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Syn- and post-tectonic cooling and exhumation in the Larsemann Hills, East Antarctica

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In this paper, we present $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende, biotite, and K-feldspar and apatite fission track thermochronological data to constrain the cooling and exhumation of high-grade rocks of the Larsemann Hills, Antarctica, synchronous with and postdated regional intense orogenesis of the early Paleozoic. Combined with Pb-Pb, U-Pb, Sm-Nd and $^{40}\text{Ar}/^{39}\text{Ar}$ age data published, a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of hornblende recorded cooling below c. 520°C at 514 ± 2 Ma at a rate of c. 40°C/Ma. This rapid cooling can be attributed to the tectonically driven exhumation along the ductile shear zones. By 514 Ma, c. 10–15 km of exhumation had achieved. Slowing of the cooling rate from c. 9°C/Ma to c. 3°C/Ma occurred during 500–490 Ma, when the geotherm dropped through the closure temperature for $^{40}\text{Ar}/^{39}\text{Ar}$ system in biotite at c. 300°C. Documented by an $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of K-feldspar, further drop of the geotherm below c. 160°C took place around 455 Ma, by which erosionally controlled exhumation had become dominant, as suggested by the very slow cooling rate at c. 3–0.3°C/Ma. The final cooling through apatite partial annealing zone happened at c. 210 Ma and could correspond to an early period of aborted rifting in the Lambert Garben region.

Introduction

The Larsemann Hills region, located on the Ingrid Christensen Coast of Prydz Bay (Figure 1a), East Antarctica, was once considered as part of an extensive Mesoproterozoic (c. 1000 Ma) high-grade terrane that extends over much of the East Antarctic Craton (e.g. Sheraton et al., 1984; Stüwe et al., 1989). The notion was first challenged by the studies of the high-grade rocks of the Larsemann Hills (Zhao et al., 1991, 1992; Ren et al., 1992; Zhou and Hensen, 1992; Dirks et al., 1993). Increasing evidence from chronological data (Zhao et al., 1992, 1993; Kinny et al., 1993; Hensen and Zhou, 1995; Zhang et al., 1996; Carson et al., 1996; Fitzsimons et al., 1997), structural analyses (Dirks et al., 1993; Dirks and Wilson, 1995; Carson et al., 1995), textural information and P–T condition estimates (Stüwe and Powell, 1989a; Ren et al., 1992; Fitzsimons, 1996; Carson et al., 1997) has verified that it is the Early Paleozoic orogenesis, rather than a Mesoproterozoic tectonothermal event, that contributed to the tectonic evolution of the Larsemann Hills and adjacent regions. However syn- and post-tectonic cooling and exhumation was poorly

constrained by thermochronological data. This paper presents $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende, biotite, and K-feldspar and apatite fission track thermochronological data, combined with Pb-Pb, U-Pb, Sm-Nd and $^{40}\text{Ar}/^{39}\text{Ar}$ age results published, to expound this problem.

Geological background and previous geochronology

The bedrocks in the Larsemann Hills consist predominantly of pelitic, psammitic and felsic paragneisses metamorphosed to peak condition of c. 7 kbar at c. 800 °C (Carson et al., 1997) and small peraluminous granite bodies and pegmatite dykes with various degrees of deformation (Stüwe et al., 1989; Dirks et al., 1993; Zhao et al., 1995; Carson et al., 1995). Decompression from the peak condition to c. 4.5 kbar at 750°C dominated the high-grade retrograde evolution of the region (Stüwe and Powell, 1989; Ren et al., 1992; Fitzsimons, 1996; Carson et al., 1997). The Sm-Nd model ages (T_{DM}) range from 2200–700 Ma (Sheraton et al., 1984; Hensen and Zhou, 1995; Zhao et al., 1995) for the gneisses and partial melting bodies of the Larsemann Hills and adjacent regions, much different from those of the Archean Vestfold Hills Block (Figure 1a), which has formed and metamorphosed around 2500 Ma (Black et al., 1991), and southern Rauer Islands gneisses with Archean components (Sheraton et al., 1984; Kinny et al., 1993). Intense Pan-African tectonism in Prydz Bay has been demonstrated by Pb-Pb zircon evaporation ages of 547±9 Ma and 556±7 Ma (Zhao et al., 1992) and SHRIMP U-Pb zircon ages of 516±7 Ma and 514±7 Ma for the syntectonic Progress Granite (Carson et al., 1996), U-Pb monazite ages of 541 ± 1 Ma and 527±1 Ma for paragneisses (Zhang et al., 1996) and SHRIMP U-Pb zircon ages of 535±13 Ma and 536±35 Ma and monazite ages of 528±4, 527±11, 518±3 and 512±13 Ma for anatectic leucogneiss (Fitzsimons et al., 1997) and Pb-Pb zircon evaporation ages and SHRIMP U-Pb zircon ages of 600–500 Ma for migmatitic paragneisses (Zhao et al., 1993, unpublished data, 1997), garnet-whole-rock Sm-Nd dates of 517–467 Ma for various gneisses (Zhao et al., 1993; Hensen and Zhou, 1995b). A poorly defined Rb-Sr isochron of 560±70 Ma for the paragneisses (Sheraton et al., 1984), previously regarded as a low- to medium-grade metamorphic overprint associated with the emplacement of granite bodies (e.g. the 500 Ma Landing Bluff Granite, Tingey, 1991), is attributed to the intense Early Paleozoic tectonothermal activities. A model of compressional (D_2) and extensional (D_3) orogenesis has been proposed for Early Paleozoic tectonism (Carson et al., 1995; Dirks and Wilson, 1995). The emplacement of late planar pegmatite dykes in the Rauer Islands at 500±12 Ma (Kinny et al., 1993), $^{40}\text{Ar}/^{39}\text{Ar}$ biotite ages of 500–486 Ma for migmatitic paragneisses, syntectonic granite and pegmatite (Zhao et al., 1992, 1993; Fu et al., 1993) as well as an $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock age of 443±3 Ma for migmatite (Takigami et al., 1992), which are similar with previously reported K-Ar ages of 405 Ma and 504 Ma for the metamorphic rocks from the regions (Picciotto and Coppez, 1963; Ravich et al., 1965), show that the

Figure 1 Map showing location of the Larsemann Hill and adjacent regions, Prydz Bay, East Antarctica (a), and sampling localities in the eastern Larsemann Hills, with apatite f-t ages and track length distributions for the samples (b). (1) Granite-pegmatite, (2) Syenogranite, (3) Gneissic leucogranite (4) High-Al-Fe-Mg-gneisses, (5) Migmatitic paragneiss, (6) Mafic gneiss, (7) Apatite f-t age, (8) Sampling locality hsz.: high strain zone.

high-grade terranes on the Ingrid Christensen Coast were cooling around 500 Ma. However, the low and medium temperature thermochronological data are still required to constrain on cooling and exhumation of the granulite terrane, although apatite fission track data from areas adjoining the Larsemann Hills region indicated cooling through temperatures below c. 100°C between about 300 Ma and 200 Ma (Arne et al., 1993).

⁴⁰Ar/³⁹Ar and apatite fission track analyses

Samples

The sampling locations are indicated in Figure 1b. The ⁴⁰Ar/³⁹Ar samples were described for Sm-Nd analyses (Zhao et al., 1993, 1995), and two of the fission track samples (ZG20405 and F22103) were described for zircon Pb-Pb dating (Zhao et al., 1992, 1995). Brief descriptions of the rest of fission track samples are given here.

FQ91, from southwestern Vikoy Island about 1 km north of Broknes Peninsula, is a medium- to coarse-grained cordierite-magnetite gneiss. LP20305, from a locality just southeast of the Aus-

tralian Law Base, is a fine- to medium-grained garnet-sillimanite gneiss. O20211, from the southernmost Mirror Peninsula, is a fine- to medium-grained biotite-garnet gneiss. O20208, about 700 m northeast of O20211, is also a fine- to medium-grained biotite-garnet gneiss.

Mineral concentrates were extracted using standard procedures including the Wilfley table, magnetic and heavy-liquid separation techniques. All minerals were finally purified by hand-picking under a binocular microscope. The grain radii of hornblende, biotite and K-feldspar for ⁴⁰Ar/³⁹Ar analyses, including biotites previously dated, are generally larger than 1 mm.

Experimental procedures

The ⁴⁰Ar/³⁹Ar analysis was performed on a MM-1200 mass spectrometer in the Laboratory of Isotope Geochronology, Institute of Geology, Chinese Academy of Geological Sciences. The samples were irradiated in the core of the facility H4 of 49-2 reactor in Chinese Academy of Atomic Energy Science. The standard biotite ZBH-25 (133.5 Ma) was used as the "flux monitor". ⁴⁰Ar/³⁹Ar ages were calculated by using the following constants, $\lambda_e = 0.581 \times 10^{-10} \text{ y}^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10} \text{ y}^{-1}$ (Steiger and Jäger, 1977). The experimental procedure was described by Fu et al. (1987). All errors quoted in Table 1 and Figure 2 are on 1σ basis.

Apatite fission track analysis was carried out in the Laboratory of the Nucleus Analysis Technique, Institute of High Energy Physics, Chinese Academy of Sciences. The procedure was outlined by Kang et al. (1990). Apatite ages were determined using the external detector method. Standard and induced track densities were measured on muscovite external detectors and fossil track densities on internal mineral surfaces. Thermal neutron fluences were monitored using NBS standard glass SRM 962. The samples were irradiated in the facility A of the heavy water reactor in Chinese Academy of Atomic Energy Science. Ages were calculated using the zeta calibration method following the procedures of Hurford and Green (1983). Errors were calculated using the method described by Naeser (1978). Their uncertainties quoted in Table 2 are at the 1σ level. Track lengths were measured in apatite grains on horizontal confined fission tracks.

The ⁴⁰Ar/³⁹Ar Data

⁴⁰Ar/³⁹Ar age spectra for hornblende, biotite and K-feldspar are shown in Figure 2, and the ⁴⁰Ar/³⁹Ar results are summarized in Table 1, with biotite and whole-rock ⁴⁰Ar/³⁹Ar results published.

Hornblende from the mafic granulite (Sample G212-3) yielded concordant plateau and isochron ages (Table 1). The plateau age for steps 4-7, accounting for 87% of the ³⁹Ar released, is 514±2 Ma, the corresponding isochron age is 515±5 Ma, with an initial ⁴⁰Ar/³⁶Ar ratio of 303±59.

Biotite from the greyish-white biotite gneiss on northern Broknes Peninsula (Sample BP20901) gave a well-defined plateau age of 506±2 Ma, for which radiogenic products are 84%. The isochron age for this sample, based on steps 5-8, is 506±5 Ma, with an initial ⁴⁰Ar/³⁶Ar ratio of 303±68.

K-feldspar was analyzed from a migmatitic paragneiss (Sample F22103), which is lithologically identical to a coarse-grained garnet-bearing leucosome with garnet segregations forming the cores and K-feldspar making up the mantles described by Stüwe and Powell (1989b). K-feldspar yielded concordant age spectra with a plateau age of 455±4 Ma for steps 6-9 (71% of the ³⁹Ar released). The isochron age for this sample is 451±5 Ma, with an initial ⁴⁰Ar/³⁶Ar ratio of 288±78. Step 8 is slightly older (460±4 Ma). Without steps 8 and 10, the rest of 8 factions gave a mean age of 449±4 Ma, similar

Figure 2 Age spectra for $^{40}\text{Ar}/^{39}\text{Ar}$ samples from the Larsemann Hills, East Antarctica, (a) hornblende (G212-3), (b) biotite (BP20901), (c) K-feldspar (F22103).

Table 1 Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ results of the Larsemann Hills

Sample	Rock type	Mineral	Plateau age (Ma)	Steps	Percent of gas	Total gas age (Ma)	Isochron age (Ma)	Initial ratio	Reference
12520	syenogranite	biotite	494±1	2-8	91	491	495±5	292±4	Zhao et al., 1992
13101	pegmatite	biotite	486±1	2-8	93	483	486±4	295±2	Zhao et al., 1992
A316	migmatite	whole-rock	443±3	3-8	94	447			Takigami et al., 1992
WM20701	paragneiss	biotite	488±2	3-7	72	487	486±7	290±38	Zhao et al., 1993
F22103	migmatitic paragneiss	biotite	500±4	2-8	96	498	502±7	289±13	Fu et al., 1993 *
		K-feldspar	455±4 (449±4)	6-9 1-7, 9	71	453	451±5	287±78	
BP20901	gneiss	biotite	506±2	2-8	84	501			this study
			507±1	5-8			506±5	303±68	
G212-3	mafic granulite	hornblende	514±2	4-7	87	514	515±5	303±59	this study

*: Recalculated by this study, mean ages reported in parentheses, 1 σ intralaboratory errors.

Table 2 Apatite fission track data of the eastern Larsemann Hills

Sample	Elevation (m)	Number of grains	Fluence ($10^{15}/\text{cm}^2$)	ρ_s ($10^5/\text{cm}^2$)	ρ_i ($10^5/\text{cm}^2$)	r	P(χ^2) %	FT-age (Ma)	Mean track length (μm)	Standard deviation (μm)
ZG20405	22	9	5.132	6.692 (1835)	4.916 (1348)	0.988	70	206±4	13.4 (138)	1.5
F22103	97	20	5.132	4.982 (992)	3.461 (689)	0.974	50	217±4	14.5 (126)	1.4
O20208	126	16	6.172	48.33 (2733)	35.38 (2001)	0.989	70	248±4	13.7 (128)	1.7
O20211	135	7	6.531	38.75 (992)	30.16 (772)	0.999	95	246±4	13.2 (127)	2.1
LP20305	82	13	6.172	17.69 (1824)	12.74 (1314)	0.989	95	252±5	13.1 (92)	2.7
FQ91	7	12	6.172	24.25 (1421)	17.51 (1026)	0.975	90	251±5	13.1 (196)	2.5

The number of tracks counted (age data) or measured (lengths) is given in parentheses, uncertainties given at the 1 σ level.

to $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of $443\pm 3\text{Ma}$ for the whole-rock sample (A316), whose main component is K-feldspar.

The closure temperatures (T_c) of $^{40}\text{Ar}/^{39}\text{Ar}$ system in hornblende, biotite and K-feldspar adopted in this study are c. 520°C, c. 300°C and c. 160°C respectively, with reference to the data summarized by McDougall and Harrison (1988).

Fission Track Data

Apatite fission track data are tabulated (Table 2), and fission track cooling ages and track length distributions are illustrated in Figure 1b. All the apatite fission track ages have passed the χ^2 test, and they are significantly younger than $^{40}\text{Ar}/^{39}\text{Ar}$ dates of K-feldspar from Sample F22103 and the whole-rock sample (A316) nearby. The dates range from 252 Ma to 206 Ma. The samples with the oldest fission track ages have the shortest mean track length of 13.1 μm and the largest standard deviations from 2.7 μm to 2.5 μm , while samples with younger fission track ages have longer mean track lengths up to 14.5 μm and lower standard deviations, 1.4–2.1 μm . The results are generally in agreement with those obtained by Arne et al. (1993) for the samples from areas adjoining the Larsemann Hills region.

Figure 3 The cooling path for high-grade rocks of the Larsemann Hills based on thermochronological data. Details of high temperature chronological data provided by inset plot.

Discussion

The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age for hornblende at 514 ± 2 Ma (Sample G212-3) is close to the zircon SHRIMP U-Pb age of 516 ± 7 Ma for the syn-deformational Progress Granite nearby (Carson et al., 1996) and similar with Sm-Nd grt-grt-WR dates of 517 Ma and 510 Ma for the paragneisses from this region (Hensen and Zhou, 1995b), which implies that rapid cooling occurred around 514 Ma.

SHRIMP U-Pb dating for Sample 261 from the syn-deformational Progress Granite generally gave age results similar to those of Sample 12520 by the single zircon Pb-Pb evaporation technique, and both methods yielded identical age results for elongated zircon grains (e.g. grain 2 and grain 5 of Sample 261, Carson et al., 1996; grain 91904 and grain 91602 of Sample 12520, Zhao et al., 1992). The technical advantage of SHRIMP U-Pb dating and its numerous analyses for one sample can give a more accurate and more reliable crystallization age of the sample, especially a crystallization age for metamorphic rims of the zircon sample underwent high-grade metamorphism, for which the single zircon Pb-Pb evaporation technique cannot give. In southern occurrence of the Progress Granite small pegmatitic units and thin pegmatitic intergrowths are pervasive and can develop into pegmatite dykes (Figure 1b). Fitzsimons et al. (1997) found high-Th monazite rims with younger mean ages of 518 ± 3 Ma and 512 ± 13 Ma around low-Th cores with mean ages of 528 ± 4 Ma and 527 ± 11 Ma and attributed the high-Th monazite growth to retrograde fluid flow along the ductile shear fabric. The Progress Granite, formed at 516 Ma and 600–700°C, occupied a high strain zone tectonically, with dextral movement sense (Dirks et al., 1993; Carson et al., 1996). The emplacement of late N- to NW-trending planar pegmatite dykes at c. 500 Ma (Kinny et al., 1993) demonstrates that high-grade terranes of the regions were cooling. Mylonite zones were developed along the planar pegmatite dyke margins, with the same dextral movement sense. Although the Progress Granite preserves the S_2 foliation and L_2 lineation identical to those of the host gneiss (Carson et al., 1996), the mineral assem-

blages, which comprise D_2 fabric of the host gneiss, yield estimates of c. 4.5–5.2 kbar at c. 750°C, that is, low-pressure granulite facies condition (Stüwe and Powell, 1989a; Ren et al., 1992; Carson et al., 1997). Geochronologically the syn- D_2 Progress Granite can not be distinguished from the syn- D_3 Progress Granite within error. Both of them are of anatectic products formed in late tectonism of the early Paleozoic orogenic episode. P-T estimates for the assemblages from D_3 high strain domains, host gneiss of the syn- D_3 Progress Granite, also give c. 4.5–5.0 kbar at c. 750–800°C. Therefore we consider that the Progress Granite was synchronous with M_3 and D_3 , that D_2 transposition and M_2 peak metamorphism occurred around 535–541 Ma (Zhang et al., 1996; Fitzsimons et al., 1997) or slightly earlier and that the early Paleozoic orogenesis of the regions could commence at c. 600 Ma (Zhao et al., 1993, unpublished SHRIMP U-Pb data, 1997; Hensen and Zhou, 1995c).

The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of hornblende (Sample G212-3) documents that the granulite grade terrane cooled below c. 520°C at 514 ± 2 Ma and constrains that exhumation from the middle crustal levels at a depth of 20–25 km to the upper crustal levels at a depth about 10 km after peak metamorphism (Carson et al., 1997) had achieved by that time. The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of hornblende approaches the Sm-Nd grt-grt-WR isochron ages at 517 ± 5 Ma and 510 ± 5 Ma as reported by Hensen and Zhou (1995b). The Sm-Nd grt-grt-WR isochron age can better represent the time at which the Sm-Nd system in the garnet cooled below its T_C than Sm-Nd grt-WR and grt-mineral-WR isochron ages. The T_C for the Sm-Nd system in garnet was argued. For example, Mezger et al. (1992) proposed that the T_C for the Sm-Nd system in garnet is c. 600–700°C, while Hensen and Zhou (1995a) suggested that, in “a memory case”, it must be more than 700–750°C. A rapid cooling rate of ≥ 40 –27°C/Ma appears reasonable after that proposed by Mezger et al. (1992) in this study (Figure 3). If we choose that suggested by Hensen and Zhou (1995a), cooling around 514 Ma would be much more rapid, at a rate ≥ 60 –70°C/Ma. This rapid cooling can be attributed to tectonically driven exhumation along ductile shear zones active during intense early Paleozoic tectonism in the regions (Fitzsimons et al., 1997).

Slowing of a cooling rate from c. 9°C/Ma to c. 3°C/Ma took place during c. 500–490 Ma, when the geotherm dropped below the T_c for ⁴⁰Ar/³⁹Ar in biotite at c. 300°C, and could approach a stable state. By the time when cooling below the T_c for ⁴⁰Ar/³⁹Ar in K-feldspar at c. 160°C occurred around 554±4 Ma, erosionally controlled exhumation had been dominant.

Because of limited elevation in the Larsemann Hills, the relationship between our apatite fission track data and sampling different erosional levels cannot be demonstrated. But our apatite fission track data show that some of the samples (e.g. ZG20405, F22103) were cooled through apatite partial annealing zone (PAZ, c. 110°C–60°C) rapidly at c. 210 Ma, while some of the samples (LP 20305, FQ91 and O20211) appear to have been severely to moderately annealed prior to cooling through apatite PAZ at c. 210 Ma, which supports the notion that final cooling below c. 100°C during the late Paleozoic and early Mesozoic corresponded to an initial period of aborted rifting in the Lambert Garben area (Arne et al., 1993). The final cooling rate was very slow at a rate of c. 0.3°C/Ma.

Conclusion

The ⁴⁰Ar/³⁹Ar plateau age of hornblende, combined with Pb–Pb, U–Pb, Sm–Nd and ⁴⁰Ar/³⁹Ar age results published, can constrain that cooling below c. 520°C happened at 514±2 Ma and that c. 10–15 km of exhumation had achieved by that time. Rapid cooling around 514 Ma at a rate of c. 40°C/Ma resulted from tectonically driven exhumation along the ductile shear zones. Therefore a complex cooling process with variable cooling rates could exist in the high-grade terrane due to different vertical movements in the crust during that time. Slowing of the cooling rate from c. 9°C/Ma to c. 3°C/Ma occurred during 500–490 Ma, when the geotherm dropped through the closure temperature for ⁴⁰Ar/³⁹Ar system in biotite at 300°C. Documented by an ⁴⁰Ar/³⁹Ar plateau age of K-feldspar, further change of the geotherm down below c. 160°C took place around 455 Ma, by which erosionally controlled exhumation had become dominant, as suggested by the very slow cooling rate at c. 3–0.3°C/Ma. The final cooling through the apatite partial annealing zone happened at c. 210 Ma and could correspond to an early period of aborted rifting in the Lambert Garben region.

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