Kinematics and Geochronology of Late Paleozoic–Early Mesozoic Ductile Deformation in the Alxa Block, NW China: New Constraints on the Evolution of the Central Asian Orogenic Belt

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1. Introduction

The Central Asian Orogenic Belt (CAOB), one of the largest accretionary orogenic collages on Earth [1–10], extends from Kazakhstan in the west to eastern Siberia in the east and separates the Siberia Craton to the north from Tarim Craton and North China Craton (NCC) to the south (Figure 1(a)) [18–10] and references therein). As many recent studies argued, this huge orogenic collage was formed by successive accretion of continental blocks, arcs, and accretionary complexes during Late Mesoproterozoic to Late Paleozoic [9–14] and then suffered large-scale strike-slip shearing during Late Paleozoic to Early Mesozoic. Shearing resulted in the lateral displacement of the orogenic segment,
oroclinal bending, mosaic block structure and vast width of the orogenic collage, and synkinematic magmatism in the southwestern CAOB [1–3, 7, 15–25].

Large-scale strike-slip faults play a key role during the evolution of the CAOB; however, controversial kinematic characteristics of large-scale strike-slip faults in the regime were suggested by different studies, which have been even highlighted by Şengör et al. [26]. Şengör et al. [1, 3] and Şengör and Natal‘in [2] proposed that many sinistral strike-slip faults (NW–SE-trending or nearly E–W-trending at present) developed in the CAOB in Late Paleozoic and transected the single arc system into many fragments to form the orogenic collage. However, other studies have indicated that numerous dextral ductile shear zones (NW–SE-trending or nearly E–W-trending at present) developed along the northern NCC in the eastern part of the southern CAOB and were suggested to be induce by the collision of the NCC and the South Mongolian Terrane [27, 33] or eastward extrusion of the continental wedge [34]. However, do the Late Paleozoic–Early Mesoozoic dextral shear zones along the northern NCC and western CAOB belong to a single approximately 3000 km long tectonic zone in the core region of Eurasian continent? And how do they link in the central part of the southern CAOB? Both issues are unknown and will be addressed in the present paper.

The Late Paleozoic–Early Mesoozoic dextral ductile shear zones in the southern CAOB represent important transcurrent deformation and are crucial for the tectonic reconstruction of the CAOB. The central part of the southern CAOB is the pivotal region connecting the coeval shear zones in the western and eastern parts. Although some authors investigated the Late Paleozoic ductile shear zones in the central

**Figure 1:** (a) Simplified tectonic map of Eurasia (modified after Liu et al. [102]) and the location of the study area. (b) Physiographic map of the central part of the CAOB showing the location of the SADSZ and the distribution of other Late Paleozoic–Early Mesoozoic dextral shear zones in the Alxa Block and Beishan Orogenic Belt (red dash line). The Cenozoic faults with different kinematics around the northeastern Tibetan and in the Alxa Block are also shown (black solid line). (c) Geological map of the southern Alxa Block and stereographic projection of mylonitic foliations (red box) and stretching lineations (blue dots) (lower hemisphere, equal area projections, and similar in following figures).
part of the southern CAOB [39–42], the timing, kinematics, spatial relationship, mechanism, relationship with the coeval ductile deformation in the eastern and western CAOB, and tectonic implications of these shear zones are still unclear due to insufficient structural and geochronological constraints. Studies focused on the ductile shearing in the central part of the CAOB will improve our understanding of the Late Paleozoic–Early Mesozoic structural evolution for this orogenic belt.

In this study, we found and documented a regional scale dextral ductile shear zone (the Southern Alxa Ductile Shear Zone, SADSZ) at the southern Alxa Block located in the central part of the southern CAOB, based on the field survey, geological mapping, and isotopic dating (Figures 1(b) and 1(c)). The rocks affected by the SADSZ are primarily Proterozoic to Cambrian metamorphic rocks, which are covered by Lower Cretaceous strata unconformably [43–45]. In order to better constrain the deformation characteristics, kinematics, and timing of the SADSZ, we conducted structural analysis and isotopic dating across the ductile shear zone, ultimately aiming to clarify its regional tectonic significance. Our results, combined with previous studies in the southern CAOB, indicate a Late Paleozoic–Early Mesozoic dextral ductile strike-slip duplex system in the Alxa Block and a continental-scale dextral shear zone developed along the southern CAOB, which were caused by the eastward migration of the orogenic collages and blocks because of the convergence among the cratons (i.e., Siberia, Baltica, and Tarim Cratons) during Late Paleozoic to Early Mesozoic.

2. Geological Setting

The Alxa Block, together with the Tarim Craton to the west and North China Craton to the east, form the southern margin of the CAOB (Figure 1(a)). A Late Paleozoic ocean-arc-back-arc basin system resulted from the subduction of the Paleo-Asian Ocean was suggested to have been developed along the northern margin of the Alxa Block [39, 46]. The closure of the Paleo-Asian Ocean gave rise to the formation of the Enger Us, Quagan Qulu, and Tepai ophiolitic mélanges [39, 46]. The formation of the Enger Us, Quagan Qulu, and Tepai ophiolitic mélanges [39, 46] has been related to the subduction of the Paleo-Asian Ocean to the east in the Mesozoic, which was caused by the combination of the easterly migration of the orogenic collage and block because of the convergence among the cratons during Late Paleozoic to Early Mesozoic.

The study area is located in the southern Alxa Block, in the area of the NW–SE-trending Kuantan Shan, Heli Shan, and Longshou Shan (Figure 1(c)). All of these mountains are dominantly composed of the Paleo- and Cambrian metamorphic rocks, the Mesoproterozoic Duzigou Group, and the Neoproterozoic Hamnushan Group [43–45]. The Longshoushan Group mainly comprises biotite-plagioclase gneiss, amphibole-plagioclase gneiss, quartzite and marble and intercalated with migmatites, mafic, and quartz-feldspathic gneisses in the lower part. All of these metamorphic rocks experienced amphibolite-facies metamorphism. The zircon U-Pb dating indicates that the Longshoushan Group formed in the Paleo- and Cambro-Ordovician and experienced regional metamorphic events at ca. 1.95–1.90 Ga and ca. 1.85 Ga [58–61]. The Duzigou Group is composed of quartzitic micaschist and marble, and the Hamnushan Group is composed of low-grade metamorphic limestone and sandstone. The Duzigou Group and Hamnushan Group are supposed deposited at Mesoproterozoic and Neoproterozoic, respectively [43–45]. In addition, the Cambrian low-grade metamorphic sandstone and volcanic rock, Ordovician pyroclastic rock, Devonian sandstone and conglomerate, and Upper Paleozoic coal-bearing marine clastic deposits are sporadically exposed along the southern Alxa Block, and no Silurian strata crop out in this region [44, 45]. All of the Precambrian metamorphic rocks and Paleozoic strata are intruded by Neoproterozoic ultramafic rocks (827 ± 8 Ma) [62, 63] and Palaeozoic granites [64, 65]. Mesozoic and Cenozoic terrestrial sediments are widespread along both sides of the mountain ranges in the southern Alxa Block and overlie the pre-Jurassic rocks unconformably [44, 45].

Since the Mesozoic, several tectonic events have occurred in the southern Alxa Block. A large number of folded or tilted Jurassic–Cenozoic strata and thrust faults and/or strike-slip faults cutting the Cenozoic strata crop out along the northern and southern sides of the Kuantan Shan, Heli Shan, and Longshou Shan [66–75]. All of these structures may be related to the combined effects of the Qiangtang-Lhasa collision to the south, closure of the Mongol-Okhotsk Ocean to the north and westward subduction of the Paleo-Pacific Ocean to the east in the Mesozoic, and the outward growth of the Qinghai-Tibetan Plateau in the Cenozoic ([73, 74] and references therein). However, strong pre-Triassic ductile shearing along the southern Alxa Block has rarely been documented and discussed.

3. Structural Geology

The NW–SE-trending SADSZ crops out in the southern Alxa Block and extends southeastward from the Kuantan Shan in the west, passes through the Hei Shan, Heli Shan, and Longshou Shan, and apparently terminates at the easternmost Longshou Shan in Wuwei City (Figure 1(c)). Farther to the east, the SADSZ is probably covered by the Tengri Desert (Figures 1(b) and 1(c)). The western end of the SADSZ may be cut off by the Altyn Tagh Fault (Figure 1(b)) [73]. The overall exposed length of SADSZ is approximately 500 km, and its width ranges from 0.15 to 2.0 km (Figure 2). The strikes of the SADSZ are overall NW–SE but turns to nearly E–W at its eastern part to the east of the Hexipu (Figure 1(c)). In order to elucidate the structural characteristics of the SADSZ, we conducted field investigations and geologic mapping across the shear zone, focusing on its geometry and kinematics. We mapped three parts of the SADSZ: the Kuantan Shan in the west, Heli Shan in the middle, and Yangqi Shao Shan of the eastern Longshou Shan in the east (Figure 1(c)). In addition, samples were collected to make oriented thin sections with the aim of better determining the kinematics and microstructure characteristics of the ductile deformation. All oriented thin sections were cut parallel to the stretching lineation and
perpendicular to the foliation, i.e., along the XZ plane of the finite strain ellipsoid. We describe the results of field mapping and investigations in the following sections.

3.1. Kuantan Shan. The Kuantan Shan is located in the western part of the SADSZ (Figure 1(c)). Cambrian quartz-chlorite schist and quartzitic micaschist in this region have been mylonitized strongly (Figure 3), whereas the amphibole-plagioclase gneiss has been only weakly mylonitized. To the west of the Kuantan Shan, a Paleozoic granite (ca. 269 Ma of zircon U-Pb age, detailed discussion is given in Section 4.2) has been mylonitized with well-developed foliation, quartz stretching lineation, and C′ shear bands (Figure 4(c)). The deformed rocks in the Kuantan Shan are overlain by Cretaceous strata unconformably (Figure 3(a)).

The deformed rocks are characterized by a well-developed foliation defined by muscovite and chlorite and a lineation formed by stretched quartz and parallelly arranged amphiboles (Figure 4(a)). Mylonitic foliations are subvertical, trend nearly NW–SE, and dip to NE or SW at 50° to 86° (Figure 3(a)). Map-scale and outcrop-scale A-type folds with hinges subparallel to the stretching lineation are also present (Figures 4(b) and 3(a)). The poles to all lineation-bearing main foliations measured in the Kuantan Shan define a great circle, pointing to its cylindrical folding, the π axis of which (094/35) is subparallel to the average plunge of the A-type fold hinges and lineations (105/44) (Figure 3(b)). Various shear sense indicators found in the XZ plane in outcrops and thin sections indicate dextral shearing, including C′ shear bands (Figure 4(c)), σ-type porphyroclasts of K-feldspar (Figure 4(d)), domino structures (Figure 5(a)), and oblique foliations composed of elongated quartz grains (Figure 5(b)).

Quartz in the mylonite exhibits obvious ductile deformation, with undulose extinction (Figure 5(d)), and the old grain is entirely replaced by slightly elongated subgrains (Figure 5(b)). The dynamic recrystallization of quartz is bulging (BLG) recrystallization to subgrain rotation (SGR) recrystallization (Figures 5(b) and 5(d)). Plagioclase primarily exhibits characteristics of internal brittle fracturing, splitting the grain up into elongate “book-shaped” fragments (Figure 5(a)), and bulging (BLG) recrystallization appears at grain boundaries (Figure 5(c)). These microstructural characteristics of quartz and plagioclase indicate that the deformation temperature of the dextral ductile shearing is approximately 400–500°C [76, 77].

3.2. Heli Shan. In the Heli Shan, located at the central part of the SADSZ (Figure 1(c)), the Proterozoic quartzitic micaschist experienced intense mylonitization (Figure 6), whereas amphibole-plagioclase gneiss has been only weakly mylonitized similar to the observations in the Kuantan Shan. The deformed rocks are primarily L-S mylonites with foliations defined by muscovite and sericite and lineations defined by stretched quartz (Figures 7(a) and 7(b)).

The shear zone in the Heli Shan crops out as a map-scale A-type synform (Figure 6(a)); the lineations in two limbs are all parallel to the synform hinge (Figure 6(b)). Quartzitic micaschist enveloped by marble in the limbs is stretched to form boudins and migrate to the hinge zone during the formation of this synform (Figure 6(a)). The π axis of the poles to all foliations measured is 280/32, which is parallel to the plunge of the A-type fold hinges and stretching lineations that have a statistically average orientation of 270/29 (Figure 6(b)). Various shear sense indicators found in the XZ plane in outcrops and thin sections, including σ-type porphyroclast structures (Figure 7(c)) and mica fish (Figure 7(d)), indicate dextral shearing.

Quartz in the mylonite exhibits obvious ductile deformation, with undulose extinction and dynamic recrystallization, predominantly as bulging (BLG) recrystallization to subgrain rotation (SGR) recrystallization (Figures 7(d) and 7(e)). Plagioclase primarily exhibits characteristics of brittle fracturing, with no obvious dynamic recrystallization. These microstructural characteristics of quartz and plagioclase indicate that the deformation temperature of the dextral ductile strike-slip shearing is approximately 400°C [76, 77].
3.3. Longshou Shan. In the central eastern part of the SADSZ, we carried out geologic mapping in the Yangjiada Shan in the eastern part of the Longshou Shan and field investigations in the Dongda Shan and Jiling areas in the western and central parts of the Longshou Shan (Figure 1(c)). In this region, the SADSZ exposed along the southern margin of the Longshou Shan strike NW–SE (Figures 1(c) and 8(a)) and turns to nearly E–W in the east (Figures 1(c) and 9).

The Longshou Shan is composed of Proterozoic quartzitic micaschist, amphibole-plagioclase gneiss and marble, and Cambrian sandstone. The stronger mylonites are found in quartzitic micaschist (Figure 10(a)), whereas the amphibole-plagioclase gneiss is weakly mylonitized. To the easternmost part of the Longshou Shan, the shear zone is intruded by an underformed granite (ca. 151 Ma of zircon U-Pb age, detailed discussion is given in Section 4.2) (Figure 10(d)). The deformed rocks are primarily L-S mylonites with a foliation defined by muscovite and sericite and a lineation formed by stretched quartz and preferred alignment of amphibole crystals (Figure 10(a) and 10(b)).

In the western and central parts of the Longshou Shan, the subvertical mylonitic foliation trends nearly NW–SE and dips to NE or SW at 35° to 85° (Figure 8(a)). The \( \pi \) axis of the poles to all foliations measured is 294/3, which is parallel to the plunge of the A-type fold hinges and lineation (Figure 8(b)). The plunge of most lineations and hinges of the A-type folds are considerably consistent, with a statistically average attitude of 300/3 (Figure 8(b)). In the eastern Longshou Shan, the mylonitic foliation trends nearly E–W and dips to either north or south at 55° to 85° (Figure 9). Map-scale and outcrop-scale A-type folds with hinges subparallel to the stretching lineation are present (Figures 9(b) and 10(c)). The \( \pi \) axis of the poles to all foliations measured is 262/10, statistically the same as the average plunge of hinges of the A-type folds and stretching lineations (260/3) (Figure 9(b)). Dextral shearing is inferred from shear sense indicators, such as \( \sigma \)-type structures (Figure 11(a)), domino structures (Figure 11(b)) and mica fish (Figure 11(c)) in the XZ plane of thin sections.

Quartz in the mylonite exhibits obvious characteristics of ductile deformation, with undulose extinction and dynamic...
recrystallization, predominantly as subgrain rotation (SGR) recrystallization (Figure 11(a)). Plagioclase primarily exhibits characteristics of brittle fracturing, with some dynamic recrystallization, predominantly as bulging (BLG) recrystallization, present at grain boundaries (Figure 11(d)). The microstructural characteristics of quartz and plagioclase indicate that the deformation temperature of the ductile shearing is approximately 400–500°C [76, 77].

4. Geochronology

4.1. Samples and Methods. Seven samples were collected along the shear zone (Figure 1(c)) for determination of the isotopic age of ductile deformation. Three samples (ZY14-13, HY01-1 and JC15-1) were collected for zircon U-Pb dating. Sample ZY14-13 was collected from a mylonitic granite in the Chijinxia area in the westernmost of the SADSZ (Figures 1(c) and 4(c)), sample HY01-1 was collected from an undeformed granite intruding the shear zone in its easternmost part (Figures 1(c) and 10(d)), and sample JC15-1 was collected from a sheared granite lens in the eastern SADSZ (Figure 1(c)). The other four samples are typically mylonitic rocks and are all of quartzitic micaschist, consisting dominantly of quartz, muscovite, biotite, and sericite (Figure 12). HL17-2 and ZY14-05 were collected from the Heli Shan in the central part of the SADSZ, and ZY14-21 and ZY14-04 were collected from the central Longshou Shan (Figure 1(c)). Muscovite from sample HL17-2, biotite from sample ZY14-21, and sericite from samples ZY14-04 and ZY14-05 were analyzed for ⁴⁰Ar/³⁹Ar dating.

Zircon separation was performed by conventional techniques. Cathodoluminescence (CL) images were performed at the Beijing Geoanalysis Company. Zircon U-Pb dating was conducted using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Natural Resources of China in Changchun. The instrument couples a quadrupole ICP-MS (Agilent 7500c) and 193 nm ArF Excimer laser (COMPexPro 102, Coherent, DE) with the automatic positioning system. For the present work, laser spot size was set to 32 μm for analyses, laser energy density at 10 J/cm², and repetition rate at 8 Hz. The procedure of laser sampling is 30 s blank, 30 s sampling ablation, and 2 min sample chamber flushing after the ablation. The ablated material is carried into the ICP-MS by the high-purity Helium gas stream with flux of 1.15 L/min. The whole laser path was fluxed with Ar (600 m L/min) in order to increase energy stability. The counting time is 20 ms for ²⁰⁴Pb, ²⁰⁶Pb, ²⁰⁷Pb, and ²⁰⁸Pb, 15 ms for ²³²Th, ²³⁸U, 20 ms for ⁴⁹Ti, and 6 ms for other elements. Calibrations for the zircon analyses were carried out using NIST 610 glass as an external standard and Si as internal standard. U–Pb isotope fractionation effects were corrected using zircon 91500 [78] as external standard. Zircon standard Plešovice (337 Ma) is also used as a secondary standard to supervise the deviation of age measurement/calculation [79].
Muscovite, sericite, and biotite separation was performed by conventional techniques. Following separation, purified grains were ultrasonically cleaned, wrapped in aluminum foil, sealed along with standard and flux monitors in a quartz bottle, and irradiated for about 1440 minutes in the Swimming Pool Reactor, Chinese Institute of Atomic Energy, Beijing. The reactor delivers a neutron flux of \( \text{ca. } 2.65 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1} \); the integrated neutron flux is about \( 2.29 \times 10^{18} \text{ n cm}^{-2} \). The monitor irradiated together with the samples is an internal standard: Fangshan biotite (ZBH-25) whose age is \( 132\pm7\text{ Ma} \) and its potassium content is 7.6% [80]. Samples ZY14-21, ZY14-04, and ZY14-05 were analyzed at the State Key Laboratory of Earthquake Dynamics, Institute of Geology, China, Earthquake Administration. The aliquots were heated using a double-vacuum resistance furnace, whose stability of temperature control and temperature accuracy is better than \( \pm 5^\circ\text{C} \). The fraction of gas released in an ultra-high vacuum system was cleaned with a cold-trap (\(-80^\circ\text{C to } -100^\circ\text{C}\)), titanium sponge, and two Zr-Al getters operated at ca. 400°C and at room temperature and then analyzed for Ar isotopes in a mass spectrometer (GV5400). 40Ar/39Ar dating of sample HL17-2 was conducted at the Institute of Geology, Chinese Academy of Geological Sciences. The sample was heated incrementally for gas extraction in a graphite furnace for 10 min for each step, and then the released gases were purified for 20 min, before analysis on a Helix MC mass spectrometer. The analysis for each temperature increment included 20 cycles, to regress to time zero to get the measured isotopic ratios. Measured isotopic ratios were corrected for mass discrimination, atmospheric Ar component, blanks, and irradiation induced mass interference. Correction factors for interfering isotopes produced during the irradiation, determined by analysis of irradiated pure K2SO4 and CaF2, are \( (^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.0002389 \), \( (^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.004782 \), and \( (^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.000806 \). All 37Ar were corrected for radiogenic decay. The decay constant of 40K used was \( \lambda = 5.543 \times 10^{-10} \text{ a}^{-1} \). The detailed analytical procedures were the same as given in Chen et al. [81] and Zhang et al. [82].

4.2. Zircon U-Pb Dating. We dated thirty zircon grains in each of the samples ZY14-13, HY01-1, and JC15-1. The ratios of isotopes, U-Pb apparent ages, and concordia plots of these three samples were plotted using ICPMSDataCal [83]. All age dates are shown on concordia diagrams and plotted on relative age probability diagrams (Figure 13). The detailed analytical results of these three samples are listed in Table 1.

Most zircons from sample ZY14-13 are transparent and euhedral with a clear oscillatory zoning, suggesting an igneous origin (Figure 13(a)). The diameters of most zircons are 60–70 \( \mu\text{m} \) (Figure 13(a)). The dating results indicate that most U-Pb ages from the 30 spots are concordant (Figure 13(a)). Twenty-seven individual spot ages yield a \( ^{206}\text{Pb}^{238}\text{U} \) weighted average age of 269 ± 1.2 Ma (MSWD = 0.15) (Figure 13(a)), which represents the crystallization age. Due to sample ZY14-13 was collected from a
mylonitic granite (Figure 4(c)), the age of ca. 269 Ma determines the maximum age of shearing. This indicates that the dextral shearing along the SADSZ in Chijinxia area occurred at least after the Middle Permian.

Most zircons from sample HY01-1 are transparent and euhedral with clear oscillatory zones (Figure 13(b)). The diameters of most zircons are ca. 50 μm (Figure 13(b)). The internal structures suggest an igneous origin, and the age obtained represents the crystallization age. The dating results indicate that U-Pb ages of 15 spots from the overall spots are concordant (Figure 13(b)), while the other spots are discordant. Fifteen concordant individual spot ages yield a \(^{206}\text{Pb} / {^{238}}\text{U}\) weighted average age of \(151 \pm 1.5\) Ma (MSWD = 0.15) (Figure 13(b)). Due to sample HY01-1 was collected from a granite lens sheared by the dextral shearing, the age of ca. 151 Ma suggests that the dextral shearing of the SADSZ in the eastern Longshou Shan took place prior to the Late Jurassic.

Most zircons from sample JC15-1 are transparent and euhedral with clear oscillatory zones (Figure 13(c)), suggesting an igneous origin. The diameters of most zircons are 70-90 μm (Figure 13(c)). The dating results indicate that most U-Pb ages from the 30 spots are concordant, and twenty-one individual spot ages yield a \(^{206}\text{Pb} / {^{238}}\text{U}\) weighted average age of \(425 \pm 2.9\) Ma (MSWD = 0.058) (Figure 13(c)), which represents the crystallization age. Due to sample JC15-1 was collected from a granite lens sheared by the dextral shearing, the age of ca. 425 Ma suggests that the dextral shearing of the SADSZ in the eastern Longshou Shan occurred after the Middle Silurian.

4.3. \(^{40}\text{Ar}/^{39}\text{Ar}\) Dating. A plateau age is obtained when the apparent ages of at least three consecutive concordant incremental heating steps representing at least 60% of the total amount of \(^{39}\text{Ar}\) released. Samples HL17-2 and ZY14-21...
dated in this study meet this requirement, whereas samples ZY14-04 and ZY14-05 do not (see discussions below). All ages are displayed at the 1σ level. The detailed results of the ⁴⁰Ar/³⁹Ar analysis are plotted as age spectra and inverse isochron diagrams in Figure 14, and the analytical results are presented in Table 2. The ⁴⁰Ar/³⁹Ar plateau and inverse isochron diagrams were calculated using ArArCALC V2.5.2 [84].

**Figure 7:** Structural characteristics of outcrops and microstructure characteristics of different minerals in the Heli Shan. (a) Quartz stretching lineation. (b) Quartz stretching lineation parallel to the dip of the foliation in the hinge zone of the fold. (c) σ-type structure of quartzite in the marble. (d) Mica-fish. (e) Quartz ribbons.

**Figure 8:** Foliation and lineation in the western central part of the Longshou Shan. (a) Equal area stereographic projection of poles to all foliations and their π diagram. (b) Equal area stereographic projection of all stretching lineations and the axis of A-type folds.
Muscovite from HL17-2 yields a plateau age of 253.3 ± 1.2 Ma (Figure 14(a)), which is concordant with the corresponding inverse isochron age of 253.4 ± 1.3 Ma (Figure 14(b)). The closure temperature of muscovite is 405–425°C [85, 86] and is assumed to be equal to the deformation temperature of the ductile shearing (400–500°C). Therefore, this ⁴⁰Ar/³⁹Ar age could represent the timing of crystallization of the analyzed muscovite and reflect the age of ductile deformation.

Biotite from ZY14-21 yield a plateau age of 240.2 ± 2.4 Ma (Figure 14(c)) which is concordant with the corresponding inverse isochron age of 241.0 ± 2.7 Ma (Figure 14(d)). Because the closure temperature of biotite is ca. 300 ± 50°C [85], which is lower than the deformation...
temperature of the dextral ductile deformation, and the plateau age of ZY14-21 is younger than that of HL17-2; therefore, the ages of $240.2 \pm 2.4$ Ma may reflect the cooling age of the ductile deformation.

Sericite from ZY14-04 and ZY14-05 do not yield plateau ages. ZY14-04 has an asymmetrical dome-shape spectrum (Figure 14(c)), and ZY14-05 shows a progressively decreasing age spectrum (Figure 14(g)), which indicate the chemically

**Figure 11:** Microstructure characteristics of different minerals in mylonites in the Longshou Shan. (a) $\sigma$-type structure of quartz. (b) Domino structure of K-feldspar. (c) Mica fish. (d) Bulging recrystallization developed along the grain boundary of plagioclase.

**Figure 12:** Photomicrographs of samples for $^{40}$Ar/$^{39}$Ar analysis (see sample locations in Figure 1(c)). (a) Quartzitic micaschist with mica-fish. (b) Quartzitic micaschist with a mylonitic fabric defined by oriented biotite and quartz ribbons. (c, d) Preferred alignment of sericite defining the mylonitic foliation. Qtz: quartz; Ms: muscovite; Bt: biotite; Ser: sericite.
heterogeneous of sericite or the mix of sericite components with different ages [87–89]. Therefore, the ages of ZY14-05 and ZY14-04 may not reflect the original age of the analyzed minerals. Inverse isochron ages of ZY14-04 and ZY14-05 are 243.2 ± 4.0 Ma and 251.9 ± 3.9 Ma (Figures 14(f) and 14(h)), respectively, but the Mean Square of Weighted

**Figure 13:** $^{207}\text{Pb}/^{235}\text{U}$ - $^{206}\text{Pb}/^{238}\text{U}$ concordia diagrams of single zircon grains and average ages of samples ZY14-13 (a), HY01-1 (b), and JC15-1 (c), see Figure 1(c) for locations.
Figure 14: $^{40}$Ar/$^{39}$Ar released spectra and $^{36}$Ar/$^{40}$Ar vs. $^{39}$Ar/$^{40}$Ar inverse isochron diagram of muscovite, biotite, and sericite of samples from the SADSZ (see Figure 1(c) for sample locations).
Deviates (MSWD) of the inverse isochron ages are much greater than unity (Figures 14(f) and 14(h)), which suggest a poor fit and reduced importance of the ages of these two samples. Therefore, the results of samples ZY14-04 and ZY14-05 are used as circumstantial evidence to constrain the age of the SADSZ.

5. Discussion

5.1. The Southern Alxa Ductile Shear Zone (SADSZ). Although the SADSZ is a regional ductile shear zone as reported in this study, it was rarely documented before, possibly for some reasons following. Firstly, the southern Alxa Block underwent extensive intracontinental deformation during Mesozoic to Cenozoic, a large number of folds, thrust faults, and strike-slip faults developed along the southern Alxa Block [66–75] and overprinted the SADSZ strongly. Secondly, the SADSZ does not crop out continuously, and many parts are covered by Mesozoic–Cenozoic strata and the Quaternary desert, such as parts close to the Jinta area at the central-western part and its easternmost part (Figures 1(b) and 1(c)). All of these destroy the completeness and continuity of the SADSZ, which make it difficult to identify. According to our geologic mapping and field investigations, different parts of the SADSZ are characterized by similar attributes, kinematics, and age; the slight change of strike and lineation trends was probably caused by the later deformation. Therefore, we propose the SADSZ as a regional ductile dextral shear zone developed along the southern Alxa Block.

The SADSZ predominantly developed in the Proterozoic and Cambrian metamorphic rocks, including the Paleoproterozoic Longshoushan Group, Mesoproterozoic Dunzigou Group, Neoproterozoic Hannushan Group, and Cambrian metamorphic sandstone and volcanic rocks (Figures 1(c) and 2). The metamorphic grade of the rocks inside the shear zone is the same as that in the north and south sides of the shear zone. Given that the rocks of the Devonian–Carboniferous strata are not metamorphic and the North Qilian Ocean to the south of the Alxa Block closed at the Early Paleozoic [90], the metamorphism of the Mesoproterozoic–Cambrian rocks may occur in the Early Paleozoic and be probably result from the collision orogeny to the south, but not related to the ductile shearing of the SADSZ. In addition, the collision orogeny of the North Qilian orogenic belt also led to the NW–SE-trending dominant fabric (e.g., schistosity, cleavage) in the southern Alxa Block, which is parallel to the North Qilian orogenic belt, and this dominant fabric controlled the subsequent structural deformation in the southern Alxa Block, including the SADSZ. Therefore, in some parts of the SADSZ, the mylonitic foliation is parallel to the lithologic boundaries (Figures 6(a) and 9(a)). However, the lithologic boundaries are also somewhat affected by the ductile shearing. For example, in the Heli Shan area in the central SADSZ, the quartzitic micaschist in the limbs of a synform is stretched to form boudins and migrate from limbs to hinge zone during the ductile shearing (Figures 6(a) and 7(c)).

5.2. Timing of Deformation. The rocks involved in the SADSZ are primarily Proterozoic quartzitic micaschist and amphibole-plagioclase gneiss and Cambrian quartz-chlorite schist (Figures 1(c), 3(a), 6(a), and 9(a)). Lower Cretaceous strata overlie unconformably the mylonitic rocks in the western and central segments (Figures 1(c) and 3(a)), which indicates that the dextral shearing occurred between Early Paleozoic and Early Cretaceous.

In the Hexipu area in the eastern segment of the SADSZ, the granite lens sheared by the dextral shearing yields a weighted average zircon age of 425 ± 2.9 Ma (Figure 13(c)). In the Chijinxia area in the western segment of the SADSZ, the granite deformed by the dextral ductile shearing yields a weighted average zircon age of 269 ± 1.2 Ma (Figure 13(a)). These two ages indicate that the dextral shearing took place at least after 269 Ma. In addition, in the Hongya Shan in the eastern segment, the shear zone was intruded by an undeformed granite with a weighted average zircon age of 151 ± 1.5 Ma (Figure 13(b)). Therefore, the dextral ductile shearing must have occurred between 269 Ma and 151 Ma. Furthermore, ⁴⁰Ar/³⁹Ar dating gives deformation/cooling ages ranging from 253 Ma to 240 Ma (Figures 14(a) and 14(c)). Due to the estimated deformation temperature is approximately 400–500°C, which is lower than the closure temperature of zircon U–Pb system, but approximately equal to that of muscovite argon system, and higher than that of biotite argon system, therefore, the zircon U–Pb age (269 Ma) of the deformed granite provides the maximum constraint for the timing of the dextral ductile shearing, the ⁴⁰Ar/³⁹Ar age of the biotite (240 Ma) represents the cooling time, and the ⁴⁰Ar/³⁹Ar age of the muscovite (253 Ma) indicates the timing of ductile ductile shearing. This is also consistent with the ⁴⁰Ar/³⁹Ar ages of the sericites from samples ZY14-04 and ZY14-05. In addition, Guan [40] and Wu et al. [41] argued that the dextral ductile shearing at the northern Alxa Block occurred at 264–257 Ma. Accordingly, we suggest that the dextral shearing of the SADSZ occurred between ca. 269 and 240 Ma, i.e., the Middle Permian to Middle Triassic.

5.3. Displacement. It’s a useful method to determine the displacement of a shear zone by the offset markers, such as lithologic layers or rock units, appearing on opposite sides of the shear zone. Along the eastern SADSZ between the Hexipu and Hongya Shan, many Early Paleozoic granites (444 ± 2 Ma and 425 ± 2.9 Ma) ([64, 91] and this study) are exposed on the north and south walls of the shear zone, respectively (Figure 15(a)). The granite on the south crops out near the Hexipu region, and the nearest granite on the north is exposed at about 6 km to the east of the Jin-Wu Road (Figure 15(a)). The shape of the granite on the north near the shear zone shows characteristic of being sheared by the dextral shearing (Figure 15(a)). In addition, some granite lenses with different sizes scattered in the shear zone (Figures 15(a) and 15(b)), which may be sheared from granite on the south wall of the shear zone. One of these granite lenses yields zircon U–Pb age of ca. 425 Ma (sample JC15-1) (Figures 13(c) and 15(b)), which is similar to the age of the underformed granite to the south (ca. 444 Ma of zircon...
Therefore, we suggest that the Early Paleozoic granites on the two walls of the SADSZ may originally belong to the same granite, and this granite is cut by the dextral shearing during the Late Paleozoic to Early Mesozoic. The spatial distance of the westernmost boundaries of the granites on two walls of the SADSZ is approximately 40 km, and that of the easternmost boundaries is approximately 50 km. Because the eastern SADSZ is covered by the Tengri Desert, no further information of sheared Early Paleozoic granite has been obtained. The calculated horizontal displacement of ca. 40–50 km may represent the least horizontal displacement of the SADSZ.

5.4. Late Paleozoic–Early Mesozoic Dextral Ductile Strike-Slip Duplex in the Alxa Block. The SADSZ underwent dextral ductile shearing during Middle Permian to Middle Triassic. Our field investigation also recognized the Late Paleozoic dextral ductile shearing during the Late Paleozoic to Early Mesozoic. The spatial distance of the westernmost boundaries of the granites on two walls of the SADSZ is approximately 40 km, and that of the easternmost boundaries is approximately 50 km. Because the eastern SADSZ is covered by the Tengri Desert, no further information of sheared Early Paleozoic granite has been obtained. The calculated horizontal displacement of ca. 40–50 km may represent the least horizontal displacement of the SADSZ.

Due to the coverage by Quaternary deserts, the spatial relationship of these shear zones is not clear. However, the aeromagnetic data show that the distribution of these shear zones is consistent with the aeromagnetic anomaly belts (Figure 17(b)). As shown by the arcuate array of the aeromagnetic anomaly belts, from the south to the north of the Alxa Block, the dominant structural trend changes from NW–SE to E–W (Figure 17(b)). Because most shear zones in the Alxa Block formed in Late Paleozoic and with similar kinematics, these shear zones could be connected to form a huge shear zone system, with an S-C-style geometry in map view, indicating dextral shearing (Figure 17(b)). This shear zone system resembles a ductile strike-slip duplex similar to the Borborema shear zone system of NE Brazil [92–95]. The SADSZ and the shear zones in northern Alxa Block outline the south and north boundaries of this strike-slip duplex, and the shear zones in central Alxa Block may represent the boundaries of the imbricate units. This duplex indicates that the SADSZ are in structural continuity with the shear zones in the northern Alxa Block, and the SADSZ does not extend eastwards, but may turn to NE–SW, and finally merge with the shear zones in the northern Alxa Block (Figure 17(b)).

5.5. Late Paleozoic–Early Mesozoic Dextral Shearing along the Southern CAOB. In addition to the SADSZ in the central CAOB, there are numerous coeval shear zones developed along the southern CAOB. In the western CAOB, the shear zones in the Tian Shan region experienced dextral shearing during ~290–240 Ma [16, 18–20, 28–32, 35–37], and the ductile dextral strike-slip in the Beishan region occurred at 323–209 Ma [32, 96]. In the eastern CAOB, the Xar Moron Fault experienced dextral shearing during 227–209 Ma [34], and the dextral ductile deformation along the northern margin of the NCC occurred at 255–241 Ma [33]. These
shear zones formed a Late Paleozoic–Early Mesozoic 3000 km long dextral ductile shear zone along the southern CAOB, extending from the Kazakhstan in the west to Tian Shan, Beishan, Alxa Block, and northern margin of the NCC in the east (Figure 18). The ductile strike-slip duplex in the Alxa Block, including the SADSZ in this study,
occupies the key location of this huge shear belt and connects the dextral shear zones developed in the western and eastern parts of the southern CAOB.

This large-scale dextral shear zone characterized the tectonic setting of the southern CAOB during Late Paleozoic to Early Mesozoic. According to the geochemical and geochronological features of the synkinematic magmatic rocks controlled by large-scale dextral strike-slip faults in the Tian Shan, a transition event from convergence to an intraplate anorogenic environment was argued occurred in the western CAOB [17–19, 24]. Therefore, the 3000 km long shear zone may mark the replacement of the orogenic environment by the regional-scale transcurrent setting of the southern CAOB during Late Paleozoic to Early Mesozoic.

5.6. Tectonic Setting of the Structural Deformation of the SADSZ. Tectonic setting of the Late Paleozoic–Early Mesozoic dextral ductile shear zone along the southern margin of the CAOB with their characteristics of the kinematic and the geochronology. CAOB: Central Asian Orogenic Belt; NCC: North China Craton; AB: Alxa Block; TC: Tarim Craton; JB: Junggar Block; YB: Yili Block; ISZ: Irtysh Shear Zone; NEF: North-East Fault; CSZ: Chara Shear Zone; CANTF: Chingiz-Alakol-North Tianshan Fault; CKF: Central Kazakhstan Fault; QNF: Qingbulak-Nalati Fault; MTSZ: Main Tianshan Shear Zone; ATF: Alty Tagh Fault; SADSZ: Southern Alxa Ductile Shear Zone; XMF: Xar Moron Fault.
Tian Shan is attributed to intracontinental adjustment after the collision between the Siberia Craton and Tarim Craton [15, 28, 29] or anticlockwise rotation of the Junggar Block [15, 16, 32]. Wang et al. [31] suggested that the dextral strike-slip in the north Tian Shan was the result of eastward post-collision extrusion of the CAOB between the Siberia Craton and Tarim Craton. In addition, dextral shearing in the Beishan region was driven by the related rotation between the Siberia Craton, Tarim Craton, and Junggar Blocks [32] or the final collage of the southern CAOB [96]. The tectonic setting of the Late Paleozoic–Early Mesozoic dextral ductile shearing in the eastern CAOB along the northern margin of the NCC is attributed to the collision between the NCC and Mongolia arc terranes [33]. Zhao et al. [34] suggested that the eastward extrusion of Eastern Central Asia resulted in the dextral shearing along the Xar Moron Fault. However, neither the models of block rotation in the western part nor the eastward extrusion of Eastern Central Asia in the eastern part could not explain the dextral shearing developed in the Alxa Block in the central part. And these models are regional and could not interpret the whole 3000 km long dextral shearing along the southern CAOB.

During Late Paleozoic to Early Mesozoic, continuous assembly of cratons (e.g., the Siberia, Tarim and Baltica cratons) resulted in the eastward migration of orogenic segments [22, 97], which led to the sinistral shearing of the Irtysh Shear Zone and the dextral shearing in the north Tian Shan [22, 97]. Wang et al. [31] also proposed that the orogenic collages of the CAOB moved eastward and resulted in the formation of the dextral ductile shearing in the western part of the CAOB. Recently, He et al. [37] suggested that the shear zones in the Tianshan Orogen were induced by eastward tectonic wedging of the blocks in western CAOB (e.g., the Kazakhstan–Yili, Central Tianshan, Junggar, and Tu-Ha blocks) in between the Siberia and Tarim cratons. This eastward migration of the orogenic collages and blocks within was supported by the published paleomagnetic data, which indicated that the Yili–Junggar Block moved eastward and wedged in between the Tarim Craton and Siberia Craton in Late Paleozoic [98, 99]. In addition, based on information from high-resolution reflection seismic data from the Junggar Basin, extensive compression occurred in the eastern and western Junggar Basin in Late Paleozoic, with an east-west shortening rate of ca. 35% [100, 101]. This compression may be related to the eastward motion of the Yili–Junggar Block. Therefore, we propose that the eastward motion of the orogenic collages and blocks of the CAOB should be the tectonic driver to lead to the formation of the Late Paleozoic–Early Mesozoic dextral ductile shearing along the southern CAOB, including the Middle Permain–Middle Triassic dextral ductile shearing developed at the southern Alxa Block (e.g., the SADSZ) (Figure 19).

6. Conclusion

Based on field investigation and geologic mapping, this paper presents evidence for a NW–SE-trending 500 km long and up to 2 km wide dextral ductile shear zone along the southern Alxa Block (SADSZ). Zircon U-Pb dating and \(^{40}\)Ar/\(^{39}\)Ar plateau ages constrain its activity to Middle Permian–Middle Triassic (ca. 269–240 Ma) with the least horizontal displacement of ca. 40–50 km. The aeromagnetic data indicate that the SADSZ is in structural continuity with the coeval shear zones in the central and northern Alxa Block and is part of a ductile strike-slip duplex in the central part of the southern CAOB. The dextral strike-slip duplex in the Alxa Block connected the dextral ductile shear zones in the western and eastern parts of the southern CAOB to form a 3000 km long E–W-trending dextral shear zone along the southern CAOB. The eastward movement of the collages and blocks caused displacement along this large-scale dextral ductile shear zone during the transition from convergence to transcurrent tectonism in the southern CAOB during Late Paleozoic to Early Mesozoic.

Data Availability

The detailed analytical results of zircons (samples ZY14-13, HY01-1, and JC15-1) are listed in Table 1, and the detailed analytical results of the muscovite (sample HL17-2), biotite (sample ZY14-21), and sericite (samples ZY14-04 and ZY14-05) are presented in Table 2.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Supplementary 1. Table 1: U-Pb geochronologic analyses of zircons by LA-ICP-MS spectrometry.
Supplementary 2. Table 2: results of \(^{40}\)Ar/\(^{39}\)Ar measurements.

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