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Ductile deformation and $^{40}Ar/^{39}Ar$ dating of the Changle–Nanao ductile shear zone, southeastern China

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Abstract

An investigation of ductile deformation, mylonitization and $^{40}Ar/^{39}Ar$ geochronology in the Changle–Nanao ductile shear zone, southeastern China, is reported in this paper. At least two phases of ductile deformation occurred in the shear zone in the Mesozoic. The first is a NE-trending foliation widely developed in metasedimentary rocks and orthogneisses, and is associated with metamorphism of amphibolite facies at 165–178 Ma. The second is a strike-slip-related ductile deformation developed both in the metamorphic rocks and the Mesozoic volcanics and includes folds, shear foliation or cleavage, *S–C* fabrics, NE-striking stretching lineation, and mylonitic microstructures. The ductile deformation and dislocation microstructures of quartz and the brittle deformation microstructures of plagioclase in the mylonites from the shear zone indicate that the second phase of ductile deformation and mylonitization occurred under greenschist facies conditions at temperatures of 300–350°C. $^{40}Ar/^{39}Ar$ plateau ages of five minerals from deformed and mylonitized rocks in the shear zone are in the range of 118–107 Ma. The plateau ages record the time of ductile deformation and mylonitization associated with strike-slip movement along the Changle–Nanao ductile shear zone.

1. Introduction

The Changle–Nanao shear zone in the coastal region of Fujian Province (Fig. 1) played an important role in the tectonic framework and evolution of southeastern coastal China in the Mesozoic (Guo et al., 1980; Yu et al., 1982; Ren et al., 1984; Xu et al., 1987, 1990; Xie and Guo, 1989; Charvet and Faure, 1989; Charvet et al., 1990, 1994; Gao et al., 1991; Li, 1993; Lu et al., 1993, 1994; Zhu et al., 1993; Wang et al., 1995; Tong and Tobisch, 1996; Wang and Lu, 1996, 1997a, b). In recent years, two contradictory views of its origin have been put forward. First, the Changle–Nanao shear zone is a large-scale ductile shear zone with sinistral strike-slip displacement during the Mesozoic of up to 227 km (e.g. Xu et al., 1987, 1990; Zhu et al., 1993). Second, it is a Mesozoic suture zone which represents the collision of two terranes, the Min-Zhe Mesozoic calc-alkaline volcanic arc and the Min-Tai microcontinent (e.g. Hsu et al., 1990; Gao et al., 1991; Li, 1993; Lu et al., 1993, 1994). Ductile deformation in the amphibolite facies metamorphic rocks of the Fujian coastal region and some Mesozoic volcanic rocks of lower greenschist facies adjacent to the shear zone has been studied in recent years (Xu et al., 1987, 1990; Charvet et al., 1990; Gao et al., 1993; Zhu et al., 1993; Lu et al., 1993, 1994; Tong and Tobisch, 1996; Wang et al., 1995; Wang and Lu, 1996, 1997a, b). It is generally believed that ductile deformation associated with strike-slip movement along the shear zone occurred mostly during the early Cretaceous, and that most of the deformed rocks are mylonitized (e.g. Ma, 1991; Tong and Tobisch, 1996; Wang et al., 1995; Wang and Lu, 1997b). However, the time of ductile deformation has mostly been determined using Rb–Sr and K–Ar ages, except for one $^{40}Ar/^{39}Ar$ age (biotite and muscovite, 99–98 Ma, Fu et al., 1989) and one U–

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Pb age (zircon, 121.5 ± 2.8 Ma, Tong and Tobisch, 1996).

In this paper we present data on ductile deformation structures and mylonitic microstructures, and use them to assess the deformation temperature. We also present here $^{40}Ar/^{39}Ar$ ages on the deformed and mylonitized samples to provide constraints on the time of ductile deformation and mylonitization associated with strike-slip movement along the Changle–Nanao ductile shear zone. This approach has been widely used to constrain the timing of deformation in deformed structural zones like the Changle–Nanao ductile shear zone (e.g. Kligfield et al., 1986; Costa and Maluski, 1988; Zingg and Hunziker, 1990; Dunlap et al., 1991; Hammerschmidt and Franz, 1992; Leloup et al., 1993; West and Lux, 1993; Barnicoat et al., 1995; Dunlap et al., 1995; Scheuber et al., 1995; Dallmeyer et al., 1997; Jacobs et al., 1997; Lepvrier et al., 1997; West and Hubbard, 1997; Foster and Ehlers, 1998; Markley et al., 1998; Wortman et al., 1998; Dezes et al., 1999).

2. Geological setting

2.1. Regional geology

There are four main rock units in the studied area: a mixed package of older metamorphic rocks, Mesozoic granites and volcanics, and mafic–ultramafic rocks of uncertain age (Fig. 1). The metamorphic rocks in the Fujian coastal region are composed of metasedimentary rocks and orthogneisses showing amphibolite facies mineralogy. The principal mineral assemblages of these rocks have been described by previous workers (e.g. Gao et al., 1991; Tong and Tobisch, 1996). The orthogneisses, mainly granitic gneisses and gneissic granitoids, partly occur within the meta-sedimentary rocks as small bodies (e.g. at Donggu and Aojiao in the Dongshan area and in the Zhongmen area), and mostly as large bodies in the Shishi, Duchuo, Geshan, Weitou and Yongning areas and in the western part of the Dongshan area (Fig. 1). The metasedimentary rocks are mainly quartzite, impure quartzite, mica schist, mica–quartz schist, andalusite or/and sillimanite–mica schist and plagioclase amphibolite. Most of them occur near Donggu and Aojiao in the Dongshan area and in the southern part of the Zhongmen area, and part of them occur within the orthgneisses as small lenses (e.g. in the Geshan area). The metamorphic rocks, including the metasedimentary rocks and orthogneisses, have been designated as late Triassic–early Jurassic age (Geology and Mineral Resources Bureau of Fujian Province, 1985). The Cambrian–Ordovician microfossils of palaeophyco-

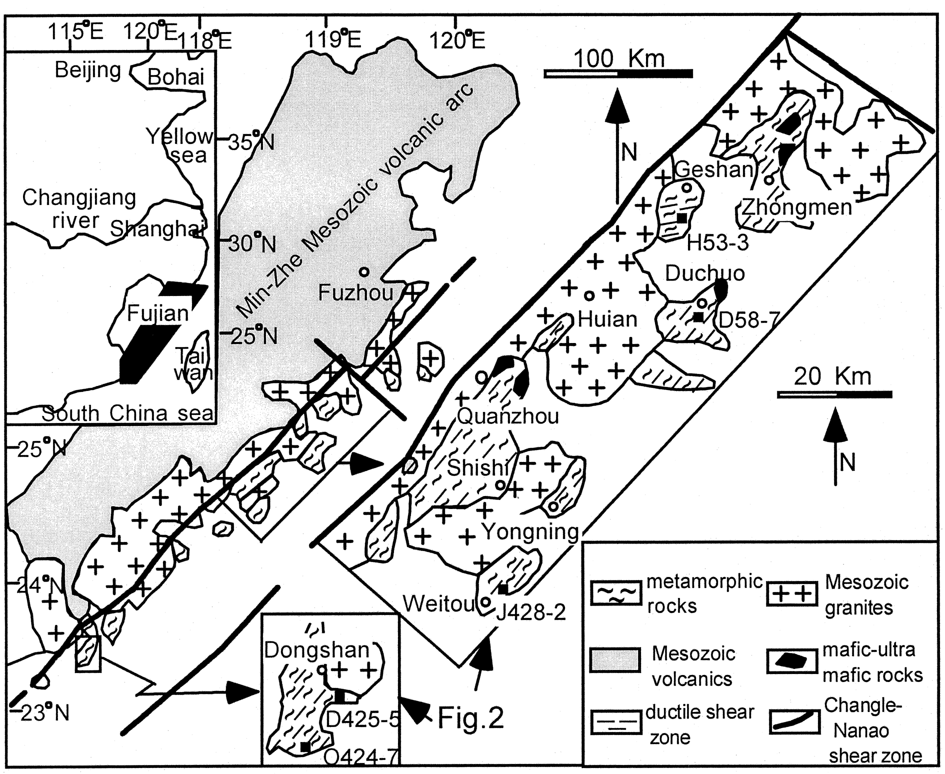

Fig. 1. Simplified geological map of Fujian coastal region, southeastern China, showing the main rock units, the Changle–Nanao ductile shear zone and the locations of $^{40}Ar/^{39}Ar$ dating samples (solid squares with numbers).

phyta and various chitinozoans found in graphitic biotite–quartz schist from the Dongshan area (Huang et al., 1988; Yu et al., 1988), and two Sm–Nd whole-rock isochron ages of 463 ± 15 and 509 ± 20 Ma from plagioclase amphibolite in the Zhongmen and Shishi areas (Huang et al., 1989), suggest that the protoliths of the metasedimentary rocks were deposited in the early Paleozoic. Intrusive ages of the orthogneisses are not well constrained. Rb–Sr isochron ages, mainly obtained from the orthogneisses and a part of metasedimentary rocks, are mostly in the range of 178–165 Ma (e.g. Jahn et al., 1976; Gao et al., 1993; Lu et al., 1994), suggesting that a large part of the orthogneisses were intruded in the period of 178–165 Ma. As Jahn et al. (1976) suggested, a tectonothermal event occurred at this time in the coastal region of southeastern China. This tectonothermal event led to the amphibolite facies metamorphism, and accompanied intense deformation within the metamorphic rocks. Temperature and pressure of the metamorphism and deformation, determined from plagioclase–amphibole and biotite–garnet thermobarometry, are 540–610°C, 0.28–0.35 GPa for plagioclase–amphibolite and 485–640°C, 0.3 GPa for mica–quartz schist, respectively (Zhang et al., 1991). However, some gneissic granitoids were intruded in the early Cretaceous (Tong and Tobisch, 1996) and their emplacement was associated with strike-slip movement or shearing along the Changle–Nanao shear zone (e.g. in the Dongshan area, Tong and Tobisch, 1996).

Mesozoic granites were not affected or only weakly affected by deformation, and their Rb–Sr and K–Ar ages are mainly in the range of 110–70 Ma (e.g. Jahn et al., 1976; Geology and Mineral Resources Bureau of Fujian Province, 1985; Gao et al., 1993). The Mesozoic granites are widely distributed, both in and outside the shear zone (Fig. 1).

Mesozoic volcanics occur mostly in the interior mountains of Fujian and Zhejiang provinces and constitute the Min (Fujian)–Zhe (Zhejiang) Mesozoic volcanic arc. Part of these volcanics lie unconformably upon the metamorphic rocks in the coastal region, e.g. in the Dongshan and Quanzhou areas. They are commonly divided into two groups: the 134–114 Ma (Zhu et al., 1988) Nanyuan Formation and the late Cretaceous Shimaoshan Group lying unconformably upon the Nanyuan Formation. The Shimaoshan Group is devoid of any deformation and metamorphism. The Nanyuan Formation near the shear zone is affected by deformation and lower greenschist metamorphism defined by the principal mineral assemblage of quartz–sericite.

The mafic–ultramafic rocks, cropping out along the northern segment of the Changle–Nanao shear zone (Fig. 1), are composed of serpentinite, tremolitite, soapstone and gabbro. There are two interpretations for these rocks: (1) small magmatic bodies intruded along the Changle–Nanao intracontinental deep fault (Geology and Mineral Resources Bureau of Fujian Province, 1985; Cao and Zhu, 1989) or into an active continental margin as the mafic end-number of calc-alkaline volcanics (Zhou et al., 1994); and (2) an ophiolite suite or ophiolite melange indicative of Mesozoic collision in the Fujian coastal region (Hsu et al., 1990; Gao et al., 1991; Li, 1993; Lu et al., 1993, 1994).

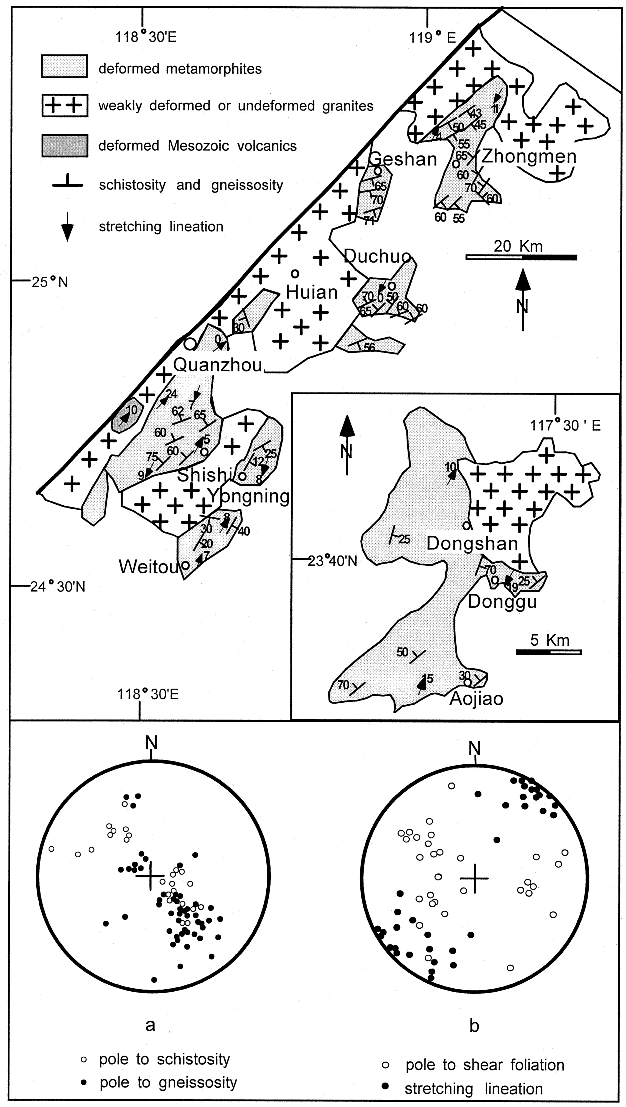

Fig. 2. Structural map showing the main structural elements in the Changle–Nanao ductile shear zone, and their stereographic projection. (a) Pole to schistosity (open circle, 24 points) and gneissosity (solid circle, 50 points); (b) pole to shear foliation (open circle, 30 points) and stretching lineation (solid circle, 36 points). Some attitudes of stretching lineation are cited from Ma (1991) and Tong and Tobisch (1996).

2.2. Ductile deformation in the ductile shear zone

The Changle–Nanao ductile shear zone is characterized by ductile deformation and metamorphism. The petrological composition and principal mineral assemblages suggest that the metamorphic rocks in the shear zone, including the metasedimentary rocks and orthogneisses, are of amphibolite facies, and the Nanyuan Formation cropping out in or near the western part of the shear zone is of lower greenschist facies. The metamorphic rocks were subjected to intense ductile deformation, which gave rise to schistosity and gneissosity, folds, *S–C* fabrics, stretching lineation, shear foliation and other mylonitization-related microstructures. The Nanyuan Formation was subjected to moderate deformation, which gave rise to folds, cleavage and stretching lineation. It is generally believed that at least two phases of ductile deformation occurred in the studied areas during the Mesozoic: in Jurassic and in early Cretaceous (e.g. Yu et al., 1982; Li et al., 1983; Ma, 1991; Gao et al., 1993; Lu et al., 1994).

2.2.1. Pre-shear deformation

A pre-mylonitization foliation in schists and gneisses is strongly and pervasively developed. It strikes N30°–70°E and dips NW or SE at variable angles (Fig. 2). As reported by some researchers (e.g. Tong and Tobisch, 1996), the foliation fabric is defined by a strong preferred alignment of sillimanite, muscovite, biotite and quartz in the metasedimentary rocks, and of quartz, biotite and metamorphic hornblende in the orthogneisses, indicating that the schistosity and gneissosity developed under amphibolite facies conditions, consistent with the aforementioned metamorphism at 178–165 Ma. Therefore we infer that most of the schistosity and gneissosity developed coevally with the metamorphism. We do not link the development of this schistosity and gneissosity to strike-slip movement along the shear zone, as the Jurassic volcanics near the western part of the shear zone were only subjected to deformation and metamorphism of lower greenschist facies. The large difference in deformation and metamorphism between the metamorphic rocks and the adjacent Mesozoic volcanics suggests that the Changle–Nanao shear zone was not formed in the Jurassic (e.g. Gao et al., 1993; Lu et al., 1994). This difference is also one of the most important lines of evidence to prompt some workers to put forward a model of accreted terrane–volcanic arc collision (e.g. Gao et al., 1991; Li, 1991; Gao et al., 1993; Lu et al., 1994).

2.2.2. Strike-slip related deformation

A series of folds are exposed at Aojiao and Donggu in the Dongshan area (e.g. Gao et al., 1993; Lu et al., 1994; Tong and Tobisch, 1996). Interlayered quartzites and biotite schists, quartz dikes and some mylonitized granitic gneisses are tightly folded. The obliquity of fold axial planes to the strike of the shear zone has been used to deduce sinistral strike-slip movement along the Changle–Nanao ductile shear zone (e.g. Tong and Tobisch, 1996).

Many shear foliations crosscut the pre-existent gneissosity and schistosity at variable angles, and deflect the latter into a sigmoidal curve, indicating sinistral or dextral shearing. Displacement along the respective foliation is small, generally several to tens of centimeters. The shear foliations stretch for tens of centimeters to several meters, are spaced tens of centimeters apart and mainly developed in granitic gneisses. They mostly strike N-NE (0°–35°), but also NW (330°–350°) (Fig. 2).

Stretching lineations, mostly defined by the preferred alignment of strongly elongated or recrystallized quartz aggregates, plunge NE or SW at gentle angles (Fig. 2). Volcanics of the Nanyuan Formation within or near the shear zone, with an age of 114–134 Ma (Zhu et al., 1988) and subjected to deformation in the lower greenschist facies, have also developed this stretching lineation (Fig. 2), implying that the strike-slip-related deformation occurred under greenschist facies conditions and developed in the early Cretaceous. This suggestion is supported by the following studies of deformation microstructures in the mylonites and $^{40}Ar/^{39}Ar$ dating on deformed and mylonitized samples from the shear zone.

3. Deformation microstructures in the mylonites

Within the Changle–Nanao ductile shear zone most metasedimentary rocks and orthogneisses were mylonitized to variable degrees from protomylonite to ultramylonite (Higgins, 1971; Sibson, 1977).

Quartz grains were strongly elongated (Fig. 3a) and intensively recrystallized. Undulatory extinction and deformation bands are common in deformed quartz grains (Fig. 3b). Dynamic recrystallization and recovery occur to a large extent within quartz grains:

1. The dynamically recrystallized quartz grains have subgrains, resulting from dislocation glide and creep, and serrated or sutured boundaries, indicating grain boundary migration during or after ductile deformation (Fig. 3c);
2. Core–mantle structure: the quartz porphyroclast (core) is encircled by neomorphic recrystallized quartz crystals (mantle) (Fig. 3d);
3. The dynamically recrystallized grains and subgrains have a well-developed lattice preferred orientation due to local shear strain. The acute angle between the microscopic foliation and the long axes of

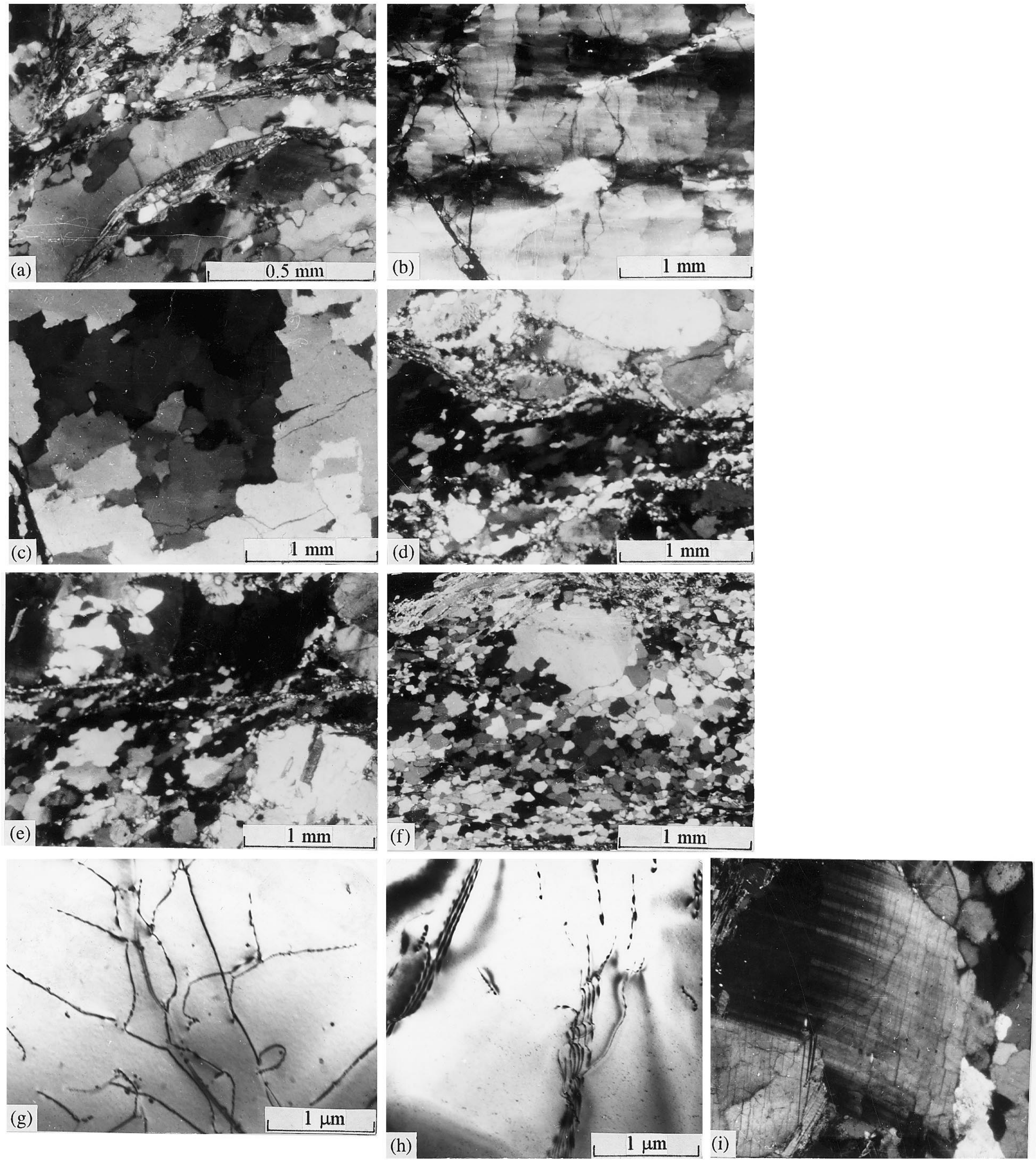

Fig. 3. Photomicrographs of microstructures in mylonites. Thin sections cut normal to mylonitic foliation and parallel to stretching lineation (*XZ* section). Crossed polarizers. (a) Oblique, elongate, recrystallized quartz grain, Yongning, Jinjiang area. (b) Undulatory and banded extinction of quartz grain, Zhongmen, Putian area. (c) Recrystallized quartz grains and subgrains with serrated or sutured boundaries, Aojiao, Dongshan area. (d) Core–mantle structure of quartz, Yongning, Jinjiang area. (e) Oblique, recrystallized quartz grains and subgrains,Yongning, Jinjiang area. (f) Recrystallized and polygonal quartz, Donggu, Dongshan area. (g) Free dislocations and dislocation tangle in a quartz crystal, Houzhu, Quanzhou area. Electron photomicrograph. (h) Free dislocations and dislocation walls in a quartz crystal, Aojiao, Dongshan area. Electron photomicrograph. (i) Curved and kinked twin of plagioclase, Duchuo, Huian area.

these grains can be used to deduce the shear sense of the ductile shear zone (Fig. 3e). This fabric is that of type-II *S–C* mylonite of Lister and Snoke (1984);

4. Polygonal strain-free quartz grains have straight grain boundaries, suggesting post-mylonitic grain growth (Fig. 3f). The sizes of polygonal quartz grains are similar to those of dynamically recrystallized quartz grains, indicating that the effect of post-mylonitic grain growth on quartz grain sizes is limited.

TEM microstructures of lines, loops, tangles (Fig. 3g), networks and walls of dislocations and subgrains (Fig. 3h) are found in dynamically recrystallized quartz grains. The co-existence of dislocation walls and tangles also suggests that the deformation micromechanics of the quartz are dislocation glide and creep.

The deformation microstructures of feldspar in mylonites are mainly asymmetric augen structures and regular re-arrangement of the plagioclase grains, which are caused by sliding and rotating between grains. Curved and kinked twins of plagioclase are also found (Fig. 3i). However the existence of a series of microfractures which are perpendicular to the twins indicates that the deformation of plagioclase is brittle.

Crystal-plastic deformation in quartz and feldspar becomes important above 300±50°C and 450±50°C, respectively (Voll, 1976; Tullis and Yund, 1977; Tullis, 1983; Sibson, 1983). The lower temperature limit where quartz can be deformed significantly by dislocation creep at geologically reasonable strain rates is about 300°C (Sibson, 1977). The ductile deformation and dislocation microstructures of quartz and the brittle deformation of feldspar in mylonites from the shear zone indicate that mylonitization occurred under greenschist facies conditions, at temperatures of about 300–350°C. Tong and Tobisch (1996) proposed that, on the basis of hornblende geobarometry for pressure and fluid inclusion studies, the temperature of ductile deformation in the shear zone was 740°C, much higher than we deduce here. These higher reported temperatures are local temperatures only and are related to contact effects around syn-shearing plutons. Our samples came from parts of the shear zone away from such affected areas and, therefore, are much more representative than the higher temperature samples.

The micas in mylonitized rocks are also deformed. In granitic gneisses, they commonly display curved twins or displaced broken grains, and in the rocks having mica-forming fabrics like mica schists, they commonly show as mica fish mainly in *S*-planes (see Wang and Lu, 1997b for details).

4. $^{40}Ar/^{39}Ar$ geochronology

4.1. Analytical method and results

Five typically deformed and mylonitized samples from the shear zone were collected for $^{40}Ar/^{39}Ar$ geochronology (see Fig. 1 and Table 1 for sample locations). Standard mineral separation techniques were used. The samples were irradiated in the 49-2 reactor at the Institute of Atomic Energy, Chinese Academy of Sciences, using Chinese Standard Samples of ZBJ (Hb, 132.9 Ma) and ZBH-25 (Bi, 132.7 Ma) as flux monitors. $^{40}Ar/^{39}Ar$ step-heating analyses were conducted at the Institute of Geology, Chinese Academy of Sciences. The system employs a double-vacuum resistance furnace for sample heating and is in line with a RAG-10 mass spectrometer. The data with estimated analytical precision ($\pm\sigma$) are corrected for system blanks, mass discrimination, and interfering neutron reactions with Ca and K. The $^{40}Ar/^{39}Ar$ analytical data and resultant ages are presented in Tables 2 and 3 and are plotted as age spectra in Fig. 4.

Donggu-Aojiao in the Dongshan area: muscovite and biotite analyses on two mica schists (D425-5, O424-7) yield plateau ages of 107.9±2.4 Ma and 108.2±2.9 Ma, respectively. The percentages of ^{39}Ar released for the plateau ages are 98.5% and 99.5%, and the isochron ages are 110.2 Ma and 111.4 Ma, respectively.

Weitou in the Jinjiang area: the plateau age of biotite from biotite granitic gneiss (J428-2) is 107.1±0.9 Ma for 98% of the gas released. The data for the plateau steps yield a four-point isochron age of 106.9 Ma.

Geshan in the Huian area: biotite analysis on biotite–plagioclase granulite (H53-3) displays a plateau age of 117.9±2.0 Ma for 99.9% of the gas released, and the isochron age corresponding to the plateau age is 119.6 Ma.

Duchuo in the Huian area: the plateau age of hornblende from augen mylonite (D58-7) is 109.2±2.2 Ma corresponding to 99% of the gas released, and an isochron plot for this sample suggests an age of 115.7 Ma.

The age spectra determined by the $^{40}Ar/^{39}Ar$ step-heating method for five mineral separates are relatively undisturbed and flat, and yield good plateau ages for a substantial portion (> 98%) of the gas released. The isochron ages corresponding to the plateau steps are substantially concordant with the respective plateau ages. All this suggests that the plateau ages of the five mineral separates are reliable. The initial $^{40}Ar/^{36}Ar$ ratios of D425-5 (Mus), J428-2 (Bi) and D58-7 (Hb) are 292.5, 297.8 and 280.7, respectively, consistent with that of the modern atmosphere (295.5). The same ratio for H53-3 (Bi) is 312.9, and its plateau age (117.9 Ma) is older than that of Hb (109.2 Ma), revealing the pre-

Table 1
Sample selection for $^{40}Ar/^{39}Ar$ dating

Sample	D425-5	O424-7	J428-2	H53-3	D58-7
Rock	muscovite–quartz schist	biotite schist	biotite granitic gneiss	biotite–plagioclase granulite	granitic gneiss
Mineral	muscovite	biotite	biotite	biotite	hornblende
Location	Donggu, Dongshen	Aojiao, Dongshen	Weitou, Jinjiang	Geshan, Huian	Duchuo, Huian

sence of excess argon in the biotite of H53-3. The initial $^{40}Ar/^{36}Ar$ ratio of O424-7 (Bi) is 228.8, lower than that of the modern atmosphere. It is unknown whether ^{40}Ar loss or other reasons have caused this deviation, but this will be resolved by further research.

4.2. Interpretation of the plateau ages

The five samples are all characteristic rocks in the Changle–Nanao ductile shear zone and have undisturbed age spectra. The plateau ages of these samples are within a limited range (118–107 Ma), even though the rocks are distributed throughout the Changle–Nanao ductile shear zone. If the $^{40}Ar/^{39}Ar$ systems were frozen when the minerals crystallized, the age spectra would be disturbed and display different plateau ages. The concordant plateau ages shown by the undisturbed age spectra probably

Table 2
$^{40}Ar/^{39}Ar$ analytical data[a]

T (°C)	$(^{40}Ar/^{39}Ar)_m$[a]	$(^{36}Ar/^{39}Ar)_m$	$(^{37}Ar/^{39}Ar)_m$	$(^{38}Ar/^{39}Ar)_m$	$^{39}Ar_k$[b] 10^{-12} mol	$(^{40}Ar^*/^{39}Ar_k) \pm 1\sigma$[c]	$^{39}Ar_k$ %	$t \pm 1\sigma$ Ma
D425-5 (Mus), $W = 0.29$, $J = 0.01171$, $Tp = 107.9 \pm 2.4$ Ma (2-5 step)								
400	11.68	0.0301	0.7252	0.0489	0.744	2.76 ± 0.01	0.91	57.4 ± 1.7
700	11.58	0.0202	0.1474	0.0219	2.57	5.63 ± 0.02	3.14	115.1 ± 3.3
900	5.63	0.0019	0.0757	0.0142	13.59	5.07 ± 0.03	16.59	104.1 ± 3.0
1050	5.27	0.0004	0.0046	0.0117	23.41	5.12 ± 0.02	28.58	105.1 ± 3.1
1250	5.61	0.0011	0.0106	0.012	41.22	5.29 ± 0.03	50.33	108.5 ± 3.2
1500	26.44	0.0383	0.2973	0.0421	0.37	15.15 ± 0.8	0.45	294.7 ± 8.2
O424-7 (Bi), $W = 0.259$, $J = 0.01171$, $Tp = 108.2 \pm 2.9$ Ma (2-4 step)								
400	156.306	0.133	0.732	0.143	0.068	126.33 ± 0.27	0.09	1638.1 ± 33.0
700	6.913	0.00609	0.075	0.0146	9.673	5.11 ± 0.00048	13.11	104.9 ± 3.1
850	5.327	0.00049	0.0673	0.0131	42.9	5.17 ± 0.00028	58.14	106.1 ± 3.1
1050	5.638	0.000134	0.095	0.0136	20.89	5.59 ± 0.00032	28.31	114.3 ± 3.3
1250	16.327	0.0190	0.0523	0.0102	0.137	10.74 ± 0.25	0.19	213.7 ± 6.1
1500	2168.539	7.079	7.023	1.371	0.124	88.71 ± 47.03	0.17	1285.1 ± 146.2
J428-2 (Bi), $W = 0.29$, $J = 0.01171$, $Tp = 107.1 \pm 0.9$ Ma (2-5 step)								
400	28.992	0.0837	0.171	0.0333	0.904	4.38 ± 0.0084	0.85	90.1 ± 2.7
700	2.350	0.00741	0.0730	0.0143	4.921	5.16 ± 0.00054	4.61	105.9 ± 3.1
850	5.510	0.00119	0.0633	0.0124	41.22	5.15 ± 0.0003	38.65	105.6 ± 3.1
1050	5.709	0.00157	0.0642	0.0125	36.59	5.24 ± 0.00033	34.31	107.3 ± 3.1
1250	6.203	0.00285	0.0642	0.0125	22.15	5.35 ± 0.00039	20.77	109.7 ± 3.2
1450	107.506	0.304	0.339	0.0662	0.868	18.31 ± 0.12	0.81	350.6 ± 11.3
H53-3 (Bi), $W = 0.29$, $J = 0.01171$, $Tp = 117.9 \pm 2.0$ Ma (1-5 step)								
400	13.919	0.0288	0.0992	0.0194	3.112	5.43 ± 0.0019	2.98	111.3 ± 3.2
700	7.093	0.00436	0.067	0.0131	24.11	5.80 ± 0.0005	23.09	118.5 ± 3.4
850	6.371	0.00178	0.0675	0.0132	14.16	5.84 ± 0.00041	13.56	119.3 ± 3.5
1050	6.359	0.00182	0.0658	0.0129	54.68	5.81 ± 0.0004	52.36	118.8 ± 3.5
1250	8.223	0.00745	0.0728	0.0142	8.285	6.02 ± 0.00068	7.93	123.0 ± 3.6
1450	560.796	1.545	1.666	0.325	0.086	107.13 ± 3.15	0.08	1466.5 ± 93.4
D58-7 (Hb), $W = 0.259$, $J = 0.01171$, $Tp = 109.2 \pm 2.2$ Ma (2-5 step)								
400	98.571	0.25	2.928	0.571	0.039	24.94 ± 0.097	0.4	462.2 ± 13.1
700	15.857	0.0357	0.256	0.05	0.196	5.34 ± 0.0025	2.01	109.4 ± 3.2
850	8.293	0.0108	0.125	0.0244	0.517	5.09 ± 0.00069	5.29	104.5 ± 3.1
1050	8.471	0.0106	0.651	0.127	1.191	5.31 ± 0.00072	12.19	108.7 ± 3.2
1250	6.324	0.00234	0.0886	0.0173	7.781	5.62 ± 0.0004	79.63	115.0 ± 3.3
1450	77.206	0.177	0.753	0.147	0.048	5.31 ± 0.06	0.49	468.2 ± 12.7

[a] $(^{40}Ar/^{39}Ar)_m$: measured values of $^{40}Ar/^{39}Ar$.
[b] $^{39}Ar_k$: measured values of ^{39}Ar which was produced by k decay.
[c] $^{40}Ar^*$: radiogenic ^{40}Ar.

Table 3
Initial $^{40}Ar/^{36}Ar$ ratios, plateau ages and isochron ages

Sample	D425-5	O424-7	J428-2	H53-3	D58-7
Mineral	muscovite	biotite	biotite	biotite	hornblende
Initial $^{40}Ar/^{36}Ar$ ratio	292.5	228.8	297.8	312.9	280.7
Plateau age (Ma)	107.9 ± 2.4	108.2 ± 2.9	107.1 ± 0.9	117.9 ± 2.0	109.2 ± 2.2
Isochron age (Ma)	110.2	111.4	106.9	119.6	115.7

indicate one tectonothermal event. The plateau ages of these samples represent the time of the tectonothermal event, which was the ductile deformation and mylonitization associated with strike-slip movement along the shear zone.

Ductile deformation and dislocation microstructures of quartz and the brittle deformation of feldspar in the shear zone indicate that the temperature of mylonitic deformation is 300–350°C (discussed above), consistent with the closure temperatures of biotite and muscovite (300°C and 350°C, McDougall et al., 1988). This conclusion demonstrates that the plateau ages reported here are the time of ductile deformation and mylonitization. The closure temperature of hornblende (480°C, Dallmeyer, 1978) is higher than that of the deformation temperature, suggesting that the hornblende in D58-7 was possibly affected by a heat source from intense shearing or syn-tectonic granites at that locality.

5. Conclusions

Ductile deformation of rocks in the Changle–Nanao

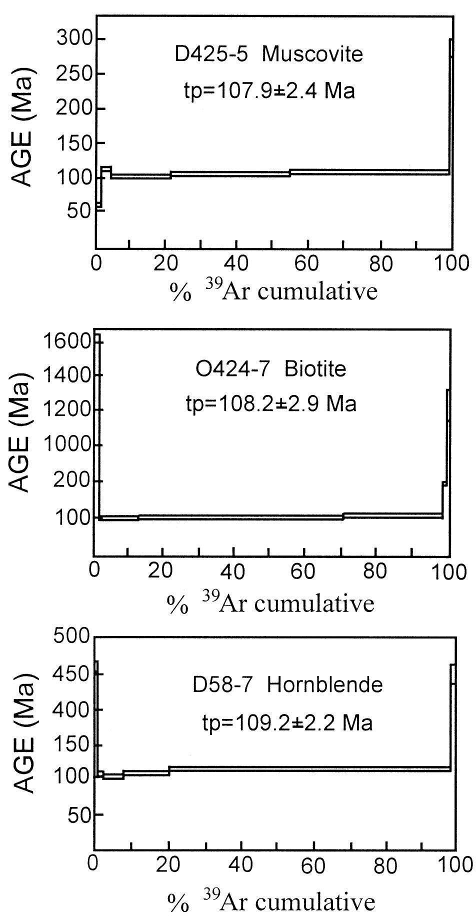

Fig. 4. $^{40}Ar/^{39}Ar$ age spectra for the mineral separates from the mylonitized rocks in the Changle–Nanao ductile shear zone. The locations of the samples are shown in Fig. 1 and in Table 1.

ductile shear zone occurred in at least two stages. Widely developed schistosity and gneissosity in the metamorphic rocks are related to metamorphism at amphibolite facies during the period 178–165 Ma. The second stage deformation, which gave rise to folds, shear foliation, *S–C* fabrics, NE-striking stretching lineation, and mylonitic microstructures, was associated with strike-slip movement along the shear zone in the early Cretaceous.

Ductile deformation and dislocation microstructures of quartz and the brittle deformation microstructures of feldspar in the mylonites from the ductile shear zone, indicate that the ductile deformation and mylonitization occurred under greenschist facies conditions at temperatures of 300–350°C.

$^{40}Ar/^{39}Ar$ plateau ages of five minerals from deformed and mylonitized rocks in the shear zone are in the range of 118–107 Ma. The concordance with their respective isochron ages and the substantial portion (> 98%) of the gas released indicate that they are reliable. The plateau ages record the formation time of the ductile shear zone. That was the time of ductile deformation and mylonitization associated with strike-slip movement along the Changle–Nanao ductile shear zone.

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