Grenville-age metamorphism in the Larsemann Hills: P-T evolution of the felsic orthogneiss in the Broknes Peninsula, East Antarctica

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ABSTRACT

The gneisses outcropping in the Larsemann Hills of East Antarctica are ideal for studying the composition and evolution of the Prydz tectonic belt. In this study, detailed petrological analyses, phase equilibrium modelling, and zircon analyses were performed on a felsic orthogneiss from the Broknes Peninsula in the Larsemann Hills. The study results show that the protolith of the felsic gneiss is granite, which is further identified to have been an S-type granitoid. The felsic orthogneiss intruded into the basement complex at ~976 Ma. The magmatic zircons in the felsic orthogneiss have lower LREE and higher HREE contents than those of the metamorphic zircons in the same rock. The felsic gneiss consists of the mineral assemblage garnet + ilmenite + plagioclase + K-feldspar + sillimanite + quartz and underwent granulite facies metamorphism in the Grenvillian period (~899 Ma), with peak conditions of ~870°C and ~9.5 kbar. The Larsemann Hills should be categorized as the orogenic process from arc-continent collision to continent-continent collision during the Grenvillian period, crust thickening (~899 Ma) and subsequent collapse (550–500 Ma).

1. Introduction

There are different perspectives on the tectonic evolution of Prydz Bay of East Antarctica: P-T paths with clockwise near isothermal decompression (ITD) indicate that it is a Pan-African collision orogeny related to crustal thickening (Ren et al. 1992, 2018; Fitzsimons 1996; Carson et al. 1997; Yu et al. 2002; Liu et al. 2006, 2007a, 2007b, 2007c; Hu et al. 2008). The creation of Prydz Bay is related to the final convergence of the East Gondwana continent (Zhao et al. 1993, 2003; Hensen and Zhou 1997; Fitzsimons 2000; Liu et al. 2002a, 2002b, 2007a, 2007b, 2007c, 2018; Harley 2003; Hu et al. 2008). Prydz Bay has experienced not only a Grenvillian (~1000 Ma) metamorphic event, but also a Pan-African (~530 Ma) tectonic thermal event (Dirks and Hand 1995; Liu et al. 1995, 2007b, 2009a; Zhang et al. 1996; Tong et al. 1998, 2002, 2017; Tong and Wilson 2006; Wang et al. 2008; Grew et al. 2012; Zhou et al. 2014). However, there is still much controversy regarding the distribution of these two tectonic events in this area and their geological significance. Some scholars hold that the P-T paths of these two metamorphic events are not related (Dirks and Hand 1995; Tong et al. 1998, 2002; Kelsey et al. 2007; Wang et al. 2007, 2008). Therefore, the Prydz belt is also considered to represent an intracontinental activity belt active in the Early Palaeozoic in Eastern Gondwana. It may be the result of the tectonic adjustment effect of the collision between two parts of the Gondwana continent (Tong et al. 2002; Phillips et al. 2007; Wang et al. 2007, 2008; Wilson et al. 2007; Grew et al. 2012; Ren et al. 2018). However, others believe that the two tectonic metamorphic events represent the aggregation of the continents of Rodinia and Gondwana, respectively, and that the Prydz tectonic belt is a collisional orogenic belt (Hensen and Zhou 1997; Fitzsimons 2000; Boger et al. 2001; Liu et al. 2002b, 2006; Zhao et al. 2003; Li and Liu 2006). Resolving these differences in perspectives is important for understanding how the East Antarctic continent formed. The Larsemann Hills are located in the heart of Prydz Bay, and the Broknes Peninsula is a major part of the Larsemann Hills. Therefore, an in-depth study of the rocks at these locations is important for establishing a complete metamorphic P-T path in this area, and is of great significance to clarify the metamorphic thermal evolution and tectonic nature of Prydz Bay.

2. Geological background

The Larsemann Hills is located in Prydz Bay in East Antarctica and is underlain by composite orthogneiss (mafic and felsic orthogneiss) and metasedimentary...
rocks, known as the Søstrene Orthogneiss and Brattstrand Paragneiss, respectively (Fitzsimons et al. 1997). After peak metamorphism, the anatexis was strongly developed in this region, and a considerable number of pegmatite veins, migmatites and garnet-bearing granites were formed along with the local syenite porphyry and monzonitic granite and ultramafic granulite (Carson et al. 1995, 2010; Grew et al. 2012; Tong et al. 2017). The Søstrene Orthogneiss and the Brattstrand Paragneiss are considered to be basement series and sedimentary cover rocks, respectively (Sheraton et al. 1984; Stüwe and Powell 1989; Fitzsimons and Harley 1991; Dirks et al. 1993; Carson et al. 1995; Dirks and Hand 1995) (Figure 1).

The Larsemann Hills experienced D1 deformation and granulite facies metamorphism in the Grenvillian period and D2-D6 phases of deformation and amphibolite to granulite facies metamorphism in the Pan-African stage (Dirks et al. 1993). Wang et al. (2008) summarized the major geological events in the Larsemann Hills (Table 1). They believed that the D1 deformation was accompanied by early (~1000 Ma) granulite facies metamorphism and intrusion of syn-orogenic granite. There is also a granulite facies metamorphism event in the Pan-African period (~500 Ma) with strong anatexis, simultaneous D2 northwestward thrust and D3 north-south extension deformation, and intrusion of syn-orogenic granite. Ren et al. (1992) obtained the peak metamorphic conditions of the early M1 (The M1 corresponds to the D1) corresponding to 9 kbar and 850°C using the Grt-Pl-Sil-Qz geothermobarometer and Opx-Cpx thermometer. Tong et al. (1995) stated that the early M1 reached higher peak metamorphic conditions of 9.5 kbar and 870°C (Grt-Opx geothermobarometer). The Pan-African tectonic activity exhibited amphibolite to granulite facies metamorphism and the peak metamorphism conditions were 7 kbar and 800–850°C (Carson et al. 1995, 1997; Fitzsimons 1996; Grew et al. 2006). Recently, the early M1 conditions of 9.3 kbar and 900–950°C are also reported from the garnet-bearing mafic granulite in the study region (Tong et al. 2019).

Figure 1. Geological map of the Larsemann Hills, Prydz Bay, East Antarctica and the sample locations, showing major lithological units (after Tong et al. (2017)). Insert shows the position of the Larsemann Hills in Prydz Bay. Abbreviations: LH, Larsemann Hills, RG, Rauer group, VH, Vestfold Hills.
However, the relationship between the early Grenvillian and late Pan-African tectonic activity is complicated.

3. Analytical methods

Analysis of the major elements and trace elements were performed at the Special Laboratory of the Geological Team of Hebei Province, Langfang, China. The major oxides were determined by X-ray fluorescence (XRF) on fused glass beads and the trace elements were analysed using a Perkin-Elmer Sciex Elan 6000 ICP-MS. Samples were dissolved using a mixture of 
HNO₃ and HF. Specific test conditions and steps can be found in Jin and Zhu (2000).

The zircons were extracted from the samples by a manual extraction method under a binocular microscope. They were then mounted in epoxy resin discs, and sectioned and polished to reveal their cross section. Cathodoluminescence (CL) imaging of zircon particles was performed using a JSM6510 scanning electron microscope (SEM; JEOL, Tokyo Japan) attached to a Gatan CL detector (Oxford, UK) at Nanjing Hongchuang Geological Exploration Technology Service Co., Ltd., China. U-Pb dating analyses were conducted using laser-ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) at the Beijing Createch Test Technology Co. Ltd., China. Laser sampling was performed using an ESI NWR 193 nm laser ablation system and an Anlyitik Jena PQMS Elite ICP-MS instrument was used to acquire ion-signal intensities. Detailed operating conditions are the same as described by Hou et al. (2009). Off-line raw data selection and integration of background and analyte signals, and time-drift correction and quantitative calibration for U-Pb dating was performed using ICPMS DataCal (Liu et al. 2010). The age calculations and Concordia diagrams were made using Isoplot (Ludwig 2003). Lu-Hf isotopes were analysed in situ in the same age zones in zircon that were analysed for U-Pb isotopes. The analyses were performed using a Neptune MC–ICP–MS equipped with a GeoLas 200 M ArF excimer 193 nm laser ablation system (MicroLas, Germany).

Electron probe micro-analysis (EPMA) of minerals was carried out on polished thin sections at the State Key Laboratory for Mineral Deposits Research of Nanjing University. A JEOL JXA-8100 electron probe micro-analyser was used with an accelerating voltage of 15 kV, and cup current of 20 nA and 1 μm for the minerals. The test results are shown in Table 2–4.

4. Petrography and mineral chemistry

The felsic gneiss (sample Z1220-21-1) studied in this paper was collected near the Nella Fjord in the Broknes Peninsula (Figure 1). Through outcrops we can see that it intrudes into the basement complex, and has a porphyroblastic texture, contains locally-developed feldspar quartz veins (Figure 2(a)). The main minerals of the felsic gneiss are coarse-grained K-feldspar (20%), plagioclase (25%), biotite (5%), garnet (15%), and quartz (45%); a small amount of sillimanite, muscovite, magnetite and ilmenite are also present(figure 2(b)). Garnet forms eucahedral porphyroblasts with diameters of more than 1 mm in the felsic orthogneiss.Most of the sillimanite and biotite are found along the grain boundaries of the other minerals (Figure 2(c)). The Si, Al and Bi may be late stage minerals. Based on the minerals in the garnets and in the matrix, two-stage mineral assemblages can be ascertained: 1) The prograde stage is characterized by the mineral assemblage of muscovite (Ms)+ biotite (Bi) + plagioclase (Pl) + microcline (Mic) + quartz (Qz) + magnetite (Mgt) occurring as inclusions in garnet. 2) The peak metamorphism stage (M₁) is defined by the mineral assemblage of garnet (Grt) + ilmenite (IIm) + plagioclase (Pl) + K-feldspar (Kfs) + sillimanite (Sil) + quartz (Qz).

The results of the electron microprobe analysis show that the garnet in the felsic gneiss has high FeO and MgO, low CaO, and almost no MnO (Table 2). The garnet has a composition of Al₉₀.₇₆Py₂₅.₂₇Gr₂.₂₄, without substantial compositional zoning from core to rim (Figure 3(a,b)). The amount of biotite in the samples is low, and only a small amount of residual crystals are present. The outlines of the biotite grains are certainly irregular – the grains look embayed. (Figure 2(b)). Electron probe data show that the biotite has high MgO and TiO₂, but lacks MnO. The feldspar in the sample is mainly microcline and plagioclase. There are two types of microcline: one type is distributed at the edges of the garnet, while the other exists in the matrix together with biotite, quartz, plagioclase. The plagioclase is mainly encircled in the interior of the perthite, either in the matrix or between them. Some are irregularly surrounded by garnet and a small
Table 2. Representative microprobe analyses of garnet of the sample (wt%).

| Sample | Z1220-21-1 |
|--------|------------|
| Spot   | 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 |
| Location | Rim Core Rim |
| SiO$_2$ | 39.18 39.19 39.29 38.58 38.87 40.30 38.33 38.76 39.07 39.99 39.08 31.97 31.99 38.28 38.78 39.16 39.22 38.32 |
| TiO$_2$ | 0.01 0.02 0.05 0.02 0.03 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01 |
| Al$_2$O$_3$ | 21.55 21.19 21.57 21.34 21.39 22.16 21.40 21.14 21.41 21.72 21.75 21.51 21.09 21.11 21.63 21.73 21.24 |
| FeO | 31.08 31.35 30.72 31.24 31.84 31.17 31.42 30.48 31.77 31.14 31.07 31.18 31.82 31.04 31.45 31.45 31.95 |
| MnO | 0.08 0.04 0.11 0.06 0.06 0.05 0.07 0.10 0.07 0.08 0.09 0.08 0.09 0.07 0.06 0.06 0.08 |
| MgO | 6.70 6.73 6.68 6.35 6.04 6.80 6.57 6.75 6.56 6.66 6.50 6.69 6.47 6.60 6.28 6.61 6.42 |
| CaO | 1.84 0.87 0.91 0.92 0.96 1.00 1.02 1.00 1.02 0.99 1.01 0.98 0.97 0.92 0.88 0.86 1.01 |
| Na$_2$O | 0.00 0.01 0.01 0.06 0.00 0.01 0.07 0.00 0.01 0.00 0.05 0.01 0.02 0.02 0.00 0.03 0.02 |
| Total | 99.42 99.36 99.35 99.30 99.18 101.51 98.87 98.23 99.93 100.60 99.60 99.51 98.81 98.61 99.51 100.00 99.05 |

Table 3. Representative microprobe analyses of biotite of the sample (wt%).

| Sample | Z1220-21-1 |
|--------|------------|
| Spot   | 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 |
| Location | Rim Core Rim |
| SiO$_2$ | 38.13 38.45 37.56 37.96 37.47 38.90 37.21 37.59 36.92 36.44 37.51 36.77 38.18 |
| TiO$_2$ | 5.54 5.24 5.47 5.23 5.59 3.79 5.19 6.16 4.72 5.00 5.45 5.23 4.48 |
| Al$_2$O$_3$ | 14.78 15.36 14.79 15.02 15.28 15.61 14.96 15.23 15.02 14.74 15.30 14.60 14.43 |
| FeO | 14.47 12.98 14.27 14.37 14.93 10.94 14.79 15.91 16.53 17.79 17.46 18.65 16.57 |
| MnO | 0.00 0.02 0.02 0.00 0.00 0.01 0.00 0.00 0.02 0.00 0.00 0.03 0.01 0.01 |
| MgO | 13.95 15.43 13.87 14.11 13.26 17.06 14.32 12.94 12.29 11.21 12.96 10.52 13.40 |
| CaO | 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 |
| Na$_2$O | 0.06 0.04 0.05 0.03 0.20 0.25 0.24 0.20 0.05 0.09 0.26 0.21 0.16 |
| K$_2$O | 9.49 10.00 9.62 9.57 9.42 9.81 9.16 9.30 9.53 9.46 8.97 9.34 9.46 |
| Total | 96.42 97.51 95.64 96.30 96.15 96.37 95.90 97.34 95.06 94.73 95.23 95.27 96.69 |

5. P-T estimates and pseudosection calculation

For estimating the metamorphic temperature and pressure conditions, previous studies mostly used the traditional mineral thermobarometers. However, in recent years, increasingly more scholars have begun to use phase equilibrium modelling methods. These methods can not only quantitatively simulate the metamorphic conditions and processes of metamorphism and melting reactions under the actual whole rock chemical composition system, but also quantitatively simulate the content and composition of minerals and melts. In this study, the metamorphic conditions and P-T path of the felsic gneiss were further constrained by phase equilibrium modelling. NCKFMASHTO (Na$_2$O - CaO - K$_2$O - FeO - MgO - Al$_2$O$_3$ - SiO$_2$ - H$_2$O - TiO$_2$ - O (Fe$_2$O$_3$)) P-T pseudosections were computed using GeoPS (Xiang; http://www.geology.ren/), which is a software based on Perple_X (Connolly, version 6.8.4 of

number are wrapped in fine grains inside the garnet. The An (~29) of the plagioclase in the matrix is slightly lower than the An (31–35) of the plagioclase in the garnet.

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2015, 2018 upgrade), and the following phases and the corresponding phase components were chosen from Holland and Powell (1998) (Holland and Powell 2011 upgrade). The solution models (details in solution_model.dat; database: hp622ver.dat) adopted are Chl(W), Grt(W), Mica(W), Crd(W), Bi(W), Ctd(W), St(W), melt(W), Fsp(C1), Sp(WPC), IIm(W), and Melt (HP). The composition used in the phase equilibrium calculation was taken from the full rock composition obtained by XRF analysis. Measured total rock composition is: SiO$_2 = 73.72\%$, TiO$_2$

Table 4. Representative microprobe analyses of plagioclase of the sample (wt%).

| Location | Z1220-21-1 |
|----------|------------|
|          | in Grt | in Grt | in Grt | in Grt | in Grt | in Grt | in Grt | in Grt | in matrix | in matrix |
| K$_2$O   | 0.31   | 0.25   | 0.24   | 0.46   | 0.62   | 0.40   | 0.25   | 0.25   | 0.56       | 0.45       |
| Na$_2$O  | 7.42   | 7.71   | 7.16   | 7.66   | 7.25   | 7.52   | 7.40   | 7.21   | 7.70       | 7.34       |
| MnO      | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00       | 0.00       |
| TiO$_2$  | 0.02   | 0.01   | 0.01   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00       | 0.00       |
| MgO      | 0.01   | 0.01   | 0.00   | 0.01   | 0.00   | 0.02   | 0.00   | 0.00   | 0.00       | 0.00       |
| CaO      | 6.73   | 6.63   | 6.90   | 7.04   | 6.97   | 7.09   | 7.36   | 7.32   | 6.59       | 6.24       |
| FeO      | 0.04   | 0.06   | 0.00   | 0.01   | 0.01   | 0.02   | 0.00   | 0.00   | 0.00       | 0.00       |
| Al$_2$O$_3$ | 26.86 | 27.15 | 27.19 | 27.36 | 27.19 | 27.21 | 27.90 | 27.64 | 26.88      | 26.43      |
| SiO$_2$  | 56.86  | 57.56  | 57.55  | 57.57  | 57.06  | 56.84  | 57.38  | 56.84  | 57.81      | 57.79      |
| Total    | 98.24  | 99.38  | 99.03  | 100.10 | 99.13  | 99.14  | 100.31 | 99.31  | 99.58      | 99.26      |
| Si       | 2.59   | 2.59   | 2.59   | 2.58   | 2.58   | 2.57   | 2.56   | 2.56   | 2.60       | 2.62       |
| Ti       | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00       | 0.00       |
| Al       | 1.44   | 1.44   | 1.44   | 1.44   | 1.45   | 1.45   | 1.45   | 1.47   | 1.47       | 1.41       |
| Fe$^{2+}$ | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00       | 0.00       |
| Mn       | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00       | 0.00       |
| Mg       | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00       | 0.00       |
| Ca       | 0.33   | 0.32   | 0.33   | 0.34   | 0.34   | 0.34   | 0.35   | 0.35   | 0.32       | 0.30       |
| Na       | 0.65   | 0.67   | 0.63   | 0.66   | 0.64   | 0.66   | 0.64   | 0.63   | 0.66       | 0.67       |
| K        | 0.02   | 0.01   | 0.01   | 0.03   | 0.04   | 0.02   | 0.01   | 0.01   | 0.03       | 0.03       |
| An       | 0.33   | 0.32   | 0.34   | 0.33   | 0.33   | 0.33   | 0.35   | 0.35   | 0.33       | 0.31       |
| Ab       | 0.65   | 0.67   | 0.64   | 0.65   | 0.63   | 0.64   | 0.64   | 0.63   | 0.66       | 0.67       |
| Or       | 0.02   | 0.01   | 0.01   | 0.03   | 0.04   | 0.02   | 0.01   | 0.01   | 0.03       | 0.03       |

Figure 2. (a) a felsic pegmatite vein in the felsic orthogneiss; (b,c) Photomicrograph of the felsic orthogneiss; (d) Inclusions of biotite (Bi)+quartz (Qz)+muscovite (Ms)+magnetite (Mt) in the garnet.
= 0.2%, Al₂O₃ = 14.01%, K₂O = 6.39%, Na₂O = 2.04%, Fe₂O₃ = 0.05%, FeO = 1.63%, MnO = 0.024%, MgO = 0.31%, CaO = 0.97%, P₂O₅ = 0.095%. The MnO content in the rock is very low (<0.1%), so MnO was not considered in the chemical system chosen for modelling. In addition, CO₂ and P₂O₅ present in the calcium carbonate and apatite were subtracted according to CaO·CO₂ and (CaO)₅·(P₂O₅)¹.₅(H₂O)⁰.₅, respectively. We used the T-X(O) pseudosection and the measured mineral assemblage equivalent line to limit the percentage of O (Pownall et al. 2015). Calculating the T-X(O) pseudosection of this sample at 6 kbar, when the O content was 0.015, ensured that the observed final phase assemblage was stable on the solid phase line (Korhonen et al. 2012; Li and Wei 2016). Using a similar method, we obtained a H₂O content of 0.38.

The phase equilibrium modelling temperature and pressure of the sample were limited to the range of 2 ~ 12 kbar and 500 ~ 1100°C. The early metamorphic mineral association (Grt + Ms + Bi + Pl + Ab + Mic + Qz + Mt) is stable in the range of ~ 560°C and 5.2 ~ 8.8 kbar, which represents the prograde metamorphic stage of the rock. The mineral assemblage (Grt + Melt + Ilm + Pl + Kfs + Sill + Qz) in the peak metamorphic stage is stable at 760 ~ 1050°C and 5 ~ 11.8 kbar. An aqueous fluid is calculated to be present in the system over a pressure-temperature range from about 2.0 to about 5.5 kbar and from about 560 to about 700°C.

According to the pseudosection (Figure 4(a)), rutile is stable at pressures > 7.0 ~ 8.8 kbar; cordierite is absent at pressures > 5.5 kbar; biotite breaks down at temperatures > 700 ~ 760°C; K-feldspar breaks down at temperatures > 940 ~ 1000°C. Garnet, quartz and plagioclase are stable over most of the pressure-temperature range covered in the pseudosection except the highest temperatures and lowest pressures where only ilmenite remains. If the isopleths for garnet Mg# are nearly parallel to the pressure axis, then garnet Mg# would change very little with pressure. Figure 4(b) shows garnet Mg# increasing with increasing temperature. If the isopleths for plagioclase An are roughly parallel to the temperature axis, then plagioclase An would not change very much with temperature. Figure 4(b) shows plagioclase An for the most part decreasing with increasing pressure for temperatures above 560 ~ 600°C, depending on the pressure. Using the Mg# of the garnets core to define the P-T condition during the formation of garnets, the Mg# is 0.261 ~ 0.274, and the An of the fine plagioclases inside the garnet is 0.311 ~ 0.354. According to the Mg# of the garnet’s core and the An of the plagioclases (0.293 ~ 0.297) in the matrix, the maximum temperature and pressure conditions for the stability of the peak (M₁) mineral combination were T = ~870°C and P = ~9.5 kbar, and the initial mineral assemblages are Grt + Melt + Ilm + Pl + Kfs + Sill + Qz. Based on the above phase equilibrium simulation results, we define a prograde P-T path (Figure 4(b)). Phase equilibrium simulation calculations provide further information on the P-T condition of the Grenvillian felsic gneiss (T = ~870°C and P = ~9.5 kbar).

6. Zircon U-Pb geochronology, and REE and Lu-Hf isotopic characteristics

The zircon U-Pb geochronology, and the trace element and Lu-Hf isotope data of the samples can be found in Table 5–7.

It can be seen from the characteristics of the zircon cathodoluminescence (CL) images that most zircons are long columnar, with ratios of length to width of 1:1 to 3:1. The size of the zircon ranges from 30 to 150 μm, and some of the zircons have developed cracks. The CL images of most of the zircon grains show relatively
uniform medium intensity (grey-grey-white) overall, oscillatory zoning in the core, and a relatively broad, dark grey overgrowth (Figure 5). In the concordia diagrams and histograms of the zircon U-Pb age from the sample, the crystallization age of the igneous precursor (protolith) to the felsic orthogneiss is ~976 Ma, and the Grenvillian metamorphic age is mainly ~899 Ma (Figure 6(a,b)). Based on the $^{207}\text{Pb}/^{235}\text{U}$ ages, Bithe 6 zircons giving ~1100 Ma ages are interpreted to be xenocrysts extracted from the country rock. Some of the zircons from the sample plot in a broad discordia array that could represent a resetting of Grenvillian ages during the Pan-African event (Tong et al. 1995, 2019; Wang et al. 2008; Grew et al. 2012). The results of the rare earth element analysis show that the magmatic and metamorphic zircons have similar rare earth partitioning patterns, all of which show low contents of light rare earth elements, heavy rare earth element enrichment, “marked negative Eu anomalies and positive Ce anomalies (Figure 7). However, the Ce anomaly of the metamorphic zircons is not as significant as that of the magmatic zircons, and compared with the magmatic zircons, the metamorphic zircons show a less steep slope for the HREE. The magmatic zircons have a significant negative Pr anomaly, but the metamorphic zircons do not show such a feature.

Figure 4. P-T pseudosection for the felsic orthogneiss modelled using the felsic orthogneiss composition; (b) The blue dotted line is the garnet composition isopleth (Mg# = Mg/(Fe + Mg)) ?the grey dotted line is the plagioclase composition isopleth (An = Ca/(Ca+Na +K)). The numbers next to the coloured squares represent the amount of coexisting minerals. Based on the measured mineral composition equivalent line, the maximum temperature conditions for the stability of the peak (M1) mineral combination are T = ~870°C and P = ~9.5 kbar, and on the above phase equilibrium simulation results, we define a prograde P-T path.

There have been a lot of studies performed on the basement complex in Prydz Bay. Isotope geochronology shows that the protolith of the basement complex intruded in 1020 ~ 1380 Ma (Sheraton et al. 1984; Zhao et al. 1995, 2003; Liu et al. 2007c, 2009b, 2013a, 2014; Wang et al. 2008; Grew et al. 2012). The zircon U-Pb crystallization age of the precursor to the felsic orthogneiss analysed in this study is ~ 976 Ma and it has intrusive contact relationships with the basement complex. Therefore, the formation age of the felsic gneiss is
later than that of the basement felsic orthogneiss, which is consistent with the field geology. Regarding the classification of granite genesis (I-S-A), is there a systematic difference in zircon trace elements in various types of granite? Wang et al. (2012) made a good attempt at answering this question; they selected samples from typical I- type and S-type granites from the southern part of the Tibetan Plateau and A-type granites from the Songpan-Ganze orogenetic belt on the northeastern margin of the Tibetan Plateau, and their zircon trace elements were identified in detail; their study is a good precedent for the identification of trace element characteristics of I-S-A granites in granite, and the geochemical characteristics of granite zircons can be effectively used to discriminate rock types and tectonic environments. Plotting the Pb and Th of the magmatic zircons of the felsic orthogneiss analysed in this study shows that the sample mainly fall within the area of the S-type granitoids.

From this we conclude that the protolith of the felsic gneiss was mainly formed by the melting of pre-existing crust.

Previous studies have shown that the genesis of mafic rocks has two modes: (1) partial melting of pre-existing crustal material, in which the \( \varepsilon_{Hf}(t) \) value of the zircons in magmatic rocks will be lower than that in chondrite; (2) new crustal material or mantle material partially melted, in which the zircon \( \varepsilon_{Hf}(t) \) value of magmatic rocks will be higher than that in chondrite. The \( \varepsilon_{Hf}(t) \) values of the felsic gneiss sample in this paper are ~2.02 to +1.41 (mean ~0.075). Most of the \( \varepsilon_{Hf}(t) \) of the zircons is located
**Table 6. REE contents (ppm) of the zircon from the sample Z1220-21-1.**

| Spot           | Y(ppm) | La(ppm) | Ce(ppm) | Pr(ppm) | Nd(ppm) | Sm(ppm) | Eu(ppm) | Gd(ppm) | Tb(ppm) | Dy(ppm) | Ho(ppm) | Er(ppm) | Tm(ppm) | Yb(ppm) | Lu(ppm) |
|----------------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Z1220-21-1-09  | 1195.86| 0.79    | 4.14    | 0.52    | 2.82    | 2.29    | 0.35    | 16.48   | 7.66    | 105.49  | 37.26   | 161.18  | 35.16   | 321.78  | 52.59   |
| Z1220-21-1-10  | 1463.82| 0.00    | 0.69    | 0.10    | 2.58    | 7.47    | 0.17    | 41.52   | 13.94   | 150.67  | 49.41   | 192.22  | 37.47   | 327.85  | 50.93   |
| Z1220-21-1-14  | 1660.51| 0.21    | 3.86    | 0.10    | 1.56    | 4.04    | 0.31    | 27.44   | 11.28   | 139.28  | 55.53   | 250.05  | 55.56   | 523.14  | 86.56   |
| Z1220-21-1-18  | 1926.07| 0.48    | 4.67    | 0.28    | 1.99    | 2.95    | 0.19    | 22.89   | 10.72   | 154.51  | 64.51   | 310.62  | 70.79   | 687.53  | 117.28  |
| Z1220-21-1-19  | 2427.55| 0.02    | 2.40    | 0.03    | 0.88    | 3.61    | 0.12    | 31.13   | 13.65   | 192.66  | 81.33   | 383.77  | 86.71   | 841.95  | 140.04  |
| Z1220-21-1-20  | 2867.76| 0.00    | 1.84    | 0.04    | 0.93    | 3.84    | 0.14    | 33.66   | 15.91   | 229.32  | 93.80   | 458.36  | 102.24  | 979.16  | 164.61  |
| Z1220-21-1-26  | 2194.57| 0.43    | 3.40    | 0.32    | 2.45    | 4.18    | 0.21    | 29.85   | 13.32   | 186.05  | 74.61   | 337.35  | 75.93   | 709.65  | 118.08  |
| Z1220-21-1-28  | 979.56 | 0.45    | 3.72    | 0.80    | 6.26    | 6.70    | 0.42    | 36.94   | 11.96   | 113.45  | 32.93   | 122.51  | 24.90   | 226.17  | 35.87   |
| Z1220-21-1-31  | 1602.73| 0.13    | 2.58    | 0.16    | 1.47    | 2.37    | 0.16    | 19.05   | 8.66    | 125.65  | 53.63   | 253.89  | 59.13   | 569.36  | 95.87   |
| Z1220-21-1-33  | 1998.01| 1.28    | 12.20   | 2.27    | 15.34   | 7.41    | 0.66    | 26.42   | 11.56   | 166.62  | 67.85   | 325.40  | 74.01   | 724.67  | 123.63  |
| Z1220-21-1-37  | 2996.15| 0.16    | 2.91    | 0.20    | 1.92    | 5.18    | 0.22    | 40.25   | 18.29   | 254.55  | 101.86  | 470.48  | 103.75  | 971.10  | 158.93  |
| Z1220-21-1-38  | 3793.76| 0.03    | 3.43    | 0.09    | 2.22    | 7.04    | 0.19    | 53.12   | 23.30   | 320.49  | 130.25  | 601.51  | 132.27  | 1231.46 | 202.57  |
| Z1220-21-1-39  | 1456.67| 6.06    | 37.51   | 7.06    | 41.12   | 14.03   | 1.73    | 32.51   | 11.64   | 140.86  | 46.46   | 193.12  | 40.50   | 348.83  | 57.89   |
| Z1220-21-1-49  | 2284.36| 0.04    | 3.35    | 0.08    | 1.14    | 4.35    | 0.23    | 31.45   | 13.85   | 189.47  | 77.49   | 363.95  | 80.99   | 796.28  | 131.57  |
| Z1220-21-1-55  | 1663.00| 0.01    | 0.67    | 0.03    | 0.75    | 3.22    | 0.08    | 25.33   | 11.67   | 151.82  | 54.56   | 242.36  | 50.08   | 468.94  | 73.96   |
below the chondrite line (CHUR), indicating that the source was mainly derived from partial melting of the pre-existing crust. In addition, the corresponding $t_{DM2}$ of the felsic gneiss sample is 1548 to 1789 Ma, (Figure 8, Table 7).

Recent studies have shown that there are two episodes of high-grade metamorphism in the eastern margin of the Amery Ice Shelf, Prydz Bay. The two episodes of metamorphism occurred at 900–1000 Ma and about 530 Ma (Hensen and Zhou 1995; Wang et al. 2008; Liu et al. 2013b, 2014; Tong et al. 2014, 2017; Liu 2018). One of the difficulties in the study of multi-stage metamorphism superposition is the precise dating of each metamorphic event. Because the zircon U-Pb system has a high blocking temperature of > 900°C (Lee et al. 1997; Cherniak and Watson 2001), it is widely used in conventional isotope dating methods. However, one or more Pb loss events may result in a relatively dispersed age within the same zircon domain (Lee et al. 1997; Cherniak and Watson 2001; Liu 2018), and may cause the so-called ‘harmonic’ age to be several tens of millions of years younger than the real age (Black and Sheraton 1990; Ashwal et al. 1999; Yoshida 2007; Grew et al. 2012).

It is difficult to find a record of two-episode metamorphism in felsic gneiss because if a large number of metamorphic zircons are formed during the early granulite facies metamorphism, they are seldom formed again during later granulite phase superposition processes, especially when the temperature during the superposition is low. Even if the main mineral assemblage reaches equilibrium during the superposition process, metamorphic zircon mainly records the earlier metamorphic events because metamorphic zircon growth requires a large amount of fluid or melt, which would have already

| Sample        | $^{176}$Yb/$^{177}$Hf | $^{26}$ | $^{176}$Lu/$^{177}$Hf | $^{26}$ | $^{178}$Hf/$^{177}$Hf | $^{26}$ | Age(t) | $\varepsilon_{Hf}(t)$ | $t_{DM}$(Ma) | $t_{DM2}$(Ma) | $t_{DM3}$(Ma) | $f_{LH}$ |
|---------------|----------------------|--------|----------------------|--------|----------------------|--------|--------|------------------------|-------------|-------------|-------------|----------|
| Z1220-21-1-7  | 0.0204               | 0.0008 | 0.0007               | 0.0000 | 0.282192             | 0.0000 | 981    | 0.75                   | 1482        | 1630        | −0.98       | 0.97     |
| Z1220-21-1-10 | 0.0191               | 0.0003 | 0.0007               | 0.0000 | 0.282111             | 0.0000 | 1012   | −1.45                  | 1594        | 1765        | −0.98       | 1.02     |
| Z1220-21-1-13 | 0.0492               | 0.0005 | 0.0018               | 0.0000 | 0.282258             | 0.0000 | 976    | 2.27                   | 1431        | 1548        | −0.95       | 0.96     |
| Z1220-21-1-14 | 0.0371               | 0.0012 | 0.0013               | 0.0000 | 0.282260             | 0.0000 | 905    | 1.12                   | 1410        | 1549        | −0.96       | 0.98     |
| Z1220-21-1-16 | 0.0087               | 0.0001 | 0.0003               | 0.0000 | 0.282212             | 0.0000 | 1055   | −0.57                  | 1440        | 1738        | −0.99       | 0.97     |
| Z1220-21-1-15 | 0.0056               | 0.0006 | 0.0016               | 0.0000 | 0.282100             | 0.0000 | 1102   | −0.29                  | 1649        | 1789        | −0.95       | 0.94     |
| Z1220-21-1-18 | 0.0534               | 0.0005 | 0.0019               | 0.0000 | 0.282227             | 0.0000 | 989    | 1.39                   | 1479        | 1603        | −0.94       | 0.98     |
| Z1220-21-1-41 | 0.0067               | 0.0007 | 0.0002               | 0.0000 | 0.282225             | 0.0000 | 1000   | −7.34                  | 1420        | 1689        | −0.99       | 1.00     |

Figure 5. The CL images and the 206Pb/238 U ages of representative zircons from the sample.

Figure 6. Concordia diagrams and histograms of zircon U-Pb age from the sample. The light blue ellipses indicate ages of the xenocrysts. The blue ellipses are related to the Pb loss.
occurred during the earlier granulite facies metamorphism. In anhydrous rock, it is difficult to offer the environment suitable for zircon growth. However, if basic magmatic rocks undergo granulite facies metamorphism, a large number of metamorphic zircons will grow despite the lack of fluid. This is because in high-grade metamorphic events, metamorphism causes Zr, previously dispersed in silicate minerals to be released to form metamorphic zircons (Wei 2018). Therefore, in this study, the zircon age mainly reflects the Grenvillian tectonic thermal event, the Pan-African metamorphic age is not well recorded, but the event is reflected by those zircons in a broad discordia array (500 ~ 900 Ma) (Figure 6). This situation is common in felsic metamorphic rocks that underwent granulite facies metamorphism in the Larsemann Hills. We further precisely define the metamorphic age of the felsic gneiss in the Broknes Peninsula to be in the Grenvillian (~899 Ma).

Our experimental data and analysis supplement Wang et al. (2008) (Table 1), and further show that granite intrusion first occurred at ~ 976 Ma in the Larsemann Hills, followed by granulite facies metamorphism at ~ 899 Ma.

7.2. P-T path and polymetamorphism

The Prydz Belt is a typical polymetamorphic belt which underwent both Grenville and Pan-African high-grade
metamorphism (Zhang et al. 1996; Tong et al. 1998, 2002; Wang et al. 2008; Grew et al. 2012).

Since pegmatites were intruded during the Pan-African phase affecting the Larsemann Hills including the felsic orthogneiss, we conclude that the felsic orthogneiss was not immune to the thermal events of the Pan-African period. Nonetheless, our analysis of the petrology, mineral texture of metamorphic reaction characteristics, mineral chemistry, phase equilibrium simulation calculation, and zircon U-Pb dating of the felsic gneiss in the Broknes peninsula leads us to conclude that granite dehydrogenation occurred in the Grenvillian period (Grt + Ms + Bi + Pl + Ab + Mic + Qz + Mt) resulting in the formation of the currently-existing felsic gneiss (Grt + IIm + Pl + Kfs + Sil + Qz). Because the temperature, pressure, and amount of chemically active fluids in the Pan-African period were not sufficient to change the minerals in the felsic gneiss, the mineral assemblages of the Grenvillian felsic gneiss were largely retained. In addition, due to the lack of sufficient fluid, the Pan-African thermal age is not well recorded.

7.3. Tectonic implications for the Larsemann Hills in the Grenvillian period

The Liegeois model (Liegeois 1998) clearly demarcates the period of plate convergence and describes the various stages that occurred after the end of convergence. At the same time, the plate construction settings and the periods are also clearly stated. In terms of concepts and terminology, the plate tectonics process during the convergence period is the most complete and reasonable. The subduction-accretion orogen and the continent-continent collision orogen correspond to the first and second orogenic processes of the plate convergence, respectively. The continent-continent collision orogen is the product of the convergence of the lithospheric plates.

The ocean between the two continental plates gradually closed and disappeared, and two or more land blocks were assembled and inlaid to form a unified composite continent. S-type granites are often associated with them, and the P-T trajectory of the metamorphism of the continent-continent collision orogenic belts is generally clockwise. This is manifested by the fact that the crustal thickening pressure rises to the maximum during the collision, and then, due to gravity equalization, the crust is lifted and subjected to rapid erosion, the pressure is gradually reduced, and the temperature reaches its highest point. This is followed by a period of near isothermal decompression (Li and Liu 2006). Liu et al. (2013b) and Tong et al. (2017, 2019) discussed that the Grenvillian event in Prydz Bay and Larsemann Hills was associated with the early Neoproterozoic Rayner orogeny that was arc-continent collison.

Combined with our data, we believe that the Larsemann Hills should be categorized as the orogenic process from arc-continent collision to continent-continent collision.

Figure 9. Simplified evolution of the Larsemann Hills, East Antarctica.
during the Grenvillian period, the arc-continent collision finished earlier than 976 Ma in the Larsemann hills, accompanied by emplacement of the S-type granite (~976 Ma), crust thickening (~899 Ma) and subsequent collapse (550—500 Ma) (Ren et al. 1992) (Figure 9). The P-T condition of the feldspar orthogneiss in this study, giving rise to isothermal decompression and then isobaric cooling P-T paths, To the broader tectonic context: we infer that the East Antarctic landmass and the Indian landmass have converged and subducted at ~ 976 Ma, and the final formation time of the Rodinia supercontinent was no earlier than ~ 899 Ma.

8. Conclusions

(1) The felsic gneiss of the Broknes Peninsula intruded at ~976 Ma. The protolith was a granite (belonging to the S-type granitoid family) mainly derived from the partial melting of the lower crust.

(2) The magmatic zircons in the felsic gneiss have lower LREE and higher HREE than the metamorphic zircons.

(3) The felsic gneiss of the Broknes peninsula experienced granulite facies metamorphism in the Grenvillian period (~ 899 Ma). The metamorphic conditions were T = ~870°C and P = ~9.5 kbar.

(4) The Larsemann Hills should be categorized as the orogenic process from arc-continent collision to continent-continent collision during the Grenvillian period.

(5) The East Antarctic landmass and the Indian landmass have converged and subducted at ~ 976 Ma, and the final formation time of the Rodinia supercontinent was no earlier than ~ 899 Ma.

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Disclosure statement

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