between the upper and lower crust during convergence, and (3) the tectonic evolution of the Pamir.

2. GEOLOGIC SETTING

The South Pamir terrane is bounded to the north by the Rushan-Pshart suture zone and the Central Pamir terrane (Burtman and Molnar, 1993). Upper Triassic to Lower Jurassic intrusive rocks on the northern margin of the South Pamir terrane (Fig. 3) may record the closure of the Rushan-Pshart ocean basin that separated the Central and South Pamir terranes (Schwab et al., 2004). The Central Pamir and South Pamir terranes are both Gondwanan fragments that were accreted to each other and to the southern margin of Asia during the Cimmerian orogeny in the Late Triassic to Early Jurassic (Angiolini et al., 2013). Prior to the accretion of the Central and South Pamir terranes, the southern Asian margin was occupied by a Triassic continental arc with a well-developed accretionary complex (Xiao et al., 2002; Schwab et al., 2004). Commonly, the upper Paleozoic southern Asian margin is referred to as the Kunlun “terrane,” the arc/accretionary complex is referred to as the Karakul-Mazar “terrane,” and collectively they are termed the North Pamir “terrane” (Xiao et al., 2002; Schwab et al., 2004; Robinson et al., 2012) (Fig. 1). Although the para-autochthonous North Pamir is not a terrane sensu stricto, we retain the terrane designation here to facilitate comparisons with previous studies (e.g., Burtman and Molnar, 1993).

When viewed down-plunge, from west to east, the South Pamir terrane in Tajikistan presents a crustal section with the lower crust exposed in the core of the Shakhdara gneiss dome to the west (Schmidt et al., 2011; Stübner et al., 2013a) and non-metamorphosed sedimentary and volcanic rocks of the upper crust exposed in the east (Vlasov et al., 1991) (Figs. 1 and 2). The South Pamir terrane is truncated on its eastern margin by the Karakoram fault (Robinson, 2009) and on its southern margin by the Tirich-Kilik suture, which separates the South Pamir terrane from the Karakoram terrane (Zanchi et al., 2000; Zanchi and Gaetani, 2011) (Fig. 2). Metamorphic ages suggest that the Karakoram terrane was accreted to the South Pamir terrane during the Late Jurassic to Early Cretaceous (Zanchi et al., 2000; Hildebrand et al., 2001), although sedimentological evidence suggests accretion by the Early Jurassic (Zanchi and Gaetani, 2011; Angiolini et al., 2013; Gaetani et al., 2013). The South Pamir terrane is equivalent to the Qiangtang terrane in the Tibetan plateau (Robinson, 2009; Robinson et al., 2012; Angiolini et al., 2013).

2.1. South Pamir Stratigraphy and Map Units

The oldest exposed rocks in the area investigated (Figs. 2–4) are Permian to Triassic metasedimentary deposits (Vlasov et al., 1991) (map unit P-Tr). These rocks are predominantly dark-gray to black phyllite and slate with tan to dark-gray limestone and dolostone that cumulatively represent a rift-to-drift succession (Angiolini et al., 2015). The Permian-Triassic rocks were complexly deformed, uplifted, and eroded during the Cimmerian orogeny (Angiolini et al., 2013). Locally overlying the Permian-Triassic unit in angular unconformity is the Lower Jurassic Darbasatash Group (map unit JrD), which consists of nonmarine, red, coarse-grained sandstone and conglomerate (Dronov et al., 2006; Angiolini et al., 2013).
Figure 2. Regional geologic map of the eastern Pamir. Map location is shown in Figure 1. The geologic map is compiled from results of this study, Vlasov et al. (1991), Lindsay (2007), Burg (2011), Zanchi and Gaetani (2011), and Robinson et al. (2004, 2007, 2012). Labeled circles are samples of the Mamazair conglomerate or Murghab Basin strata analyzed in this study.
Figure 3. Geologic map of part of the South Pamir terrane, based on field mapping. Map location is shown in Figure 2. Sample information is presented in Table 1. Fm. — Formation; Gr. — Group; ZFT — zircon fission-track; AHe — apatite (U-Th)/He thermochronology; ZHe — zircon (U-Th)/He thermochronology.
The Darbasatash Group is overlain conformably by Jurassic limestone belonging to the Gurumdi Group (Dronov et al., 2006; Angiolini et al., 2013). For mapping purposes, we informally divided the Gurumdi Group into lower (Jrₜ) and upper (Jrₜ) units (Figs. 3, 5A, and 5B). The lower unit consists of tan to dark-brown, thinly bedded limestone and siltstone that vary in thickness from a few tens of meters to ~300 m. The upper unit consists of light-gray to white, massive, fossiliferous limestone up to ~400 m thick. We did not distinguish specific Jurassic formations during mapping. The fossiliferous upper unit is interpreted to be equivalent to the Gurumdi Group reef facies of Dronov et al. (2006). A fine-grained unit of thinly bedded gray to tan limestone, shale, and siltstone locally overlies the upper Gurumdi Group and was mapped as upper Jurassic (Jrₜ), although its age is unknown.

Unconformably overlying the Jurassic section in the South Pamir terrane are nonmarine red to orange conglomerate and coarse-grained sandstone previously mapped as undifferentiated Paleogene(?) (Vlasov et al., 1991). We refer to this informal lithostratigraphic unit as the Mamazair conglomerate (Kₘ), named after the village of Mamazair, following stratigraphic nomenclature rules defined by the International Stratigraphic Code (Salvador, 1994). North of the Rushan-Pshart suture zone, in the Central Pamir terrane, red conglomerate and sandstone mapped as undifferentiated Paleogene(?) by Vlasov et al. (1991) unconformably overlie Jurassic and older rocks. We adopt the nomenclature of Rutte et al. (2017a, 2017b) who referred to this unit as the “Murghab Basin” (map unit Kₘ). Sparse paleontological data at the base of the Murghab Basin strata suggest that the unit is of Maastrichtian age (Yushin et al., 1964). Additional rocks mapped as undifferentiated Paleogene(?) by Vlasov et al. (1991) are present north of the Muskol gneiss dome in the northern Central Pamir terrane (Fig. 2), but these rocks were not investigated in this study. Leven (1995) described Jurassic-Cretaceous metasedimentary rocks of the Bakalash Formation in the Rushan-Pshart suture zone, between the South and Central Pamir terranes (Fig. 3). The Bakalash Formation was not investigated in this study, but could be correlative with either the Murghab Basin or the Mamazair conglomerate. Igneous rocks, including granitoid and andesite are exposed in the South Pamir terrane and are mapped according to their radiometric ages (Figs. 3 and 4).

3. GEOLOGIC MAPPING

Geologic mapping of the South Pamir terrane was conducted over about eight weeks spanning the 2014 and 2015 field seasons, focused on a transect from the Shakhdara-Alichur gneiss dome in the south to the Rushan-Pshart suture zone in the north (Figs. 3, 6, and 7), and a region near the Kyzylrabot village in the southeast Pamir (Fig. 4). The regional geologic map in Figure 2 is adopted from previous geologic mapping in the Pamir (Vlasov et al. 1991; Robinson et al., 2004, 2007, 2012; Lindsay, 2007; Stübner et al., 2013a; Rutte et al., 2017a), Karakoram (Zanchi and Gaetani, 2011), and Kohistan (Burg, 2011). Compiled maps were locally supplemented with mapping based on spectral-band combinations from Landsat data and satellite imagery, which were mainly used to fill in gaps between previously published maps, check the geometry of unit boundaries and contacts, and reconcile differences between existing maps.

3.1. Stratigraphy and Sedimentology

New mapping in the South Pamir terrane is generally consistent with previous mapping in the region (Vlasov et al., 1991). One of the main features mapped is the post-Cimmerian angular unconformity above the Permian-Triassic rocks and below the Darbasatash Group, which was recently recognized and defined by Angiolini et al. (2013). The post-Cimmerian unconformity is the primary stratigraphic feature used to distinguish the Jurassic carbonate section from carbonate units within the Permian-Triassic section (Figs. 2, 5A, and 5B). The Darbasatash Group varies in thickness from 0 to ~200 m and appears to fill in local topographic lows on the post-Cimmerian unconformity surface. In some areas, the Darbasatash Group contains a basal, clast-supported, well-rounded
Figure 5. Photographs from the South Pamir terrane. (A) Cimmerian angular unconformity (ang. uncf.) beneath the Darbasatash Group (Gr.) (ridge location: 37.73N, 73.83E). (B) Representative stratigraphy of the South Pamir terrane (peak location: 38.0N, 74.07E). (C) Basal conglomerate (cong.) in the Darbasatash Group (hammer height is ~42 cm; location: 37.77N, 73.24E). (D) Distinctive red and yellow clasts in the Darbasatash Group (pen height is ~14 cm; location: 74.05N, 37.75E). (E) Monomict limestone karst breccia in the upper Gurumdi Group (hammer height ~33 cm; location: 37.95N, 74.0E). (F) Paleokarst in the upper Gurumdi Group (ridge location: 37.92N, 74.06E). (G) Faulted strata of the Murghab Basin and basalt flow; Jurassic (?) rocks are conglomerates of the Central Pamir terrane (hillside location: 38.26N, 74.06E). (H) Growth strata in the Mamazair conglomerate displaying progressive bedding rotation and internal angular unconformities (ball-stick symbols show bedding dip; filled symbols are upright bedding; hollow symbols are overturned; hillside location: 37.84N, 74.09E). (I) Similar location to H. Folded Mamazair conglomerate in the footwall of the Mamazair fault (M. Gadoev for scale; outcrop in foreground location: 37.842N, 79.091E). (J) Recycled conglomerate clasts in the Mamazair conglomerate (hammer height ~33 cm; location same as H). (K) Informal units of the Mamazair conglomerate in the footwall of the Kyzylrabot fault (hillside location: 37.47N, 74.76E). (L) Volcanic pebble-cobble conglomerate in the Mamazair conglomerate. Part of Unit 3 shown in photo K (hammer height ~33 cm; location similar to photo K). Fm.—Formation.
pebble-to-cobble conglomerate up to ~10 m thick, composed of purple and green quartzite clasts (Fig. 5C). Elsewhere in the map area, the Darbasatash Group consists of dark red sandstone to subrounded pebble conglomerate and is characterized by “ketchup and mustard” colored sandstone (red) and dolostone (yellow) clasts (Fig. 5D). Previous petrographic analyses of sandstones of the Darbasatash Group by Angiolini et al. (2013) indicate that it was derived in part from a volcanic arc. The Darbasatash Group is interpreted to have been deposited subaerially.

The lower unit of the Jurassic Gurumdi Group is in depositional contact with the Darbasatash Group and consists of several tan to gray tabular limestone beds up to several meters thick separated by relatively thin (~1 m) shale beds, giving the outcrops a flaggy appearance (Fig. 5B). The upper unit of the Gurumdi Group consists of massive white to light-gray fossiliferous limestone and contains widespread features indicative of dissolution and paleokarst (cf. James and Choquette, 1988). Sheet, pod-like, and irregularly shaped bodies of clast-supported, angular to subrounded, monomict, light- to dark-gray limestone pebble to granule breccia with red clay to red siltstone matrix are common throughout the map area (Fig. 5E). Limestone clasts are almost exclusively derived from the local host rock. Breccias that are laterally continuous for up to a few km are interpreted as mantling karst breccias and paleosols (e.g., north of Jarty Gumbez, Fig. 3). Pod-like and irregular exposures are up to ~150 m in diameter and are interpreted as collapse and intraformational karst breccias (Fig. 5F).

3.1.1. Mamazair Conglomerate

Throughout much of the map area in the South Pamir terrane, the Gurumdi Group is the youngest sedimentary unit present, apart from Quaternary deposits (Vlasov et al., 1991). However, in a few locations, the Mamazair conglomerate unconformably overlies the upper unit of the Gurumdi Group or older units. We made a concerted effort to visit and sample every known location of the Mamazair conglomerate in the southeastern Pamir (Fig. 2).

The largest contiguous outcrop of the Mamazair conglomerate is located ~40 km south-southeast of the town of Murghab and ~20 km east of the village of Mamazair, in the footwall of the Mamazair thrust fault (Figs. 3 and 6). The Mamazair conglomerate is exposed in an open, upright to overturned syncline and rests unconformably on the upper Gurumdi Group (Fig. 6). In a measured section of the Mamazair conglomerate at
this location, it is ~420 m thick and contains at least two intraformational angular unconformities (Figs. 5H, 5I, and 6). The younger unconformity delineates a prominent color change from dark red (older) to pale orange (younger) (Figs. 5H and 6). The lower, red half of the section is not present in the southern limb of the syncline, which suggests it was eroded or not deposited (Fig. 6). The predominant lithofacies in the lower, red section comprise well-organized, horizontally stratified, clast-supported, rounded to subangular, pebble-to-cobble conglomerate. Individual beds are up to ~2 m thick and massive. Thin (10s of cm) and laterally discontinuous lenses of red, coarse-grained sandstone are locally present between conglomerate beds. Gray limestone clasts are most abundant, but red sandstone, dolostone, chert, and quartzite are also common. Granitic and volcanic clasts are absent. The limestone and dolostone clasts are similar in appearance to exposures of Permian-Triassic carbonate rocks in the upper, orange section include stratified clast-supported granule-to-cobble conglomerate. Individual beds are ~1-m-thick rhyolitic tuff near the base of the section. The Mamazair conglomerate here consists of interbedded orange, coarse-grained sandstone and orange-red, subangular, clast-supported, rhyolite pebble-to-cobble conglomerate. The stratigraphic position and scarcity of limestone clasts suggest that the rocks were deposited in a growing footwall syncline during slip on the Mamazair thrust fault.

Approximately 90 km southeast of the Mamazair locality (Figs. 2 and 4), the Mamazair conglomerate is exposed in the footwall of the Kyzylrabot thrust fault where it consistently dips moderately toward the north-northeast (Fig. 4). The Kyzylrabot section can be divided into four informal units (units 1–4; lowest to highest) (Fig. 5K). Unit 1 is exposed along the small creek valley that drains into the Aksu River, located west of the Kyzylrabot village. Unit 1 consists of brown and red, fine- to medium-grained sandstone with occasional beds of matrix-supported, subangular, quartzite granule conglomerate up to 1.5 m thick. Trough cross-stratification is locally present in the sandstone beds. Unit 2 is an easily weathered, light orange and pink, clast-supported, angular, limestone pebble conglomerate with interbedded arkosic, pink, coarse-grained sandstone (Fig. 5K). Volcanic and granitic clasts are absent. Unit 3 is a dark-purple to brown, clast-supported, subangular, andesite and limestone pebble conglomerate with interbedded sandstone layers. Unit 4 is a dark-red, matrix-supported, angular, limestone and sandstone clast, granular to pebbly conglomerate with interbedded sandstone layers. Limestone clasts are dominant in the lower part of the unit but decrease in abundance up-section, where red sandstone clasts are more common. No volcanic or granitic clasts are present in Unit 4. Also in the Kyzylrabot area, ~5 km east of the lake Salon-kul (Fig. 4), the Mamazair conglomerate rests unconformably on Cretaceous volcanic rocks and contains an ~1-m-thick rhyolitic tuff near the base of the section. The Mamazair conglomerate here consists of interbedded orange, coarse-grained sandstone and orange-red, subangular, clast-supported, rhyolite pebble-to-cobble conglomerate. The stratigraphic position and scarcity of limestone clasts is most similar to Unit 1 described above.
Directly north of the Kyzylrabot fault, the Mamazair conglomerate is preserved in the footwall of the Karasu fault (Fig. 4), where it is a red, medium- to coarse-grained arkosic sandstone up to a few tens of meters thick. Along strike of the Karasu fault to the northwest, ~20 km south of Murghab, the Mamazair conglomerate rests unconformably on the upper Gurumdi Group in the footwall of the fault, which is steeply north-dipping at this location (Fig. 3). This exposure consists of several tens of meters of massive, clast-supported, angular carbonaceous conglomerate with a fine-grained pale red siltstone matrix. The local stratigraphic relationships are unclear, and it is possible that this exposure is a sheet breccia or mantling karst breccia. The final exposure of the Mamazair conglomerate we examined is located in the southern Taxkorgan valley (China) where it occurs in angular unconformity with the Gurumdi Group in the core of a syncline (Fig. 2). The Mamazair conglomerate here consists of up to a few tens of meters of well-bedded red, coarse-grained sandstone with trough cross-bedding preserved locally.

3.1.2. Murghab Basin

Strata of the Murghab Basin are exposed along the north side of the Rushan-Pshart suture zone, in the southermost part of the Central Pamir terrane (Rutte et al., 2017a; Fig. 3). In the southern Akbaital valley, ~10 km northeast of Murghab, the Murghab Basint strata rest unconformably on Paleozoic(? ) schist. The base of the Murghab Basin unit here consists of ~150 m of thinly bedded (<50 cm) pale-green to orange shale, carbonate-rich fine-grained sandstone, and dolostone. Ripple cross-lamination is present in most sandstone layers. The unit is overlain by ~175 m of massive, red, clast-supported cobble conglomerate that is capped by an ~100-m-thick basalt flow. Radiometric and thermochronologic dating of the basalt have been inconclusive (Rutte et al., 2017b). The basalt and surrounding sedimentary section are offset by a small south-dipping normal fault at this location (Figs. 3 and 5G). Overlying the basalt is an unknown thickness (>300 m) of interbedded dark-red sandstone, granule-pebble conglomerate, and siltstone. This upper unit locally contains stacked calcic paleosols with carbonate nodules and calcrite layers (e.g., Mack et al., 1993).

3.2. Structural Geology

Structural features in the South Pamir terrane can be grouped into four categories based on the timing of deformation and structural style. These are (1) Cimmerian deformation, (2) the South Pamir thrust belt (SPTB), (3) gneiss dome (north-south–directed) extension, and (4) dextral strike-slip deformation and limited east-west extension. Rutte et al. (2017a) referred to the region containing the SPTB and overprinted by dextral strike-slip faults as the Murghab-Aksu-Southeast Pamir thrust-wrench belt. In addition to geologic maps (Figs. 3, 4, 6, and 7), structural features in the South Pamir terrane are presented in cross section A–A’ (see Figure 3 for line of section), which was constructed based on structural measurements and observations in the field (Fig. 8).

3.2.1. Cimmerian Deformation

Permian-Triassic rocks, below the Cimmerian unconformity, are complexly deformed and record deformation associated with the Cimmerian orogeny (Fig. 5A). Angiolini et al. (2013) suggested that Cimmerian deformation is characterized by N-S to NNW-SSE–trending folds and high-angle reverse faults. The deformed Paleozoic rocks shown at depth in Figure 8 are schematic and are consistent with north-verging, tight folds shown below the Cimmerian unconformity in Rutte et al. (2017a). No attempt was made in this study to rigorously map structural associations with the Cimmerian orogeny, and the role of Cimmerian deformation in constructing the Pamir remains an outstanding question (Villarreal et al., 2015). Discontinuous exposures of carbonate units within the Permian-Triassic section are oriented subparallel to foliation/cleavage suggestive of locally transposed bedding. In some locations, the Permian-Triassic section exhibits type A fold interference patterns (basin and dome structures; Ramsay, 1967), which likely record re-folding of Cimmerian structures during Cretaceous or later episodes of shortening.

3.2.2. South Pamir Thrust Belt (SPTB)

The SPTB consists of a series of thrust faults and folds with axial surfaces that strike E-W to SE-NW (Fig. 3). These structures, including the Mamazair and Kyzylrabot thrust faults, offset Jurassic limestone and have locally preserved syntectonic Mamazair conglomerate in their footwalls. The Aksu fault (Figs. 3 and 8) is not well exposed but is here interpreted as a gently north-dipping (blind?) thrust fault based on structural relief on the Cimmerian unconformity, gently north-dipping (20–25°) bedding in the Jurassic carbonate section ~12 km east of Murghab, and a tight syncline ~10 km south of Murghab interpreted as a footwall syncline. Bedding of Jurassic strata in the hanging walls of other thrust faults in the SPTB also generally dips gently to the north-northeast, consistent with displacement above moderate to gently dipping thrust ramps (Fig. 8). The inferred moderate dips of major thrust faults in the SPTB suggest a relatively shallow basal décollement (<10 km depth) that is estimated to be in the Permian-Triassic section, consistent with the interpretation of Rutte et al. (2017a) for the Murghab-Aksu-Southeast Pamir thrust-wrench belt. Major folds in the SPTB are upright and open with the dip of bedding in Jurassic units rarely exceeding 40°, except adjacent to the Karasu fault (Figs. 3 and 8). When viewed down-plunge (to the southeast), the
northwest trend of the Mamazair fault, Karasu fault, and unnamed faults in the Murghab area suggest they root into the Rushan-Pshart suture zone (Fig. 2). Many thrust faults south of the Rushan-Pshart suture in the SPTB exhibit top-to-the-south displacement with south-vergent subsidiary anticlines, although north-directed faults are present in the southeast Pamir (Fig. 2). Vertical displacement on individual faults in the SPTB, based on structural relief of the Cimmerian unconformity, decreases toward the south, and the southernmost thrust faults tip out over relatively short distances (<30 km) along strike (Figs. 3 and 6).

East of Kyzylrabot, through-going thrust faults are not obvious and the SPTB is characterized by a series of folds (Fig. 2). It is unclear if deformation in the SPTB extends south of the Alichur gneiss dome. The Rushan-Pshart suture zone (the region south of the Rushan-Pshart fault and north of the Murghab River) is interpreted to be part of the SPTB (i.e., part of the South Pamir terrane). Rutte et al. (2017a) interpreted the northern limit to the Rushan-Pshart suture zone as a north-dipping thrust fault that places Permian-Triassic rocks on Murghab Basin strata (Figs. 3 and 8). Assuming minimal initial structural relief, line-length balancing of the Jurassic Gurumdi Group is used to restore cross section A–A′ (inset, Fig. 8). Whereas Burtman and Molnar (1993) suggested up to 50 km (~50%) of internal shortening within the SPTB, our initial assessment of shortening suggests significantly less shortening (~10 km), on the order of several percent over the ~100 km length of the cross section and less if the entire South Pamir terrane is included (south of the Alichur gneiss dome).

3.2.3. Extension and Strike-Slip Faulting

Other than the normal-sense shear zones bounding the Shakhdara-Alichur gneiss dome, we observed little evidence for structures that might accommodate north-south–directed extension in the South Pamir terrane, consistent with the observations of (Stübner et al., 2013a). There are no deep extensional (supra-detachment) basins adjacent to the gneiss dome and few east-west–striking normal faults in the hanging wall of the gneiss dome with significant displacement (Figs. 2 and 3). The scarcity of normal faults in the hanging wall of the gneiss domes in the South Pamir terrane contrasts with models for extensional provinces and core complexes, where numerous normal fault arrays are present in the hanging wall (Wernicke and Burchfiel, 1982; Lister and Davis, 1989).

Although extensional structures oriented parallel to the Alichur gneiss dome are scarce, approximately north-south striking normal faults bounding north-south–trending valleys are more common in the South Pamir terrane (Fig. 3; cf. Schurr et al., 2014). These normal faults offset older reverse faults associated with the SPTB. For example, a prominent normal fault is interpreted to juxtapose upper Jurassic limestone against Permian-Triassic rocks near the village of Mamazair (Fig. 3). Offsets of Jurassic strata across these faults are generally <1 km. Similar sets of young, north-south–striking faults in the South Pamir terrane (Figs. 3 and 4). Offsets of Jurassic strata across these faults are generally <1 km. Similar sets of young, north-south–striking faults in the South Pamir terrane (Figs. 3 and 4). Offsets of Jurassic strata across these faults are generally <1 km. Similar sets of young, north-south–striking normal faults in the hanging wall of the gneiss dome with significant displacement (Figs. 2 and 3). The scarcity of normal faults in the hanging wall of the gneiss domes in the South Pamir terrane contrasts with models for extensional provinces and core complexes, where numerous normal fault arrays are present in the hanging wall (Wernicke and Burchfiel, 1982; Lister and Davis, 1989).

Offset river terraces document active dextral strike-slip displacement on the Karasu fault, which connects the Rushan-Pshart suture zone to the dextral Karakoram fault (Figs. 2 and 3) (Strecker et al., 1995). The Karasu fault appears to have cut or reactivated a thrust fault associated with the SPTB and a vertical component of offset across the fault (up to a few km) is likely related to earlier thrust belt deformation (Fig. 8). Other dextral strike-slip faults may be active in the South Pamir terrane as well (Schurr et al., 2014; Rutte et al. 2017a). An unnamed fault north of the Karasu fault and south of the Aksu fault (Figs. 3 and 7B) dips steeply north and may accommodate primarily strike-slip motion as suggested by Rutte et al. (2017a). Large changes in vertical displacement (>1 km) of the Cimmerian unconformity over short distances (<10 km) along strike of this unnamed fault and the steep dip of the fault is consistent with strike-slip motion, and may have reactivated an older thrust fault. Rutte et al. (2017a) also suggested that the easternmost Aksu fault (Figs. 3 and 8) is a Neogene or younger dextral strike-slip fault, which could have reactivated an older thrust fault. We did not observe evidence for strike-slip motion on faults (e.g., subhorizontal slickenlines, offset geologic markers) south of the Karasu fault in the SPTB (Figs. 3, 4, and 7A), but overall low magnitudes of slip on faults in this region may have obscured a component of strike-slip motion.

4. GEOCHRONOLOGY AND THERMOCHRONOLOGY RESULTS

A detailed description of methods used for zircon U-Pb geochronology, zircon fission track thermochronology, and zircon and apatite (U-Th)/He thermochronology can be found in Data Repository File DR1.

4.1. Zircon U-Pb Geochronology

4.1.1. Igneous Rocks

Four igneous rocks were analyzed for zircon U-Pb geochronology (10–30 grains analyzed per sample). Age estimates for igneous samples are presented on the geologic maps in Figures 3 and 4, a summary of sample locations and age information is presented in Table 1, and complete zircon U-Pb data are presented in Data Repository File DR2. The analyzed rocks are porphyritic andesite (samples: 14-74, 14-76, 14-77, 14-88) from near the village of Kyzylrabot in the southeastern Pamir and have middle Cretaceous (ca. 105 Ma) zircon U-Pb ages (Table 1; Fig. 4). Additional zircon U-Pb ages of igneous rocks presented in Figures 3 and 4 (shown only for samples with new thermochronological data) are from Chapman et al. (2018).

4.1.2. Sedimentary Rocks

Eight sandstone samples were analyzed for detrital zircon U-Pb geochronology (100–400 grains analyzed per sample) from the Mamazair conglomerate and Murghab Basin strata (Fig. 9A). Six samples (14-83, 14-85, GUM-02, DV-7-16-15-2, DV-7-15-15-7, and AR-5-27-00-5) are from the Mamazair conglomerate. All of the Mamazair conglomerate samples, except AR-5-27-00-5, were collected from the footwalls of thrust faults in the South Pamir terrane (Figs. 3 and 4). Detrital zircon U-Pb data is presented in a series of probability density plots in Figure 9A. Sample GUM-02 was collected in the footwall of the Mamazair thrust fault and has a minimum age population of ca. 112 Ma (Fig. 9A). Samples 14-83 and DV-7-16-15-2 were collected ~40 m below (in the footwall) the Kyzylrabot thrust fault and sample 14-85 was collected ~160 m stratigraphically below sample 14-83 (Fig. 4). The detrital age spectra for samples 14-83 and 14-85 are nearly identical and are combined into a single age probability function in Figure 9A. Sample 14-83/85 has a minimum age population of ca. 112 Ma and a large detrital age population at ca. 104 Ma. Sample DV-7-16-15-2 has a minimum age population of ca. 97 Ma. Sample DV-7-15-15-7 was collected in the footwall of the Karasu fault and has a minimum age population of ca. 154 Ma. The easternmost sample analyzed, AR-5-27-00-5, was collected from the core of a syncline and has a minimum age population of ca. 141 Ma. Several Mamazair conglomerate...
samples contain detrital age populations in the 140–150 Ma range in addition to younger age populations (Fig. 9A). Samples DV-7-15-15-2 and AR-5-27-00-5 may have been deposited before the other samples.

Two samples (15-28 and 14-56) were collected from Murghab Basin strata just north of the Rushan-Pshart suture zone in a footwall syncline in the Central Pamir terrane (Figs. 2 and 3). Sample 14-56 has a minimum age population of ca. 84 Ma and sample 15-28 has a minimum age population of ca. 106 Ma (Table 1; Fig. 9A).

4.2. Zircon Fission-Track Thermochronology

A subset of zircon grains analyzed for detrital U-Pb geochronology, described above, were analyzed for zircon fission-track (ZFT) analysis (“double-dating”). Three samples were selected for detrital ZFT analysis (30–100 grains per sample). ZFT data are shown as kernel density estimate (KDE) plots in Figure 9B, and constituent age populations in each sample were identified and deconvolved using DensityPlotter (Vermeesch, 2012). Complete ZFT data are presented in Data Repository File DR3. Sample GUM-02 yielded ZFT single-grain ages ranging from 59 ± 13 Ma to 754 ± 188 Ma and has one prominent detrital ZFT age population of 103 ± 5 Ma, which is similar to the youngest zircon U-Pb age population (112 Ma; Fig. 9B). All of the individual zircons with Cretaceous and younger ZFT ages from sample GUM-02 have corresponding (doubled-dated) Cretaceous U-Pb ages. ZFT single-grain ages in sample 15-28 range from 108 ± 23 Ma to 1054 ± 225 Ma and the sample exhibits two detrital ZFT age populations of 235 ± 19 Ma (65% of grains) and 160 ± 26 Ma (22% of grains) (Fig. 9B). The small number of zircon grains with Cretaceous U-Pb ages (n = 3) explains the lack of a recognizable younger ZFT age population. Four (out of 100) zircons in sample 15-28 yielded Cretaceous ZFT cooling ages (134–108 Ma). These four individual analyses had U-Pb ages ranging from Cretaceous to Proterozoic. The ca. 235 Ma detrital ZFT age population in sample 15-28 is similar to detrital zircon U-Pb age populations in samples 15-28 and 14-56 (Fig. 9B). Single-grain ZFT ages from sample 14-83 range from 68 ± 20 Ma to 715 ± 168 Ma. Sample 14-83 has two detrital ZFT age populations of 111 ± 5 Ma (44% of grains) and 264 ± 18 Ma (45% of grains) (Fig. 9B). The youngest detrital ZFT age population (ca. 111 Ma) in sample 14-83 compares favorably to the prominent ca. 104 Ma zircon U-Pb detrital age population in the same sample (Fig. 9). Individual zircons with Cretaceous ZFT detrital ages in sample 14-83 have zircon U-Pb ages ranging from Cretaceous to Proterozoic (Data Repository File DR3). The older ZFT age population (ca. 264 Ma) in sample 14-83 is similar to the ca. 235 Ma ZFT age population in sample 15-28.

4.3. (U-Th)/He Thermochronology Results

To constrain the magnitude of exhumation in the South Pamir terrane, six granite samples (with Jurassic to Cretaceous zircon U-Pb crystallization ages) and two sandstone samples (with Triassic to Cretaceous detrital zircon U-Pb maximum depositional ages) were collected for zircon (U-Th)/He (ZHe) and apatite (U-Th)/He (AHe) thermochronology. Weighted mean ZHe and AHe sample ages (based on three to five single-grain analyses) are presented in Table 1 and shown in Figures 3 and 4. Single-grain ZHe and AHe data are presented in Data Repository File DR4. Uncertainties (2σ) for average ages are calculated using internal (weighted analytical uncertainty) and external (standard deviation of aliquot ages) errors. Three samples (granitoids 14-73, 14-60, and 16-22) were collected in the Rushan-Pshart suture zone and have weighted-mean ZHe cooling ages of ca. 15–20 Ma. Five samples (Cretaceous granitoids 13P101 and 14-87, Cretaceous dike 14-89, Cretaceous sandstone 16-23, and Triassic sandstone 13P99) were collected from the interior of the South Pamir terrane. Weighted mean average ZHe ages from samples in the South Pamir terrane range from 34 to 102 Ma and weighted mean average AHe ages range from 44 to 56 Ma (Table 1). The mean ZHe ages for samples 14-87 and 14-89 are within 10% of the zircon U-Pb age. All other (U-Th)/He ages are >10% younger than their crystallization or depositional age. Sample 16-22, a Paleozoic (?) schist, yielded a ZHe cooling age of 15.1 ± 0.7 Ma (Fig. 3; Table 1). Sample 16-23, a sandstone clast collected from the Mamazair conglomerate, yielded an AHe cooling age of 46 ± 16 Ma, similar to the AHe cooling age recorded from the igneous sample 14-89 collected nearby (56 ± 17 Ma). All of the mean AHe ages have large uncertainties, which may reflect a complicated cooling history, although none of the samples exhibited age versus effective uranium concentration (eU) trends (Data Repository File DR4), and ZHe age uncertainties from the same samples were lower than the AHe uncertainties (e.g., sample 14-89).

5. DISCUSSION

5.1. Exhumation in the South Pamir Terrane

Two igneous ZHe samples (14-87 and 14-89) from the SPTB in this study have Cretaceous cooling ages that are as much as 10 m.y. younger than the zircon U-Pb ages from the same samples (Table 1; Figures 3

TABLE 1. SAMPLE INFORMATION AND AGE SUMMARY OF GEOCHRONOLOGIC AND THERMOCHRONOLOGIC DATA

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude (DD)</th>
<th>Longitude (DD)</th>
<th>Maximum depositional age</th>
<th>U-Pb (Ma)</th>
<th>ZFT (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detrital Samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murghab Basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-28</td>
<td>38.2719</td>
<td>73.6290</td>
<td>106</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>14-56</td>
<td>38.2594</td>
<td>74.0476</td>
<td>84</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td>Mamazair Conglomerate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GUM-02</td>
<td>37.5936</td>
<td>74.0888</td>
<td>112</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>14-83/88</td>
<td>37.4755</td>
<td>74.7648</td>
<td>76</td>
<td>111</td>
<td></td>
</tr>
<tr>
<td>DV-7-16-15-2</td>
<td>37.4750</td>
<td>74.7660</td>
<td>97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DV-7-15-17-7</td>
<td>37.5500</td>
<td>74.6900</td>
<td>157</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AR-5-27-00-5</td>
<td>37.2191</td>
<td>75.3657</td>
<td>141</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bedrock Samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rushan-Pshart Suture Zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-73</td>
<td>38.2081</td>
<td>74.0284</td>
<td>198 ± 7</td>
<td>17 ± 3</td>
<td></td>
</tr>
<tr>
<td>14-60</td>
<td>38.1289</td>
<td>73.8556</td>
<td>109 ± 5</td>
<td>20 ± 7</td>
<td></td>
</tr>
<tr>
<td>16-22</td>
<td>38.2495</td>
<td>74.0225</td>
<td>15 ± 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Pamir Thrust Belt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13P101</td>
<td>37.5027</td>
<td>73.7301</td>
<td>120 ± 4</td>
<td>34 ± 4</td>
<td></td>
</tr>
<tr>
<td>14-89</td>
<td>37.7840</td>
<td>73.9593</td>
<td>104 ± 3</td>
<td>56 ± 17</td>
<td>102 ± 11</td>
</tr>
<tr>
<td>16-23</td>
<td>37.7975</td>
<td>73.7743</td>
<td>46 ± 16</td>
<td>69 ± 13</td>
<td></td>
</tr>
<tr>
<td>13P99</td>
<td>37.4931</td>
<td>74.6112</td>
<td>105 ± 3</td>
<td>44 ± 19</td>
<td>96 ± 10</td>
</tr>
<tr>
<td>14-74</td>
<td>37.5505</td>
<td>74.4665</td>
<td>111 ± 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-76</td>
<td>37.5230</td>
<td>74.3929</td>
<td>105 ± 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-77</td>
<td>37.5487</td>
<td>74.5235</td>
<td>105 ± 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-88</td>
<td>37.5102</td>
<td>74.5779</td>
<td>105 ± 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Maximum depositional ages are based on the youngest zircon U-Pb or zircon fission-track (ZFT) population (Fig. 9). DD—decimal degrees, AHe—apatite (U-Th/He), ZHe—zircon (U-Th/He). Complete zircon U-Pb data are located in Data Repository File DR3 (see text footnote 1). Complete ZFT data are located in Data Repository File DR2. Complete AHe and ZHe data are presented in Data Repository File DR4.
and 4). These ZHe ages are interpreted to represent cooling following magmatic emplacement and suggest less than 4 km of exhumation or burial during the Cenozoic. The other bedrock ZHe and AHe cooling ages in the SPTB range from Late Cretaceous to late Eocene and may record a regional exhumation signal associated with the initiation of the India-Asia collision (e.g., Rohrmann et al., 2012). An interpretive cooling path for the southern SPTB is presented in Figure 10A. The thermochronologic data from the SPTB are consistent with limited Cenozoic exhumation in much of the South Pamir terrane as suggested by the low-relief landscape, preservation of the low-angle Cimmerian unconformity, and uneroded remnants of a volcanic carapace in the Kyzylrabot area (Fig. 4). The results from this study are also consistent with Stübner et al. (2013b) who calculated cooling rates as low as ~0.1 mm/yr since the mid-Cretaceous in the South Pamir terrane, outside of the Shakhdara gneiss dome.

Figure 10B is a compilation of thermochronologic data from this study (10 new cooling ages, most located in the SPTB) and previous studies (Data Repository File DR5) plotted against the distance south from the Pamir thrust, which bounds the Pamir Mountains to the north (Fig. 1). The y-axis in Figure 10B is closure temperature divided by cooling age for each sample, a proxy for exhumation rate, but not a well-defined cooling rate, which should be calculated from multiple thermochronometers.

Not surprisingly, inferred exhumation rates in the SPTB are relatively low compared to the Pamir gneiss domes and the Rushan-Pshart suture zone (Stübner et al., 2013b; Rutte et al., 2017b) and are more akin to exhumation rates in the North Pamir terrane (Amidon and Hynek, 2010; Sobel et al., 2013), which is not interpreted to have experienced internal shortening during the Cenozoic (Burtman and Molnar, 1993; Robinson et al., 2004, 2007).

The Rushan-Pshart suture zone is characterized by Miocene low-temperature thermochronologic cooling ages, yielding relatively high Miocene to Recent exhumation rates (Figs. 3 and 10; Table 1) that are interpreted to reflect rock uplift and erosion within the suture zone. The new data support the conclusions of Rutte et al. (2017b), who suggested low (<2 °C/m.y.) cooling rates in the Late Cretaceous to the Miocene and accelerated cooling rates (up to ~30 °C/m.y.) from the Miocene to the present.

5.2. Age of the Mamazair Conglomerate and Murghab Basin Strata

The Murghab Basin strata and the Mamazair conglomerate have previously been associated with Cenozoic deformation and growth of the Pamir orogen during India-Asia collision (Burtman and Molnar, 1993;
Rutte et al., 2017a). However, the results of this study do not yield evidence for a Cenozoic age for these deposits, and instead suggest older depositional ages.

Samples DV-7-15-15-2 and AR-5-27-00-5 (both interpreted to be correlative with the Mamazair conglomerate) from the southeastern SPTB have Upper Jurassic to Lower Cretaceous zircon U-Pb minimum age populations interpreted as maximum depositional ages (141–154 Ma). Because of the widespread exposures of mid-Cretaceous igneous rocks in the region and abundant mid-Cretaceous detrital zircon U-Pb ages present in other samples of the Mamazair conglomerate from the same area (Figs. 2, 4 and 9), we interpret samples DV-7-15-15-2 and AR-5-27-00-5 to have been deposited prior to the mid-Cretaceous. Growth strata were not observed where these samples were collected, and it is unclear if these strata are syntectonic or were deposited prior to SPTB deformation.

Detrital zircon U-Pb and detrital ZFT minimum age populations for the rest of the Mamazair conglomerate samples cluster in the mid-Cretaceous (112–76 Ma) (Fig. 9) and are interpreted as maximum depositional ages. Cenozoic igneous rocks are exposed in the Central and South Pamir terranes, and Cenozoic leucogranite and migmatises are exposed within the Pamir gneiss domes (Ducau et al., 2003; Schwab et al., 2004; Jiang et al., 2012; Stübben et al., 2013a; Carrapa et al., 2014a; Stearns et al., 2015; Chapman et al., 2018), which could have contributed detrital zircon to the Mamazair conglomerate or Murghab Basin strata if these formations are Cenozoic in age. Furthermore, detrital zircon U-Pb ages from modern streams draining the Central and South Pamir, and from Oligocene-Miocene sediments from the northeast margin of the Pamir, yield a strong Eocene signal (Lukens et al., 2012; Bershaw et al., 2012; Carrapa et al., 2014a) that is not present in the Mamazair conglomerate and Murghab Basin samples.

The detrital ZFT data from the Mamazair conglomerate indicate that the unit was not buried deeply enough to exceed a temperature of ~240 °C for significant periods of time and exhibit a detrital (not reset) thermochronologic signal. None of the samples have Cenozoic detrital ZFT age populations (Fig. 9B), and very few (not statistically significant) single-grain ZFT analyses produced Cenozoic ages (Data Repository File DR3). In contrast, samples from the Pamir gneiss domes and Rushan-Pshart suture zone have Cenozoic ZFT exhumation ages (Stübben et al., 2013b; Stearns et al., 2015; Rutte et al., 2017b). Crustal thickening in the Pamir is interpreted to have occurred during the late Eocene to Oligocene (Smit et al., 2014; Stearns et al., 2015; Rutte et al., 2017b), which might also be expected to have produced a detrital ZFT signature in the Mamazair and Murghab basin samples.

Finally, interbedded volcaniclastic and tuffaceous beds in the Mamazair conglomerate from the Kyzylrabot area also support a mid- to Late Cretaceous depositional age (Figs. 4, 5K, and 5L), as the age of the volcanic units in the Kyzylrabot area were recently reclassified from Paleogene (?) to mid-Cretaceous (Aminov et al., 2017; Chapman et al., 2018).

We emphasize that because the new detrital zircon U-Pb and detrital ZFT ages are maximum depositional ages, the Mamazair conglomerate and Murghab Basin could be Cenozoic in age. However, we adopt a Late Cretaceous age consistent with the available detrital zircon U-Pb data, detrital ZFT data, previous biostratigraphic age control (Maastrichtian; Yushin et al., 1964), locally interbedded tuffaceous beds, and similarly aged red-colored units that occur in the Karakoram (the Tupaloo and Darbaand Formation; Gaetani et al., 1993).

5.3. Cretaceous Tectonics in the South Pamir Terrane

The upper Gurumdi Group contains extensive dissolution features and paleokarst breccia, which indicate that the South Pamir terrane was uplifted above sea level during the Late Jurassic to Early Cretaceous (Figs. 3, 5E, and 5F). Robinson (2015) suggested Upper Jurassic deformation and uplift of the South Pamir terrane based on Late Jurassic ⁴₀Ar/³⁹Ar cooling ages in the Rushan-Pshart suture zone presented in Schwab et al. (2004) and the absence of Upper Jurassic marine rocks (Pashkov and Budanov, 1990). Rutte et al. (2017b) suggested that the Late Jurassic ⁴₀Ar/³⁹Ar cooling ages in the Rushan-Pshart zone are magmatic cooling ages associated with nearby Jurassic intrusions (Schwab et al., 2004).

Either shortly after or contemporaneously with uplift and karst weathering, continental arc magmatism migrated into the Pamir, related to northward directed subduction of oceanic lithosphere (Debon et al., 1987; Crawford and Searle, 1992; Fraser et al., 2001; Schwab et al., 2004; Ravikant et al., 2009). The oldest Cretaceous igneous rocks identified in

![Figure 10](https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/10/4/494/4262347/494.pdf)
the South Pamir terrane are ca. 120 Ma (Fig. 3) and in the Kyzylrabot area, mid-Cretaceous (ca. 105 Ma) volcanic rocks were deposited unconformably on Jurassic carbonate rocks (Aminov et al., 2017; Chapman et al., 2018; this study) (Fig. 4).

The Mamazair conglomerate is primarily exposed in the footwall of thrust faults that form the SPTB. Syndepositional deformation recorded by growth strata and recycled clasts in the Mamazair conglomerate link the timing of deposition and SPTB deformation (Figs. 5H, 5J, and 6). If our interpretation of the age of the Mamazair conglomerate is correct, this suggests that post-Cimmerian (post–Late Triassic) upper crustal shortening in the SPTB occurred during the Late Cretaceous. This interpretation supports a growing body of evidence for Cretaceous shortening throughout the Pamir: (1) the Tajik and Tarim basins and northern Pamir foreland contain thick, coarse-grained, clastic Cretaceous deposits that were derived from the Pamir (Hamburger et al., 1992; Sobel, 1999; Burttman, 2000; Bershaw et al., 2012; Carrapa et al., 2015); (2) the North Pamir terrane experienced Cretaceous Barrovian metamorphism and shortening, including reactivation and southward-directed thrusting along the Tanymsa fault (Robinson et al., 2004; Robinson, 2015); and (3) the Karakoram terrane experienced Cretaceous metamorphism and crustal thickening (Searle et al., 1999; Fraser et al., 2001; Hildebrand et al., 2001).

5.4. Comparison of the South Pamir Terrane to Tibet

The Mesozoic geology of the Pamir Mountains and Tibetan plateau share many characteristics. Like the South Pamir terrane, the laterally equivalent Qiangtang terrane was uplifted above sea level during the Late Jurassic to Early Cretaceous (Dewey et al., 1988; Leeder et al., 1988; Kapp et al., 2005). Early Cretaceous igneous rocks are prevalent in the northern Lhasa terrane and southern Qiangtang terrane, with a peak in magmatism at ca. 110 Ma (Zhu et al., 2009, 2016; Sui et al., 2013), similar to the South Pamir terrane (Schwab et al., 2004; Aminov et al., 2017; Chapman et al., 2018). Although the Yarlung suture zone and parts of the Gangdese arc underwent significant (>6 km?) Cenozoic exhumation (Copeland et al., 1987, 1995; Carrapa et al., 2014b), the northern Lhasa terrane and Qiangtang terrane experienced minimal (<3 km) post-Eocene burial and/or exhumation north of the suture zone (Kapp et al., 2005; DeCelles et al., 2007; Hetzel et al., 2011; Rohrmann et al., 2012; Wang et al., 2014), similar to the South Pamir terrane outside of the gneiss domes and suture zones (Fig. 10B).

In central Tibet, the majority of upper-crustal shortening was concentrated along the Bangong suture zone during the Jurassic–Early Cretaceous and propagated southward into the northern Lhasa thrust belt during the Late Cretaceous (Murphy et al., 1997; Kapp et al., 2005, 2007b; DeCelles et al., 2007; Volkmer et al., 2007, 2014; Raterman et al., 2014). The timing of shortening, the relationship to Mesozoic suture zones, and the overall southward vergence of the northern Lhasa thrust belt is similar to the South Pamir thrust belt (Figs. 3 and 8). One difference between the South Pamir terrane and southern Tibet is in the magnitude of Cretaceous shortening, which exceeded 50% within the Bangong suture zone and northern Lhasa terrane, but was only moderate in the South Pamir terrane. There are also Cretaceous red beds in the Qiangtang terrane, Bangong suture zone, and northern Lhasa terrane that are associated with Cretaceous deformation (DeCelles et al., 2007; Kapp et al., 2007b; Leier et al., 2007; Raterman et al., 2014; Sun et al., 2015) and may be equivalent to the Murghab Basin strata and Mamazair conglomerate in the Pamir.

5.5. Crustal Thickening in the Pamir

Based on work by Burttman and Molnar (1993), Schmidt et al. (2011) provided a summary of total Cenozoic shortening for the Pamir Mountains in order to examine models for crustal thickening. Schmidt et al. (2011) showed that if the precollisional thickness of the Pamir crust was similar to global averages (35–40 km), 400–600 km of plane-strain shortening is required to account for the present-day crustal thickness of the Pamir. The results of this study, combined with other recent investigations of the Pamir Mountains, enable a revised estimate of total shortening. Cenozoic shortening estimates are summarized below, from north to south.

No Cenozoic upper crustal shortening has been documented within the North Pamir terrane (Burttman and Molnar, 1993; Amidon and Hynek, 2010; Robinson, 2015). Rutte et al. (2017a) suggested ≤75 km of Cenozoic extension in the Central Pamir gneiss domes, yielding ~165 km of total extension in the Pamir. Although the magnitude of Cenozoic extension in the Pamir is not precisely constrained, these estimates raise the possibility that the upper crust of the Pamir interior could be characterized by net extension rather than net shortening (~165 km extension minus ~100 km of shortening) during the Cenozoic.

In contrast, Stübner et al. (2013a) estimated up to ~90 km of Cenozoic extension associated with the Shakhdara-Alichur gneiss dome, and Rutte et al. (2017a) suggested ≤6 km of Cenozoic extension in the South Pamir gneiss domes. Given the relatively small extent of Cenozoic extension compared to Cretaceous shortening, Cenozoic shortening is an important component of the Pamir crustal thickening budget, and a revised estimate of total shortening is given below.

5.5.1. Cenozoic Internal Shortening Model

Cenozoic shortening associated with India-Asia collision is a common explanation for the thick crust in the modern Pamir Mountains (Burttman and Molnar, 1993; Robinson et al., 2007; Schmidt et al., 2011; Stearns et al., 2013, 2015; Hacker et al., 2017; Rutte et al., 2017a). Thrust sheets and internal shortening in the Central Pamir terrane, documented by Rutte et al. (2017a, 2017b), explains the modern thickness of the crust in the Central Pamir terrane as well as the prograde metamorphic history of the Central Pamir gneiss domes (Smit et al., 2014; Stearns et al., 2015; Hacker et al., 2017). The Shakhdara-Alichur gneiss dome in the South Pamir terrane has a similar metamorphic history to the Central Pamir gneiss domes (Stübner et al., 2013b; Smit et al., 2014; Stearns et al., 2015; Hacker et al., 2017) and ideally, a similar model for crustal thickening could be applied to the South Pamir terrane. However, the results of this study suggest low magnitudes of internal shortening, which could not have buried the rocks in the Shakhdara-Alichur gneiss dome to mid-to-lower crustal depths (≥50 km) as indicated by thermobarometry (Hacker et al., 2017). In addition, the Shakhdara-Alichur gneiss dome does not display ductile nappe (shortening) structures like the Central Pamir gneiss domes (Stübner et al., 2013a; Rutte et al., 2017a). Internal crustal thickening also does not explain the current thickness of the North Pamir terrane crust.

5.5.2. Mesozoic Internal Shortening Model

The crust of the Pamir Mountains may have been significantly thickened during the Mesozoic (Robinson et al., 2004, 2012; Robinson, 2015),
similar to some models for crustal thickening in Tibet (Murphy et al., 1997; Kapp et al., 2005, 2007a; Raterman et al., 2014). Robinson et al. (2004, 2012) presented evidence from the North Pamir terrane for Cretaceous shortening and crustal thickening, which could help explain the modern crustal thickness. Results of the current study suggest that internal shortening occurred in the South Pamir terrane during the Mesozoic, but the magnitude of this shortening was not sufficient to significantly thicken the South Pamir crust. This model also does not explain the Eocene to Miocene prograde metamorphic ages recorded within the Pamir gneiss domes that indicate protracted Cenozoic burial (Robinson et al., 2004, 2007; Schmidt et al., 2011; Stearns et al., 2013, 2015; Hacker et al., 2017).

Smit et al. (2014) proposed that Eocene Lu-Hf garnet (prograde) metamorphic ages from the Pamir gneiss domes may reflect high mantle heat flow associated with breakoff and foundering of the Neoethyian oceanic slab, which would not require Cenozoic burial, although the protracted nature of prograde metamorphism within the gneiss domes (20–25 m.y.; Stearns et al., 2015; Hacker et al., 2017) is generally inconsistent with a short-lived thermal pulse following slab breakoff (Mahéo et al., 2002).

5.5.3. Underthrusting Model

Lithosphere external to the Pamir may have been underthrust and incorporated into the Pamir orogen, helping to compress and thicken the crust (Butler and Coward, 1989; Kufner et al., 2016; Chapman et al., 2017), again analogous to some models for Tibet (Zhuo and Morgan, 1987; Nelson et al., 1996; DeCelles et al., 2002; Kapp and Guynn, 2004; Nábelek et al. 2009; Gao et al., 2016). The northern margin of the Pamir and the eastern Tajik fold-thrust belt record ∼30 km of Cenozoic shortening (Leith and Alvarez, 1985; Hamburger et al., 1992; Bekker, 1996; Coutand et al., 2002; Li et al., 2012; Chapman et al., 2017). Some studies suggest that the Tajik-Tarim (Asian) lower crust was underthrust southward beneath the Pamir and incorporated into the orogen (rather than subducted), which could account for Cenozoic thickening and surface uplift in the North Pamir terrane without significant exhumation (Amidon and Hynek, 2010; Kufner et al., 2016; Chapman et al., 2017). On the southern margin of the Pamir, the Pakistan Himalayan fold-thrust belt, south of the Indus-Yarlung suture zone, records 400–600 km of upper crustal shortening (Butler and Coward, 1989). Underthrust Indian mantle lithosphere is interpreted to directly underlie much the Pamir crust today (Schneider et al., 2013; Sipl et al., 2013; Kufner et al., 2016), which implies that the overlying Indian lower crust has been incorporated into the upper plate. In addition to Indian lithosphere, studies of the northern Karakoram sedimentary sequences suggest significant (but unconstrained) upper crustal shortening during the Cenozoic in the Karakoram terrane (Zanchi and Gaetani, 2011). Part of the Karakoram terrane could also have been thrust beneath the South Pamir terrane and thickened the crust (e.g., Duca et al., 2003).

An attractive aspect of the end-member model for underthrusting of Indian, Asian, or Karakoram lithosphere to thicken the Pamir lower crust is that it could drive extension in the mid-to-upper crust, resulting in the formation of the Pamir gneiss domes (Robinson et al., 2007; Stübner et al., 2013b). This model suggests mechanical decoupling (a mid-crustal shear zone) between a contractional lower crust and an extensional upper crust in the Pamir (Robinson et al., 2007; Stübner et al., 2013b). Similar mechanisms have been proposed to explain extension in the upper crust in Tibet (DeCelles et al., 2002; Liu and Yang, 2003; Kapp and Guynn, 2004; Copley et al., 2011; Styron et al., 2015). However, northward underthrusting of Indian lithosphere or the Karakoram terrane will not cause upper crustal thrust stacking or burial in the South Pamir terrane and it is difficult to explain the prograde metamorphic history of the Shahkhdara-Alichur gneiss dome with this model. Hacker et al. (2017) reported that the rocks in the Pamir gneiss domes originated at ≤15–20 km depth prior to burial. For the underthrusting model to be viable, the mid-crustal shear zone envisioned for the Pamir (Robinson et al., 2007; Stübner et al., 2013b) would need to exist above (shallower than) this depth. Deep seismic reflection data from the Tibetan Plateau suggest that Indian lower crustal rocks are incorporated into the Himalayan-Tibetan orogen at depths ≥25 km (Gao et al., 2016), although it is uncertain if this geometry is applicable to the Pamir, located ∼1000 km away along strike.

5.5.4. Crustal Thickening Summary

The results of this study, in conjunction with previous studies, suggest that crustal thickening was heterogeneous in time, space, and style within the Pamir Mountains. Crustal thickening in the North Pamir terrane is best explained by Cretaceous upper crustal shortening (Robinson et al., 2004, 2012) and Cenozoic underthrusting of Tajik-Tarim Basin lithosphere and lower crust (Chapman et al., 2017). Crustal thickening in the Central Pamir terrane is best explained by Cenozoic stacking of upper crustal thrust sheets and mid-crustal ductile nappes (Rutte et al., 2017a). Despite the difficulties in explaining the prograde metamorphic history of the Shahkhdara-Alichur gneiss dome, the results of this study are most consistent with models that propose that underthrusting of Indian lithosphere thickened the lower crust of the South Pamir terrane (Kufner et al., 2016). Underthrusting of the Karakoram terrane and/or Central Pamir terrane lithosphere also could have thickened the South Pamir terrane lower crust (e.g., Robinson et al., 2012); however, this possibility still does not resolve the prograde (burial) history of the Shahkhdara-Alichur gneiss dome. Although the timing of prograde metamorphism is comparable between the Central Pamir terrane gneiss domes and the Shahkhdara-Alichur gneiss dome in the South Pamir terrane, Hacker et al. (2017) estimated that the rate of burial of rocks in the Shahkhdara-Alichur gneiss dome was twice as fast (2–8 km/m.y.) and reached nearly twice the depth (≥50 km) of the rocks in the Central Pamir gneiss domes. These differences may indicate contrasting mechanisms for burial in the South Pamir terrane compared to the Central Pamir terrane.

6. SUMMARY AND CONCLUSIONS

Geologic mapping in the South Pamir terrane documents distributed deformation in an overall south-vergent thrust belt, the South Pamir thrust belt (SPTB) that offsets otherwise undeformed Jurassic shallow marine limestone and shale of the Gurumdi Group. Field observations of the SPTB indicate relatively minor amounts of shortening since the Jurassic. Paleokarst dissolution features and karst breccia in the upper Gurumdi Group suggest that the South Pamir was uplifted above sea level during the Late Jurassic to Early Cretaceous. Unconformably overlying the Gurumdi Group in the South Pamir terrane are coarse, clastic, synorogenic sedimentary rocks of the Mamazair conglomerate, which are exposed primarily in the footwall of thrust faults in the SPTB. Growth strata and recycled conglomerate clasts indicate that deformation in the SPTB was synchronous with deposition of the Mamazair conglomerate. New detrital zircon U-Pb and detrital ZFT data from the Mamazair conglomerate are consistent with it having been deposited during the mid- to Late Cretaceous, with maximum depositional ages between 112 Ma and 76 Ma, but do not preclude a younger depositional age. These results suggest that the majority of upper crustal shortening in the South Pamir terrane could have occurred during the Cretaceous rather than the Cenozoic as previously proposed (Vlasov et al., 1991; Burttman and Molnar, 1993). Mid-Cretaceous zircon U-Pb ages (105–122 Ma) from intrusive rocks in the South Pamir terrane and interbedded volcanioclastic and tuffaceous units in the Mamazair conglomerate suggest that arc magmatism was in part coeval with shortening. New AHe and ZHe data from rocks in the
Response to slab dynamics and erosion: Geology, 42, p. 443-445, https://doi.org/10.1130/G35350.1


