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The ^{40}Ar-^{39}Ar ages of hornblendes in Grt-Pl-bearing amphibolite from the Larsemann Hills, East Antarctica and their geological implications

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Abstract In this paper we reported the ^{40}Ar-^{39}Ar dating results of hornblendes in Grt-Pl-bearing amphibolite from the Larsemann Hills, East Antarctica. Their apparent ages respectively are 1586 Ma, 1011-1080 Ma, 761 Ma, 529 - 582 Ma. Their plateau ages of 1036 Ma and 554 Ma as well as an Ar-Ar isochron age of 1010 Ma have also been obtained respectively. These isotopic dating results for the first time by the Ar-Ar method for hornblendes completely record almost all the structural-metamorphic thermal events that this region experienced, and provide an answer to the controversial question on the structural-metamorphic thermal events of this region in recent several years, namely, which one is more important, the late Proterozoic 1000 Ma event (Grenvillian) or the early Palaeozoic 500 Ma event (Pan-African), as well as whether the former exists or not. The ^{40}Ar-^{39}Ar dating results of hornblendes show that the Larsemann Hills experienced a complicated poly-metamorphic evolutionary history, and their protoliths were probably formed in early to mid-Proterozoic. The late Proterozoic 1000 Ma event (Grenvillian) has been confirmed to be a predominant tectonothermal event whilst the early Palaeozoic 500 Ma event (Pan-African) has been confirmed just to be the last strong tectonothermal event in this region.

Key words East Antarctica, Grt-Pl-bearing amphibolite, hornblendes, ^{40}Ar-^{39}Ar ages, tectonothermal events.

1 Introduction

As part of extensive late Proterozoic mobile belt of East Antarctica, the upper amphibolite to granulite facies high-grade metamorphic complex outcropping on the Larsemann Hills has commonly been believed to have experienced major low pressure granulite facies metamorphism during the ~1000 Ma event (Grenvillian) and passively overprinted a greenschist facies metamorphism during the late 500 Ma event (Pan-African) (Sheraton *et al.* 1984; Stüwe *et al.* 1989; Stüwe and Powell 1989; Fitzsimons and Harley 1991). In recent years, however, Zhao *et al.* (1992) undertook the single grain $^{207}Pb/^{206}Pb$ isotopic evaperation age dating for the zircons from the syenogranite of moderate to weakly gneiss foliation and obtained the age results of 556 Ma and 547 Ma, and further believed the Pan-African thermal event (~500 Ma) to be regionally important, which led Ren *et al.* (1992) to believe that the major low pressure granulite facies metamorphic event of this region occurred during the ~500 Ma rather than the ~1000 Ma, in addition, the relic representative of an early medium-pressure metamorphic event has also been recognized. This further led Dirks *et al.* (1993) and Carson *et al.* (1995) to restudy the structural deformation and metamorphic evolution in this region.

The further research results of structural deformation show that this region experienced at least four-phases of structural deformation (D_1, D_2, D_3-D_4 or D_6), including two major deformational-metamorphic stages, which correspond to the two unrelated structural-metamorphic thermal events and occur independantly in this region: the early compressional structures represented by thrusting probably formed during the 1000 Ma event (Grenvillian), whilst the late decompressional structures as a result of extension probably occurred during the 500 Ma event (Pan-African). Both of events occurred at similar temperatures but the latter with somewhat lower pressure (Dirks *et al.* 1993; Carson *et al.* 1995), nevertheless, the former failed to be confirmed in absent of direct isotopic age result.

Meanwhile, however, several workers also obtained much more isotopic age data of around 500 Ma by Sm-Nd, Rb-Sr and U-Pb dating methods from the other lithologies in the region and the neighbouring area (Zhao *et al.* 1993, 1995; Kinny *et al.* 1993; Hensen and Zhou 1995), and emphasized that the 500 Ma Pan-African thermal event was a major granulite facies high-grade structural-metamorphic event in this region, the early 1000 Ma structural-metamorphic thermal event did not exsist in the reigon, and further explained that the rocks of this region formed during the Neoproterozoic, the 1000 Ma age just represented a magmatic intrusive event and had no involvement in high-grade metamorphism (Zhao *et al.* 1995), only in the Sϕstrene Island on the west of this region did the relics of the early 1000 Ma structural-metamorphic thermal event exsist (Hensen and Zhou 1995), whereas Harley *et al.* (1995) considered that the 990 – 1030 Ma ages of zircon U-Pb SHRIMP dated by Kinny *et al.* (1993) from the orthogneisses and leucogneisses on the Rauer Group provided excellent constraints on the age of the 1000 Ma granulite-facies structural-metamorphic thermal event, all of the above stimulated a great controversy (Carson *et al.* 1995; Dirks and Wilson 1995; Harley and Fitzsimons 1995).

Carson *et al.* (1995), Dirks and Wilson(1995) as well as Harley and Fitzsimons (1995) pointed out that the age results of ~500 Ma obtained by Zhao *et al.* (1992, 1995) as well as Hensen and Zhou(1995) through the $^{207}Pb/^{206}Pb$ stepwise evaporation method of zircon and the garnet-mineral and garnet-whole-rock Sm-Nd isochron method seemed to be unaccurate because the $^{207}Pb/^{206}Pb$ evaporation technique can not account for Pb loss during the later overprints of tectonothermal events (Kober 1986), particularly with at least two major tectonothermal events in the region. Therefore, the $^{207}Pb/^{206}Pb$ system suffered serious radiogenic Pb loss and was reset during the later thermal event, being taken as a minimum age estimate only. On the other hand, the clousure temperature of the Sm-Nd isotopic systematics for metamorphic garnet has been believed to be as low as 600 ℃ (Mezger *et al.* 1992), whilst the low pressure granulite-facies metamorphic temperature of the region was as high as 750 ℃ (Stüwe and Powell 1989), and in D_3 normal shearing zone the peak metamorphic temperature may be as high as 800 ℃ (Carson *et al.* 1995), and thus the Sm-Nd isotopic systematics for metamorphic garnet mineral were equally reset during the later structural-metamorphic thermal event. In summary, the reasonable explanation should be that the $^{207}Pb/^{206}Pb$ and Sm-Nd isotopic systematics were all reset during the later structural-metamorphic thermal event, and the $^{207}Pb/^{206}Pb$ and Sm-Nd ages of around 500 Ma were just only representative of the Pan-African resetting ages in the region. Because D_3 in the region was the last strong thermal event with metamorphic temperature in excess of 600 ℃, the age results of around 500 Ma have been considered at least to be still indicative of the late D_3 structural-metamorphic thermal event in this region (Dirks and Wilson 1995).

On the basis of the controversy above, more workers have done further research work on istopic chronology and metamorphism of this region and its neighbouring area. Carson *et al.* (1996) undertook U-Pb SHRIMP age dating for the zircons from the late-tectonic-formed syenogranite in the region, whereas Zhao *et al.* (1997) undertook ^{40}Ar-^{39}Ar age dating for the hornblendes from the mafic granulite and the biotites from the gray white biotite gneiss in the region, while Fitzsimons *et al.* (1997) undertook U-Pb SHRIMP age dating for the zircons and monazites from the anatectic leucogneisses in the Brattstrand Bluffs coast, as well as Hensen and Zhou (1997) also undertook Sm-Nd age dating for several types of lithologies in the Prydz Bay area, the age results of around 500 Ma have been obtained by all of them. Because they have not yet obtained the direct and reliable age data of around 1000 Ma, the Pan-African event of around 500 Ma is still considered to be a major granulite-facies metamorphic thermal event in this region and the Prydz Bay area (Carson *et al.* 1997; Fitzsimons 1997). We think that these age results still reflect the late strong structural-metamorphic thermal event in this region and the neighbouring area (see above and following). Because Carson *et al.* (1995) and Dirks and Hand (1995) have respectively identified mafic-felsic basement orthogneiss in this region and the nearby Bolingen Islands on the west, which is similar lithologically to that of Archaean and Palaeoproterozoic ages in the southeastern Rauer Group (Sheraton *et al.* 1984). In addition, Zhang *et al.* (1996) obtained the high-precise U-Pb isotopic age results of both upper intercept 1000 – 1100 Ma and lower intercept 500 – 550 Ma from monazites and zoned zircons in paragneisses (garnet-biotite-bearing quartzites) of the region, and confirmed the existence of the early 1000 Ma structural-metamorphic thermal event in this region, and also confirmed that the 500 Ma Pan-African thermal event was an important thermal event (Liu *et al.* 1995; Zhang *et al.* 1996). Furthermore, the earlier remnant sapphirine-bearing mineral assemblages of higher P-T conditions that the authors reported recently further supported the point of view above from petrographical and textural evidence (Tong *et al.* 1997a, b; Tong and Liu 1997). The study results of these earlier remnant sapphirine-bearing mineral assemblages of higher P-T conditions showed that the early 1000 Ma structural-metamorphic thermal event of this region was characterized by an anticlockwise near-isobaric cooling P-T path (Tong *et al.* 1997a; Tong and Liu 1997), which was consistent with P-T evolutionary history of the high grade metamorphic rocks from the Northern Prince Charles Mountains (NPCM) that Thost and Hensen (1992) reported. More recently, Hensen *et al.* (1997) undertook further Sm-Nd isotopic age dating for the high grade metamorphic rocks from the NPCM, and identified multiple high grade metamorphic events in the NPCM, e.g. the 1000 Ma and 800 Ma as well as 500 Ma events coexisted in the NPCM, and they also believed that the Sm-Nd isotopic systematics for metamorphic garnet formed during the 1000 Ma metamorphic event were completely reset during the subsequent events. This further supports the point of view above that the isotopic systematics were reset and the early 1000 Ma metamorphic event exsisted in this region. The age results in this paper will suggest that the Larsemann Hills had not only the similar P-T evolutionary history to the NPCM, but also the comparable isotopic age results with the NPCM (see the latter part of the paper).

Then, what are the relationships between the early 1000 Ma structural-metamorphic thermal event and the late Pan-African event of around 500 Ma in this region? Which one is more important than the other? The further direct and reliable isotopic age evidence is still absent for this, whilst it is extremely important for us to know the history of the structural evolution in the region and even in the whole East Antarctica, and this has become one of the research frontiers for the earth sciences of East Antarctica in recent several years. In this paper we try to further answer the question through the Ar-Ar age dating method of hornblende.

2 Geological setting

Located in the middle of the Prydz Bay area, East Antarctica, the Larsemann Hills are composed mainly of three big peninsulas and a number of islands (Fig. 1). The region consists mostly of upper-amphibolite-granulite facies paragneiss, orthogneiss, migmatitic paragneiss, quartzite, and some mafic granulite as well as less ultramafic xenolith. Generally, the region is taken as a part of late Proterozoic high-grade metamorphic terranes of East Antarctica, which underwent low pressure granulite facies metamorphism during the late Proterozoic Grenvillian event of around 1000 Ma and overprinted a greenschist facies metamorphism during the Pan-African event of around 500 Ma (Sheraton *et al.* 1984; Stüwe *et al.* 1989; Stüwe and Powell 1989; Fitzsimons and Harley 1991), with peak metamorphic P-T conditions of 0.45 GPa and 750 ℃ and post-peak decompression of 0.05 – 0.10 GPa (Stüwe and Powell 1989).

However, the study results of chronology and metamorphism as well as structural deformation in recent years show that the 500 Ma (Pan-African) event was more important than what had been previously thought (Ren *et al.* 1992; Zhao *et al.* 1992; Dirks *et al.* 1993; Hensen and Zhou 1995; Carson *et al.* 1995), furthermore, the main low pressure granulite facies metamorphic event of this region is believed to have occurred during the 500 Ma rather than the 1000 Ma (Grenvillian) (Ren *et al.* 1992; Zhao *et al.* 1993, 1995; Hensen and Zhou 1995), and the region is composed of at least two major unrelated high grade metamorphic events, one at the 1000 Ma and another event at the 500 Ma at comparable temperatures but slightly lower pres-

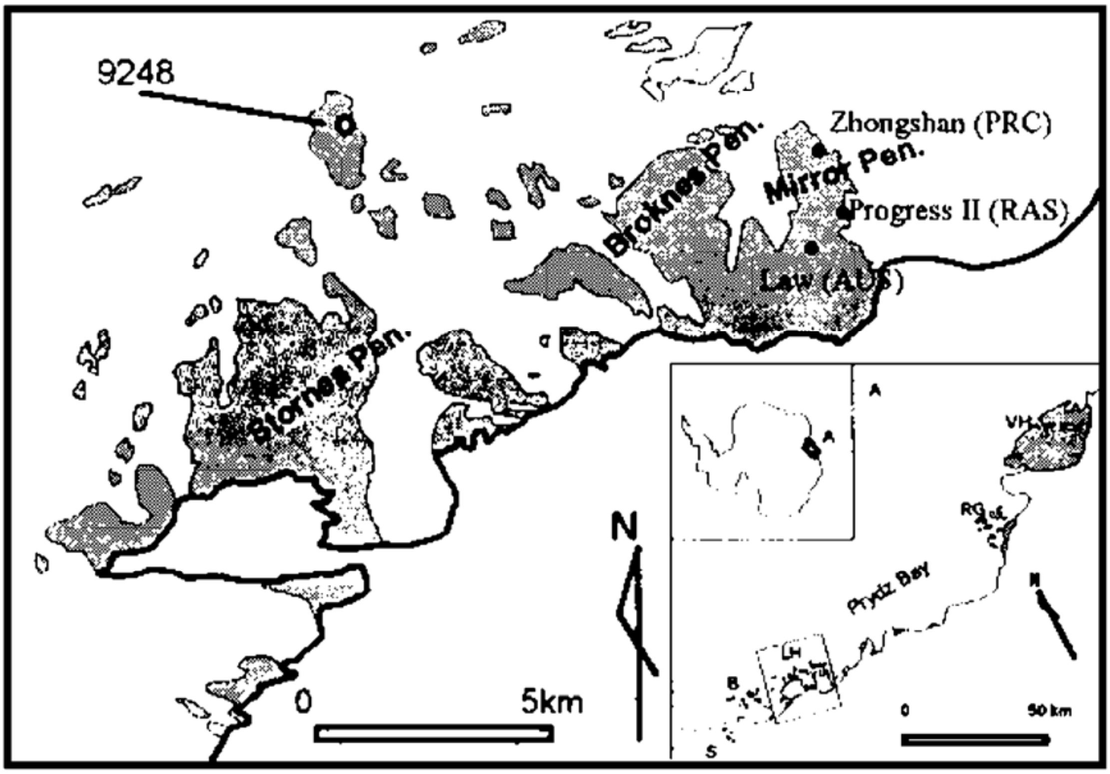

Fig. 1. The sampled location of the Larsemann Hills. VH: Vestford Hills; RG: Rauer Group; LH: Larsemann Hills; B: Bolingen Island; S: Søstrene Island.

sure (Dirks *et al.* 1993; Dirks and Wilson 1995; Carson *et al.* 1995).

Meanwhile, Ren *et al.* (1992) and Wang *et al.* (1994) as well as Carson *et al.* (1995, 1997) have all identified an early medium pressure granulite facies metamorphic event and its mineral assemblages with peak metamorphic conditions of 0.9 GPa and 850 ℃, 0.63 GPa and 750 ℃, 0.7 GPa and 780 ℃ respectively. Although some workers ascribed this newly recognized medium-pressure granulite facies metamorphic event to 600 Ma (Zhao *et al.* 1993, 1995; Ren and Liu 1995), the recent new U-Pb zircon age dating result obtained from medium-pressure mafic granulite in this region suggests that the medium pressure granulite facies metamorphic event appears to have occurred at about 770 Ma (Tong *et al.* 1995a, b). In addition, the authors have further identified earlier remnant mineral assemblages such as sapphirine + spinel + magnetite + sillimanite + corundum ± gedrite and orthopyroxene + plagioclase + phlogopite as well as cordierite + sillimanite + biotite from several lithologies of this region, with peak metamorphic P-T conditions of 0.95 GPa and 870 ℃ by garnet-orthopyroxene thermobarometry, and the metamorphic evolution is characterized by an anticlockwise near-isobaric cooling P-T path (Tong *et al.* 1997a, b; Tong and Liu 1997). The recent high-precise U-Pb isotopic age results of monazites and zoned zircons in the garnet-biotite-bearing quartzites from the region show that these earlier remnant mineral assemblages of higher P-T conditions were formed during the early 1000 Ma structural-metamorphic thermal event (Liu *et al.* 1995; Zhang *et al.* 1996). The earlier anticlockwise near-isobaric cooling P-T path of higher P-T metamorphic conditions is completely different from the late clockwise near-isothermal decompression P-T path of medium-low pressure metamorphic conditions in this region (Ren *et al.* 1992; Carson *et al.* 1995, 1997; Tong and Liu 1997).

3 Sample and experimental method

3.1 Sample and fast neutron irradiation

The garnet-plagioclase-bearing amphibolite sample (9248) was collected from the northern Kolloy Island in 1991 – 1993 austral winter (Fig. 1). This kind of rock occurs as lenses or layers with dark colour, and is composed of garnet (20%), plagioclase (25%), hornblende (30%), orthopyroxene (10%), magnetite (10%) and quartz (5%), with less sphene and others as accessory minerals. In the medium-grain granoblastic texture, the thin garnet corona texture transposed from hornblende can be seen under microscope. Hornblende grains were separated by conventional separation techniques, with grain size of 0.2 – 0.3 mm and purity over 98%.

The selected sample hornblendes and K_2SO_4, CaF_2, KCl that were used as inducing isotope correction of K, Ca, Cl, as well as the standard monitor samples, were wrapped together according to certain requirements, and stacked in the made-special reaction ampouple. These samples were irradiated by a fast neutron flux in Beijing 49-2 reactor using a next-to-core B5 facility. During the irradiation period, the sample capsule was shielded by cadmium and rotated in order to keep the gradient of the neutron flux, and the exit water temperature was below 42 ℃. The duration was 52 h and 15 min with a fast neutron flux of about 2×10^{13} n/(cm^2 • s) and an integral neutron flux of about 3.76×10^{18} n/cm^2. The interlaboratory age standards being used as the neutron flux monitor were the international standard BSP-1 hornblende and two China' standards ZBH-25 biotite and ZBJ hornblende with the monitor ages of (2060±8) Ma and (132.7±1.2) Ma and (132.8±2.4) Ma respectively.

3.2 Experimental method

The isotope dating and analyses were performed at the Laboratory of Isotope Geochronology in the Institute of Geology of the Chinese Academy of Sciences.

The irradiated samples have strong radioactivity. When cooling to safe dosage (below 10 microgal), the appropriate samples were selected and put into the united system of the modified RGA-10 mass spectrometer and the Ar degassing instrument, and then the ^{40}Ar-^{39}Ar stepwise heating experiment was undertaken. In static vacum mode of $133.32\times5\times10^{-7}$ Pa ($=6.67\times10^{-5}$), the samples were heated and melted by high-frequency induction, and the melting temperatures ranged from 500 ℃ to 1500 ℃. The released gases passed through the copper oxide and 5 Å-molecular sieve and titanium sponge, and the active gas was purified out. At last the inert gas Ar directly flowed in the RGA-10 mass spectrometer and the static Ar isotope spectrum analysis was done. The sensitivity of the RGA-10 mass spectrometer was 8.4×10^{-3} A/Pa (corresponding to 1.42×10^{-14} mol/mV), and the interlaboratory static vacum was 7×10^{-7} Pa. Six sets of Ar isotope spectrum peak were generally measured, and besides measuring ^{36}Ar, ^{37}Ar, ^{38}Ar, ^{39}Ar and ^{40}Ar, furthermore, the m/e values of 35 and 41 were monitored. The former was used to check whether there was Cl inference in gas, and the latter was used to decide whether there was remnant hydrocarbon in gas.

The peak data of Ar isotope were obtained by using the peak values to reduce the average value between the former and the latter basic lines, and then the memory effect, the fractional effect, the backgroungd and the inducing isotope correction of K, Ca, Cl and the radioactive decay correction of ^{37}Ar were undertaken for the peak data. The interlaboratory correction factors were as follows: $(^{36}Ar/^{37}Ar)_{Ca}=2.64\times10^{-4}$, $(^{40}Ar/^{39}Ar)_K=3.05\times10^{-2}$, $(^{39}Ar/^{37}Ar)_{Ca}=6.87\times10^{-4}$, $(^{38}Ar/^{39}Ar)_K=0.01$, $(^{37}Ar/^{38}Ar)_{Ca}=3.81\times10^{-5}$, $(^{38}Ar/^{36}Ar)_a=0.1869$, $(^{40}Ar/^{36}Ar)_a=294.1$, $(^{36}Ar/^{38}Ar)_{Cl}$ as a function of time and 4.35×10^{-4} was selected this time. The $t_{1/2}$ of ^{37}Ar is 35.1 d and the decaying constant of ^{40}K is 5.543×10^{-10}/a. The ratios of $^{40}Ar^*/^{39}Ar$, apparent ages, plateau ages and isochron ages were calculated by the formula that Wang *et al.* (1985) and Wang (1992) published.

4 Experimental results and geological explanation

The isotopic data and age spectrum of ^{40}Ar-^{39}Ar for hornblendes in Grt-Pl-bearing amphibolite (9248) are presented in Table 1 and Fig. 2.

Table 1. Isotopic data of ^{40}Ar-^{39}Ar step heating analysis of hornblendes in Grt-Pl-bearing amphibolite (9248)

Step	Temperature/°C	$(^{40}Ar/^{39}Ar)_m$	$(^{36}Ar/^{39}Ar)_m$	$(^{37}Ar/^{39}Ar)_m$	$(^{38}Ar/^{39}Ar)_m$	$^{39}Ar_K$ /10^{-12}mol	$^{39}Ar_K$ /%	$(^{40}Ar^*/^{39}Ar_K)_m$	Apparent age /(Ma±1σ)
1	500	63.103	0.1034	2.0514	0.2414	0.064	6.82	32.84±0.19	529.2±7.8
2	650	77.442	0.1395	2.9078	0.1628	0.093	9.91	36.67±0.24	581.7±8.3
3	800	87.778	0.1296	8.1682	0.1852	0.052	5.54	50.53±0.27	760.7±12.5
4	900	139.756	0.2317	15.862	0.1463	0.089	9.49	73.59±0.18	1023.8±19.2
5	1000	97.924	0.0943	17.806	0.1321	0.114	12.2	72.41±0.16	1011.2±18.8
6	1150	95.349	0.0756	19.398	0.1047	0.184	19.6	75.59±0.18	1045.0±20.0
7	1300	89.764	0.0629	58.917	0.1338	0.275	29.3	78.97±0.22	1080.1±23.5
8	1500	192.581	0.2258	56.051	0.4194	0.067	7.14	135.69±0.53	1585.8±38.2

Notes: Plateau age tp_1=(1035.9±14.1) Ma; Plateau age tp_2=(553.8±26.2) Ma; Specimen weight W=0.3 g; J=0.01038.

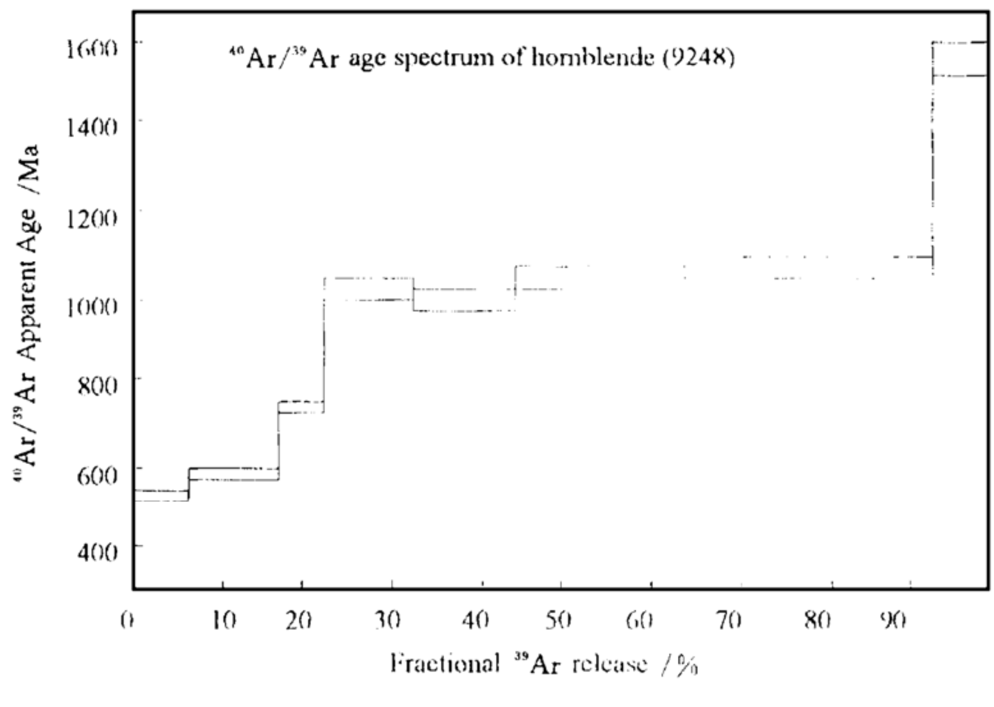

Fig. 2. $^{40}Ar/^{39}Ar$ step heating age spectrum of hornblende.

The hornblendes released Ar through eight heating stages. During the first two stages from 500 ℃ to 650 ℃, the amount of ^{39}Ar release was fairly large and accounted for 16.7% of the total amount. The two apparent ages of 529 Ma and 582 Ma and one plateau age of (554±26) Ma have been obtained respectively, and they are just the age record of the Pan-African event of about 500 Ma and suggest that the Pan-African event was the last strong structural-metamorphic thermal event of this region. During the third heating stage of 800 ℃, the amount of ^{39}Ar release accounted for 5.5% of the total amount, and an apparent age of 761 Ma has been obtained, which is consistent with the U-Pb zircon age of 770 Ma obtained from the mafic granulite in the region (Tong *et al*. 1995a, b). Because the amount of ^{39}Ar release at this stage exceeded 5%, this probably reflects that the position of high lattice energy in hornblende preserved part of the early-formed $^{40}Ar^*$, and it could be the record of the information on the tectonothermal event of about 770 Ma in this region.

During the four heating stages from 800 ℃ to 1300 ℃, the ratios of $^{40}Ar^*/^{39}Ar$ and the apparent ages were stable, and the spectra were plain, whilst the amount of ^{39}Ar release was the largest and accounted for 70.6% of the total amount, corresponding to a plateau age of (1036±14) Ma. After the four sets of data in the plateau zone were treated by the $^{40}Ar/^{36}Ar$ - $^{39}Ar/^{36}Ar$ isochron, a well-regressed isochron was obtained, with an isochron age of (1010±30) Ma (Fig. 3). The $(^{40}Ar/^{36}Ar)_i$ initial value of 289.0 was very approximate to the Nier value (295.5±5), showing that these hornblendes did not capture the atmospheric Ar during their formation. The correlation coefficient is 0.9991, and the linear is very well. The isochron age is consistent with the plateau age, which precludes the excess Ar release, and this suggests that the ^{40}Ar-^{39}Ar ages of hornblendes are real and confident. Both the plateau age and the isochron age suggest that the major structural-metamorphic thermal event of this region occurred during the ~1000 Ma rather than the ~500 Ma.

An older apparent age of 1586 Ma was obtained at the last heating stage. The

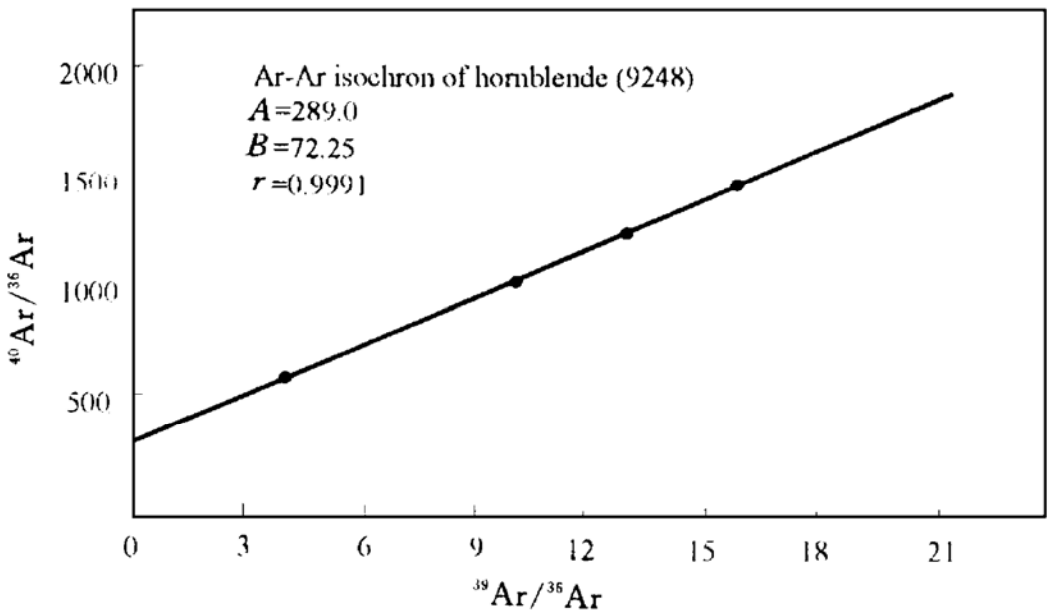

Fig. 3. $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ isochron diagram of hornblende.

amount of ^{39}Ar release accounted for 7.1%, this implies the formation age of the rock itself, and probably preserves the older protolith age information of the region. This apparent age is well comparable with the U-Pb zircon age of 1616 Ma that Zhang *et al*. (1996) reported from the quartzites in the region.

The varying characteristics of their apparent ages in the age spectrum of the hornblende show that it is a typical spectrum of suffering thermal disturbing. During the eight heating stages, the changes of the apparent ages indicate an uprising trend. The apparent ages range from 529 Ma to 1080 Ma with the ^{39}Ar release. This age spectrum obviously reflects that these hornblendes were affected by the 1000 Ma (Grenvillian) and the 500 Ma (Pan-African) tectonothermal events during their formation, namely, the complicated ^{40}Ar-^{39}Ar age spectrum of the hornblende suggests that this mineral systematics suffered a strong effect of multiple structural-metamorphic thermal events. However, from the fourth to the seventh stages, the amount of ^{39}Ar release accounted for 70.6% of the total amount, and this suggests the major effect of the Grenvillian thermal event.

5 Discussion

In this paper, we undertook the ^{40}Ar-^{39}Ar stepwise heating isotopic age dating for hornblendes in Grt-Pl-bearing amphibolite from the Larsemann Hills, East Antarctica, and the ideal results have been obtained. These isotopic dating results record almost all the ages of the structural-metamorphic thermal events that this region experienced, and provide a nice answer to the controversial question on the structural-metamorphic thermal events of this region in recent several years.

In recent several years, the study results of chronology and metamorphism as well as structural deformation on the Larsemann Hills suggest that the Pan-African thermal event of about 500 Ma was a more important structural-metamorphic thermal event than previously thought (Zhao *et al*. 1992; Ren *et al*. 1992; Dirks *et al*. 1993; Carson *et al*. 1995; Hensen and Zhou 1995). However, there are completely different points of view as to which one is more important, the earlier 1000 Ma (Grenvillian) event or the late 500 Ma (Pan-African) event, as well as whether the former exists or not. One of the viewpoints is that the Pan-African event of around 500 Ma was the major granulite facies structural-metamorphic thermal event in the region and the neighbouring area (Ren *et al*. 1992; Zhao *et al*. 1993, 1995; Hensen and Zhou 1995). It is further emphasized that the rocks of this region were formed during the Neopreterozoic, the major granulite facies metamorphic event occurred during the 500 Ma event rather than the 1000 Ma event, the early medium pressure granulite facies metamorphic event occurred during the 600 Ma, the earlier 1000 Ma structural-metamorphic event did not exist at all in the region, and the 1000 Ma just represented a magmatic intrusive event not involving high-grade metamorphism (Zhao *et al*. 1993, 1995). Only in the Søstrene Islands to the west of this region did the relics of the earlier 1000 Ma structural-metamorphic thermal event exist (Hensen and Zhou 1995, 1997). The other opinion holds that at least two equally important granulite facies structural-metamorphic events existed in this region, e.g. the early medium pressure granulite facies metamorphic event probably occurred during the 1000 Ma, and the late low pressure granulite facies metamorphic event occurred during the 500 Ma, both of which occurred at similar temperatures but the latter with somewhat lower pressure (Dirks *et al.* 1993; Carson *et al.* 1995). Meanwhile, Carson *et al.* (1995) and Dirks and Hand (1995) respectively identified mafic-felsic basement orthogneiss in this region and the nearby Boligen Islands west which they thought to be lithologically similar to the mafic-felsic basement orthogneiss of Archaean and Palaeoproterozoic formation ages from the southeastern Rauer Group (Sheraton *et al.* 1984). Furthermore, Harley *et al.* (1995) also considered that the zircon U-Pb SHRIMP isotopic ages of 990-1030 Ma ages that Kinny *et al.* (1993) reported from the orthogneisses and leucogneisses on the Rauer Group provided excellent constraints on the age of the 1000 Ma granulite facies structural-metamorphic event. Because the direct isotopic ages of 1000 Ma were absent in this region, whether the 1000 Ma Grenvillian event existed or not and a number of uncertaities of the 500 Ma induced a great controversy (Carson *et al.* 1995; Dirks and Wilson 1995; Harley and Fitzsimons 1995).

More recently, although the much more isotopic ages of around 500 Ma have been obtained from the region and the neighbouring area, because the direct and reliable age data of around 1000 Ma have not yet obtained, the Pan-African event of around 500 Ma is still considered to be a major granulite-facies metamorphic thermal event in this region and even in the Prydz Bay area (Carson *et al.* 1996, 1997; Fitzsimons 1997; Fitzsimons *et al.* 1997; Hensen and Zhou 1997; Zhao *et al.* 1997). We believe that these age results still reflect the late strong structural-metamorphic thermal event in this region and the neighbouring area, because Zhang *et al.* (1996) recently obtained the high-precise U-Pb isotopic age results of both upper intercept 1000 – 1100 Ma and lower intercept 500 – 550 Ma by conventional U-Pb method for monazites and zoned zircons in the garnet-biotite-bearing quartzites from this region, and confirmed the coexistence of the earlier 1000 Ma event and the late 500 Ma event in this region (Liu *et al.* 1995; Zhang *et al.* 1996). Furthermore, a series of petrographical and textural evidences also supported the existence of the earlier 1000 Ma event in the region, with peak metamorphic P-T conditions of 0.95 GPa and ~900 ℃, and the metamorphism was characterized by an anticlockwise near-isobaric cooling P-T path (Tong *et al.* 1997a; Tong and Liu 1997). In the Sϕstrene Island 25 km west of this region, the earlier granulite facies metamorphic event of higher P-T conditions (1.0 GPa and ~900 ℃) that Thost *et al.* (1991) reported has been confirmed to occur during the Grenvillian structural-metamorphic thermal event of around 1000 Ma (Hensen and Zhou 1995), this further supports the existence of the earlier 1000 Ma metamorphic event in the region. However, what the relationships between the earlier 1000 Ma event and the late 500 Ma event are, and which one is more important than another, these questions have never been well resolved because of the complexity of the structural deformation and metamorphism.

The ^{40}Ar-^{39}Ar isotopic age dating results for the hornblendes in garnet-plagioclase-bearing amphibolite show that the Larsemann Hills experienced a complicated multiple structural-metamorphic evolutionary history. The apparent age of 1586 Ma is well consistent with the solid U-Pb age of 1616 Ma that Zhang *et al*. (1996) reported from the region, this probably reflects that the rocks of the region were formed during the early to mid-Proterozoic rather than the Neoproterozoic (Zhao *et al*. 1995). The obtained plateau age of 1036 Ma and the isochron age of 1010 Ma for the first time revealed that the Grenvillian event of around 1000 Ma was just the major structural-metamorphic thermal event in this region, and these ages of about 1000 Ma correspond to the earlier granulite facies metamorphic event of higher P-T conditions (0.95 GPa and ~900 ℃) recognized recently from the region (Tong *et al*. 1997a; Tong and Liu 1997), which is consistent with the earlier granulite facies metamorphic event of higher P-T conditions (1.0 GPa and ~900 ℃) that Thost *et al*. (1991) reported from the Søstrene Island 25 km west of this region and formed during the 1000 Ma event (Hensen and Zhou 1995). The second plateau age of 554 Ma suggests that the Pan-African event of around 500 Ma was the late overprinted strong structural-metamorphic thermal event in this region, which represents the age of the late low pressure granulite facies metamorphic event in the region, whilst the apparent age of 761 Ma probably represents the medium pressure granulite facies metamorphic event that occurred during the ~770 Ma (Tong *et al*. 1995a, b). This suggests that the 1000 Ma, 770 Ma and 500 Ma events coexisted in this region, whereas the earlier 1000 Ma event was characterized by an anticlockwise near-isobaric cooling P-T path (Tong *et al*. 1997a; Tong and Liu 1997), which shared a similar P-T evolutionary history with the the high grade metamorphic rocks that Thost and Hensen (1992) reported from the Northern Prince Charles Mountains (NPCM). This shows a complete consistence with the conclusion that multiple high grade metamorphic events (e.g. the 1000 Ma, 800 Ma and 500 Ma) coexisted in the NPCM which Hensen *et al*. (1997) reported recently.

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References

Carson CJ, Dirks PHGM, Hand M *et al*. (1995): Compressional and extensional tectonics in low-medium pressure granulites from the Larsemann Hills, East Antarctica. Geol. Mag., 132(2): 151 – 170.

Carson CJ, Fanning CM, Wilson CJL(1996): Timing of the progress granite, Larsemann Hills: additional evidence for Early Palaeozoic orogenesis within the East Antarctic Shield and implications for Gondwana assembly. Austral. J. Earth Sci., 43(5): 539 – 553.

Carson CJ, Powell R, Wilson CJL *et al*. (1997): Partial melting during tectonic exhumation of a granulite terrane: an example from the Larsemann Hills, East Antarctica. J. Metamorphic Geol., 15(1): 105 - 126.

Dirks PHGM, Carson CJ, Wilson CJL (1993): The deformational history of the Larsemann Hills, Prydz Bay: the importance of the Pan-African (500 Ma) in East Antarctica. Antarctic Sci., 5(2): 179 - 192.

Dirks PHGM, Hand M(1995): Clarifying temperature-pressure paths via structures in granulite from the Bolingen Islands, Antarctica. Austral. J. Earth Sci., 42(2): 157 - 172.

Dirks PHGM, Wilson CJL (1995): Crustal evolution of the East Antarctic mobile belt in Prydz Bay: continental collision at 500 Ma? Precam. Res., 75(3): 189 - 207.

Fitzsimons ICW, Harley SL (1991): Geological relationships in high-grade gneiss of the Brattstrand Bluffs coastline, Prydz Bay, East Antarctica. Austral. J. Earth Sci., 38(5): 497 - 519.

Fitzsimons ICW (1997): The Brattstrand Paragneiss and the Søstrene Orthogneiss: A Review of Pan-African Metamorphism and Grenvillian Relics in Southern Prydz Bay. In:Ricci CA, ed. The Antarctic Region: Geological Evolution and Processes, Siena: Terra Antartica Publication, 121 - 130.

Fitzsimons ICW, Kinny PD, Harley SL (1997): Two stages of zircon and monazite growth in anatectic leucogneiss: SHRIMP constraints on the duration and intensity of Pan-African metamorphism in Prydz Bay, East Antarctica. Terra Nova, 9: 47 - 51.

Harley SL, Fitzsimons ICW (1995): High-grade metamorpfism and deformation in the Prydz Bay region, East Antarctica: terranes, events and regional correlations. Mem. Geol. Soc. India, 34: 73 - 100.

Harley SL, Snape I, Fitzsimons ICW (1995): Regional correlations and terrane assembly in East Prydz Bay: Evidence from the Rauer Group and Vestfold Hills. Terra Antartica, 2(1): 49 - 60.

Hensen BJ, Zhou B (1995): A Pan-African granulite facies metamorphic episode in Prydz Bay, Antarctica: Evidence from Sm-Nd garnet dating. Austral. J. Earth Sci., 42(3): 249 - 258.

Hensen BJ, Zhou B (1997): East Gondwana Amalgamation by Pan-African Collision? Evidence from Prydz Bay, East Antarctica. In: Ricci CA, ed. The Antarctic Region: Geological Evolution and Processes, Siena: Terra Antartica Publication, 115 - 119.

Hensen BJ, Zhou B, Thost DE (1997): Recognition of Multiple High Grade Metamorphic Events with Garnet Sm-Nd Chronology in the Northern Prince Charles Mountains, Antarctica. In: Ricci CA, ed. The Antarctic Region: Geological Evolution and Processes, Siena: Terra Antartica Publication, 97 - 104.

Kinny PD, Black LP, Sheraton JW(1993): Zircon ages and the distribution of Archaean and Proterozoic rocks in the Rauer Islands. Antarctic Sci., 5(2): 193 - 206.

Kober B (1986): Whole-grain evaporation for $^{207}Pb/^{206}Pb$ age investigations on single zircons using a double-filament thermal ion source. Contrib. Mineral. Petrol., 93(4): 482 - 490.

Liu XH, Tong LX, Li JL *et al*. (1995): Tectonic evolution of East Antarctic Shield during Mesoproterozoic and Early Palaeozoic. In: Program and extended Abstracts (II), Conference on Geology across the Taiwan Strait, 22 - 23 March, Dept. Geol., Nat'l Univ., Taipei, 165 - 169.

Mezger K, Essene EJ, Halliday AN (1992): Closure temperatures of the Sm-Nd system in metamorphic garnets. Earth Plan. Sci. Lett., 113(3): 397 - 409.

Ren LD, Zhao Y, Liu XH *et al*. (1992): Re-examination of the metamorphic evolution of the Larsemann Hills, East Antarctica. In: Yoshida Y *et al*., ed. Recent Progress in Antarctic Earth Science, Tokyo: TERRAPUB, 145 - 153.

Ren LD, Liu XH (1995): Age of the metamorphic event of the garnet-pyroxene granulite from the Søstrene Island, Prydz Bay, East Antarctica and its relation to the neighbouring area. Anatrctic Research (Chinese Edition), 7(3): 13 - 17.

Sheraton JW, Black LP, McCulloch MT (1984): Regional geochemical and isotopic characteristics of high-grade metamorphics of the Prydz Bay area: the extent of Proterozoic reworking of Archaean continental crust in East Antarctica. Precam. Res., 26(2): 169 - 198.

Stüwe K, Braun HM, Peer H (1989): Geology and structure of the Larsemann Hills area, Prydz Bay, East Antarctica. Austral. J. Sci., 36(2): 219 - 241.

Stüwe K, Powell R (1989): Low pressure granulite facies metamorphism in the Larsemann Hills, East Antarctica: petrology and tectonic implications for the evolution of the Prydz Bay area. J. Metamorphic Geol., 7(4): 465 - 483.

Thost DE, Hensen BJ, Motoyoshi Y (1991): Two-stage decompression in garnet-bearing mafic granulites from Sϕstrene Island, Prydz Bay, East Antarctica. J. Metamorphic Geol., 9(3): 245 - 256.

Thost DE, Hensen BJ (1992): Petrology of granulite facies gneisses of the Pathos and Athos ranges, Northern Prince Charles Mountains, East Antarctica: constraints on the prograde and retrograde P-T path. In: Yoshida Y *et al.*, ed. Recent Progress in Antarctic Earth Science, Tokyo: TERRAPUB, 93 - 102.

Tong LX, Liu XH, Chen FK *et al.* (1995a): The U-Pb dating of Zircon in the Mafic Granulite from the Larsemann Hills, East Antarctica and its geological implications. Anatrctic Research(Chinese Edition), 7(4): 65 - 70.

Tong LX, Liu XH, Zhang LS *et al.* (1995b): The U-Pb Zircon Chronology of Mafic Granulite from the Larsemann Hills, East Antarctica and its possible geological implications. Terra Antartica, 2(2): 123 - 126.

Tong LX, Liu XH, Xu P *et al.* (1997a): Discovery of sapphirine-bearing hyperthene quartzite in the Larsemann Hills, East Antarctica and its geological significance. Chinese Science Bulletin, 42(2): 324 - 327.

Tong LX, Zhang ZY, Liu XH *et al.* (1997b): Mineralogical characteristics of cordierites in Krn-Hy-Crd Granulites from the Larsemann Hills, East Antarctica. Acta Petrologica Sinica, 13(3): 395 - 405 (in Chinese).

Tong LX, Liu XH (1997): The prograde metamorphism of the Larsemann Hills, East Antarctica: evidence for an anticlockwise P-T path. In: Ricci CA, ed. The Antarctic Region: Geological Evolution and Processes, Siena: Terra Antartica Publication, 105 - 114.

Wang SS, Sang HQ, Hu SL *et al.* (1985): $^{40}Ar/^{39}Ar$ age determinon using 49-2 reactor and $^{40}Ar/^{39}Ar$ age spectrum for amphibolite from Qianan, China. Act Petrologica Sinica, 2(3): 35 - 44(in Chinese).

Wang SS (1992): Constraits of chlorine on $^{40}Ar/^{39}Ar$ dating and calculation of high-precise $^{40}Ar/^{39}Ar$ ages. Sciencia Geologica Sinica, 27(4): 369 - 378(in Chinese).

Wang YB, Zhao Y, Ren LD *et al.* (1994): Geochemical characteristics and medium pressure granulite facies metamorphism of mafic granulite rocks from the Larsemann Hills, East Antarctica. Antarctic Research (Chinese Edition), 6(3): 1 - 11.

Zhang LS, Tong LX, Liu XH *et al.* (1996): Conventional U-Pb ages of the high-grade metamorphic rocks in the Larsemann Hills, East Antarctica. In: Pang ZH *et al.*, ed. Advances in Solid Earth Sciences, Beijing: Science Press, 27 - 35.

Zhao Y, Song B, Wang YB *et al.* (1992): Geochronology of the late granite in the Larsemann Hills, East Antarctica. In: Yoshida Y *et al.*, ed. Recent Progress in Antarctic Earth Science, Tokyo: TERRAPUB, 155 - 161.

Zhao Y, Song B, Zhang ZQ *et al.* (1993): Early Paleozoic ("Pan-African") thermal event of the Larsemann Hills and its neighbours, Prydz Bay, East Antarctica. Science in China (series B), 23(9): 1001 - 1008(in Chinese).

Zhao Y, Liu XH, Song B *et al.* (1995): Constraints on the stratigraphic age of metasedimentary rocks from the Larsemann Hills, East Antarctica: possible implications for Neoproterozoic tectonics. Precam. Res., 75(3): 175 - 188.

Zhao Y, Liu XH, Wang S *et al.* (1997): Syn- and post-tectonic cooling and exhumation in the Larsemann Hills, East Antarctica. Episodes, 20(2): 122 - 127.