Late Caledonian Ductile Thrusting Deformation in the Central East Kunlun Belt, Qinghai, China and Its Significance: Evidence from Geochronology

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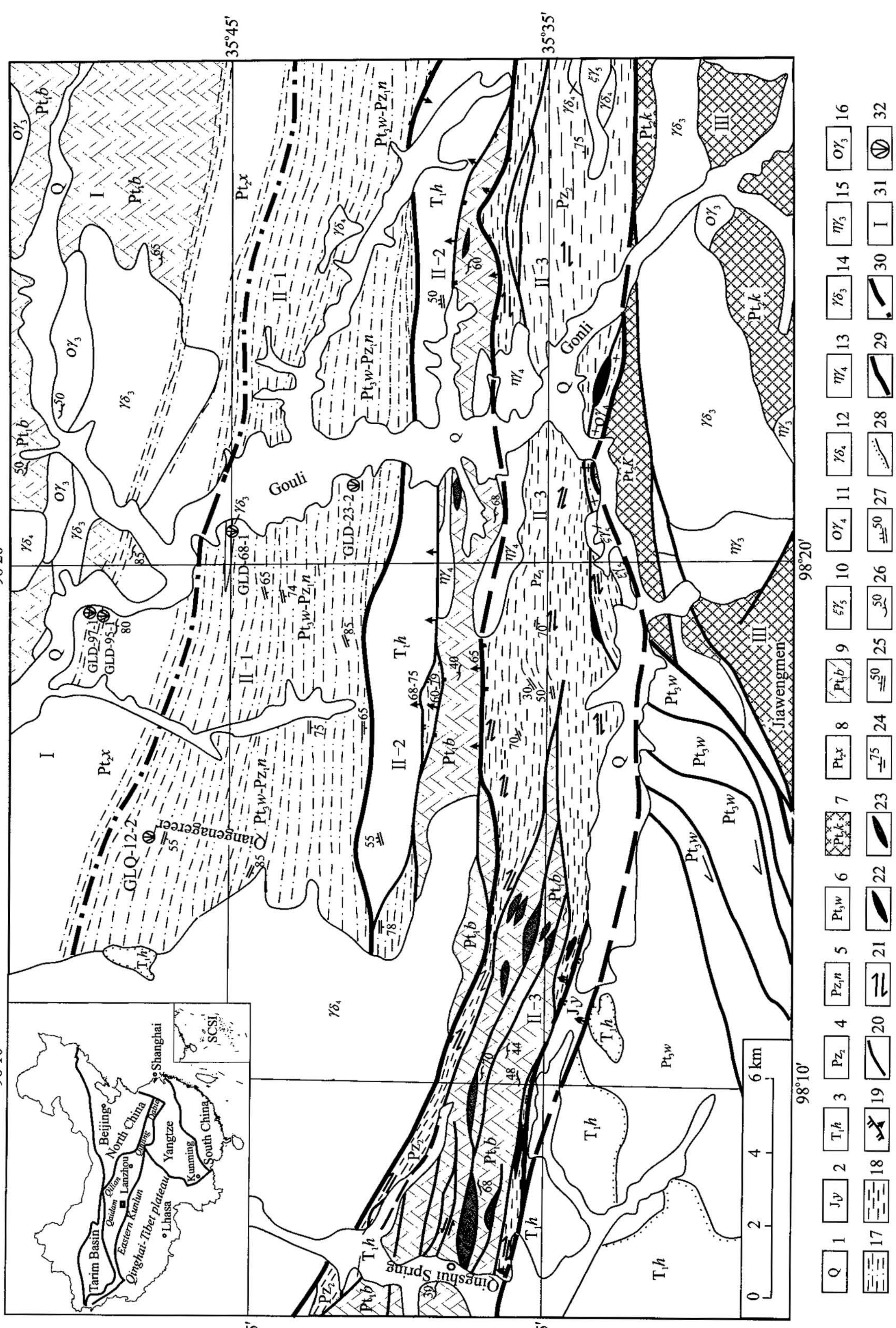
Abstract A high-angle ductile thrusting deformation with top-to-the-north movement penetratively developed in the Proterozoic-Early Paleozoic metamorphic rocks along the Central East Kunlun belt. The deformed rocks suffered epidote-amphibolite facies metamorphism. On the basis of our previous study, we present more data in this paper to further support that the ductile thrust deformation occurred in the later Caledonian and more detailed information about the deformation. A zircon U-Pb concordant age of 446±2.2 Ma of a deformed granodiorite in the ductile thrust zone was obtained and can be interpreted as the lower limit of the deformation. A syntectonically crystallized and also strongly deformed hornblende Ar/Ar dating gives an Ar/Ar plateau age of 426.5±3.8 Ma, which represents the deformation age. A strongly orientated muscovite gives an Ar/Ar plateau age of 408±1.6Ma, representing the cooling age after the peak temperature, constraining the upper limit of the ductile thrust deformation. This ductile thrust deformation can be interpreted as the result of the closing of the Central East Kunlun archipelago ocean. To the north, Ar/Ar plateau ages of 382.9±0.2 Ma and 386.8±0.8 Ma of muscovite in the deformed Xiaomiao Group represent the uplift cooling ages of deeper rocks after the thrusting movement. The original thrusting foliation has a low angle. A rotation model was put forward to explain the development of the foliation from the original low-angle to present high-angle dipping.

Key words: ductile thrust deformation, geochronology, Central East Kunlun Belt, Qinghai, China

1 Introduction

Extending in E-W along the Kunlun Mountains, the Central East Kunlun Belt is a regional tectonic belt with complex components and textures and plays a very important role during the development of the Kunlun orogenic belt (Sun et al., 2000; Bian et al., 2001). According to the MT data, the Moho depth and the lithosphere thickness on the two sides of the belt vary abruptly (Yang et al., 1992). The Moho and the lower interface of the lithosphere to the north are 9 km and 21 km higher than those of the south, respectively, showing a distinct fault step. It is also a magnetic gradient zone and a gravity gradient zone (Gu et al., 1996) and composed of different blocks in different ages from the Proterozoic to Mesozoic. It is also usually recognized as a suture zone, the so-called Central Kunlun Suture Zone, because of a series of ophiolite blocks discovered along this belt (Yang et al., 1992; Gu et al., 1996). However, the age of the oceanic crust represented by the ophiolites and the closure age are in dispute. Zheng (1992) considered that the central Kunlun oceanic crust formed during the Middle Proterozoic based on a Sm-Nd isochron age of 1297 Ma of an ophiolite and closed at the end of the Early Paleozoic. Gao et al. (1988 and 1990) also put the closing time at the end of the Early Paleozoic because they recognized that the geological development and sedimentary facies on the two sides of the suture zone are quite different in the Neoproterozoic-Early Paleozoic but there was a common sedimentary cover in the Late Paleozoic. However, Jiang et al. (1992) noted that this zone still separated different sedimentary facies during the Carboniferous-Permian. On account of a great number of Carboniferous fossils in the ophiolite-bearing strata, they took the Carboniferous for the forming time of the ophiolite and Permian for the closure time. By summarizing the dating data and distribution of the ophiolite blocks, Gu (1994) and Xie (1998) proposed that there are ophiolites of two different periods, i.e. Neoproterozoic and Early Permian. In recent years, we also noticed that there existed different ophiolite assemblages along this belt. Ophiolite assemblages of three different periods were distinguished by their different geological occurrences, geochemical characters and deformation styles (Zhu et al., 1999). We once suggested that this Central East Kunlun Suture Zone is not a simple monocycle suture zone but one of a polycycle open-and-close development (Wang et al., 1999).

The above studies mostly emphasized the analyses of strata ages without direct dating constraint on tectonite, the product of tectonic movement and deformation. The geochronological constraint on the deformation will help us to further understand the tectonic processes. Although in our previous study (Chen et al., 2002), the age of the thrust


35°45'
35°35'
98°10'
98°20'
Gouli
Gonli
Jiawengmen
Qingshui Spring
Tarim Basin
Beijing
North China
Yangtze
South China
Shanghai
Kunming
Lanzhou
Lhasa
Qinghai-Tibet plateau
Eastern Kunlun
Qaidam
Qilian
SCSI
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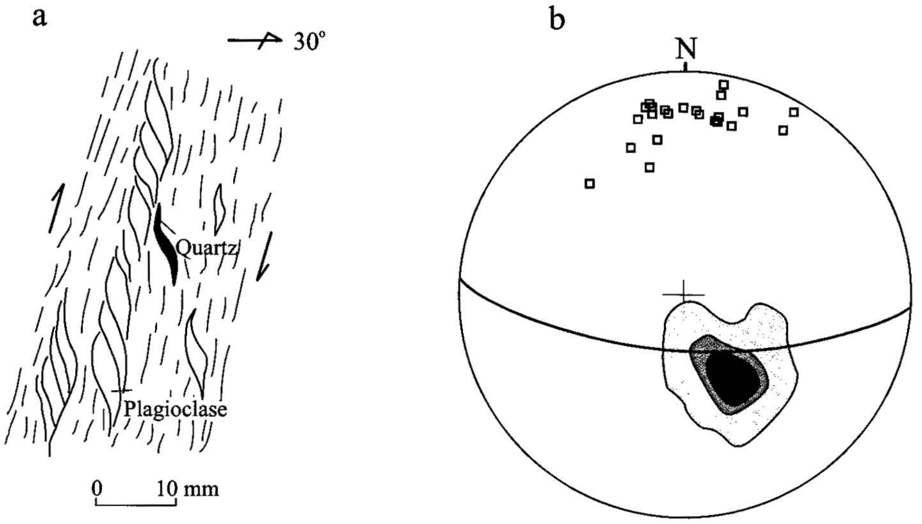

Fig. 2. Kinematics of the ductile thrusting zone in the Qiangenagereer area in the Central East Kunlun Belt.
a – σ-shaped feldspar mortar texture and S-C fabric of schist, showing top-to-the-north ductile thrusting in the XZ plane. b – Equatorial projection of mylonite lineation and foliation in the ductile thrusting zone. The isogram of the lineation, n=55, contour line: 1.9%–18.5%–27.8%–37.0%. The scattered points are the poles of the mylonite foliation, and n=23.

deformation and metamorphic event was preliminarily constrained, the complex processes of the thrust deformation has not been reported in detail and the relationship between the thrust and the medium- to high-grade metamorphic basement needs further study. Based on results of earlier studies and more isotopic data, this research aims at a quantitative constraint on the age of the ductile thrusting deformation in the Gouli area of the eastern part of the Central East Kunlun Belt and describes the complex development of the thrust deformation and studies the relationship between the deformation and the basement. Based on the study, we demonstrate that the late Caledonian movement played a very important role in the development of the Central East Kunlun Belt.

2 Geological Background of the Gouli Area

The geological structure in the Wutou-Gouli area is very complex (Fig. 1). Mapping in detail reveals that the area contains a series of rock slices with different ages and rock assemblages, including upper amphibolite-facies to granulite-facies gneiss and marble, epidote amphibolite-facies meta-volcanic rocks, mica quartz schist and marble, green schist-facies metamorphic molasse, basalt, carbonatite and siliceous pelite, very low-grade metamorphic detrital rocks and coal-bearing detrital rocks, mafic-ultramafic rocks of different ages, etc.

The high amphibolite-facies to granulite-facies gneiss and marble are located at Qingshuiquan (Fig. 1) and can be compared characteristically with the Paleoproterozoic Jinshuikou Group in the Northern East Kunlun Unit. The epidote amphibolite-facies metamorphic rocks are the main target of this paper. The sedimentation age may be the Neoproterozoic-Early Paleozoic as is indicated by the discovery of a series of Acritarch fossils, *Granomarginata squanmaceas, Lophospheridium sp., Goniosphaeridium sp., Prototracheiter porus* and *Geniosphaeridium sp.*, and the Pb-Pb age of 507 Ma of euhedral zircons in the metamorphosed intermediate-acid volcanic rocks. The metamorphosed molasses belong to the Devonian Maoniushan formation, which is covered conformably by volcanic rocks with whole-rock Rb-Sr age of 396.68±18 Ma (Qinghai Geological Survey, 1995). The greenschist-facies metamorphic basalt, carbonate rock and siliceous pelite belong to the Carboniferous-Permian, which is supported by the discovery of Spumellina in siliceous pelite and the Fusulinida, *Verbeekina sp.*, in the carbonate rock.

These rocks constitute a series of high-angle structural

Fig. 1. Sketch map of the Gouli area in the Central East Kunlun Belt.
1. Quaternary; 2. Lower Jurassic Yangqu Formation; 3. Lower Triassic Hongshuichuan Group; 4. Upper Paleozoic, including the Devonian Maoniushan Formation, Lower Carboniferous Halaguole Formation and Carboniferous-Permian Haoteluowa Formation; 5. Lower Paleozoic Naj Tal Group; 6. Neoproterozoic Wanbaogou Group; 7. Mesoproterozoic Kuhai Complex; 8. Mesoproterozoic Xiaomiao Group; 9. Paleoproterozoic Baishahe Group; 10. Jurassic moyite; 11. Hercynian plagiogranite; 12. Hercynian granodiorite; 13. Hercynian adamellite; 14. Caledonian granodiorite; 15. Caledonian adamellite; 16. Caledonian plagiogranite; 17. Caledonian thrusting ductile shear zone; 18. Hercynian dextral strike-slip ductile shear zone; 19. brittle reverse fault; 20. character-unclear brittle fault; 21. strike-slip shearing direction; 22. Hercynian ultramafic rocks; 23. Neoproterozoic ultramafic rocks; 24. attitude of mylonite foliation; 25. attitude of schistosity; 26. attitude of gneissosity; 27. attitude of axial-plane cleavage; 28. unconformity; 29. brittle fault boundary of different structural belt or sub-belt; 30. ductile boundary of different structural belt or sub-belt; 31. structural belt number; 32. sample site. I: East Kunlun-Qaidam microplate; II-1: Caledonian thrusting ductile shear zone; II-2: Mesozoic brittle imbricated fault zone; II-3: Hercynian dextral strike-slip ductile shear zone; III: Jiawengmen block.

Table 1 GLD-68-1 single-grain zircon U-Pb dating results

Number	Character of zircon	Rate of isotope atom*					Apparent age (Ma)		
		$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
1	Lilac transparent	11043	0.1897	0.07169 (43)	0.05471 (46)	0.05535 (30)	446.3	443.1	426.5
2	columnar or long columnar	3334	0.1667	0.07152 (64)	0.5546 (91)	0.05624 (75)	445.3	448	461.7

* $^{206}Pb/^{204}Pb$ thinner and experimental vacancy (Pb=0.050 ng, U=0.002 ng) have been proofread. The lead isotopes of the other rates are radiogenic lead. The numbers in the bracket are 2σ absolute errors, for example, 0.07169(43) can be expressed as 0.07169±0.00043(2σ).

slices with different deformation assemblages and polycyclically superimposed deformation. Among them, the Neoproterozoic-Early Paleozoic meta-volcanic rocks, mica-quartz schist and marble slices are located in the northern part of the belt with an E-W strike (Fig. 1, II-1). A high-angle dipping ductile thrusting foliation is homogeneously developed in the slices. The other slices extend in the southern part of the belt (Fig. 1, II-2 and II-3). They show different styles of deformation. Ductile flow deformation occurred extensively in the Paleoproterozoic high-grade metamorphic rocks, gneiss and marble. In the Late Paleozoic low-grade metamorphic rocks, deformation was dominated by an E-W trending dextral strike-slip ductile shearing under greenschist-facies conditions in the Middle Permian. In addition, there were also a series of E-W trending high-angle brittle thrusting in the Mesozoic and brittle sinistral strike-slipping in the Cenozoic along the boundaries of the slices.

To the north of the Central East Kunlun Belt is the Northern East Kunlun Unit. There expose mainly granitoids of different ages and some scattered basement metamorphic rocks, the Paleoproterozoic Baishahe Group and the Mesoproterozoic Xiaomiao Group. In the study area, the boundary between the Central East Kunlun Belt and the basement metamorphic rocks of the Northern East Kunlun Unit is a strongly ductile shearing transition.

The microstructure, deformation mineral assemblage, paired-mineral geothermometry and fluid inclusion thermometry of quartz in the mylonite indicate that the thrusting ductile shearing occurred in a medium-pressure epidote amphibolite-facies *P-T* condition (China University of Geosciences, 2001).

3 Thrusting Ductile Shearing

Here we aim at the thrusting ductile shearing deformation in the Neoproterozoic-Early Paleozoic metamorphic rocks of the northern part of the Central East Kunlun Belt (Fig. 1, II-1). The rocks include mica-quartz schist, quartzite, gneiss, amphibolite, albite-actinolite schist, marble, calc-schist, calcic-silicate gneiss, etc. An E-W trending, high-angle dipping ductile thrusting foliation was homogeneously developed in these rocks. The foliation mostly dips to the south with a dip angle of over 70°. The deformed rocks, which can also be named structural schist, felsic mylonite, ultramylonite, phyllonite, etc., show strongly ductile shearing and flowing texture. The homogeneous stretching lineation along the foliation statistically parallels the dip of the foliation (Fig. 2a). Sheath folds, whose hinges are approximately parallel to the stretching lineation, occur in the calc-mylonite. A series of macroscopic shear sense, such as rotated porphyroclastic, S-C fabric and domino structure, show top-to-the-north, high-angle ductile thrusting (Fig. 2b).

Under the microscope, the microstructure of the deformed rocks shows strong mineral orientation, especially in the case of chlorite, epidote, biotite, honblende and sericite. Quartz has strong intracrystal plastic deformation characterized by subgrain, polygonization, core-rim texture and polycrystal band texture. Feldspar usually shows porphyroclastic texture and often appears as σ- or δ-shaped objects. But some feldspar shows grain-boundary migration recrystallization. Anomaly sutured boundary can be seen between fine-grained homogeneously recrystallized feldspar grains and their mother grains. Some mineral growth sequences can be determined by their relationships. Some porphyroclastic biotites, which are surrounded by foliation consisting of very fine minerals, are of pre-tectonic crystallization. Many needle honblendes indicate that they were syn-tectonically formed, but some columnar honblendes that cut the foliation must be of post-tectonic crystallization. Micro-shear senses, marked by σ- or δ-shaped objects and S-C fabric, also indicate a top-to-the-north ductile thrusting.

To the north of this thrusting ductile shear zone, metamorphic rocks that was originally included in the Mesoproterozoic Xiaomiao Group, were also strongly influenced by the ductile thrusting shear deformation resulting in straight schistosity or gneissosity parallel to the southern shear zone. The boundary shows a transitional zone of about 100–200 meters wide, which is composed of rocks from both sides.

Microsturcture, typical mineral assemblage, paird-mineral geothermometry and fluid inclusion thermometry of quartz in the mylonite indicate the deformation occurred at a medium-pressure epidote amphibolite-facies *P-T*

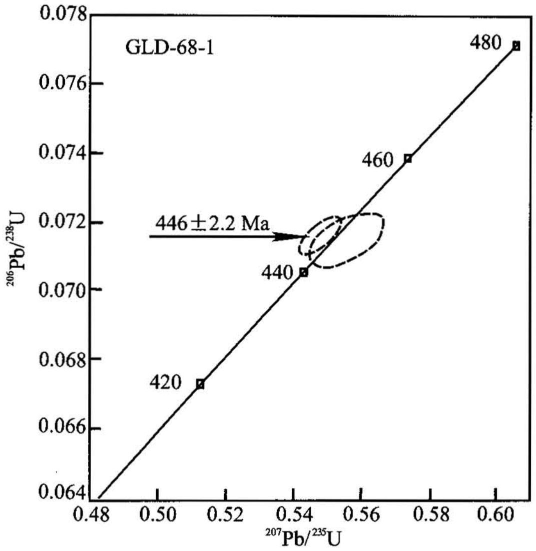

Fig. 3. Zircon U-Pb concordant age of the deformed granodiorite (GLD-68-1) intruding the ductile thrust belt.

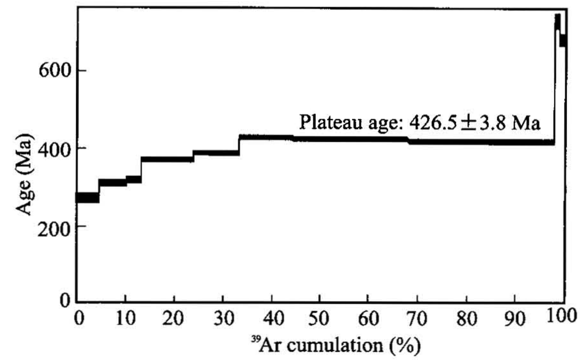

Fig. 4. Ar-Ar age spectrogram of syntectonically crystallized hornblende of the hornblende schist (GLQ-12-2) in the ductile thrusting zone in the Qiangenagereer area.

condition (China University of Geosciences, 2001).

4 Geochronology of the Ductile Thrust Shearing Deformation

As described above, the ductile thrust shearing deformation homogeneously occurred in the Neoproterozoic-Early Paleozoic metamorphic rocks of the northern part of the Central East Kunlun Belt, and strongly influenced the Mesoproterozoic Xiaomiao Group to the north. In the southern part of the Central East Kunlun Belt, the Late Paleozoic low-grade metamorphic rocks show a completely different style of deformation that is dominated by dextral strike-slip ductile shearing (Wang et al., 1999). Thus, we can determine that the ductile thrust shearing deformation is earlier than the sedimentation of the Upper Paleozoic, at least the Upper Devonian. For more detail, we introduce isotope geochronology dating below.

4.1 Age dating

Based on the *P-T* conditions described above, we selected three different kinds of mineral isotopic age dating systems that have different isotope closure temperatures. There are zircon U-Pb (T_c>700°C), hornblende K-Ar and Ar/Ar (T_c≈500–540°C) and muscovite Ar/Ar (T_c≈300–350°C) dating.

The samples were taken from a strongly ductile shearing zone in the Qiangenagereer-Gouli area. The sample locations are shown in Fig. 1. Sample GLD-68-1 is a mylonitized granodiorite in which the deformation is the same ductile thrusting system as that of the country rocks. The homogeneous foliation in it coincides with that of the country rocks. We separated the zircon and dated the zircon by the U-Pb method to try to get the intrusion age, so as to get the lower age limit of the ductile thrusting deformation. Sample GLQ-12-2 is a strongly orientated hornblende schist. The hornblende in it is also strongly orientated and needle-shaped and syn-tectonically crystallized. So, we dated the needle-shaped hornblende by the K-Ar and Ar/Ar methods and try to get the deformation age as close as possible because the closure temperature of hornblende Ar is close to the deformation temperature. Sample GLD-23-2 is from a strongly deformed muscovite-quartz schist. We dated the muscovite by the Ar/Ar method and try to obtain the upper age limit of the ductile thrusting deformation because the closure temperature of muscovite Ar is lower than the deformation temperature. Samples GLD-95-1 and GLD-97-1 are also strongly deformed miscovite-quartz schists but are collected in the deformed Xiaomiao Group to the north. We also dated the muscovite by the Ar/Ar method for a comparison analysis. The dating results are listed in Tables 1 and 2.

4.2 Interpretation of the ages and discussion

The zircon U-Pb age dating of Sample GLD-68-1 gives a concordant age of 446±2.2 Ma (Fig. 3). The shapes of the dated zircons reflect a genesis of magmatic crystallization. Because their U-Pb isotope have a much higher closure temperature than the ductile thrusting deformation temperature and must have not been reset by the deformation or metamorphism, the concordant age of 446±2.2 Ma can be recognized as the magmatic crystallization age of the granodiorite. The deformation must be younger than about 446 Ma.

The K-Ar dating of hornblende of Sample GLQ-12-2

Table 2 Step heating data for Ar/Ar dating of hornblende (GLQ-12-2) and muscovite (GLD-23-2, GLD-95-1 and GLD-97-1)

Sample	T (°C)	$(^{40}Ar/^{39}Ar)_m$	$(^{36}Ar/^{39}Ar)_m$	$(^{37}Ar/^{39}Ar)_m$	$^{*40}Ar/^{39}Ar$	^{39}Ar (mol) (10^{-14})	Apparent age (Ma)	Cumulating ^{39}Ar (%)
GLQ-12-2 (hornblende)	500	22.8571	0.0357	3.5345	12.5851	70.00	269.6±11.3	4.70
	600	20.7805	0.0244	11.3740	14.5074	82.00	307.4±8.2	10.20
	700	20.7191	0.0225	12.0631	15.0753	44.50	318.4±7.7	13.19
	800	20.0316	0.0108	11.1685	17.8017	158.00	370.5±5.3	23.79
	900	21.2230	0.0115	11.1111	18.7723	139.00	388.6±5.6	33.12
	1000	22.5610	0.0085	11.0631	21.0049	164.00	429.7±5.4	44.13
	1100	22.5978	0.0092	11.0994	20.8421	358.00	426.8±5.5	68.15
	1200	22.4719	0.0094	10.9511	20.6363	445.00	423.0±5.5	98.02
	1300	88.0000	0.1667	7.4973	39.5153	15.00	738.7±19.5	99.03
	1400	66.2069	0.1035	6.2047	36.2541	14.50	688.0±14.7	100.00
GLD-23-2 (muscovite)	400	20.3077	0.0077	0.0656	18.0354	65.00	288.0±3.8	1.71
	500	24.3636	0.0045	0.0388	23.0191	110.00	360.0±4.2	4.59
	610	25.8152	0.0027	0.0232	25.0096	184.00	388.0±4.4	9.42
	700	26.8818	0.0023	0.0197	26.2072	220.00	404.7±4.5	15.20
	780	27.0629	0.0017	0.0149	26.5429	572.00	409.3±4.6	30.21
	890	27.0000	0.0015	0.0129	26.5487	330.00	409.4±4.5	38.87
	990	27.0175	0.0018	0.0149	26.4957	285.00	408.7±4.5	46.35
	1070	26.8534	0.0012	0.0101	26.5003	423.00	408.7±4.5	57.45
	1160	26.6515	0.0007	0.0121	26.4459	878.00	408.0±4.4	80.50
	1220	26.9842	0.0020	0.0169	26.3970	506.00	407.3±4.5	93.78
	1315	27.5161	0.0032	0.0275	26.5606	155.00	409.6±4.6	97.85
	1400	32.6585	0.0122	0.1040	29.0599	82.00	443.7±5.6	100.00
GLD-95-1 (muscovite)	400	11.3478	0.01449	0.00303	7.0607	138.00	118.3±3.9	3.54
	500	19.7360	0.01563	0.00435	15.1180	96.00	244.4±4.7	6.00
	610	26.4065	0.00645	0.00270	24.4955	155.00	380.9±4.5	9.97
	700	25.2923	0.00192	0.00161	24.7194	260.00	384.0±4.3	16.63
	780	25.1654	0.00165	0.00077	24.6719	544.00	383.3±4.3	30.57
	890	25.2000	0.00167	0.00139	24.7028	300.00	383.8±4.3	38.26
	990	25.7083	0.00417	0.00348	24.4726	120.00	380.5±4.4	41.34
	1070	24.9631	0.00123	0.00103	24.5945	406.00	382.2±4.2	51.74
	1160	24.9403	0.00074	0.00061	24.6883	1360.00	383.6±4.0	86.60
	1220	25.0168	0.00140	0.00117	24.5994	358.00	382.3±4.5	96.77
	1315	25.0625	0.00089	0.00373	24.7942	112.00	385.0±4.2	98.64
	1400	28.8302	0.00943	0.01577	26.0391	53.00	402.4±5.0	100.00
GLD-97-1 (muscovite)	400	20.7273	0.0091	0.0079	18.0368	55.00	288.0±4.0	1.23
	500	23.3636	0.0045	0.0040	22.0160	110.00	345.8±4.1	3.70
	610	25.1392	0.0032	0.0028	24.1996	158.00	376.7±4.3	7.24
	700	26.1667	0.0556	0.0024	24.5204	180.00	381.2±4.5	11.28
	780	25.5000	0.0017	0.0007	25.0028	600.00	388.0±4.3	24.73
	890	25.5022	0.0019	0.0006	24.9350	683.00	387.0±4.3	40.04
	990	25.4687	0.0016	0.0014	25.0024	320.00	387.9±4.3	47.21
	1070	25.1093	0.0010	0.0009	24.7999	485.00	385.1±4.3	58.08
	1160	25.3214	0.0008	0.0006	25.0787	1366.00	389.1±4.4	88.70
	1220	25.5515	0.0018	0.0015	25.0036	272.00	387.9±4.5	94.80
	1315	26.0000	0.0033	0.0029	25.0105	150.00	388.1±4.4	98.16
	1400	32.6585	0.01220	0.0053	29.0506	82.00	443.6±5.6	100.00

* GLQ-12-2 (hornblende), weight =347.3 mg, J=0.012806; GLD-23-2 (muscovite), weight=98 mg, J=0.009596. GLD-95-1 (muscovite), weight=128.3 mg, J=0.009596; GLD-97-1 (muscovite), weight=99.65 mg; J=0.009596.

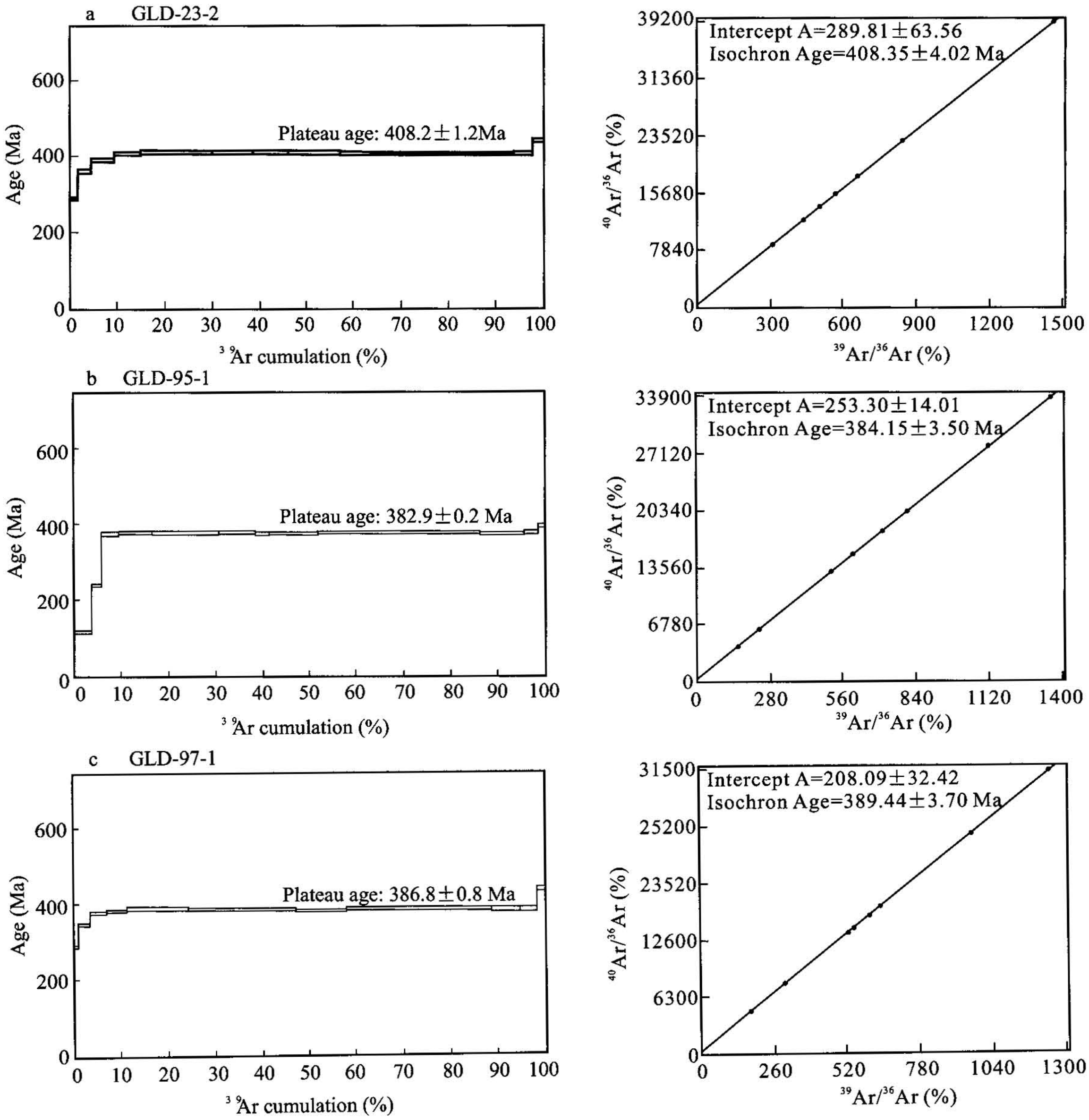

Fig. 5. Muscovite Ar-Ar ages of deformed rocks in the ductile thrust in the Gouli area.
(a) – Ar-Ar age spectrogram of orientated muscovite and isochron age of the muscovite-quartz schist (GLD-23-2) in the ductile thrusting belt; (b) and (c) – Ar-Ar age spectrogram of muscovite and isochron ages of muscovite-quartz schist (GLD-95-1, GLD-97-1) in the deformed Xiaomiao Group to the north of the Central East Kunlun Belt.

yieldedd an age of 431.1±9.9 Ma. Its Ar/Ar age dating shows that, although stepped plateaus occurred in the lower-temperature periods, 53.89% of ^{39}Ar was released in the three higher-temperature steps of 1000°C, 1100°C and 1200°C. The apparent ages in these three stages are 429.7±5.4 Ma, 426.8±5.5 Ma and 423.0±5.5 Ma, respectively. They form a wide high-temperature plateau age of 426.5±3.8 Ma (Fig. 4). Because the hornblendes are syn-tectonically crystallized and the Ar/Ar closure temperature of the hornblendes is close to that of the deformation and metamorphism temperatures, 426.5±3.8 Ma can in principle be taken as the crystalization age of the hornblendes, and thus, the ductile thrusting age.

The Ar/Ar dating of muscovite in the muscovite-quartz schist (Sample GLD-23-2) gives a very good plateau age of 408±1.6 Ma (Fig. 5A) that is concordant with the isochron age (408.35±4.02 Ma). The isochron brings about a $(^{40}Ar/^{36}Ar)_0$ ratio of 289.81±63.56, very close to the $^{40}Ar/^{36}Ar$ ratio of the atmosphere (295.5), showing that there was little influence of excess argon. Because of the relatively low closure temperature of muscovite Ar isotope (~300°C), this age should be the cooling age after the peak thermo-tectonic event (about 440–540°C) and can be regarded as the upper age limit of the ductile thrusting

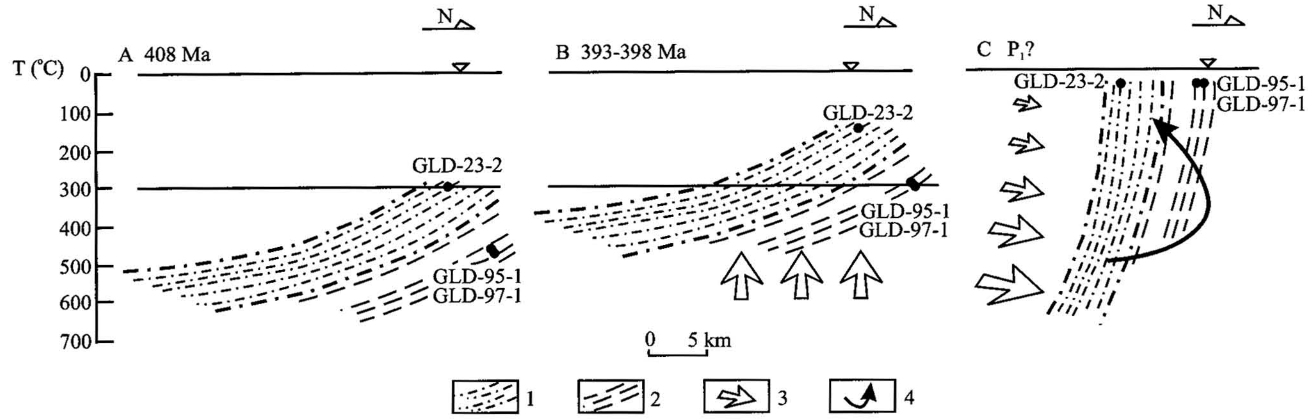

Fig. 6. Cartoon model showing the possible situation of the thrusting shear belt after ductile thrusting.
1. Ductile thrusting shear foliation in the Neoproterozoic Wanbaogou Group-Early Paleozoic Naj Tal Group; 2. folication in the Mesoproterozoic Xiaomiao Group; 3. stress; 4. rotation direction.

deformation.

Samples GLD-95-1 and GLD-97-1 from the deformed Xiaomiao Group to the north of the Central East Kunlun Belt give similar ages. Their plateau ages and isochron ages, all showing good coherence, are 382.9±0.2 and 384.15±3.5 Ma for Sample GLD-95-1, and 386.8±0.8 Ma and 389.44±3.7 Ma for Sample GLD-97-1 (Fig. 5b and c). The $(^{40}Ar/^{36}Ar)_0$ values of the two samples are 253.3±14.01 and 208.09±32.42 respectively, also indicating almost no influence of excess argon. The Ar/Ar ages of these two samples are younger than that of Sample GLD-23-1 (see Fig. 5a). If these muscovite Ar/Ar ages represent the uplift cooling caused by the ductile thrusting, according to the closure temperature theory, the upthrown side must give an older age than that of the downthrown side, the ages should be older and older from the south to north because of the top-to-the-north ductile thrusting movement. Obviously, this explanation is conflicting to our observation. A reasonable interpretation is that the Ar/Ar cooling ages of Samples GLD-95-1 and GLD-97-1 are completely independent of the ductile thrusting. That is to say, the top-to-the-north thrusting must have ended before about 383–390 Ma if we still assume there existed a top-to-the-north brittle-ductile thrusting. The comparatively younger muscovite Ar/Ar cooling ages of the deformed Xiaomiao Group represent a single exhumation period during the Early Devonian because it was just the period of strong exhumation and the occurrence of molasses. In this period, Sample GLD-23-2 should not have been at the same level as Samples GLD-95-1 and GLD-97-1. The latter two were located at a deeper level than the former. This means that the high-angle dipping foliation we see today should be low-angle before about 383–390 Ma (Fig. 5a and b). A rotation model may illustrate the development from the original low-angle to present high-angle dipping (Fig. 6). We still have not enough data to constrain this rotation event. An utmost probability is that the rotation was caused by the subduction or closure of the Paleo-Tethys ocean crust during the Permian along the southern part of the Central East Kunlun Belt.

In summary, the top-to-the-north ductile thrusting event occurred during 446–408 Ma or at about 426.5 Ma in the late Caledonian.

5 Conclusion

Our geochronology study proves that there was an intensive thrusting deformation in the late Caledonian period. Regionally, the Central East Kunlun Belt and the Southern East Kunlun Belt to the south were an archipelago consisting of a series of Precambrian blocks, islands, and different kinds of ocean basins during the Neoproterozoic-Early Paleozoic (Yin and Zhang, 1998). The protolith of the deformed and metamorphosed Neoproterozoic-Early Paleozoic rocks were volcanic lava–volcaniclastic rocks-carbonate pelites, representing a limited ocean basin between the Jiawengmen block to the south and the Northern East Kunlun-Qaidam microplate to the north. The top-to-the-north ductile thrusting is the dominating deformation in this assemblage of rocks and can be ascribed to the collision between the Jiawengmen block and the Northern East Kunlun-Qaidam microplate. Therefore, the age of 446–408 Ma or ~426.5 Ma should be associated with the time of the closing of the archipelago. The top-to-the-north ductile thrusting indicates that the collision was an obduction with the small Jiawengmen block overriding the Northern East Kunlun-Qaidam microplate. This thermo-tectonic event made the Neoproterozoic-Early Paleozoic rocks in the Central East Kunlun Belt sealed with the basement rocks of the Northern East Kunlun-Qaidam microplate, followed by an open-and-close development of the Paleo-Tethys archipelago along the southern part of the

Central East Kunlun Belt during the Carboniferous-Permian. There were more complicated Hercynian-Indosinian tectonic melanges in the southern part of the Central East Kunlun Belt (Fig. 1, II-2 and II-3) (Wang et al., 1999). The Hercynian-Indosinian movement did not change the order of the ductile thrust belt discussed in this paper, but probably rotated the foliation from low-angle to high-angle dipping.

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