

Structural analysis and tectonic evolution of the western domain of the Eastern Kunlun Range, northwest Tibet

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ABSTRACT

The Tibetan Plateau, the largest highland on Earth, formed due to the collision of India-Asia over the past 50-60 m.y., and the evolution of the Tibetan Plateau impacts our knowledge of continental tectonics. Examination of the northernmost margin of the Tibetan Plateau is key to unravelling the deformation mechanisms acting in northern Tibet. The left-slip Altyn Tagh fault system defines the northwest margin of the Tibetan Plateau, separating the Western and Eastern Kunlun Ranges in the southwest. Both Cenozoic and pre-Cenozoic crustal deformation events at this junction between the Altyn Tagh and Kunlun Ranges were responsible for the construction of northwestern Tibet, yet the relative contribution of each phase remains unconstrained. The western domain of the Eastern Kunlun Range is marked by active NE-trending, left-slip deformation of the Altyn Tagh fault and an E-striking Cenozoic thrust system developed in response India-Asia collision. To better constrain the Paleozoic Altyn Tagh and Kunlun orogens and establish the Cenozoic structural framework, we conducted an integrated investigation involving detailed geologic mapping (~1:50,000 scale), U-Pb zircon geochronology, and synthesis of existing data sets across northwestern Tibet. Our new zircon analyses from Paleoproterozoic-Cretaceous strata constrain stratigraphic age and sediment provenance and highlight Proterozoic-Paleozoic arc activity. We propose a tectonic model for the Neoproterozoic-Mesozoic evolution

of northwestern Tibet wherein restoration of an ~56-km-long balanced cross section across the western domain of the Eastern Kunlun suggests that Cenozoic minimum shortening strain was ~30% (~24 km shortening). Field evidence suggests this shortening commenced after ca. 25–20 Ma, which yields an average long-term shortening rate of 1.2–0.9 mm yr⁻¹ and strain rates of 4.7×10^{-16} s⁻¹ to 2.3×10^{-16} s⁻¹. Geometric considerations demonstrate that this contractional deformation did not significantly contribute to left-slip offset on the Altyn Tagh fault, which has ~10 mm/yr slip rates.

INTRODUCTION

The Tibetan Plateau is bounded by the NEstriking, left-slip Altyn Tagh fault in the northwest and three thrust systems: the NW-trending Oilian Shan in the northeast, the N-trending Longmen Shan in the southeast, and the WNWtrending Himalaya to the south (Fig. 1A). Most of the present-day topography (Fig. 1B), crustal thickness, and presently active structures were generated during Cenozoic India-Asia collision (e.g., Yin and Harrison, 2000; Tapponnier et al., 2001; Royden et al., 2008). However, preexisting structures may have played a decisive role in controlling the kinematics and dynamics of Tibetan Plateau formation. Over the past five decades, intense study of the Tibetan Plateau has led to a series of end-member models for its formation, varying from vertically uniform lithospheric shortening, lower-crustal flow, continental subduction, and convective removal of mantle lithosphere to large-scale underthrusting (e.g., Dewey and Burke, 1973; Molnar and Tapponnier, 1975; England and Houseman, 1986, 1989; Dewey et al., 1988; Royden, 1996;

Murphy et al., 1997; Clark and Royden, 2000; Tapponnier et al., 2001; DeCelles et al., 2002; Harrison et al., 1992; Zhou and Murphy, 2005; Wang et al., 2008b, 2011; Ye et al., 2015; Zuza et al., 2016, 2019).

Deformation on the major continental-scale faults in the Indo-Asian collision zone and pre-Cenozoic tectonic history figure importantly in this debate (e.g., Yin and Nie, 1996; Zhou and Graham, 1996; Sobel and Arnaud, 1999; Cowgill et al., 2003; Gehrels et al., 2003a; Pullen et al., 2008; Yin, 2010; Zhang et al., 2015; Wu et al., 2016a, 2017, 2019a; Zuza and Yin, 2017; Zuza et al., 2018, 2019; L. Wu et al., 2019c; Haproff et al., 2019). There is strong geologic evidence for numerous pre-Cenozoic collisional events that undoubtedly influenced how the Cenozoic Himalayan-Tibetan orogen evolved from initial India-Asia collision, including in the Kunlun and Altyn Tagh Ranges (e.g., Jolivet et al., 2001; Sobel et al., 2001), Karakoram-Pamirs in the west (e.g., Fraser et al., 2001; Robinson et al., 2003), Qilian Shan in the north (e.g., Wu et al., 2017; Liu et al., 2018, 2019; Zuza et al., 2018, 2019), Songpan-Ganzi in the east (e.g., Roger et al., 2011; Zhan et al., 2018), and Lhasa and Qiangtang terranes in the south (e.g., Murphy et al., 1997; Ding and Lai, 2003; Kapp et al., 2005, 2007). Detailed knowledge of the initial lithospheric conditions prior to India-Asian collision, including the existence of any precollisional topography in Tibet (e.g., England and Searle, 1986; Kong et al., 1997; Murphy et al., 1997; Kapp et al., 2005, 2007; Liu-Zeng et al., 2008; Yang and Liu, 2009; Xiao et al., 2009, 2012; Zuza et al., 2019), is required to quantify Cenozoic deformation and advance our understanding of continental tectonics.

These tectonic models make specific predictions for the deformation history, location, and

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Figure 1. (A) Map of the Himalayan-Tibetan orogen showing the location of map in C. The northern edge of Indian lithosphere is from Nábělek et al. (2009), and the southern edge of Asian lithosphere is from Ye et al. (2015). Blue line shows 2000-km-long profile for topography plots in B. (B) Topography along the 2000-km-long profile across the Himalayan-Tibetan orogen. (C) Map of Cenozoic regional tectonics in northern Tibet based on Burchfiel et al. (1991), Gaudemer et al. (1995), Yin and Harrison (2000), Taylor and Yin (2009), Zuza et al. (2016), Wu et al. (2019a), and Zuza et al. (2019). Also shown is approximately 600-km-long profile (orange line) for topography plot in D. (D) Topography along the 600-km-long swath profile across the northwestern Tibet. The blue and gray lines encompass the maximum and minimum values in the swath profile, respectively.

kinematics of crustal structures, and the strain distribution in north Tibet (e.g., Meyer et al., 1998; Lease et al., 2012; F. Cheng et al., 2017a; Zuza and Yin, 2016, 2018). The last few decades have witnessed prolific research across north Tibet, focusing on the style, magnitude, and timing of continental-scale fault deformation, including the Altyn Tagh fault system (e.g., Wang, 1997; Yin et al., 2002; Cowgill et al., 2000, 2004; Mériaux et al., 2004, 2005; Cowgill, 2007; Zhao et al., 2006; L. Wu et al., 2019c), the ~1000-km-long Kunlun left-slip fault (e.g., Fu et al., 2005; Yuan et al., 2013; Duvall et al., 2013; Clark et al., 2010; Zuza and Yin, 2016, 2017; Wu et al., 2019a, 2019b), and Qilian Shan thrust system (e.g., Duvall et al., 2011; Wu et al., 2017; Ye et al., 2015; Zuza and Yin, 2016, 2017; Zuza et al., 2016, 2018, 2019; Wang et al., 2019). The active, left-slip Altyn Tagh fault system defines

the northwest margin of the Tibetan Plateau; at its northeastern end, the fault links with thrust belts in the Nan Shan–Qilian Shan, separating the Western and Eastern Kunlun Ranges in the southwest (Fig. 1C). Interpretations of the relative roles of Cenozoic versus pre-Cenozoic crustal deformation at the junction between the Altyn Tagh and Kunlun Ranges have also been proposed for the construction of northwestern Tibet; however, the kinematic picture and pre-Cenozoic tectonic history are less clear in this region.

To address some of these issues, we conducted an integrated geologic field and analytical study involving detailed geologic mapping (~1:50,000 scale), structural analysis, sedimentology, and geochronology across the western domain of the Eastern Kunlun Range, near the Cherchen and Aksu River Valleys in the Xinjiang and Qinghai Provinces of western China. This study is unique because it may juxtapose Qilian suture structures (i.e., northwest of the Altyn Tagh fault) against Kunlun suture (i.e., southeast of the Altyn Tagh fault) structures. Our interdependent goals were to (1) establish the structural framework and quantify the magnitude of Cenozoic crustal shortening across the junction of the Altyn Tagh and Kunlun fault systems, and (2) improve our understanding of the pre-Cenozoic geology of northwestern Tibet and specifically provide new constraints on the Paleozoic Altyn Tagh and Kunlun orogens.

GEOLOGIC FRAMEWORK

The northwestern Tibetan Plateau has an average elevation of \sim 4.0 km, and this high topography decreases rapidly to <1.0 km in the Tarim Basin to the northwest (Fig. 1D). The northwestern boundary of the Tibetan Plateau is presently the left-slip Altyn Tagh fault and western part of the Eastern Kunlun thrust belt, which is also referred to as the Qimen Tagh thrust belt (Fig. 1C). These Cenozoic features overprint complex geological relationships that include Paleozoic orogeny and Mesozoic extension. The brief discussion below is concerned primarily with the geology of Altyn Tagh and Eastern Kunlun Ranges.

Altyn Tagh Range

The Altyn Tagh Range marks the northwestern margin of the Tibetan Plateau, separating the Tarim Basin in the north from the Tibetan Plateau in the south. Lithologically, the Altyn Tagh Range consists of Archean and Proterozoic metamorphic gneisses along its northeastern edge, whereas Precambrian marble, schist, and quartzofeldspathic gneisses dominate in the west. The Altyn Tagh Archean metamorphic complex together with the Archean-Paleoproterozoic complex of the northeast margin of the Tarim Basin are considered to be the basement of the Tarim craton (Xinjiang BGMR, 1993; Che and Sun, 1996). Proterozoic stromatolite-bearing sedimentary sequences, consisting mostly of thickly bedded quartzite and cherty limestone, are present in the central and eastern range (Xinjiang BGMR, 1993; Chen et al., 2003). Early Paleozoic volcanic and marine sediments are exclusively exposed in the eastern Altyn Tagh Range; they are apparently absent in the western part of the range. Coal-bearing Jurassic continental sediments are also scattered throughout the Altyn Tagh Range, whereas Cretaceous strata are only exposed in the southwestern edge of the range east of Qiemo (Xinjiang BGMR, 1993; Cowgill et al., 2000, 2004; Chen et al., 2003).

Two E-trending early Paleozoic suture zones have been proposed at the northeastern and southwestern portions of the Altyn Tagh Range; both typically consist of sparse ultramafic fragments and are laterally discontinuous (Fig. 1C; e.g., Che et al., 1995; Sobel and Arnaud, 1999; Yin and Harrison, 2000; Chen et al., 2003). They were both highly modified by the subsequent Mesozoic and Cenozoic deformation (Chen et al., 2003). The Early-Middle Cambrian to Early Silurian (ca. 524-437 Ma) mélange zone is ~10-50 km wide and extends from Hongliugou eastward to Lapeiquan for ~200 km (e.g., Guo et al., 1999; Liu et al., 1999; Zhang et al., 2001, 2008; Xiu et al., 2007; Yang et al., 2008; Liu et al., 2009, 2012). It is bounded by the Altyn Tagh Archean basement to the north and the Mesoproterozoic and Neoproterozoic block to the south (Liu et al., 2009). Phengite and paragonite separated from blueschist and eclogite within the mélange complex yielded consistent ³⁹Ar-⁴⁰Ar ages of 512–491 Ma (Zhang et al., 2005). An early Paleozoic subduction-collision complex (ca. 510–445 Ma) outcrops principally in the southwestern Altyn Tagh and extends 250 km from west of Mangnai to south of Qiemo (e.g., Liu et al., 1998). The high-pressure/ultrahigh-pressure metamorphic rocks of this complex have metamorphic ages of ca. 510–480 Ma and Neoproterozoic protolith ages of ca. 1000–750 Ma (Liu et al., 1998, 2007, 2009; Liu et al., 1999; Zhang et al., 1999, 2004, 2005).

Numerous early Paleozoic granitoid plutons are exposed throughout the north Altyn Tagh region. These plutons have been assigned ages ranging from 500 Ma to 405 Ma, divided into three stages: (1) 500-480 Ma island-arc magmatism related to oceanic crust subduction (e.g., Qi et al., 2005; Wu et al., 2006, 2009; Kang et al., 2011); (2) 475-445 Ma syncollision magmatism (e.g., Wu et al., 2006, 2009; Hao et al., 2006), with the exception of a ca. 443 Ma porphyritic granite pluton that is related to the continental margin subduction event (Chen et al., 2003); and (3) 435-405 Ma calc-alkaline magmatism related to postcollisional extension (e.g., Qi et al., 2005; Wu et al., 2006, 2009). Late Cambrian-Silurian granitic plutons (491-414 Ma) sporadically occur in the south Altyn Tagh region (e.g., Sobel and Arnaud, 1999; Xinjiang BGMR, 1993; Dong et al., 2011). The apparent absence of Neoproterozoic and late Paleozoic granitoids in the south Altyn Tagh Range, as reported in regional geologic maps and published papers, is most likely a result of the lack of detailed geologic studies.

Mesozoic regional extension is thought to have affected much of northern Tibet (e.g., Vincent and Allen, 1999; Chen et al., 2003; Yin et al., 2008a, 2008b; Zuza et al., 2016, 2108), which is expressed by the development of extensive Jurassic and Cretaceous extensional and transtensional basins. Early Paleozoic muscovite ⁴⁰Ar/³⁹Ar ages from the footwall of Cretaceous normal faults at the southwestern Altyn Tagh Range indicate that the magnitude of Cretaceous normal faulting was relatively minor (<~10 km; Chen et al., 2003).

The ~600-km-long Altyn Tagh Range lies within the Cenozoic Altyn Tagh fault system as a tectonic sliver (Figs. 1C and 2; Yin and Harrison, 2000; Cowgill et al., 2000, 2004; Dupont-Nivet et al., 2004; Cowgill, 2007). The active, left-slip Altyn Tagh fault system (Molnar and Tapponnier, 1975; Meyer et al., 1996; Wang, 1997; Rumelhart et al., 1999; Bendick et al., 2000; Ritts and Biffi, 2000; Cowgill et al., 2000, 2003, 2004; Cowgill, 2007; Yin et al., 2002; Yue et al., 2005, 2004; Mériaux et al., 2004; Zhao et al., 2006; L. Wu et al., 2019c) is the largest strikeslip system in Asia-it lies along the northwest margin of the Tibetan Plateau and extends from the Cherchen fault in the northwest to the Altyn Tagh fault, ~100 km to the southeast (Fig. 2; e.g., Cowgill et al., 2004). The left-slip Altyn Tagh fault defines the southern edge of the Altyn Tagh Range and appears to have initiated by ca. 49 Ma (Yin et al., 2002). The North Altyn fault separates the Altyn Tagh Range to the south from the Tarim Basin to the north (Cowgill et al., 2000), and its western end is dominated by left-slip motion with a subsidiary component of thrusting (Fig. 2). The Cherchen fault is a steeply dipping, left-slip structure that strikes parallel to the Altyn Tagh fault (Fig. 2) and mostly cuts Paleozoic through Quaternary rocks (e.g., Cowgill et al., 2004; Zhao et al., 2006).

Eastern Kunlun Range

The Eastern Kunlun Range, with an average elevation of ~5000 m, consists of Precambrian gneisses, Ordovician to Triassic arc assemblages, and scattered Jurassic to Cenozoic continental strata (e.g., Harris et al., 1988; Mock et al., 1999; Yin and Harrison, 2000; Cowgill et al., 2003; Robinson et al., 2003; Roger et al., 2003; Pan et al., 2004; Bian et al., 2005; Lu and Xiong, 2009; Wu et al., 2016a, 2019a, 2019b; Yu et al., 2017; Dong et al., 2018). The Precambrian basement was intruded by Ordovician to Silurian (some to Late Devonian), and Permian to Triassic arc sequences, including the prominent Permian-Triassic Kunlun batholith exposed in the Eastern Kunlun Range (e.g., Cowgill et al., 2003; Robinson et al., 2003; Gehrels et al., 2003a; Mo et al., 2007; Chen et al., 2012; Li et al., 2015; Wu et al., 2016a, 2019a; Lu et al., 2017). U-Pb zircon ages of Phanerozoic plutonic rocks across the Eastern Kunlun Range comprise two distinct groups: 290-195 Ma and 490-375 Ma. Neoproterozoic granitic gneisses are scatted within the eastern and western ends of the range (see a summary and references in Wu et al., 2016a, 2019a). Late Devonian to early Carboniferous shallow-marine strata may have been deposited during back-arc extension between the arc events (Yin and Harrison, 2000). The Triassic Yidun arc, bounding the eastern side of the Songpan-Ganzi terrane, is the eastern extension of the Permian-Triassic Kunlun batholith and is locally intruded by Cretaceous (ca. 105-95 Ma) granites (Reid et al., 2005; C. Wu et al., 2016a). Scattered Jurassic to Cenozoic continental strata overlie the highly folded Triassic strata across the Eastern Kunlun Range (Pan et al., 2004). At the western end of the Eastern Kunlun Range, a Cretaceous (74 \pm 3 Ma) pluton has also been documented (Robinson et al., 2003).



Figure 2. Regional tectonic map of the western domain of the Eastern Kunlun Range and its adjacent regions (modified from Cowgill et al., 2004). Major faults are denoted with black lines. Underlying base map is from www.geomapapp.org (Ryan et al., 2009).

Tectonically, the Eastern Kunlun Range forms a large transpressional fault system, consisting of the E-trending, left-slip Kunlun fault that merges with the WNW-trending Qimen Tagh and Bayanhar thrust belts (Fig. 1C; e.g., Yin and Harrison, 2000; Fu et al., 2005; Fu and Awata, 2007; Yin et al., 2008a, 2008b; Duvall et al., 2013; Yuan et al., 2013; Li et al., 2016, 2018). The thrust belts show a remarkable symmetry with respect to the Kunlun fault, both having a triangular shape and widening away from the central segment of the Kunlun fault (Yin and Harrison, 2000; Zuza and Yin, 2016). The Kunlun fault terminates in the west at WNWtrending thrusts and N-trending rifts (Yin et al., 1999; Yin and Harrison, 2000; Jolivet et al., 2003; Zuza and Yin, 2016) and in the east at the N-trending Longmen Shan thrust belt (Arne et al., 1997; Li et al., 2016). Clockwise rotation has defined northern Tibet's deformation for most of the Cenozoic (Zuza and Yin, 2016). Although earthquakes occur in the Western Kunlun Range at mantle depths of >70 km (e.g., Kidd and Molnar, 1988; Jolivet et al., 2003; Fu et al., 2005; Tocheport et al., 2006; X.G. Cheng et al., 2017b), they are entirely restricted to the upper and middle crust in the Eastern Kunlun Range (e.g., Chu et al., 2009), with thrust and strike-slip mechanisms (Chen et al., 1999; Zhu et al., 2006). Cenozoic tectonic models of the Eastern Kunlun Range all emphasize the presence of a major S-dipping, range-bounding thrust, which links with the Qilian Shan thrust belt via a S-dipping detachment (Burchfiel et al., 1989; Chen et al.,

1999). However, field studies have so far failed to recognize such a structure (e.g., Zhu and Helmberger, 1998; Pan et al., 2004; Yin et al., 2007, 2008b). Less is known about the Cenozoic shortening across the Eastern Kunlun Range, although Yin et al. (2007, 2008b) documented >30 km of shortening (>30% strain) across some of the northern ranges of the Qimen Tagh thrust system at the western margin of the Eastern Kunlun Range (Fig. 1C).

In the western domain of the Kunlun fault system, the wall rocks on the south side of the fault host a series of splaying structures that include linked left-slip and extensional faults, commonly defining elongate pull-apart basins bounded by NNE-striking normal faults (Fig. 1C; e.g., Jolivet et al., 2003; Yin, 2000). Initial field work along the northwestern margin of the Eastern Kunlun Range indicated that the contact between Cenozoic sediments of the Qaidam Basin and the Paleozoic bedrock of the Kunlun Range is depositional (Yin et al., 2007). Seismic reflection profiles across the southern Qaidam Basin indicated that the dominant structures are S-directed thrusts, carrying Qaidam Basin strata with an average elevation of ~2800 m in their hanging wall as a large piggyback basin (Yin et al., 2008b). All major thrusts across the Eastern Kunlun Range north of the Kunlun fault are S-directed, with only one exception, i.e., the Mubuyan thrust (Fig. 2). Some of the thrusts are linked with Estriking, left-slip faults subparallel to the Kunlun fault or terminate at NW-striking, left-slip faults of the Altyn Tagh fault system (Fig. 2). As an example, the ~100-km-long, ENE-striking Kadzi fault is a left-slip fault located in the northwestern Eastern Kunlun Range (Fig. 2), which branches from the Altyn Tagh fault at a slightly oblique angle and likely accommodates a portion of left-slip along the Altyn Tagh fault system (Cowgill et al., 2004).

GEOLOGY OF THE WESTERN DOMAIN OF THE EASTERN KUNLUN RANGE

Detailed field observations during this study focused on the junction between the Kunlun and Altyn Tagh along the southern Cherchen River (Fig. 3). The river valley, at elevations of ~3000 m, is bounded by approximately NEtrending ranges with moderate relief. The goal in focusing on this location was to relate Cenozoic deformation across the western domain of the Eastern Kunlun Range to provide an integrated view of the development of the northern Tibetan Plateau.

Stratigraphic age assignments of the major lithologic units are primarily from Pan et al. (2004) and Wang et al. (2013), and the more detailed framework used in this study is based on Xinjiang BGMR (1993) and our own field observations (Fig. 4). Lithostratigraphic units range in age from Paleoproterozoic and Mesoproterozoic to Quaternary, and they are described below. Specifically, more detailed geologic mapping (~1:50,000 scale) and structural analysis were conducted along the Aksu and Qiemo Rivers,



Figure 3. Regional geologic map of the western domain of the Eastern Kunlun Range based on a compilation of Xinjiang BGMR (1993), Xinjiang BGMR (2003), and our own geologic mapping and structural interpretations. The map units are from a tectonostratigraphic scheme presented in Figure 4; location is shown in Figure 2.

which drain the Tibetan Plateau to the north and east (Fig. 5). The Qiemo River is a southern tributary of the Cherchen River.

Metamorphic Basement and Sedimentary Units

Metamorphosed basement rocks (labeled Pt_a in the Altyn Tagh Range or Pt_k along the Aksu River in Fig. 3) are widespread in the mapping area and were divided into three unit groups from older to younger: gneiss, metavolcanic, and paraschist (Xinjiang BGMR, 2003). The gneiss unit is composed of quartzofeldspathic gneiss,

mylonitic biotite orthogneiss, and paragneiss. These rocks are inferred to be Paleoproterozoic in age based on previous geologic maps (e.g., Qinghai BGMR, 1991b105b105b104b147b146; Pan et al., 2004). An ~2 km migmatite layer was developed within the gneiss unit (Fig. 6A). The metavolcanic unit consists of gray-green metaultramafic and mafic rocks, and foliated garnet amphibolite. The paraschist is characterized by mica \pm garnet schist, quartzite, marble and local limestone, and local phyllite and slate; these rocks have been interpreted as part of a Proterozoic passive margin. Metamorphosed basement rocks are characterized by mica quartz schist, marble, and local limestone. Slightly foliated Paleozoic granitoid rocks intrude both the carbonate and schist units.

The oldest sedimentary strata (labeled Pt_{2-3}) exposed in the western domain of the Eastern Kunlun Range consist of massive-bedded limestone and schistose quartz sandstone. The carbonate rocks have a distinct massive blue/ gray appearance. The stratigraphic thickness of this unit probably exceeds ~3 km but is poorly constrained because its basal contact with the underlying metamorphosed basement is not observed, and internal deformation has affected the original stratigraphy. The regional geologic map

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Figure 4. Lithostratigraphy of the western domain of the Eastern Kunlun Range, specific to the Qiemo and Aksu Rivers. Age assignments are from Xinjiang BGMR (1993), Xinjiang BGMR (2003), Pan et al. (2004), and our own observations. Also shown are U-Pb detrital zircon samples of major units (black stars; see Figs. 3 and 5) and geochronology results from Figure 7. Grain-size abbreviations: cl—clay; si—silt; ss—sandstone; cg—conglomerate.

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Figure 5. Top: Geologic map of a region in the northwestern domain of the Eastern Kunlun Range produced for this study. Underlying base map is from www.gscloud.cn. Bottom: Cross-section A–A', where the brown line is the topographic line, and the dashed boxes are the possible interpretation for the extension of the section A–A'.

of Pan et al. (2004) gave this unit a Changchengian age (i.e., Mesoproterozoic) on the basis of the regional geologic survey (Xinjiang BGMR, 2003). Foliated early Paleozoic granitoid rocks intrude both the gneiss and schist units. The foliations within in all of the metamorphic units are parallel across lithologic contacts, and all units are variably mylonitized (Fig. 6B). All of these metamorphic rocks are inferred to have Precambrian protolith ages (Xinjiang BGMR, 1993; Gehrels et al., 2003a; Pan et al., 2004), which is verified by our new geochronology data, discussed later herein.

The Ordovician–Silurian Qimen Tagh Group (labeled O) consists of low-grade metamorphosed sandstone, siltstone, conglomerate, and slate with minor carbonate rocks, with volcanic rocks in the uppermost section. Although the chronostratigraphy has been long debated, evidence from paleontology and zircon chronology suggests that the lower sandy slate section of this group is Lower Ordovician, and the uppermost volcanic section has yielded an age ca. 428 Ma (e.g., Qi et al., 2014). All Ordovician-Silurian rocks are strongly deformed, and the original sedimentary relationships are obscured. Devonian strata are absent from the study area, but they are found elsewhere in the western section of the Eastern Kunlun Range (e.g., C. Wu et al., 2016a; Yu et al., 2017). The rocks unconformably overlie the Ordovician-Silurian Qimen Tagh Group and are covered by biogenic carbonate rocks, which are often isoclinally folded, with transposed bedding (Pan et al., 2004; Xi et al., 2010).

Carboniferous strata are mainly divided into the lower Tuokuzidaban Group (labeled C_1) and upper Halamilanhe Group (labeled C_2). The Lower Carboniferous rocks have a basal unit of massive, cross-bedded, gray-green arkosic sandstone with minor sandy conglomerate overlain by volcanic layers (Fig. 6C) and carbonate rocks. The Upper Carboniferous rocks are dominated by basal limestone and cross-bedded arkosic and quartz sandstone with minor calcareous siltstone. Conformably overlying these rocks, there are Lower Permian strata, which have a basal conglomerate and overlying arkosic sandstone interbedded with calcareous siltstone, and limestone layers.

Jurassic strata overlie the Lower Carboniferous rocks with a regional angular disconformity, and they are divided into the Lower-Middle Dameigou Formation (labeled J_{1-2}) and Upper Caishiling (labeled J_3) Formation. The



Figure 6 (on this and following page). Satellite and field photographs from the northwestern domain of the Eastern Kunlun Range displaying important geologic relationships discussed in text. Locations of photograph are shown in Figures 3 and 5. (A) A late granite dike intrudes into the Kuhai Group migmatite. (B) Mesoproterozoic and Neoproterozoic metamorphic rocks are placed over Lower-Middle Jurassic deposits; the photo shows an antithetic fault surface with steeply plunging fault striations and sample location. Photo was taken near fault f6 in Figure 5. (C) Carboniferous rocks are placed over Late Jurassic sediments; photo was taken at fault f3a in Figure 5.

lower-middle unit consists of a basal conglomerate overlain by arkosic sandstone interbedded with siltstone, organic-rich shale, and numerous coal beds (Fig. 6D). Upper Jurassic rocks consist of a basal conglomerate with overlying arkosic sandstone interbedded with calcareous siltstone. Cretaceous rocks (labeled K) consist of polymictic conglomerate and coarse sandstone that is reddish in color. Cenozoic rocks are predominantly Lower Eocene in age (labeled E; Qinghai BGMR, 1991; Xinjiang BGMR, 2003). They consist of red fluvial and lacustrine sediments. Conglomerate, sandstone, and mudstone have a clay, marl, or limestone matrix. Quaternary sediments consist of alluvial, fluvial, and glaciofluvial deposits (Qinghai BGMR, 1991; Xinjiang BGMR, 2003).

Igneous Units

Numerous NE- to E-trending elongate early Paleozoic granitoid plutons are exposed throughout the Aksu and Qiemo River valley region, and most are attributed to arc and/or orogenic magmatism. These plutons have been assigned ages ranging from Early Cambrian– Ordovician to early Carboniferous (e.g., Xinjiang BGMR, 2003; Pan et al., 2004; this study), of which early Carboniferous magmatic activity is strongest in the south (Fig. 6E). Several large (up to ~200 km²) and some minor (1–10 km²) plutonic bodies are exposed as batholiths and stocks in the mapping area. They range in composition from calc-alkali low-K tholeiitic series to mafic to acidic rocks. These bodies

intrude the Proterozoic gneiss and schist and the early Paleozoic mélange, but they are thrust overlain by Lower Carboniferous and younger strata. Furthermore, these plutons intrude the contact between the Lower Carboniferous and Proterozoic basement units (Figs. 3 and 5), which requires that Carboniferous sediments were deposited on Proterozoic basement prior to intrusion. The units are mapped as undifferentiated granitoid (gr), except where a crystallization age has been determined, either from this study or other work. Our geochronology results presented later indicate that these plutons crystallized between ca. 446 and ca. 331 Ma. Minor dikes with compositions similar to the granitoids were also mapped and occurred within the migmatite in the mapping



Figure 6 (*Continued*). (D) Early Jurassic sediments interbedded with coal layers. (E) Photo taken at fault f1a within the Carboniferous Jianxia Shan granitoid pluton in Figure 5. (F) View of south-verging hangingwall anticline in thrust fault f1a shown in Figure 5. (G) Carboniferous rocks are placed over Late Jurassic sediments; photo was taken at fault f3b in Figure 5. (H) Carboniferous rocks are placed over Jurassic sediments along the Aksu River.

area. The late Paleozoic–early Mesozoic granitoids and dikes are scatted in the mapping area (Fig. 6A). Detailed geochronology and geochemistry analyses for Paleozoic–Mesozoic magmatism are in preparation and will be presented elsewhere.

An ultramafic and mafic complex, locally referred to as the Munabulake ophiolite suite (Liu et al., 2009; Cao et al., 2013), is exposed in the northern portion of the mapping area. In the north flank of the Qiemo River, gabbroic plutonic rocks, diabase dikes, alkali feldspar granite, and basaltic volcanic rocks are found in Munabulake ophiolitic complex of the Southern Altyn mélange zone. This complex variably consists of ophiolitic mélange and fragments of an incipient oceanic arc and has been assigned an Ordovician age based on reported geochronologic studies (Liu et al., 2009; Cao et al., 2013; this study). The unit consists of ultramafic to mafic rocks, basaltic andesite, gneiss, foliated granodiorite, marble, and limestone, and quartzite-sandstone knockers. In addition, there are outcrops of massive plagioclase-pyroxene gabbro. There is significant deformation within the complex, and the lithologic contacts are highly sheared (Fig. 5). Taken together, this unit represents part of the Southern Altyn Tagh suture zone, which connects with the Mangnai ophiolite to the southeast. The complex units are only juxtaposed against the Mesoproterozoic and Neoproterozoic marble unit, and, where observed, the Mesoproterozoic and Neoproterozoic unit is always structurally beneath the ophiolite suite (Fig. 5).

Although this tectonic contact may have been reactivated in the Cenozoic, this relationship suggests that the Mesoproterozoic and Neoproterozoic strata were originally thrust beneath the obducted ophiolite suite during the South Altyn Tagh orogeny.

As discussed above, foliated granitoid dikes (granodiorite to quartz diorite) intrude Proterozoic metamorphic rocks. This unit is variably mylonitized with well-defined stretching lineations, and in certain locations both quartz and feldspar grains appear to have deformed ductilely and recrystallized. Our geochronology results indicate that this foliated granitoid has crystallization ages of ca. 817 Ma. This age provides a minimum-age bound for the protolith of the metamorphic complex into which it intrudes.

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Figure 6 (Continued). (I) Ripple bedding structure on the Late Jurassic sandstone. (J) View of north-verging hanging-wall anticline near thrust fault f5 shown in Figure 5. (K) Early-Middle Jurassic rocks placed over Cretaceous sediments: photo was taken at fault f5 in Figure 5. Inset shows the Jurassic ultramafic/mafic conglomerate. (L) Mesoproterozoic and Neoproterozoic metamorphic rocks are placed over Lower-Middle Jurassic deposits; photo was taken at fault f6 in Figure 5. (M) High-resolution satellite image showing the active left-slip Altyn Tagh fault with blue line along the Qiemo River (see Fig. 3). Inset shows deflection of a through-going channel (arrowed) at 86°25'E (e.g., Cowgill, 2007).

Regional Unconformities

Three distinct Phanerozoic unconformities are recognized in the mapping area, and they are named for the unit that overlies the unconformity. The oldest unconformity, which is also the most widespread, consists of Jurassic strata overlying Proterozoic basement (e.g., Kuhai Group along the Aksu River; Mesoproterozoic to Neoproterozoic rocks along the south bank of the Cherchen River) and Ordovician–Silurian strata (i.e., Qimen Tagh Group). This requires the Proterozoic basement and Ordovician rocks to have been at or near the surface at the time of Jurassic deposition. This unconformity is a key marker horizon in the balanced cross-section restorations.

The Mesozoic unconformities, with a variety of angular unconformities at the base of Jurassic and Cretaceous rocks, were caused by regionally extensive tectonic events across northern Tibet (e.g., Vincent and Allen, 1999; Chen et al., 2003). In one locality along the southern bank of the Cherchen River, Cretaceous rocks unconformably overlie Carboniferous and Jurassic rocks. This observation provides two important constraints. First, the Carboniferous and Jurassic rocks were both at or near the surface at the time of Cretaceous deposition. Second, an event is required to have tilted the Jurassic unconformity and Carboniferous–Permian rocks prior to the deposition in the Cretaceous.

Cenozoic rocks, assigned a Paleocene to early Eocene age, are only exposed in the eastern portions of the mapping areas (Figs. 3 and 5). They were deposited on top of Cretaceous and Lower Jurassic strata, which indicates that prior to Cenozoic deformation, these Mesozoic rocks were closest to the surface. The development of this unconformity represents the initiation of Cenozoic deformation related to the Tibetan orogen. Further interpretation of the depositional setting



of these Cenozoic rocks is not within the scope of this study.

Structural Geology

Structures dominantly trend NE, including the strike of sedimentary units, strike of foliations within the metamorphic units, trend of the ranges, and surface traces of major faults. Deformation can be categorized into three distinct regimes: (1) left-lateral shearing and faulting associated with the Altyn Tagh fault, (2) Cenozoic dip-slip contractional structures, including thrust faults and folds, and (3) early Paleozoic faulting, ductile shearing, and metamorphism. There is no direct evidence of Mesozoic deformation or normal faulting, but our field observations are consistent with earlier work that suggests that Jurassic and Cretaceous sedimentation was caused by regional extension (Vincent and Allen, 1999; Chen et al., 2003; Yin et al., 2008b; Zuza et al., 2019), including fining-upward sequences and growth strata relationships.

We interpret deformation of Carboniferous and younger strata to be Cenozoic in age based on the following observations: (1) Most observed faults and folds of Lower Carboniferous and younger rocks merge with active rangebounding thrust faults; (2) these faults truncate Cenozoic terrestrial deposits and Quaternary alluvium; and (3) Jurassic and Cretaceous strata were probably extension related (e.g., Vincent and Allen, 1999; Chen et al., 2003; Yin et al., 2008a, 2008b; Zuza et al., 2019), so contractional structures involving these rocks must be Cenozoic in age. This also implies that folding and duplication of the Jurassic unconformity occurred in the Cenozoic.

Next, we present a detailed structural analysis of each river valley, including juxtaposition geometries, map-view relationships, kinematic indicators, and alternative interpretations, starting with the north flank of the Aksu River valley in the south and progressing to the north (Fig. 3). The NE- to E-striking thrust faults are labeled



f1 through f8, from south to north, respectively (Fig. 5), and are discussed in this order below.

Fault f1

The WNW-striking fault dips 28° to the NE, juxtaposes early Carboniferous granitoids (Fig. 6E) against Lower Carboniferous strata (C1), and truncates overlying Jurassic sediments to the west (Fig. 5). In the west, this fault is labeled f1a, and it is a W-striking, S-dipping feature that places the hanging wall of early Carboniferous granitoids over Lower-Middle Jurassic strata (J_{1-2}) . Fault 1a must be relatively low angle (~20°S) based on its map trace. This fault merges to the east with fault f1b. In the east, f1b branches into several fault splays, which variably place early Carboniferous granitoids and Lower Carboniferous strata over other granitoids. Fault f1b cuts the granitoid and overlying shallow-marine, lacustrine, and continental shelf sedimentary strata, but offset diminishes within the folded granitoid (Fig. 6F). The foliation data from the Carboniferous rocks were compiled and analyzed in several stereonets (Fig. 5) using Stereonet 9 (software by Rick Allmendinger). In the south of f1, the foliations are variable, generally striking NW (Fig. 5).

Fault f2

This W-striking, S-dipping thrust fault (thrust dipping 18°S-20°S) places Proterozoic metamorphic basement (Pt_{K}) and early Carboniferous granitoids (gr) over Upper Jurassic strata (J₃). Here, we denote the western and eastern traces of these faults as f2a and f2b, respectively. Fault 2a places Proterozoic Kuhai Group metamorphic rocks over Late Jurassic Caishiling Formation sediments, and a minor (~150-m-wavelength) hanging-wall anticline forms in the hanging wall of this thrust fault. This fault is truncated to the east by f1b. At the eastern portion, f2a branches into several fault splays, which variably place Proterozoic (Pt_K) rocks over Jurassic sediments and early Carboniferous granitoids. Fault f2b places early Carboniferous granitoids thrust Neoproterozoic granite dike intrudes into the Mesoproterozoic and Neoproterozoic schist. (O) Photo and inset showing the tuff sample within the Lower Carboniferous Tuokuzidaban Formation.

Figure 6 (Continued).

(N)

over Late Jurassic sediments, and it is relatively low angle (~18°S) based on its map trace. Upper Jurassic strata in the footwall of f2 are internally deformed, with numerous 100-m-wavelength folds and faults.

Fault f3

SW

This thrust fault places early Carboniferous sediments as a klippe over Upper Jurassic strata. In the west, this fault is labeled as f3a, and it merges to the west with f4. Where this fault is exposed in a minor footwall syncline of this thrust, the fault surface dips 20°N. At this locality, the Carboniferous strata in the hanging wall are parallel to the fault, and Jurassic rocks in the footwall are oblique to the fault surface (Fig. 6G). In the east, this fault is labeled as f3b. There is a prominent ~1-km-wide anticline in the hanging wall of f3b, and the fault surface dips 35°N. This fault is overturned in the north, and the fault surface dips 18°S. The fault trace to the west is obscured by Aksu River (Fig. 6H).

Fault f4

The NE-striking thrust fault dips 32-45°SE and places early Carboniferous strata (C1) and Late Jurassic strata (J_3) over Lower Cretaceous sediments (K). The fault trace of f4 to the east is covered by Quaternary sediments, but it is assumed that the fault is truncated to the west by f1b. Fault f4 branches into several fault splays, which variably juxtapose early Carboniferous and Late Jurassic strata over other Late Jurassic sediments, but the offset diminishes within the Late Jurassic sediments. Where observed, this splay fault surface dips 72°S within the Jurassic strata. The fault has a footwall syncline with <1 km wavelength in the east; at this locality, the hanging-wall Jurassic strata are overturned. Sedimentary marks, such as ripples, on the bedding surface of the Late Jurassic sandstones indicate the southward direction of the paleocurrent (Fig. 6I). In the Late Jurassic rocks to the south of f4, the bedding is roughly parallel and dips to south (Fig. 5).

Fault f5

The NE-striking thrust fault dips 39-56°NW, and the fault places an ~10-km-wide hangingwall anticline of Lower-Middle Jurassic strata $(J_{1,2}; Fig. 6J)$ over a minor footwall syncline of Lower Cretaceous sediments (K; Fig. 6K). This fault appears to either be truncated by, or merge with, f1b in the west, although this relationship is not directly observed (Fig. 5). Map view relationships suggest that offset increases to the east, but exposure is obscured by Quaternary sediments (Fig. 6K). Ultramafic and mafic rocks are the major components of the conglomerate layer of the Lower-Middle Jurassic strata (Fig. 6K), which indicates that the Altyn Tagh Range to the north is the main possible provenance of these sediments.

Fault f6

The ENE-striking thrust fault f6 dips 30°-38° to the NW, and the fault places Mesoproterozoic to Neoproterozoic undifferentiated massive marble and schist with intrusions over footwall syncline of Lower-Middle Jurassic strata (J₁₋₂; Fig. 6L). This fault merges to the northeast with the Altyn Tagh fault (Fig. 3) and represents the southernmost termination structure of this major strike-slip fault, which strikes parallel to the Altyn Tagh fault (Fig. 1B). Although no direct fault kinematic measurements were made for this fault, the fold axes are parallel to the fault strike, which may suggest that this fault is primarily a dip-slip structure (Fig. 6B). Fault offset must be <1 km based on the map-view relationships, and the tight (~1-km-wavelength) hanging-wall folds accommodate a similar magnitude of shortening. The fault is covered by Quaternary river deposits in the northeast, and its western extent is unknown. The fault strike is parallel to the nearly E-W-trending Qiemo River (Fig. 5).

Fault f7

The active, left-slip Altyn Tagh fault was not observed in the field along the southern Cherchen River, but the morphologic expression of the fault trace is very distinct for much of its length. The fault trace crosses the extreme western end of Tula Basin (Fig. 2) and has clearly disrupted Quaternary alluvial deposits (Fig. 6M). No offset geologic markers associated with this fault from which slip magnitude may be estimated were evident in the outcrops of the mapping area. Rather, left-slip displacement, which appears to be best characterized at the Cherchen River site (~86.4°E), yielded a revised slip rate of 9.4 ± 2.3 mm/yr (Fig. 6M; Cowgill, 2007), consistent with data from the Sulamu Tagh site (~87.4°E) ~20 km to the east (Mériaux et al., 2005).

Fault f8

The ENE-striking thrust fault f8 dips 74° to the NW and places Mesoproterozoic to Neoproterozoic metamorphic rocks against the ultramafic and mafic complex. The ultramafic and mafic complex in the footwall of f7 is internally strongly deformed and sheared, with numerous 100-m-wavelngth folds and faults, and the timing of their activity is unconstrained in this study. Fault f7 is covered by an early Paleozoic pluton in the east but crosscuts the Neoproterozoic igneous dikes (Fig. 6N). Although this tectonic contact may have been reactivated in the Cenozoic, this relationship suggests that the fault contact may originally been from the early Paleozoic. The Proterozoic schist unit has strongly developed foliations and minor stretching lineations. These fabrics are inferred to have developed in the early Paleozoic as a result of the Altyn Tagh arc and subsequent orogeny. Our new geochronologic analyses suggest that this broad shear zone was active in the Early Ordovician, and ductile shearing ceased by ca. 446 Ma, when the foliated metamorphic rocks were crosscut by an undeformed granitoid with a U-Pb age of 446 ± 1 Ma (i.e., sample WC072716-8). The foliation data from the Mesoproterozoic and Neoproterozoic metamorphic rocks were compiled and analyzed in several stereonets (Fig. 5) using Stereonet 9. In the metamorphic rocks to the north of f8, the foliations are roughly parallel, near vertical, and strike NW. South of f8, the data are more diverse, and the foliations are variable, generally NE striking (Fig. 5). The rocks to the north of the Altyn Tagh match or correlate with features such as the Qilian arc (Wu et al., 2016a, 2017; Zuza et al., 2018).

METHODS

Sandstone Petrography

We used a cross-polarization microscope to observe the petrographic features, including mineral composition, grain size, sorting, and roundness. Modal compositions were then determined utilizing the modified Gazzi-Dickinson point-counting method (Ingersoll et al., 1984). A minimum of 370 points were counted per sample. Raw point-counting data are summarized in the supplementary material.¹ Samples were classified and plotted on the ternary diagrams using the scheme outlined in Dickinson et al. (1983). We followed the mineral abbreviation of Dickinson and Suczek (1979) to better describe our results: Qt for total quartz, Qm for monocrystalline quartz, F for feldspar, L for lithic rock fragments, and Lt for total lithic grains, including polycrystalline quartz. Detailed data for these five sandstones are shown in the supplementary material Table DR1 (see footnote 1).

U-Pb Zircon Geochronology

Zircon grains for U-Pb dating were separated from 9 sandstones, 5 igneous rock samples, and 1 metamorphic rock sample by traditional methods and mounted in epoxy with standard zircons. Individual zircon grains were picked by hand under a binocular microscope. Zircons of each sample were randomly selected, mounted in epoxy resin, and polished, in order to conduct U-Pb dating. Most zircons were analyzed using an Agilent 7500a inductively coupled plasma-mass spectrometer (ICP-MS) coupled with a New Wave Research UP193FX excimer laser at the Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing. The laser-ablation (LA) multicollector (MC) ICP-MS analytical methods were described in Gehrels et al. (2011) and are briefly summarized here. The measurements were made on a Micromass Isoprobe using Faraday detectors for ²³⁸U, ²³²Th, and ²⁰⁸Pb-²⁰⁶Pb and an ion-counting channel for 204Pb on the LA-MC-ICP-MS. Common Pb corrections were made using the measured 204Pb and assuming an initial Pb composition from Stacey and Kramers (1975). The primary standard used was GJ1 (Jackson et al., 2004). The secondary standards were 91500 (238U/206Pb age of 1065 Ma), and Plesovice (238U/206Pb age of 337 Ma).

Ages presented are ²⁰⁶Pb*/²³⁸U ages for grains younger than ca. 1000 Ma and ²⁰⁶Pb*/²⁰⁷Pb* ages for grains older than ca. 1000 Ma. To interpret the crystallization ages for the igneous samples, we only examined zircon analyses with discordance of <10%. We focused on the dominant population of younger analyses, and we interpreted the weighted mean age of the youngest cluster $(n \ge 3)$ of zircon ages as the crystallization age (Table 1). Anomalously younger zircon ages probably were the result of Pb loss due to a younger metamorphic event, and older zircon grains were interpreted as inherited grains. Uncertainties on individual analyses are given at the 1σ level and plotted as the 2σ level. All uncertainties, including analytical and systematic, of the weighted mean ages are reported at the 95% confidence level. The weighted mean ages and probability density distributions were calculated and plotted using Isoplot 3.0 of Ludwig (2003). For the detrital zircon age data, we only

¹GSA Data Repository item 2019388, including Jurassic sandstone petrography raw point-counting data, and zircon U-Pb isotopic data for the igneous, metamorphic, and detrital samples, is available at http://www.geosociety.org/datarepository/2019 or by request to editing@geosociety.org.

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Sample	Rock type	Latitude (°N)	Longitude (°E)	Interpreted age (Ma)	MSWD	п
Igneous and meta	amorphic samples			Crystallization age		
WC071516-2	Tuff	37°20.123'	86°23.768'	357 ± 2	1.15	16 out of 38
WC072716-3	Foliated granitic dike	37°38.873′	86°15.623'	817 ± 4	2.4	16 out of 62
WC072716-8	Granodiorite	37°39.136'	86°17.028′	446 ± 1	4.1	28 out of 41
WC071615-9	Granite	37°27.276′	86°25.017'	362 ± 2	0.18	26 out of 30
WC071715-2	Granite	37°25.067'	86°27.925'	264 ± 3	3.5	8 out of 19
WC071715-1	Migmatite	37°25.067′	86°27.925'	1868 ± 24	3.5	3 out of 42
Sedimentary and	metasedimentary samples			Maximum depositional age		
WC062715-4	Foliated quartz schist	37°38.172′	86°18.316'	1014 ± 18	0.53	3 out of 97
WC071716-2	Quartz schist	37°42.929'	86°51.374′	507 ± 16	4.1	3 out of 89
WC072715-4	Quartzite	37°28.522'	86°43.579′	400 ± 12	7	3 out of 98
WC072715-3	Sandstone	37°32.588'	86°26.987'	359 ± 8	7	3 out of 50
WC062715-5	Coarse-grained sandstone	37°37.916′	86°37.916′	242 ± 28	1.29	3 out of 100
WC072715-1	Fine-grained sandstone	37°37.499′	86°32.688'	227 ± 7	4.9	3 out of 85
WC072715-6	Medium-grained sandstone	37°30.622'	86°28.837'	193 ± 1	0.33	3 out of 83
WC072715-7	Pink-brown sandstone	37°15.176′	86°43.923'	156 ± 2	0.51	3 out of 96
WC072615-9	Sandstone	37°34.869′	86°24.622'	124 ± 10	0.66	3 out of 59
Note: MSWD-	mean square of weighted deviates.					

considered analyses that were <30% discordant or <5% reversely discordant (Table 1; e.g., Gehrels et al., 2011). Normalized probability density plots were used to compare the different data sets using 2010 software provided by the Arizona LaserChron Center. The geochronologic data are provided in Table DR2 (see footnote 1).

SAMPLE DESCRIPTIONS AND RESULTS

Igneous and Metamorphic Zircon Geochronology Results

Tuff sample WC071516-2 was collected on the volcanic tuff layer interbedded within the Lower Carboniferous Tuokuzidaban Group (C₁; Figs. 6O and 7A). Thirty-eight zircons were analyzed, and U-Pb ages ranged from 343 Ma to 666 Ma (Fig. 8A). The weighted average of 16 concordant analyses was 357 ± 2 Ma (mean square of weighted deviates [MSWD] = 1.15), which we interpret as the crystallization age of the tuff (Table 1). The other analyses were excluded because of discordance or low radiogenic Pb. The zircons with these ages might have originated from the source region of the magmatic rocks, or they may have been incorporated from country rocks during magma eruption.

Neoproterozoic foliated granitic dike sample WC072716-3 was collected from a foliated granitic dike that intrudes into the medium- to low-grade metamorphosed unit (Pt₂₋₃) located in the hanging wall of the fault f7 (Figs. 6N and 7B). Analyses of zircon grains from sample WC072716-3 yielded 62 concordant yet diverse ages, ranging from a U-Pb age of 752 Ma to 983 Ma (Fig. 8B). The older population of 13 grains yielded a weighted mean age of 888 \pm 5 Ma (MSWD = 2.1), which is interpreted to be inherited. The younger population of 16 analyses yielded a weighted mean age of 817 \pm 4 Ma (MSWD = 2.4), which is interpreted

as the crystallization age of this Neoproterozoic granite (Table 1).

Early Paleozoic granodiorite sample WC072716-8 is part of a slightly foliated granite sill located along the northwestern flank of the Qiemo River (Figs. 5 and 7C). Forty-one grains were analyzed, and all yielded concordant ages ranging from 378 Ma to 1265 Ma (Fig. 8C). One single age was distinctly younger (ca. 378 Ma), which may have resulted from Pb loss during a younger metamorphic event, and one population of ages was distinctly older, possibly due to older zircon-grain inheritance. The weighted mean of the average population of 28 ages is 446 ± 1 Ma (MSWD = 4.1), which we interpret as the best estimate of a crystallization age (Table 1).

Lower Carboniferous granite porphyry sample WC071615-9 is part of Jianxia Shan pluton located along the eastern flank of the Aksu River (Figs. 5 and 7D), which intrudes into the Proterozoic Kuhai Group medium- to high-grade metamorphic rocks (PtK). Thirty grains were analyzed, and all yielded concordant ages ranging from 358 Ma to 2033Ma (Fig. 8D). The weighted mean of the average population of 26 ages was 362 ± 2 Ma (MSWD = 0.18), which we interpret as the best crystallization age of the Lower Carboniferous-latest Late Devonian granitoid pluton (Table 1). One single early Paleozoic age is distinctly older (ca. 459 Ma), possibly due to older zircon-grain inheritance (Fig. 8D). In addition, a Paleoproterozoic inherited zircon core age of ca. 2033 Ma also occurred in this granite sample (Fig. 8D), which is possible related to the metamorphic basement of the western domain of the Eastern Kunlun Range.

Undeformed late Paleozoic granite dike sample WC071715-2 was collected from a granite dike that intrudes the internally deformed migmatite (Figs. 6A and 7E). Nineteen zircons were analyzed, and U-Pb ages ranged from 221 Ma to 322 Ma (Fig. 8E). The weighted average of eight concordant analyses was 264 ± 3 Ma (MSWD = 3.5; Table 1). The other analyses were excluded because of discordance or low radiogenic Pb.

Migmatite sample WC071715-1 was collected from the migmatite layer of the Kuhai Group (Figs. 6A and 7F). Analyses of zircon grains from sample WC071715-1 yielded 52 concordant yet diverse ages, ranging from a U-Pb age of 260 Ma to a Pb-Pb age of ca. 2435 Ma (Fig. 8F). Several distinct age populations were observed, and there was significant zircon inheritance. The cathodoluminescence-dark rims with oscillatory zoning showed much higher U and lower Th/U (usually 0.02-0.61; Table DR2) and were strongly discordant (207Pb/206Pb ca. 1.0-2.4 Ga; Fig. 8F). When all data are plotted on a concordia diagram, they align in a discordia with an upper intercept at 1907 ± 40 Ma and lower intercept at 680 ± 110 Ma (Fig. 8F). However, it is evident that some of the most discordant data points (all with very high U contents) are slightly off the discordia and closer to the concordia (Fig. 8F), which suggests that they may be younger. No clear regional signals of the lower-intercept Neoproterozoic overprint are shown by the zircons from this sample. Furthermore, a single inherited core has a 207Pb/206Pb age of 2435 ± 8 Ma, and this is the oldest zircon found in this sample. The age population near the upper intercept is concordant and yielded a weighted mean 207 Pb/ 206 Pb age of 1868 ± 24 Ma (MSWD = 3.5; Fig. 8F), which is taken as the best estimate of the magmatic crystallization age of this sample (Table 1). Alternatively, these other young ages may reflect later pulsed intrusion or slow cooling.

Sandstone Petrographic Results

In order to ascertain the tectonic settings of the sedimentary units from which our samples were collected, we performed sandstone composition analysis for the Jurassic samples (Fig. 9).



Figure 7. Photomicrographs of the igneous and metamorphic samples in this study. Abbreviations for minerals: qtz—quartz; pl—plagioclase; bt—biotite; kfs—K-feldspar; ms—muscovite; hbl—hornblende; grt—garnet. All photomicrographs were taken under cross-polarized light.



Figure 8. U-Pb concordia diagrams showing results of single shot zircon analyses and relative probability plots of zircon ages for each sample. Error ellipses are 2σ , and gray shaded ellipses show individual analyses that were excluded from weighted mean calculations. Only concordant ages are plotted in probability distributions, and crossed out peaks were not included in weighted mean calculation. All weighted mean ages are U-Pb ages (unless specified) at the 95% confidence level. See text for further discussion of rationale and Figures 3 and 5 for sample locations. Plots were created with Isoplot 4.1 of Ludwig (2003). See Table DR2 (see text footnote 1) for detailed data set. MSWD-mean square of weighted deviates.

The reason we did not conduct sandstone composition analysis on other samples was due to the effects of metamorphism and grain size. Specifically, the grain size of the Lower Cretaceous sample was too fine (<0.0625 mm) to be appropriate for sandstone composition analysis (Dickinson, 1970, 1985). Carboniferous, Ordovician, and Proterozoic samples are metamorphosed sandstones, with grain recrystallization and the development of cleavage schistosity.

Sample WC062715-5 was collected from a gray-brown, coarse-grained sandstone that lies

at the base of a sequence of interbedded sandy conglomerate, conglomerate-bearing coarse sandstone, and carbon-rich shale. The sequence is the lower part of the Lower–Middle Jurassic Dameigou Formation exposed locally along the southern bank of the Qiemo River. Detrital modes were found to be: Qt:F:L = 65:21:14and Qm:F:Lt = 62:21:17 (Table DR1). Sample WC072715-1 was collected from a gray-green, medium- to fine-grained sandstone that lies at the base of a sequence of interbedded fine-grained sandstone, siltstone, and carbon-rich shale. This sequence is the upper section of the Lower– Middle Jurassic Dameigou Formation exposed locally along the southern bank of the Cherchen River. Detrital modes are Qt:F:L = 55:21:24 and Qm:F:Lt = 49:21:30 (Table DR1). These sandstones are moderately well sorted with rounded to subrounded framework grains, calcite cement, and secondary hematite. Monocrystalline quartz is the secondary component, while polycrystalline quartz is rare. The quartz grains are commonly subrounded to rounded. Zircon, muscovite, and magnetite are common accessory



Figure 9. Ternary diagrams (QtFL and QmFLt) indicating modal abundances recalculated from raw point-counting data (Table DR1; see text footnote 1) for sandstone samples. The provenance fields of Dickinson et al. (1983) are shown to aid in potential source interpretation. Qt—total quartz, Qm—monocrystalline quartz, F—feldspar, L—lithic rock fragments, Lt total lithic grains, including polycrystalline quartz.

Upper Jurassic: ■ Sample WC072715-6 □ Sample WC072715-7

minerals. Results for both samples plot in the "recycled orogen" field in the QtFL diagram featuring recycled source areas, and in the "mixed" field in the QmFLt diagram (Fig. 9).

Sample WC072715-6 was collected from a red-brown, medium-grained sandstone that lies at the base of a sequence of interbedded sandy conglomerate, argillaceous siltstone, and finegrained sandstone. The sequence is part of the Upper Jurassic Caishiling Formation exposed locally between faults f2b and f3b along the eastern bank of the Aksu River. Sample WC072715-7 was collected from a pink-brown, medium-grained sandstone that locally exposed the upper layer of the regional unconformity at the base of the Upper Jurassic strata, which unconformably overlie Paleoproterozoic Kuhai Group metasedimentary rocks. These sandstones are mostly poorly sorted, include siliceous or calcareous cements, and feature angular to subrounded grains. Detrital modes of sample WC072715-6 are Qt:F:L = 70:17:13 and Qm:F:Lt = 64:17:19, whereas the modal compositions for sample WC072715-7 are

Qt:F:L = 62:19:19 and Qm:F:Lt = 59:19:22 (Table DR1). These modal abundances of Caishiling Formation sandstones plot in the "recycled orogen" and "quartzose recycled" fields on the ternary diagrams, featuring recycled source areas (Fig. 9).

Detrital Zircon Geochronology Results

Mesoproterozoic and Neoproterozoic (Pt₂₋₃) foliated quartz schist sample WC062715-4 has zircon populations of 1200–1000 Ma and 1600–1300 Ma, with two prominent peaks at ca. 1120 Ma and ca. 1445 Ma, respectively (Fig. 10A). A minor age population also occurs at Neoarchean ages (Fig. 10A). The three youngest zircons grains of this sample with overlapping ages have a weighted mean age of 1014 ± 18 Ma (MSWD = 0.53), which suggests an Upper Mesoproterozoic–Lower Neoproterozoic age for the Pt₂₋₃ schist unit (Table 1).

Ordovician Qimen Tagh Group quartz schist sample WC071716-2 has zircon populations of

700–500 Ma and 1000–900 Ma, with two prominent peaks at ca. 620 Ma and ca. 940 Ma, respectively (Fig. 10B). Minor age populations also occur at 2000–1800Ma and 2650–2500 Ma, with peaks of 1920Ma and 2520 Ma, respectively (Fig. 10B). The three youngest zircons grains of this sample with overlapping ages have a weighted mean age of 507 ± 16 Ma (MSWD = 4.1), which suggests a Lower Ordovician age for the early Paleozoic rock unit (Table 1).

Lower Carboniferous Tuokuzidaban Group quartzite sample WC072715-4 has a main zircon population of 530-400 Ma, with prominent peak at ca. 440 Ma; minor age populations also occur at 1000-700 Ma, with a peak of ca. 900 Ma (Fig. 10C). The three youngest zircon grains from this sample with overlapping ages have a weighted mean age of 400 ± 12 Ma (MSWD = 7.0; Table 1). The Lower Carboniferous Tuokuzidaban Group slightly foliated sandstone sample WC072715-3 has a main zircon population of 500-355 Ma with prominent peak at ca. 408 Ma (Fig. 10D); the three youngest zircon grains from this sample with overlapping ages have a weighted mean age of 359 ± 8 Ma (MSWD = 7.0), which suggests a Lower Carboniferous age for the sedimentary rock unit (Table 1).

The Lower-Middle Jurassic Dameigou Formation coarse-grained sandstone sample WC062715-5 has a main zircon population of 510-400 Ma, with prominent peak at ca. 427 Ma, and a minor age peak also occurs at ca. 260 Ma (Fig. 10E). The three youngest zircon grains of this sample with overlapping ages have a weighted mean age of 242 ± 28 Ma (MSWD = 1.29; Table 1). Another medium- to fine-grained sandstone sample WC072715-1 has a zircon population of 320-220 Ma, with prominent peak at ca. 241 Ma, and a minor age peak also occurs at ca. 420 Ma (Fig. 10F). The three youngest zircon grains of this sample with overlapping ages have a weighted mean age of 227 ± 7 Ma (MSWD = 4.9; Table 1).

The Upper Jurassic Caishiling Formation medium-grained sandstone sample WC072715-6 has a zircon population of 500-200 Ma, with two prominent peaks at ca. 225 Ma and ca. 405 Ma, and a minor age peak also occurs at ca. 1000 Ma (Fig. 10G). The three youngest zircon grains of this sample with overlapping ages have a weighted mean age of 193 ± 1 Ma (MSWD = 0.33; Table 1). Another pink-brown sandstone sample WC072715-7 has a zircon population of 480-200 Ma, with two prominent peaks at ca. 230 Ma and ca. 407 Ma, and a minor age peak also occurs at ca. 950 Ma (Fig. 10H). In addition, Paleoproterozoic-Neoarchean grains are present in this sample (Fig. 10H). The youngest single-zircon grain of this sample



Figure 10. Normalized relative probability plots of detrital zircon U-Pb ages from the Mesoproterozoic and Neoproterozoic to Cretaceous sediments in the Qiemo River mapping area from this study. See Table DR2 (text footnote 1) for the detailed data set.

yielded a U-Pb age of 156 ± 2 Ma, which suggests an Upper Jurassic age for the sedimentary rock unit (Table 1).

Lower Cretaceous Quanshigou Formation sandstone sample WC072615-9 has zircon populations of 160–120 Ma and 300–200 Ma, with two prominent peaks at ca. 144 Ma and ca. 240 Ma, respectively (Fig. 10I). A minor age population also occurs at 600–400 Ma, with a peak at 430 Ma (Fig. 10I). The three youngest zircon grains of this sample with overlapping ages have a weighted mean age of 124 ± 10 Ma

(MSWD = 0.66), which suggests a Lower Cretaceous age for the Mesozoic sedimentary rock unit (Table 1). In addition, a 3.5 Ga grain was present in this sample (Table DR2).

DISCUSSION

Stratigraphic and Provenance Analysis

Our new detrital zircon age data from this study can aid in detailed stratigraphic analysis for each geologic mapping unit and explore provenance implications that derive from comparisons between the previously published data sets and our paleocurrent data. The discussion is organized by age of deposition and is keyed to previous reconstructions for the preferred provenance interpretations.

The Kuhai Group, recognized as the old metamorphic basement of the western domain of the Eastern Kunlun Range, is locally exposed in the eastern portion of the mapping area. Our new geochronology result for a migmatite sample shows an upper-intercept weighted mean ${}^{207}\text{Pb}/{}^{206}\text{Pb}$ age of 1868 ± 24 Ma (Fig. 8F), which we interpret as the age of protolith deposition. We suggest a Paleoproterozoic age for the basement of the western domain of the Eastern Kunlun Range (i.e., ca. 1.87 Ga). The Mesoproterozoic and Neoproterozoic schist yielded rather simple detrital zircon age spectra characterized by a large number of 1.2-1.0 Ga and 1.5-1.3 Ga zircon grains (Fig. 10A). The younger component of this age range is correlative with plutonic rocks along the northern margins of the Kunlun-Qaidam terrane and Qilian Shan (e.g., Gehrels et al., 2003a, 2003b; Zhang et al., 2005; Wu et al., 2016a, 2017, 2018, 2019a; He et al., 2016a, 2016b, 2018; Liu et al., 2018, 2019; Zuza et al., 2018), whereas the older component of the age clustering at ca. 1.5-1.3 Ga is uniquely correlative to the Qilian Shan to the northeast, corresponding to the North China craton (Fig. 11; e.g., Wu et al., 2017; Liu et al., 2018, 2019; Zuza et al., 2018). Although 1.4 Ga A-type granites were reported in the south Tarim (Ye et al., 2016), the outcrop exposure was poor, and it was too far west from the study area. We suggest that the Mesoproterozoic and Neoproterozoic unit was deposited between ca. 1014 Ma and ca. 817 Ma based on our detrital zircon data (i.e., sample WC062715-4; Fig. 10A) and the intrusive relationships with the Neoproterozoic granitoid (i.e., sample WC072716-3; Fig. 8B).

The Lower Ordovician Qimen Tagh Group mainly formed age peaks at 700–500 Ma and 1.1–0.9 Ga (Fig. 10B). The younger component of this age range implies that the South Altyn Tagh Range and Qilian were not the main provenance areas, which is possibly correlative with

Figure 11. Normalized probability plot of zircon ages from

the Eastern Kunlun Range,

Qilian Shan, and Altyn Tagh

Range. U-Pb ages were used for

zircons younger than 1000 Ma,

and Pb-Pb ages were used for

older zircons, which corre-

spond to widespread tectonic

events as discussed in the text.



the Eastern Kunlun Range (e.g., Bian et al., 2000; Zhang et al., 2005), whereas the older component of the age clustering is uniquely correlative to the northern margins of the Kunlun-Qaidam terrane and Qilian Shan (e.g., Cowgill et al., 2003; Gehrels et al., 2003a; Zhang et al., 2005; Wu et al., 2016a, 2017, 2019a; He et al., 2016a, 2016b; Liu et al., 2018, 2019; Zuza et al., 2018). The minor Paleoproterozoic-late Archean zircon grains are the basement of north Tibet, which may possibly be derived from the Tarim-North China cratons (Wu et al., 2017, 2019a; Zuza et al., 2018; Liu et al., 2018, 2019). Both the Lower Carboniferous Tuokuzidaban Group samples yielded rather simple detrital zircon age spectra characterized by early Paleozoic zircon grains, which may possibly be derived from the South Altyn Tagh Range (e.g., Liu et al., 2015; Kang et al., 2016; C.L. Wu et al., 2016b; Zhu et al., 2019; this study) and western margin of the Eastern Kunlun Range (i.e., Qimen Tagh terrane; Fig. 11; e.g., C. Wu et al., 2016a; Yu et al., 2017; Dong et al., 2018). The Carboniferous zircon grains of these samples are uniquely correlative to the local plutonic rocks of the western domain of the Eastern Kunlun Range, i.e., Jianxia Shan pluton in the mapping area (i.e., sample WC071615-9; Fig. 5). We suggest that the Tuokuzidaban Group in the Eastern Kunlun Range was deposited at ca. 358 Ma, based on our detrital zircon data (i.e., samples WC072715-4 and WC072715-3; Figs. 10C and 10D) and the volcanic tuff sample (i.e., sample WC071516-2; Fig. 8A).

All four Jurassic sandstone samples show two prominent Phanerozoic age populations with ca. 500-400 Ma and ca. 300-200 Ma groups (Figs. 10E-10H), corresponding to the bimodal age distribution characteristic of the Kunlun batholith (e.g., Cowgill et al., 2003; Gehrels et al., 2003a; C. Wu et al., 2016a). However, southward paleocurrent indicators in the Jurassic strata (Fig. 4) suggest that the South Tarim and/ or Altyn Tagh Range to the north acted as a possible source for the older component age cluster of these sediments (Fig. 11). However, the exact location of the Altyn Tagh Range in the Jurassic is unclear. Post-Jurassic left-lateral offset along the Altyn Tagh fault may imply that rocks exposed in the Altyn Tagh Range were located northeast of their present-day position, and thus may not have provided a source for Jurassic sediments. The Permian-Triassic zircon grains are uniquely correlative to the local plutonic rocks of the western margin of the Eastern Kunlun Range (e.g., Roger et al., 2003; Li et al., 2013; Wu et al., 2016a, 2019a). The Lower Cretaceous sandstone sample exhibits two significant populations at 160-120 Ma and 300-200 Ma (Fig. 10I), corresponding to the characteristic ages of the Eastern Kunlun Range. A third age population spans 600-400 Ma. Therefore, the Lower Cretaceous sediments were probably locally derived at the western domain of the Eastern Kunlun Range (Fig. 11; e.g., Zhang et al., 2005; Li et al., 2013; Wu et al., 2016a, 2019a).

Neoproterozoic–Mesozoic Tectonic Evolution of Northwestern Tibet

In the late Mesoproterozoic-early Neoproterozoic, sediments were deposited along the southern and northern edges of the Altyn Tagh and Eastern Kunlun Ranges, respectively (Wu et al., 2016a, 2019a; Meng et al., 2017; Yu et al., 2017; this study). The sediments consisted of ca. 1.45 Ga and ca. 1.1 Ga detrital zircon grains derived from the linked Tarim-North China craton to the north and minor local granitoids (e.g., Gehrels et al., 2003b, 2003b; He et al., 2016a; Wu et al., 2016a, 2019a; this study). Early Neoproterozoic (i.e., ca. 0.9-1.0 Ga) magmatism across North Tibet was followed by local deformation (e.g., Wu et al., 2016a, 2017, 2019a; He et al., 2016b, 2018; Meng et al., 2017; Zuza and Yin, 2017; Zuza et al., 2018). Leucogranites and metamorphic zircon rims with ages of ca. 0.9-0.81 Ga in the Eastern Kunlun and South Altyn Tagh Ranges (i.e., ca. 817 Ma of sample WC072716-3; Fig. 8B; e.g., Gehrels et al., 2003a; Wu et al., 2017; Zuza et al., 2018; this study) are associated with the inferred collision between the linked North China-Tarim craton and the Songpan-Ganzi terrane by no later than ca. 750 Ma during closure of the proto-Kunlun ocean (e.g., Wu et al., 2016a, 2019a; Zuza and Yin, 2017). In the late Neoproterozoic, rifting of this joined continent initiated at variable times, resulting in the opening of the South Altyn Tagh and paleo-Kunlun oceans, from north to south, respectively (e.g., Wu et al., 2016a, 2019a; Zuza and Yin, 2017). The earliest phase of rifting and the opening of the paleo-Kunlun ocean initiated during or immediately following the aforementioned collision (e.g., Wu et al., 2016a, 2019a; Zuza and Yin, 2017; Zuza et al., 2018). The emplacement of ca. 733 Ma mafic dikes in the Eastern Kunlun Range associated with the development of a passive margin as diking was coeval with the deposition of the shallow-marine sequence (i.e., Wanbaogou Formation; Wu et al., 2016a, 2019a).

The onset of paleo-Kunlun ocean subduction along the southern margin of the Kunlun-Qaidam terrane could have occurred as early as the end of the Neoproterozoic (e.g., Jiang et al., 1992; Yang et al., 1996; Yin and Harrison, 2000; Mo et al., 2007; Wu et al., 2016a, 2019a), and protracted arc magmatism lasted until the Devonian (e.g., Yin and Harrison, 2000; Cowgill et al., 2003; Gehrels et al., 2003a; Chen et al., 2012; Wu et al., 2016a, 2019a). In the north, the oceanic crust of the Kunlun-Qaidam terrane began to subduct northward by ca. 520 Ma, creating a dominant Cambrian arc along the southern margin of the Altyn Tagh Range. This is evidenced by the emplacement of ca. 520-500 Ma I-type adakitic granitoid dikes in the South Altyn Tagh Range associated with the development of a passive margin coeval with the deposition of the shallow-marine sequence in the Eastern Kunlun Range (e.g., Wang et al., 2013; Wu et al.,



Figure 12. Structural balanced cross section of the Qiemo section (located in Fig. 5), showing section lengths, fault slip, and shortening magnitudes in two specific stages from T1 to T5. The strata symbols are the same as those in Figure 4; the gray line is the topographic line.

2016a, 2019a). A weak peraluminous granite with an age of ca. 495 Ma experienced peak metamorphism (Liu et al., 2015) as abundant metamorphic monazite was being formed (Zhu et al., 2019), suggesting that closure of the South Altyn Tagh ocean occurred at this time. The final closure of the subducted South Altyn Tagh ocean did not occur before the Middle Ordovician associated with the development of the ca. 480 and ca. 465 Ma Mangnai-Munabulake and Qingshuiquan ophiolites, from north to south, respectively (e.g., Liu et al., 2015; Zhu et al., 2019). Abundant ca. 460-445 Ma S-type granitoids provide further evidence for this interpretation (e.g., Cao et al., 2010; Yang et al., 2012; Kang et al., 2013; this study). The Late Silurian-Middle Devonian (i.e., ca. 426-385 Ma) alkaline granitoids suggest a postcollisional crustal extension setting in the South Altyn Tagh Range (e.g., Wu et al., 2007; C.L. Wu et al., 2014a; Liu et al., 2015; Wang et al., 2008a; Kang et al., 2016). If we restore Altyn Tagh offset, the rocks northwest of the Altyn Tagh fault in our study should get close to the Qilian Shan. We further demonstrate (1) that the geology on either side of the Altyn Tagh fault is different, (2) that the rocks to the north of the Altyn Tagh match or correlate with features in the Qilian Shan, such as the Qilian arc (e.g., Wu et al., 2017; Liu et al., 2018, 2019; Zuza et al., 2018), and (3) that the detrital zircon signatures differ between the existence and the closure of the South Altyn Tagh ocean.

Final consumption of the paleo-Kunlun ocean and continental collision occurred by 399-360 Ma, which is evidenced by the Late Devonian-early Carboniferous (ca. 360 Ma) metaluminous granite observed in the Eastern Kunlun Range (Wu et al., 2019a). Exhumation of the Late Devonian-early Carboniferous granitoids in the western domain of the Eastern Kunlun Range may have been associated with the syn- and postcollision processes between the Kunlun-Qaidam and Songpan-Ganzi terranes. However, the lack of a definitively recognizable geochemistry signature in this study makes this interpretation uncertain. Across the Eastern Kunlun Range, the wide belt of late Paleozoicearly Mesozoic arc plutons (i.e., granite sample WC071715-2 in this study) that generally young to the southwest can be explained by southward steepening of the subducting Paleo-Tethyan (also referred as the Neo-Kunlun) oceanic slab (Wu et al., 2016a, 2019a), which was induced by fluid-fluxing melting of an enriched lithospheric mantle (Chen et al., 2015; Wu et al., 2019a). The Mesozoic sediments in the western domain of the Eastern Kunlun Range were derived from the South Altyn Tagh Range to the north and local recycled material.

Cenozoic Deformation and Shortening Estimates across the Western Domain of the Eastern Kunlun Range

Our detailed mapping and structural analysis, presented in the form of a balanced cross section, provide quantitative estimates of the Cenozoic deformation that has affected northwestern Tibet. The ultimate goal of our field-based structural analyses and balanced cross-section restorations was to determine the kinematics of this region, which may have involved left-slip faulting related to the proximal Altyn Tagh fault and north-directed thrusting during widespread contractional deformation in central-northern Tibet (e.g., Meyer et al., 1998; Zuza et al., 2016, 2017; Allen et al., 2017). Balanced cross sections were constructed using Midland Valley's 2D Move software, and the restoration was developed using inverse kinematic modeling by this software package. Because of thick-skinned deformation and large variations/uncertainties in stratigraphic thicknesses, we used the linebalancing method to restore deformation, as opposed to an area balance (e.g., Chamberlin, 1923; Suppe, 1983; Mitra and Namson, 1989; Judge and Allmendinger, 2011).

Deformed-state cross sections were developed with a fault-bend fold geometry (Suppe, 1983). The construction of balanced cross sections relies on four assumptions: (1) The folding and rock uplifting are both controlled by the fault slip, (2) stratigraphic layers were originally horizontal before the deformation, (3) parallel folding is assumed to have been accommodated by flexural slip along bedding horizons, and (4) layer lengths and bed areas both remained constant during the deformation. In addition, we assumed dip-slip faulting on all thrust faults, which is reasonable based on our fault observations (Figs. 5 and 6). Complex overprinting dip-slip versus strike-slip deformation affected this region, and the most significant strike-slip shearing occurred in the Qiemo River valley, where exposed units consist of deformed Proterozoic rocks and ultramafic mélange. We did not attempt to quantitatively interpret the complex deformation in the Qiemo River valley because the lack of bedded units and abundant strike-slip shearing make any interpretations ambiguous and nonunique. The balanced cross section and kinematic restoration are only presented for the region just south of the Qiemo River, where deformation is predominately dip-slip, and Carboniferous-Cretaceous bedded strata provided geometric information to be included in the cross-section models. We acknowledge that the geology north of our section line A-A' was affected by out-of-plane left-lateral transpressional deformation associated with the Altyn Tagh fault (Fig. 5). Our cross section

of contractional strain outlined herein shows the minimum shortening required to produce the observed rock geometries and unit juxtapositions. That said, the significance of out-of-plane strikeslip deformation is unconstrained.

The balanced and restored cross-section models are presented in Figure 12. The deformedstate cross sections adhere to the map-view relationships and structural observations discussed above. The restoration of these sections involved restoring slip along the mapped faults to reposition the early-to-middle Mesozoic unconformity surfaces (e.g., the Early Jurassic unconformity horizon) back to horizontal. Pin lines were placed through undeformed strata. Additional cross-section-specific explanations are presented along with cross section in Figure 12. A detachment depth of at least ~14 km blow Earth's surface was calculated using areabalance methods for the western domain of the Eastern Kunlun Range cross section (Chu et al., 2009; Sloan et al., 2011; Zuza et al., 2018, 2019). This section shows a major thrust-wedge duplex (triangle-zone structure), and southeast-directed back-thrust in the northern part (Fig. 12). The Lower Carboniferous strata developed as a klippe in contact with the Upper Jurassic sediments in the middle, whereas the Cretaceous strata, which were first thrust over Jurassic rocks, are represented as a structural window beneath Jurassic rocks that were thrust over in a later phase (Figs. 5 and 12). The minimum magnitude of north-south shortening estimated from cross-section restoration is ~24 km (30% strain) for profiles A-A'.

The initiation age for this deformation is not constrained. The most direct evidence for shortening initiation is the truncation of Eocene terrestrial strata by thrust faults (Fig. 3). Based on sedimentological and thermochronology evidence, Wang et al. (2017) suggested a middle to later Eocene (i.e., ca. 40 Ma) deformation initiation age in the western domain of the Eastern Kunlun Range. Using this age yields a long-term shortening rate across the western domain of the Eastern Kunlun Range of 0.6 mm yr-1. Regionally, it is apparent that Cenozoic thrusting in northwest Tibet initiated locally at 50-45 Ma in the North Qaidam thrust belt, and deformation migrated southward to the Qimen Tagh thrust belt by 25-20 Ma (e.g., Jolivet et al., 2001, 2003; Yin et al., 2007, 2008a, 2008b; F. Cheng et al., 2017a; Shi et al., 2018; Wu et al., 2019b). Alternatively, if deformation initiated later at ca. 25-20 Ma, as in the western Eastern Kunlun thrust belt, the shortening rate would be 1.2-0.9 mm yr-1. Given the range of initiation ages, the thrust belt experienced contractional strain rates of 4.7 $\times 10^{-16}$ s⁻¹ to 2.3×10^{-16} s⁻¹, which overlap with established bulk Cenozoic strain rates across much of the Himalayan-Tibetan orogen (Clark, 2012; Zuza et al., 2019).

The ~24 km value of Cenozoic shortening (~30% strain) estimated via the restoration of the balanced cross section along our ~80 km traverse (Fig. 12) is comparable to regional shortening estimates across the region (Yin and Harrison, 2000; Yin et al., 2007, 2008a, 2008b). Yin et al. (2007) estimated a minimum of ~150 km of shortening (46% strain) across the Qimen Tagh-Yousha Shan thrust belt to the northeast. Compared to the west of the study area, X.G. Cheng et al. (2017b) estimated a minimum of ~27 km of shortening (~32% strain) across the Western Kunlun thrust belt. In a thesis, Yakovlev (2015) reported ~9 km (~20%) of shortening across a 36-km-long traverse of the Guaizi Liang range to the east of our study area. Integrated cosmogenic radionuclide dating suggests Quaternary shortening rates of ~1.7 mm/yr across the Yakovlev (2015) section, which is broadly comparable to our rates.

Because of their similar present-day physiography, we extrapolated these shortening magnitudes of ~20%-30%, from this and other studies (Yin et al., 2007; Yakovlev, 2015), over a ~100-km-long traverse across the Jianxia Shan to the Tula Basin, which yielded a minimum of Cenozoic 25-42 km of shortening. Whether this shortening initiated at ca. 40 Ma or 25-20 Ma yields north-south shortening rates of 0.6-1.1 mm/yr or 1.0-2.1 mm/yr, respectively. We note that these strain values could thicken crust that was originally ~40 km thick prior to the Cenozoic to thicknesses of 50-57 km, assuming pure-shear thickening and the rationale outlined in Zuza and Yin (2016). These values match present-day crustal thickness estimates based on receiver function data recorded by a large-scale dense array (i.e., Xu et al., 2013, 2018), which emphasizes that crustal shortening was sufficient here to thicken the crust.

North-south shortening can be converted to northeast-striking left-lateral shear through simple geometric arguments. The contribution of shortening magnitude, sh, to strike-slip shear, ss, is given by $ss = sh \sin(\theta)$, where θ is the angle between the strike of the thrust faults and the strike-slip faults. Given that our cross-section profile strikes north and the Altyn Tagh fault here strikes ~N70°E, strike-slip shear from ~25-42 km of shortening equates to $25-42 \text{ km} \times \sin(20^\circ) = 8.5-14.4 \text{ km}$. Similarly, shortening rates of 1 mm/yr to 2 mm/yr convert to 0.3-0.7 mm/yr. These calculations demonstrate that the contractional deformation observed in this study did not significantly contribute to left-slip offset on the Altyn Tagh fault, which has ~10 mm/yr slip rates (e.g., Cowgill et al., 2009).

CONCLUSIONS

The integrated results of our study involving detailed geologic mapping, structural analysis, balanced cross-section restoration, sedimentology, and new geochronology across the western domain of the Eastern Kunlun Range, together with existing work across northern Tibet, led to the following interpretations.

We suggest a Paleoproterozoic age for the basement of the western domain of the Eastern Kunlun Range, i.e., ca. 1.87 Ga, whereas the Mesoproterozoic and Neoproterozoic unit was deposited between ca. 1.0 Ga and ca. 0.82 Ga. The Lower Ordovician Qimen Tagh Group records a return to relatively local derivation from the Tuokuzidaban Group in the Eastern Kunlun Range, which was deposited at ca. 358 Ma based on our detrital zircon data and the volcanic tuff age. The detrital zircon results clearly distinguish the Early Ordovician Qimen Tagh Group schist from the Carboniferous sandstone samples, which were related to the evolution of the South Altyn Tagh Range. The southward paleocurrent indicators in the Jurassic strata imply that the South Tarim and/or Altyn Tagh Range to the north acted as a possible source for the older component age clusters of these sediments, and Cretaceous strata have contributions from local sources, with grains ultimately derived from the Kunlun orogenic systems.

Restoration of an ~56-km-long balanced cross section across the western domain of the Eastern Kunlun Range suggests that Cenozoic minimum shortening strain was ~30% (~24 km of shortening). Field evidence suggests that this shortened commenced after ca. 25–20 Ma, and the thrust belt experienced a shortening rate of 1.2–0.9 mm yr⁻¹ and strain rates of 4.7 × 10⁻¹⁶ s⁻¹ to 2.3 × 10^{-16} s⁻¹, which overlap with established Cenozoic strain rates across much of the Himalayan-Tibetan orogen. The contractional deformation observed in this study did not significantly contribute to left-slip offset on the Altyn Tagh fault, which has ~10 mm/yr slip rates.

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