Metamorphic Evolution of Calc-silicate Body Enclosed in Charnockitic Gneiss at West Ongul Island, Lützow-Holm Complex, East Antarctica

Penchan Thaworndumrongsakul¹, John Booth¹, Prayath Nantasin¹*, Yoonsup Kim²

¹ Department of Earth Sciences, Faculty of Science, Kasetsart University, Thailand
² Department of Earth and Environmental Sciences, College of Natural Science, Chungbuk National University, Republic of Korea
*Corresponding author email: fscipyn@ku.ac.th

Abstract. This paper provides a report of a study of a series of boudined bodies of mineralogically zoned calc-silicate bodies, some over 1 m thick, enclosed in granulite facies charnockitic gneisses on West Ongul Island, Lützow-Holm Complex, East Antarctica. Zircons extracted from the centre of one of the calc-silicate bodies indicate that they were metamorphosed around 532.3 ± 0.8 Ma and that the cores of these zircons were inherited from igneous rocks intruded 738.5 ± 1.8 Ma and possibly 605.0 ± 1.2 Ma. The meionite content of scapolite indicates that the peak metamorphic temperature reached a minimum of 790 °C. In the outermost rim of the calc-silicate scapolite is partially replaced by clinopyroxene, probably as a result of the influx of Mg bearing fluids from the surrounding charnockite gneiss during uplift and decompression. An influx of hydrous fluid resulted in the almost complete retrogressive alteration of plagioclase to sericite throughout the calc-silicates, with minor growth of amphibole after clinopyroxene and calcite after scapolite only in the innermost zone.

1. Introduction

The Lützow-Holm Complex stretches along the Prince Olav Coast of East Antarctica (figure 1). The dominant lithologies in the entire region are various types of gneiss, migmatite, granite and pegmatite [1,2]. Along the coast the metamorphic grade changes from granulite facies in the west to amphibolite facies in the east [3,4]. The Ongul Islands, where this study area is located, lie within the granulite facies terrane. Minor bodies of calc-silicate rocks are widespread throughout the Lützow-Holm Complex. A summary of the principle locations where they outcrop, their structural setting and mineral assemblages is provided by [5].

This paper reports on the petrology, mineral chemistry and constraints on the timing and PT conditions of the metamorphism of calc-silicates exposed on West Ongul Island. It is based on samples collected by Prayath Nantasin, during a field season in 2017 when he was attached to the 58th Japanese Antarctic Research Expedition, under the Asian Forum for Polar Science.

2. The general geology of West Ongul Island and location of sampling points

The Ongul Islands, which cover an area of 5 by 2.5 km, are situated near the northeast of Lützow-Holm Bay. Published 1 : 5000 scale geology maps [6,7] are available for the four largest islands, including West Ongul (figure 1). The islands consist of a variety of granitic and pyroxene, hornblende, garnet-biotite bearing gneisses, with subordinate garnet-orthopyroxene amphibolite, metabasite and pegmatite.
Among these gneisses are minor layers of marble and lenses of calc-silicate rocks [7], the later being the focus of this study. All of this area has been metamorphosed to granulite facies [1,8]. The dominant structural fabric is a moderately dipping strong schistosity and gneissic foliation that strikes NNW – SSE and is axial planer to a first generation of isoclinal folds [9]. A second deformation episode produced a series of closed to open folds, with wavelengths up to 2 km, with steeply dipping axial planes striking ESE – WNW [10].

Three large, boudin shaped calc-silicate bodies, between 0.5 and 1.5 m in thickness, are exposed within 30 m of each other in the sampling area (figure 1), each surrounded by a smaller lenses and blocks. They are enclosed in a strongly foliated charnockite gneiss, which unfortunately was not sampled due to transportation weight restrictions. In the field four different zones were distinguished in these calc-silicates, based on colour and hand-lens mineral identification (figure 2). A total of 9 large hand specimens were collected, representing all the zones and their contacts.

3. Petrography and reaction textures
The zonation pattern that was recognised in the field was largely based on the different modal amounts of plagioclase, clinopyroxene and scapolite (figure 2). The innermost zone consists of pods that composed largely of anorthitic plagioclase. The intermediate zone is composed predominantly of diopsidic clinopyroxene, with moderate amounts of meionitic scapolite. The outer zone consists of scapolite and clinopyroxene, with scapolite predominating. Between the clinopyroxene rich and scapolite rich zones there is a discontinuous, thin zone rich in biotite.

A total of 13 samples were cut from the hand specimens, covering the 4 mineral zones recognised in the field and their mutual contacts (figure 2). Polished thin sections were made from each of these samples for analysis by electron-microprobe. Powders for XRF analysis were prepared from all samples, except specimen E, which instead was crushed to extract zircons for Pb-U dating. The modal composition of each mineral zone is shown in figure 3, which is a composite derived from point counts, excluding accessory phases, of all 13 thin sections.
Figure 2. Calc-silicate bodies at locations 1 and 2. Hammer 40 cm
White central patches plagioclase rich zone, dark green clinopyroxene rich zone and pale grey scapolite rich outer zone. The thin biotite zone between scapolite and cpx not shown.

Figure 3. Modal composition of mineral zones based on thin section analysis

3.1 Plagioclase rich zone
This zone takes the form of isolated pods in the innermost part of each calc-silicate body. It is composed primarily of plagioclase, which is almost entirely altered to sericite, with large muscovite flakes clearly visible (figure 4.A). The zone contains moderate amounts of clinopyroxene, calcite and scapolite, the latter extensively altered to calcite (figure 4.A). Clinopyroxene frequently, but not always, is altered to actinolite, apparently where it is in contact with calcite (compare figures 4.A and B). Titanite and zircon are common accessories, with single titanite grains sometimes showing a mantle of smaller crystals, indented into adjacent clinopyroxene and plagioclase (figure 4.C). The breakdown of scapolite to calcite and the growth of a mantle around titanite suggests either a second metamorphic event at lower pressure, or equilibration during uplift induced decompression. The alteration of plagioclase and clinopyroxene probably resulted from retrograde reactions driven by an influx of a fluid rich in $\text{H}_2\text{O}$ rather than $\text{CO}_2$. Where calcite is present plagioclase often exhibits rounded, possibly corroded edges (figure 4.A).
3.2 Clinopyroxene rich zone
This is the thickest of all the zones, comprising around three quarters of the width of the main calc-silicate bodies (figure 2). It is predominantly composed of light green clinopyroxene, with significant amounts of scapolite, the later becoming more important towards the outer edge of this zone. Biotite is a minor component, but plagioclase is entirely absent. Titanite is the main accessory phase. Clinopyroxene and scapolite grains are equidimensional and form a granoblastic texture (figure 4.D). Neither phase exhibits any alteration or indication of instability. The transition into the plagioclase rich zone is sharp, with clinopyroxene crystals showing only minor indentation into plagioclase. Likewise the transition into the biotite rich zone, where present, is sharp, with no indication of reaction textures between mineral phases.

3.3 Biotite (phlogopite) rich zone
There is an intermittently developed biotite rich zone along the outer edge of the clinopyroxene rich zone. Around half of this zone consists of relatively small crystals of chestnut brown coloured biotite, which, together with equally small grains of clinopyroxene and scapolite, are surrounded by altered plagioclase (figure 4.E). The main accessory phase is green hercynite spinel, which does not occur in any of the other zones. The transition outwards into to scapolite rich zone is sharp, with no evidence of any reaction textures between phases.

3.4 Scapolite rich zone
A little over half of this zone is composed of scapolite, with most of the remainder being clinopyroxene and minor biotite. Titanite is the main accessory phase and in places can comprise several percent of the rock volume. The inner part of this zone (figure 4.F) displays an equigranular granoblastic texture, with all phases appearing to be stable and in equilibrium. In contrast, in the outer part of this zone there is extensive replacement of scapolite by clinopyroxene. There are two different replacement textures. Large grains of scapolite, which show no internal alteration, are mantled by clinopyroxene (figure 4.G). Unmantled scapolite contains a multitude of small rod shaped clinopyroxene grains, forming a variety of distinct patterns, including fans, stripes and ellipses (figure 4.H). In many places mutual extinction shows that now separated areas of unaltered scapolite are in fact one crystal. Many large clinopyroxene grains display optically visible zonation in cross-polars illumination, with distinct inner cores that contain exsolution lamelli and belbs, which, based on their crystallographic orientation and low birefringence are assumed to be orthopyroxene (figure 4.I).

4. Whole rock and mineral chemistry
Major element whole rock composition was determined by X-ray fluorescence on powdered samples prepared from 12 of the 13 specimens from which thin sections were made. These were analysed at the Korea Polar Research Institute. The results are summarised in table 1. The different mineral zones are chemically quite distinct, however, the same zone from different calc-silicate bodies have very similar chemical compositions (table 1 and figure 5) This is taken as indicating they are all part of the same original sedimentary body and underwent similar metasomatic processes during metamorphism.

It is evident from figure 5 that at locations 1 and 2 the scapolite rich zones are moderately richer in Si and significantly richer in Al than the adjacent clinopyroxene rich zones. There are insufficient data points for the other mineral zones to make any sensible inferences, other than to note that the two samples from the plagioclase rich zone have markedly different chemistries.
Figure 4. Photomicrographs showing assemblages and textures typical of all mineral zones
Width of field of view 3 mm, except H which is 1.2 mm

The chemical composition of all mineral phases was analyzed using a JEOL JXA-8530F field-emission electron microprobe at Korea Polar Research Institute (KOPRI), with 15kV accelerating voltage, 10 nA beam current and 3 um beam diameters. Standard materials used for the calibration include natural silicates and synthetic oxides. Representative analyses and molar compositions of the relevant minerals are provided in Table 2.

**Scapolite.** Scapolite grains within the plagioclase rich zone proved too altered to produce a reliable composition. Within the clinopyroxene rich zone scapolite varies in composition between 65 – 73% meionite content, although individual grains do not show optical zoning. In the inner part of the scapolite rich zone different specimens display minor (core – rim 77 – 72 % meionite) to moderately significant zonation (core – rim 57 – 67% meionite).

**Clinopyroxene.** In all zones clinopyroxene is diopside, having very little Fe or Al content. It has a pale green colour and displays little pleochroism. The exception is sample PN-I1, where it is distinctly rose-red coloured in hand specimen and shows marked pleochroism from rose pink to light green. Compositionally this also diopside, but contains up to 2.47 wt% titanium.

**Biotite.** In all zones biotite has an Xmg ratio of 70 – 75. This phlogopite content is reflected in its medium chestnut brown to light brown pleochroic scheme.

**Amphibole.** The amphiboles replacing rims of clinopyroxene found in the plagioclase rich zone are actinolite.
Table 1. Whole rock major element composition corresponding to samples used to make thin sections

| Sample     | Calc-silicate zone and location | LOI (%) | Sum (%) | SiO₂ (%) | TiO₂ (%) | Al₂O₃ (%) | Fe₂O₃ (%) | MnO (%) | MgO (%) | CaO (%) | Na₂O (%) | K₂O (%) | P₂O₅ (%) |
|------------|---------------------------------|---------|---------|----------|----------|-----------|-----------|---------|---------|---------|----------|---------|----------|
| PN-B       | Scp rich zone Loc. 1            | 3.01    | 100.04 | 50.23    | 0.26     | 13.08     | 4.22      | 0.11    | 7.15    | 19.04   | 2.30     | 0.55    | 0.10     |
| PN-C       | Scp rich zone Loc. 1            | 2.63    | 99.88  | 48.82    | 0.08     | 15.01     | 3.18      | 0.09    | 7.20    | 20.47   | 1.68     | 0.46    | 0.27     |
| PN-G1      | Scp rich zone Loc. 1            | 4.12    | 100.50 | 48.21    | 0.05     | 16.38     | 2.37      | 0.09    | 6.94    | 18.96   | 2.16     | 0.83    | 0.38     |
| PN-H       | Scp rich zone Location 2        | 3.09    | 99.71  | 45.14    | 1.96     | 18.28     | 3.90      | 0.07    | 3.34    | 20.93   | 1.71     | 0.57    | 0.70     |
| PN-G2      | Scp rich to Bt rich zones Loc. 1| 2.02    | 98.51  | 43.78    | 1.46     | 8.90      | 8.85      | 0.10    | 16.49   | 10.84   | 0.15     | 5.44    | 0.47     |
| PN-G3      | Bt rich to Cpx rich zones Loc. 1| 1.89    | 98.15  | 51.66    | 0.19     | 2.11      | 5.28      | 0.14    | 15.57   | 22.53   | 0.19     | 0.59    | 0.01     |
| PN-A       | Cpx rich zone Loc. 1            | 1.92    | 99.88  | 51.16    | 0.16     | 7.54      | 4.71      | 0.14    | 11.42   | 21.06   | 1.25     | 0.47    | 0.04     |
| PN-D2      | Cpx rich zone Loc. 1            | 0.71    | 99.82  | 53.03    | 0.11     | 1.00      | 4.89      | 0.14    | 15.92   | 23.67   | 0.12     | 0.22    | 0.02     |
| PN-I1      | Cpx rich zone (red) Loc. 2      | 0.76    | 100.11 | 48.33    | 0.89     | 8.52      | 3.84      | 0.09    | 12.87   | 23.92   | 0.34     | 0.23    | 0.32     |
| PN-I2      | Cpx rich zone (green) Loc. 2    | 1.47    | 100.27 | 51.04    | 0.17     | 7.27      | 5.62      | 0.13    | 11.00   | 22.46   | 0.86     | 0.18    | 0.07     |
| PN-D1      | Plagioclase to Cpx Loc. 1       | 5.48    | 99.89  | 44.62    | 0.04     | 34.12     | 0.54      | 0.09    | 1.60    | 5.79    | 0.73     | 6.86    | 0.01     |
| PN-F       | Plagioclase rich zone 3         | 4.72    | 99.89  | 44.59    | 0.08     | 22.40     | 2.17      | 0.15    | 5.42    | 17.71   | 0.87     | 1.78    | 0.01     |

Figure 5. SCM and ACM plots of whole rock compositions showing systematic differences in chemical composition of between mineral rich zones

Table 2. Representative mineral compositions and formulas from different calc-silicate zones

| Scapulite-rich zone | Biotite-rich zone | Clinopyroxene-rich zone | Plagioclase-rich zone |
|---------------------|------------------|-------------------------|-----------------------|
| Si                  | Ti                | Al                  | Cr                    | Fe                   | Mn                   | Mg                  | CaO                  |
| 3.96                | 100.00            | 50.23               | 0.26                  | 13.08                | 4.22                 | 0.11                | 7.15                 |
| 100.04              | 50.23             | 0.26                | 13.08                 | 4.22                 | 0.11                 | 7.15                | 19.04                |
| 2.30                | 0.55              | 0.10                |                      |                      |                      |                     |                      |
| Na                  | K                 | ZnO                 | Total                |
| 99.88               | 99.89             | 99.33               | 99.05                |
| 93.49               | 94.13             | 94.13               | 94.13                |
| 99.48               | 99.33             | 99.33               | 99.33                |
| 99.99               | 99.99             | 99.99               | 99.99                |
| 99.14               | 99.14             | 99.14               | 99.14                |
| 99.98               | 99.98             | 99.98               | 99.98                |
| 99.33               | 99.33             | 99.33               | 99.33                |
| 99.05               | 99.05             | 99.05               | 99.05                |
| 99.46               | 99.46             | 99.46               | 99.46                |

| %Si                | %Al               | %Cr                 | %Fe                  | %Mn                | %Mg                |
|--------------------|-------------------|---------------------|---------------------|--------------------|-------------------|
| 3.96               | 100.00            | 50.23               | 0.26                | 13.08              | 4.22              |
| 100.04             | 50.23             | 0.26                | 13.08               | 4.22               | 0.11              |
| 2.30               | 0.55              | 0.10                |                     |                    |                   |

| %Na               | %K                | %ZnO                | Total               |
|-------------------|-------------------|---------------------|---------------------|
| 99.88             | 99.89             | 99.33               | 99.33               |
| 93.49             | 94.13             | 94.13               | 94.13               |
| 99.48             | 99.33             | 99.33               | 99.33               |
| 99.99             | 99.99             | 99.99               | 99.99               |
| 99.14             | 99.14             | 99.14               | 99.14               |
| 99.98             | 99.98             | 99.98               | 99.98               |
| 99.33             | 99.33             | 99.33               | 99.33               |
| 99.05             | 99.05             | 99.05               | 99.05               |
| 99.46             | 99.46             | 99.46               | 99.46               |

| %Sum               | %%Me              | %EqAn               |                    |
|--------------------|-------------------|---------------------|--------------------|
| 15.92             | 15.94             | 15.96               | 15.92              |
| 4.00              | 3.99              | 4.00                | 15.72              |
| 2.42              |                    |                     |                    |
| 15.93             | 15.95             | 4.00                | 3.99               |
| 15.06             |                    |                     |                    |
| 5.02              | 5.00              | 3.98                | 15.20              |
| 0.70              | 0.70              | 0.70                | 0.70               |
| 0.66              | 0.66              | 0.66                | 0.66               |
| 0.729             |                    |                     |                    |
| 0.656             |                    |                     |                    |
**Plagioclase.** Although almost entirely altered to sericite in all specimens, a few large plagioclase crystals in the central zone have unaltered patches, which microprobe analyses show to range from 91 to 95% anorthite.

5. Metamorphic pressure and temperature conditions
The mineral assemblages of these calc-silicates are such that well established geothermo-barometry cannot be applied. The surrounding charnockitic gneisses were not sampled, but several previous studies have shown that they were metamorphosed to >6 kbar and >780°C [11]. Scapolite in calc-silicates of this grade, which lack garnet and/or wollastonite almost certainly formed by the reaction anorthite + calcite = meionite (Ca scapolite). This reaction has been experimentally investigated at 7 kbar [12], establishing a relationship whereby the temperature can be determined based on the meionite content of scapolite. As previous studies of this region indicate its metamorphism probably occurred in the range of 7 kbar and 810°C [11], the temperatures derived from the meionite content of the scapolite in these rocks are probably reasonable estimates.

The meionite content of scapolite in the clinopyroxene zone is consistent with metamorphism at a minimum temperature of 770 – 790°C. Scapolites in the inner part of the scapolite zone are clearly zoned and produce estimated temperatures ranging from core to rim of around 730 to 760°C respectively. In the outer part of the scapolite zone, where scapolite is partially replaced by clinopyroxene, temperature estimates derived from unaltered, clinopyroxene mantled grains (figure 4.G) are in the order of 775 – 780°C.

6. Zircon Pb-U determined ages of protolith and metamorphism
A suite of 103 zircons were extracted from sample E in the plagioclase zone of the location 3 calc-silicate. These were analysed using a SHRIMP at the Korea Basic Science Institute. A back scattered electron image (figure 6) does not show any obvious reabsorption features. The zircons have euhedral to subhedral cores and two separate mantles. The part of the mantle has a much darker colour and contains sets of fractures radiating out from its contact with the core, indicating radiation damage.

![Figure 6. Possible clusters of zircon ages. BSE image of a portion of sampled zircons](image)

Three analyses were made for each of 12 zircons, corresponding to what visually appeared to be core, inner mantle and outer mantle positions, of which 34 lie on a concordia and were accepted for further analysis. Twelve rim analyses points yield a weighted mean average $^{206}\text{Pb}/^{238}\text{U}$ age of 532.2 ± 0.8 Ma (figure 6). The core and inner mantle analyses points have a significant spread of ages, with two possible clusters (figure 6) with wma $^{206}\text{Pb}/^{238}\text{U}$ ages of 738.5 ± 1.8 Ma and 605.0 ± 1.2 Ma.
7. Conclusions

Pb-U dating of zircons from within the plagioclase rich zone in the core of one of these calc-silicate bodies indicates a single episode of metamorphism at 538.5 ± 1.8 Ma. The two clusters of ages for core and inner mantle analyses points are assumed to indicate inheritance of zircon grains from igneous events at 738.5 ± 1.8 Ma and 605.0 ± 1.2 Ma.

For the most part, from the inner portion of the scapolite rich zone to the plagioclase rich core, these calc-silicates are characterised by equigranular, granoblastic textures with no textural evidence of phase disequilibrium. Throughout these rocks the plagioclase has been almost completely altered to sericite, with large flakes of muscovite often evident. Within the innermost, plagioclase rich, zone scapolite is fairly extensively altered to calcite and rims of clinopyroxene are often altered to actinolite. These features suggest that during the retrogressive phase of this region's PT path a hydrous fluid phase entered these calc-silicates.

In the outer part of the scapolite rich zone these is textural evidence for a second episode of clinopyroxene growth. This involves clinopyroxene mantling both older clinopyroxene grains and apparently unaltered scapolite grains. The rest of the scapolite, which makes up the bulk of the rock, is partially replaced by small rods of clinopyroxene that form geometric arrays, probably reflecting control by the underlying crystal structures of the host scapolite. This alteration may not represent a separate metamorphic event, but rather result from the influx of a fluid from the surrounding during uplift and decompression, with Mg migrating into the outer edge of the calc-silicate body.

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