Granulite from the Bunger Hills, Eastern Antarctica: Mineral parageneses and terms of metamorphism

I.A. Abdrakhmanov

Postgraduate student, Saint-Petersburg Mining University, St. Petersburg, Russia

Yu.L. Gulbin

Doctor of geological and mineralogical Sciences, Saint-Petersburg Mining University, St. Petersburg, Russia

ABSTRACT: The article presents the results of mineral thermobarometry and physicochemical modeling of mineral parageneses in garnet-sillimanite-cordierite gneiss from the Mesoproterozoic metamorphic unit of the Bunger Hills, East Antarctica. Therefore, a clockwise R-T path was inferred using petrographic and mineralogical data. It is shown that peak temperature of metamorphism could exceed 900 °C. Such temperature conditions in combination with post-peak decompression records the collision-related tectonic evolution of the studied area.

Keywords: thermobarometry, granulites, Bunger Hills, East Antarctica

1 INTRODUCTION

The problem of the generation of the continental crust in Precambrian is one of the leading ones in modern geology. Therefore, the reconstruction of processes of sedimentation magmatism, and subsequent metamorphism during the formation of Precambrian complexes are the most important tasks of the petrological study of the folded basement of the East Antarctic shield. The relevance of this kind of research is all the more undeniable in the light of the discussion of the evolution of the supercontinent Rodinia. One of the key sites capable for understanding the geological history is the Bunger Hills in the eastern part of the Antarctic Shield.

2 GEOLOGICAL SETTING

The Bunger Hills is a narrow strip of a land, free from ice, stretching along the Antarctic coast in the area of Wilkes Land. The geological structure of this territory was studied by Soviet and Australian geologists (Ravich et al., 1965; Sheraton et al., 1995).

A variety of plagiogneisses and crystalline gneisses, which are largely granitized and migmatized, take part in the geological structure of the Bunger Hill (Figure 1).

In the thickness of these rocks, there are concordant intrusions of metabasites and layers of silicate marbles and calciphyres, bored and weakly granitized. In addition to the most diverse migmatites, shadow granites and numerous veins of granite composition arise. Massifs of charnockites also occur among migmatites. Dolerite dikes cut through all other rocks. The thickness of migmatized plagiogneisses and crystalline gneisses are deformed into large folds, whose wings are complicated by smaller folds of higher orders. Three fault systems, along which there are zones of milonites and diaphthoritic schists, broke this section of the crystalline basement into separate blocks, mostly slightly moved relative to each other.

Figure 1. Geological map of the Bunger Hills, East Antarctica (Ravich et al., 1965).

According to the U–Pb dating of syngenetic zircon, the igneous protolith of orthogneisses formed in the interval 1700–1500 Ma, while the appearance of plutons took place at the turn of 1170–1150 Ma (Sheraton et al., 1995). The age of metamorphism, according to in situ U–Pb dating of monazite from paragneisses, is 1240–1150 Ma (Tucker et al., 2016, 2017, 2018) and closely coincides with the formation of the Albany–Fraser orogenic belt (southwestern Australia) during the amalgamation of Rodinia.

3 SAMPLE DESCRIPTION AND ANALYTICAL METHODS

Samples utilized in this study were collected during the 2nd Soviet Antarctic Expedition of 1956-57. Sample 651a (from the Krylatyy peninsula) contains quartz (30 vol.%), alkali feldspar (25), cordierite (20), garnet (10), biotite (7), sillimanite (5), ilmenite (2), albite (1), spinel (hercinite) <1, rutile, zircon $\ll$ 1. The rock has a medium-fine-grained texture and banded structure due to the alternation of lenticular quartz layers with cordierite-garnet-sillimanite-biotite sections.

The bulk chemical composition of the rock was determined with the XRF method in VNNII-Okeangeologiya. Chemical compositions of minerals were obtained using JSM-6510LA elec-tron microprobe equipped with EDS JED-2200 (JEOL) at the Institute of Precambrian Geology and Geochronology of the Russian Academy of Sciences (Saint Petersburg, Russia).

The method of isochemical diagrams (pseudosection modeling) was applied to retrieve P-T history of the rock. This method implements the fundamental principle of metamorphic fa-cies. By this method, P-T phase diagrams are calculated that show which mineral assemblage stability field takes place for the rock of a given chemical composition under given temperature and pressure conditions. The modeling was done in the system NCKFMASHT using Theriak/Domino program (de Capitani, Petrakakis, 2010) with an internally consistent thermodynamic database tcd55c2d (Holland, Powell, 1998, with changes) and different solid solution activity models for feldspars, garnet, biotite, cordierite, spinel, ilmenite, orthopyroxene, and osumilite. Quartz, sillimanite, kyanite, rutile, and titanite were considered as pure phases.

4 RESULTS

According to microprobe analysis, garnet is non-zonal and characterized by increased contents of almandine and pyrope end members ($X_{Fe}0.69 - 0.71$, $X_{Mg}0.27 - 0.29$), low contents of Ca and Mn ($X_{Ca}0.01 - 0.02$, $X_{Mn}0.01 - 0.02$). In garnet rims next to the Crd-Bt aggregate (which replaces garnet) X_{Mg}^{Grt} decreases (to 0.25), and X_{Fe}^{Grt} increases (up to 0.74). This points to the partitioning of Fe and Mg between garnet, cordierite and biotite during retrograde metamorphism (Figure 2).

Sillimanite is characterized by a composition close to stoichiometric; it contains minor FeO (0.4-0.9 wt %).

Alkali feldspar is a mesoperthite with K-rich feldspar host (Ort84-89Ab16-11An0) and almost pure albite lamellae Ab94-95An5-2Ort3-1 (Figure 3). It contains minor barium (BaO 0.3-1.3 wt %).

Figure 2. Change the composition of garnet rim next to the Crd-Bt aggregate. Points of analysis: point 19 is biotite, point 20 is sillimanite, point 21 is cordierite.

Figure 3. Mesoperthite rims around garnet crystals with Sil (II) inclusions. BSE images.

Table 1. Chemical composition for sample 651a.

SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Σ
74.88	0.70	12.82	1.14	4.18	0.09	2.20	0.01	1.32	1.36	0.11	0.90	99.71

The mineral of the spinel group corresponds to hercynite, which contains minor zinc (ZnO 4.5–7.7 wt %; 0.09–0.16 a.p.f.u.), chromium (Cr₂O₃ 0.3–7.8 wt %; 0.01–0.19 a.p.f.u.) and nickel (NiO up to 0.4–0.6 wt %; Up to 0.01 a.p.f.u.). The content of the hercynite end-member in spinel varies from 0.52 to 0.65, while the magnetite one does not exceed 0.04. The average formula ($n = 6$): (Fe²⁺_{0.61}Mg_{0.28}Zn_{0.12})_{1.01}(Al_{1.86}Fe³⁺_{0.07}Cr_{0.04}Si_{0.01})_{1.98}O₄.

Ilmenite contains minor magnesium (MgO up to 0.4–1.2 wt % and up to 0.02–0.04 a.p.f.u.) and manganese (MnO up to 0.1–0.6 wt % and up to 0.01 a.p.f.u.). The content of ilmenite end member varies from 0.92 to 0.99. Rutile contains minor FeO (0.3–2.9 wt %).

Cordierite is moderately magnesian with X_{Mg} in the range 0.68 - 0.77. Biotite is characterized by low alumina content (Al₂O₃ 17.1–19.1 wt %) and high titanium content (TiO₂ up to 6.0 wt %).

Bulk compositions of the studied sample are reported in Table 1.

During modeling, special attention was paid to the assessment of water activity in the system. To this end, P-T diagrams were constructed at different values of a_{H_2O} . As a result, water activity was limited by 0.2 because spinel observed in the rock disappears from the model assemblages at higher water activities (Figure 4, 5). In the diagram calculated for system with $a_{H_2O} = 0.12$ (Figure 5), the Grt–Crd–Kfs–Qz–Ilm assemblage consists of spinel at a pressure of 5–6 kbar and a temperature exceeding 870 °C.

5 DISCUSSIONS

Pseudosection modeling and mineralogical analysis show the clockwise P–T path that starts in the rutile stability field ($P > 9$ kbar) and records the pressure decrease to 6 kbar. The decompression temperature range is 850–950 °C; it could occur against the background of a rise in temperature, or under conditions close to isothermal. This form of the P–T path follows from the assumption that at the early stage of metamorphism the assemblage Grt+Sill+Kfs+Qz+Rt±Ilm was stable in the studied rock. According to the GRAIL geobarometer (Bohlen et al., 1983), such equilibrium could take place in the pressure range of 6–8 kbar at 900 °C. As a result of the decompression, rutile was replaced by ilmenite and hercynite began to crystallize.

The described scenario is consistent with the data of Tucker and Hand (2016), who also noted the presence of the high-pressure assemblage in the Bunger granulites. But at the same time, it cannot be ruled out that rutile in the studied sample was late and formed due to ilmenite oxidation at low temperatures at the retrograde stage (Bohlen et al., 1983), as indicated by the morphology of ilmenite–rutile intergrowths (Figure 6).

Figure 4. Isochemical P-T phase diagrams for sample 651a calculated for different values of α_{H_2O} . Quartz is in excess.

At the second stage, the Grt–Crd–Sp–Qz–Ilm assemblage stabilized and the rock experienced partial melting as a result of isobaric heating at $P = 5\text{--}6.5$ kbar and $T > 870$ °C. The growth of garnet crystals during heating promoted capture of spinel inclusions. The calculated composition of spinel ($Hc_{68-73}Sp_{30-24}Usp_{2-3}$) agrees closely with the observed one ($Hc_{60-83}Sp_{40-17}$) without taking into account minor elements. Signs of partial melting in the rock (according to Holness et al., 2011) are intergranular quartz films and numerous mesoperthite rims around crystals of cordierite, sillimanite, and garnet (Figure 3, 7).

According to the modeling data, solidus temperature in the studied system is 960 °C at pressure of 6.2 kbar and water activity of 0.12. Partial melting is accompanied by the disappearance of alkali feldspar from the Grt–Crd–Sp–Qz–Ilm assemblage. The calculated composition of the melt is $Qz_{29}Ab_{36}Kfs_{24}Sil_{10}$ whereby quartz, feldspar, and sillimanite are formed due to its crystallization. All these minerals are observed in the studied rock as melt crystallization products (Figure 3, 7). However, in contrast to the calculated composition of feldspar ($Ab_{60}Kfs_{40}An_0$), the reintegrated composition of mesoperthite observed in the sample is characterized by the predominance of the orthoclase mineral ($Ab_{37-49}Kfs_{62-50}An_1$).

It should be noted that the lower temperature limit of stability of hercynite, calculated in the NCKFMASHT system at a given water activity (870 °C), can shift to lower temperatures in the case of spinel enriched with minor elements (Fe^{3+} , Zn, Cr).

At the third stage, isobaric cooling to 750–800 °C occurred. At these temperatures, garnet and cordierite were equilibrated. Evidences of the equilibrium are: (1) the intersection of

Figure 5. Isochemical P-T phase diagram for sample 651 calculated for $a_{H_2O} = 0.12$. Quartz is in excess. Rutile and spinel stability fields are gray. The solidus line is marked in bold. Red arrow represents the P-T path inferred on the basis of petrographic and mineralogical data.

Figure 6. Intergrowth of ilmenite and rutile.

isopleths X^{Grt}_{Fe} , X^{Grt}_{Mg} , X^{Crd}_{Mg} corresponding to observed compositions of garnet and cordierite in the range of 750–800 °C at 5 kbar (Figure 5), (2) temperature estimates obtained with the Grt–Crd geothermometer (Bhattacharya et al., 1988) which vary from 700 to 770 °C at 5 kbar. According to the Ti-in-biotite geothermometer (Henry et al., 2005), high-titanium biotite stabilized under similar conditions (740–770 °C). The latter indicates an increase in water activity at the retrograde stage (as modeling shows biotite is stable up to a temperature of 760 °C at $a_{H_2O} = 0.12$ and $P = 5$ kbar).

Figure 7. Mesoperthite rims around crystals of cordierite, sillimanite and garnet. Transmitted light, crossed polars.

6 CONCLUSIONS

The following results emerge from the study:

- (1) it is shown that granulite metamorphism in the Bungar Hills undergoes at moderate pressure (5–10 kbar), low water activity ($a_{H_2O} < 0.2$), and peak temperature possibly exceeding 900 °C;
- (2) the evolution of metamorphism is described by a clockwise P-T path with near-isothermal decompression in the early stage and near-isobaric cooling in the late stage of orogeny that is typical for P-T path associated with collision events

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