Metamorphic Evolution of Calc-silicate Rocks at Akarui Point, Lützow-Holm Complex, East Antarctica

Bowornlak Amnatmetta¹, 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. We report on the petrology and metamorphic history of boudined bodies of zoned calc-silicate rock, up to 1 m in width, which are enclosed in gneisses, transitional between upper amphibolite to granulite facies, at Akarui Point, Lützow-Holm Complex, East Antarctica. Zircons extracted from a closely related body of Mn-exhalative derived calc-silicates indicate that the metamorphism occurred in two separate events, at 546.6 ± 0.6 and 524.3 ± 0.6 Ma, during the Pan African Orogeny. Based on the meionite content of scapolite from different mineral zones in the calc-silicates, we derive a metamorphic history that involved a peak temperature of a minimum 810–820 °C, followed by a fall to 760–800 °C and then to 690–765 °C during uplift and decompression to 5.5–7 kbar. GAP geothermo-barometry indicates that the enclosing gneiss partially re-equilibrated during retrogression at 500–580 °C.

1. Introduction
The Lützow-Holm Complex is located on the Prince Olav Coast of East Antarctica (figure 1). This entire region is largely composed of various types of gneiss, migmatite, granite and pegmatite [1,2]. Along the coast the metamorphic grade changes from granulite facies (west) to amphibolite facies in the east [3,4,5]. Akarui Point, the location of this study, lies the transition zone between these facies [1]. Minor bodies of calc-silicate rocks are widespread throughout the Lützow-Holm Complex. A regional study [6] provides data on the mineral assemblages and reaction textures within these calc-silicates. Another review of the occurrence and mineral assemblages of calc-silicate bodies at several key localities along the Prince Olav Coast is provided by [7], which includes a brief description on the field relationships of the calc-silicates at Akarui Point. This paper reports on the petrology, mineral chemistry and constraints on the timing and PT conditions of the metamorphism of calc-silicates at Akarui Point. 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 Akarui Point and location of sampling points
Akarui Point is located in what Hiroi [1] proposed is a 75 km or so wide transition zone between regions of amphibolite facies (east) and granulite facies (west) metamorphism within the Lützow-Holm Complex (figure 1). Exposures are composed predominantly of biotite granitic gneiss and varieties of hornblende and biotite gneisses, with minor amounts of pyroxene gneiss, amphibolite, mafic granulite, granite and pegmatite [8].
Of particular interest are rare pelitic units with assemblages that include sillimanite and garnet, the later containing relict kyanite inclusions. These pelites were used by Hiroi [6] to demonstrate that the metamorphism of rocks at Akarui Point followed a clockwise PT path. Iwamura [9] examined sapphire–spinel bearing mafic granulites from at Akarui Point and determined that during prograde metamorphism PT conditions reached peak pressures of around 11 – 12 kbar, at 900°C, followed by an increase in temperature to around 920°C during uplift and decompression to 5 – 6 kbar.

Figure 1. Location of Akarui Point along the Prince Olav Coast and general geology map

The region around Akarui Point has undergone multiple regional deformational events. Yanai [8] identified two episodes of folding, while Ikeda [10] suggested that there was an additional earlier phase of deformation. All of the calc-silicate bodies were drawn out into boudins during the formation of the strong regional foliation, which generally strikes NW – SE. This obscures the nature of their original contacts with the surrounding gneisses, although they are assumed to be of sedimentary origin. Two types of mineralogically zoned calc-silicate bodies were sampled at three closely space localities in the north-western part Akarui Point (figure 1). They are up to 1 m in width and enclosed in a biotite and garnet bearing hornblende gneiss. The calc-silicates from locations 1 and 2 are rather simple, consisting of a mafic, clinopyroxene rich core, separated from the enclosing gneiss by a very thin band of hornblende. The other, from location 3, is multiply zoned, with a mafic core very rich in red garnets, separated from an outer felsic layer by two thin zones rich in clinopyroxene and hornblende respectively. There is also a thin hornblende rich seam at the contact with the gneiss. Other calc-silicates at Akarui Point, part of a separate study, include a type with separate domains rich in epidote and red garnets [7] and at location 4 (figure 1) a complexly zoned type containing Mn-pyroxenoids and other Mn phases. This later type probably originated as an exhalative deposit.

3. Petrography and reaction textures

The gneiss that surrounds the calc-silicate bodies is mesocratic, largely composed of plagioclase, hornblende and brown biotite, with minor amounts of quartz and occasional garnet (figure 2). The garnets are skeletal, apparently being replaced by an intergrowth of bright green hornblende plagioclase, which is much finer grained that that in the matrix (figure 3).
3.1 Calc-silicate without garnet
This type of calc-silicate was sampled at locations 1 and 2 (figure 1) where the boudins are up to 1 m thick and rather simply divided into two main mafic zones (figure 2). The core zone, which comprises the bulk of both bodies sampled and has a coarse granoblastic texture, is composed of clinopyroxene and dark green-brown hornblende, with minor scapolite and plagioclase. Accessories are calcite, quartz, apatite, epidote and opaques (figure 3). Clinopyroxene is partially replaced by pale green hornblende. Plagioclase shows relatively minor alteration to sericite. When viewed in crossed polars interference colours indicate that the scapolite is chemically zoned (figure 3). The outer zone is only a few cm thick and composed predominantly of green-brown hornblende, with minor to trace amounts of plagioclase (in places altering to muscovite) and scapolite. The enclosing gneiss for up to 5 cm from the contact is noticeably leucocratic, being composed almost entirely of plagioclase feldspar.

3.2 Garnet-bearing calc-silicate
This calc-silicate is around 1 m in thickness and more complexly zoned (figure 2). The core zone, which comprises the bulk of the boudin, is coarse grained and consists of garnet, plagioclase and subordinate scapolite, with minor bright blue-green clinopyroxene and opaques. Accessories are titanite, zircon and apatite. The scapolite does not exhibit optical zoning. The entire core zone displays a fabric consisting of skeletal garnets surrounded by coarse grains of plagioclase and scapolite enclosing irregular shaped blebs of garnet (figure 4). There is a secondary fabric with symplectite intergrowth of a bright blue-green clinopyroxene and plagioclase replacing garnet (figure 4). Two combined thin sections show that the outermost portion of this calc-silicate body, equivalent to zones 2, 3 and 4 in figure 2, can be divided into 9 separate zones over a distance of only 7 cm (figure 5). The innermost zone, incomplete at the edge of the sample, consists of garnet and marialite (Na-scapolite), passing outwards to a zone of plagioclase-garnet symplectite, followed by a zone consisting of plagioclase-hedenbergite symplectite, with only a few remaining grains of garnet, which is absent from all further zones. There are then four zones with various combinations of plagioclase, diopsidic clinopyroxene, brown-green hornblende and biotite, within which the clinopyroxene is partially replaced by a pale green hornblende. The final zone (zone 4 in figure 2) consists entirely of plagioclase and quartz.
Figure 3. Photomicrographs location 2 Width of field of view 3 mm
a) enclosing gneiss, garnet surrounded by hornblende – plagioclase symplectite
b) scapolite from the core zone showing optical zoning

Figure 4. Photomicrographs location 3 garnet rich core zone. Width of field of view 3 mm
a) coarse plagioclase and scapolite crystals enclosing irregular belbs of garnet
b) symplectite of green clinopyroxene and anorthite replacing garnet

4. Mineral chemistry
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 5 μm beam diameter. 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 1.

**Garnet.** Within the calc-silicate bodies garnets have high grossular and subordinate almandine components (Alm\textsubscript{33.38} Prp\textsubscript{0.1} Grs\textsubscript{58.64} Sps\textsubscript{0.1}). In the host gneiss garnets are predominantly almandine pyralspite, with a significant grossular content (Alm\textsubscript{41.47} Prp\textsubscript{20.24} Grs\textsubscript{13.29} Sps\textsubscript{7.14}).

**Clinopyroxene.** In calc-silicates that do not contain garnet the clinopyroxene is diopside, with X\textsubscript{Mg} values ranging from 0.71 to 0.83. The only clinopyroxene present in the garnet-bearing calc-silicate is within a symplectite with anorthite replacing garnet. It is hedenbergite, with X\textsubscript{Mg} values between 0.34 and 0.37.

**Amphibole.** All of the amphibole in both the calc-silicates and the enclosing gneisses is hornblende (classification of Leake et al., 1997).

**Scapolite.** Composition of scapolite is conventionally expressed in terms of its EqAn % content following the scheme of Evans [11], with the theoretical end member of pure meionite having an EqAn value of 100%. In the core zone of the calc-silicate without garnet at location 2 scapolite is optically zoned, with EqAn values ranging from 62 to 76% from rim to core respectively. At location 3, the garnet bearing core zone contains unzoned scapolite with EqAn values between 77 and 80%. In the outer part of this calc-silicate body there is a zone containing marialite scapolite, identified optically from low 1st
order birefringence colours. Further out in the rim zones scapolite replacing plagioclase ranges in composition from marialite (EqAn 41 – 47%) to more meionitic (EqAn 56 – 64%).

![Figure 5](image)

**Figure 5.** Thin sections showing complex zonation in the outer part of location 3 calc-silicate

**Plagioclase.** In the calc-silicate without garnet, plagioclase is bytownite, with anorthite content in the range 86 to 90%. However, in the leucocratic boundary zone of the host gneiss it is andesine to labradorite, with anorthite content ranging from 32 to 53%. In the garnet-bearing calc-silicate, plagioclase in the leucocratic zone between the unaltered gneiss and the calc-silicate is almost pure anorthite (An$_{93.96}$).

5. Metamorphic pressure and temperature conditions

The mineral assemblage of the gneiss that encloses the calc-silicate body at location 1 consists of plagioclase, hornblende, garnet and quartz. Using this gneiss, a range of possible pressure and temperature values for its metamorphism was calculated using the GTB program (version 2.1 by F.S. Spear), with calibrations Kohn and Spear [12] and Graham and Powell [13] for pressure and temperature respectively. This iterative analysis derived a temperature range of 500 - 580 °C and pressure range from 5.5 - 7 kbar (figure 6).

Hiroi [6] noted that nearby pelites contain sillimanite, with kyanite relics included in garnets. As shown in figure 6 the transition from kyanite to sillimanite at a pressure of 7 kbar should occur at around 665 °C. This suggests that the temperature estimates derived from the surrounding gneiss reflect conditions from a portion of the retrograde PT path of this area.

| Table 1. Representative scapolite compositions and formulas from all calc-silicate zones |
|-----------------------------------------------|
| **Location 2 central zone** | **Location 3 central zone** | **Location 3 outer zones** |
| Location 2 central zone | Location 3 central zone | Location 3 outer zones |
| SiO$_2$ | 42.87 | 45.05 | 42.61 | 45.27 |
| TiO$_2$ | 0.00 | 0.00 | 0.00 | 0.04 |
| Al$_2$O$_3$ | 28.48 | 26.24 | 28.60 | 26.11 |
| FeO | 0.13 | 0.22 | 0.13 | 0.19 |
| Na$_2$O | 0.05 | 0.04 | 0.02 | 0.02 |
| MgO | 0.00 | 0.00 | 0.00 | 0.01 |
| CaO | 19.31 | 16.83 | 19.74 | 16.38 |
| Na$_2$O | 0.18 | 0.23 | 0.13 | 0.22 |
| K$_2$O | 2.15 | 3.49 | 1.98 | 3.73 |
| SO$_2$ | 1.42 | 2.90 | 1.48 | 2.34 |
| Cl | 0.17 | 0.29 | 0.14 | 0.40 |
| CO$_2$ | 3.68 | 2.69 | 3.67 | 2.85 |

| Location 3 central zone | Location 3 outer zones |
|-------------------------|------------------------|
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| SiO$_2$ | 42.87 | 45.05 | 42.61 | 45.27 |
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| CO$_2$ | 3.68 | 2.69 | 3.67 | 2.85 |

| Location 3 central zone | Location 3 outer zones |
|-------------------------|------------------------|
| Location 3 central zone | Location 3 outer zones |
| SiO$_2$ | 45.80 | 46.07 | 47.67 | 50.02 |
| TiO$_2$ | 0.06 | 0.05 | 0.05 | 0.07 |
| Al$_2$O$_3$ | 29.15 | 28.75 | 28.91 | 29.05 |
| FeO | 0.26 | 0.38 | 0.28 | 0.31 |
| Na$_2$O | 0.10 | 0.01 | 0.02 | 0.03 |
| MgO | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 20.50 | 20.33 | 20.28 | 19.95 |
| Na$_2$O | 0.08 | 0.11 | 0.11 | 0.11 |
| K$_2$O | 1.48 | 1.64 | 1.59 | 1.73 |
| SO$_2$ | 0.00 | 0.00 | 0.00 | 0.00 |
| Cl | 0.00 | 0.00 | 0.00 | 0.00 |
| CO$_2$ | 4.65 | 4.62 | 4.65 | 4.70 |

| Location 3 outer zones | Location 3 outer zones |
|------------------------|------------------------|
| Location 3 outer zones | Location 3 outer zones |
| SiO$_2$ | 45.80 | 46.07 | 47.67 | 50.02 |
| TiO$_2$ | 0.06 | 0.05 | 0.05 | 0.07 |
| Al$_2$O$_3$ | 27.01 | 26.72 | 25.77 | 24.71 |
| FeO | 0.34 | 0.18 | 0.27 | 0.24 |
| Na$_2$O | 0.14 | 0.12 | 0.06 | 0.10 |
| MgO | 0.10 | 0.10 | 0.10 | 0.11 |
| CaO | 18.06 | 17.64 | 16.07 | 13.68 |
| Na$_2$O | 0.28 | 0.20 | 0.36 | 0.59 |
| K$_2$O | 3.14 | 3.48 | 4.30 | 5.46 |
| SO$_2$ | 0.35 | 1.03 | 1.20 | 1.44 |
| Cl | 0.26 | 0.20 | 0.55 | 1.12 |
| CO$_2$ | 4.23 | 3.92 | 3.42 | 2.64 |
Based on the fact that garnets in mafic gneisses contain garnet being replaced by orthopyroxene – plagioclase – spinel symplectites, Hiroi [6] inferred that there was an initial phase of relatively high pressure and low temperature metamorphism, followed by uplift and decompression, resulting in the symplectite growth. Iwamura [9] examined sapphire – spinel bearing mafic granulites found at Akarui Point and determined that during prograde metamorphism PT conditions reached peak pressures of around 11 – 12 kbar, at 900 °C, followed by uplift decompression to 5 – 6 kbars, during which temperature increased to around 920 °C.

Some zones of the calc-silicates contain meionite scapolite, which in such lithologies is usually produced by the reaction anorthite + calcite = meionite (Ca scapolite). This reaction is independent of X_{Na} in the accompanying fluid phase. Baker and Newton [14] investigated this reaction at 7 kbar and produced a relationship whereby the temperature can be determined based on the meionite content of scapolite. As is shown in figure 6, using the scapolite analyses provided in table 1, this relationship suggests that scapolite was first formed in the inner zone of the calc-silicates at a minimum temperature of around 810 – 820 °C. The scapolite in the inner zone of location 2 comprises large, granoblastic grains that are zoned, with the composition of their rims indicating a decline in temperature from 800 – 760 °C. The marialite rich scapolite in the innermost of the outer zones at location 3, which has a granoblastic texture, appears to have equilibrated at temperatures as low as 710 – 690 °C. In zones further out of this the composition of minor scapolite replacing granoblastic plagioclase indicates a temperature of 740 – 765 °C.

6. Zircon Pb-U determined ages of protolith and metamorphism

A suite of 125 zircon grains were extracted from a sample at location 4, from a body of a metamorphosed Mn rich exhalative deposit. These were analysed using a SHRIMP at the Korea Basic Science Institute. A core and mantle pattern is evident from a back scattered electron image (figure 7). Most cores are rounded and anhedral to subhedral in shape, with no obvious zoning. However, a number of the zircons contain euhedral to subhedral cores, with multiple zoning evident.

Core – mantle pair points were analysed for 13 zircons. Of these, 1 point was rejected on the basis that its error range was too large. All of the accepted points lie on a concordia. One point, a core probably represents an inherited grain, indicated an age of around 680 Ma. The other 24 analyses points clearly separate into two groups (figure 7). The rim analyses indicate a metamorphic event at around 524 Ma. The second cluster, a composite of rim and apparent mantle points, at 545.6 ± 0.6 Ma could also be due to a metamorphic event.

| C|corr | 0.04 | 0.06 | 0.03 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.04 | 0.12 | 0.25 | 0.34 | 0.39 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total | 98.39 | 97.90 | 98.48 | 97.48 | 98.04 | 98.12 | 98.14 | 98.93 | 99.71 | 99.65 | 99.70 | 99.92 | 100.17 | 100.22 |
| Si | 7.12 | 6.73 | 6.70 | 7.14 | 6.59 | 6.66 | 6.65 | 6.68 | 7.08 | 7.13 | 7.33 | 7.58 | 7.72 | 7.74 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Al | 4.88 | 5.27 | 5.30 | 4.86 | 5.41 | 5.34 | 5.35 | 5.32 | 4.92 | 4.87 | 4.67 | 4.42 | 4.28 | 4.26 |
| Fe | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.05 | 0.04 | 0.04 | 0.04 | 0.02 | 0.03 | 0.03 | 0.03 | 0.02 |
| Mn | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 |
| Mg | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Ca | 2.85 | 3.25 | 3.33 | 2.77 | 3.46 | 3.43 | 3.41 | 3.32 | 2.99 | 2.92 | 2.65 | 2.22 | 2.03 | 1.91 |
| Na | 0.05 | 0.04 | 0.03 | 0.05 | 0.02 | 0.02 | 0.02 | 0.02 | 0.05 | 0.04 | 0.07 | 0.11 | 0.14 | 0.10 |
| K | 1.07 | 0.66 | 0.60 | 1.14 | 0.45 | 0.50 | 0.49 | 0.52 | 0.94 | 1.05 | 1.28 | 1.60 | 1.80 | 1.98 |
| SO₃ | 0.34 | 0.17 | 0.17 | 0.28 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.12 | 0.14 | 0.16 | 0.06 | 0.06 |
| Cl | 0.08 | 0.05 | 0.04 | 0.11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.05 | 0.14 | 0.29 | 0.38 | 0.44 |
| CO₂ | 0.58 | 0.79 | 0.79 | 0.62 | 1.00 | 0.99 | 1.00 | 1.00 | 0.89 | 0.83 | 0.72 | 0.55 | 0.56 | 0.50 |
| Total | 17.00 | 16.96 | 16.98 | 16.99 | 16.96 | 17.01 | 16.96 | 16.91 | 17.08 | 17.08 | 17.07 | 17.02 | 17.05 | 17.05 |
| EqAn% | 75.67 | 62.80 | 76.69 | 61.87 | 80.19 | 78.07 | 78.48 | 77.23 | 64.02 | 62.40 | 55.65 | 47.18 | 42.54 | 41.87 |
| Xme | 0.82 | 0.72 | 0.84 | 0.70 | 0.88 | 0.87 | 0.87 | 0.86 | 0.75 | 0.73 | 0.66 | 0.56 | 0.51 | 0.48 |
Figure 6.  
a) PT ranges derived from enclosing garnet bearing hornblende gneiss at location 1  
b) PT estimates from this study compared to previous published work  

Figure 7.  
a) 2sigma error age ranges for selected zircon analyses showing evidence of two metamorphic events. BSE image showing zircon morphology and zoning pattern  

7. Conclusions  
The calc-silicates at Akarui Point were metamorphosed at around 525 Ma and possibly by an earlier event at 546 Ma, during the Pan African Orogeny. If these are indeed two metamorphic events, they may correspond to the two episodes of folding identified by Yanai [8]. These ages may also correlate with the dual metamorphic history determined by Iwamura [9] from sapphire–spinel bearing mafic granulites (initial phase 11–12 kbar, 900°C, followed by decompression uplift to 5 – 6 kbar, 920°C. The large grains of meionite in the central zones of the calc-silicate bodies appear to have replaced plagioclase and after the exhaustion of the co-reactant calcite to have equilibrated, forming a granoblastic texture. The meionite content of this scapolite indicates it equilibrated at a minimum temperature of 800 – 820°C.  
The rims of zoned scapolites from the inner calc-silicate zones and the scapolite replacing plagioclase in the outer zones, may have been formed during the second metamorphic event at a minimum
temperature of 760 – 800 °C. The development of a plagioclase-hedenbergite symplectite replacing garnet is consistent with decompression during subsequent uplift. The low temperature estimates of 500 – 580 °C derived from the enclosing garnet bearing hornblende gneiss suggests re-equilibration during a later part of the retrograde portion of the area’s PT path. That the calc-silicates did not significantly suggests the lack of an invasive hydrous fluid.

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