Pressure and Temperature Determination of Metamorphism on the Eastern Shore of Northern Utö, Stockholm Archipelago

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Abstract
This study was an investigation of the temperature and pressure of metamorphism in an area on Utö in Stockholm’s archipelago. The pressure and temperature that was calculated were 5.3 ± 0.9 kbar and 580 ± 14°C, respectively. The area was first geologically mapped and different rock units were classified as skarn, marble, metagreywacke, quartz porphyry, pegmatite and metavolcanic rock. Samples were collected in the field and prepared for making thin sections. A petrographic analysis was made on these thin sections and samples were selected for analysis by Electron Microprobe Analyzer (EMPA). Compositional data obtained by the EMPA were used for geothermobarometry on samples of a garnet bearing metagreywacke from the eastern shore of northern Utö. The computer software AX 2 and THERMOCALC were used to calculate pressure and temperature.
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Introduction
Utö is an island located in the Bergslagen region which has been of great economic significance in the past because of easily accessible ore deposits. The rocks found on Utö are well preserved and are also typical for the Bergslagen area. The fact that the different rock types are confined to a relatively small area makes Utö an ideal place to observe this geology. This study is a part of Metamorphic Map of Sweden which is a project financed by SGU (Sveriges Geologiska Undersökning). The main goal for Metamorphic Map of Sweden is to assemble a geological map with metamorphic pressure, temperature and fluid conditions. The area investigated in this thesis is located on the northern part of Utö, see area in Figure 1.

Geological background
According to Lundström and Koyi (2003) the different rock types that can be observed on Utö were created over a timespan of about 80 Ma and can be divided into three different phases:

- the pre volcanic
- the main volcanic
- the late volcanic

The pre volcanic phase includes the deposition of sedimentary rocks in a deep water environment. Greywackes deposited from turbidites were metamorphosed to form minerals such as garnet and andalusite. There are two generations of andalusites in the greywacke which probably are related to two events of regional metamorphism in Bergslagen which are dated by Andersson et al, (2006) cited in Talbot (2008) to be 1.87 and 1.78 Ga or younger. Turbidites are created through submarine avalanches and are characterized by graded bedding where coarser material has been deposited prior to the finer material. Through many observations of this structure on the eastern shore of northern Utö, the lithological unit has been shown to young towards the NW.

The main volcanic phase started with deposition of sandstone and conglomerates. The reason why these sedimentary rocks are considered part of the main volcanic phase is that they were deposited in a new depositional environment created by uplift due to volcanism. These were
likely deposited in a shallow ocean based on the lack of sedimentary structures that have been disturbed by water activity. Pyroclastic rocks were then deposited along with felsic lava flows. Also sulphide deposits were found interlayered with the pyroclastic rocks.

Carbonate rocks were deposited during calmer periods of the volcanism in the late volcanic phase and are found interlayered with volcanic ash-siltstone (Lundström and Koyi, 2003). The ore deposits occur as banded iron formations which were formed on the seafloor as ferrous iron reacted with seawater and can be found interlayered with carbonate and siltstone.

Pegmatites intruded through the preexisting rocks after the folding of the other lithological units and are the youngest rocks found on Utö with U-Pb ages determined by Romer and Smeds (1994) to be $1821 \pm 16$ Ma. Siliceous fluids from the pegmatite intrusions altered the preexisting rocks (Mansfeld, 2012). All of these rock units have since then been metamorphosed which has altered the mineralogy and structures of the rocks.

**Aim**

The aims of this study was to:

- Investigate the pressure and temperature conditions of metamorphism in the study area by a two-step modelling approach based on compositional analysis of collected rock samples.
- Compile a geological map based on field observations and thin section analysis.

**Method**

An area of approximately 1 km$^2$ was mapped from 8th till the 15th of April 2015. During the mapping, the different rock types encountered were classified and foliation and bedding measurements were taken. The rock classification was determined in the field by observing the mineralogy visually with a hand lens and also with the aid of a steel key to determine the hardness of minerals. An acid solution with 10% HCl was used in the field as an indicator of the presence of carbonate in the rocks. Acid was only applied to fresh rock surfaces. Based on the mineralogy some rocks that seemed useful for geothermobarometry were chosen for thin section preparation. These were the ones with minerals like garnet and andalusite, with stability fields constrained by certain pressures and temperatures.

**Map assembly**

The map was digitalized in ArcMap 10.2.2. Using this computer program, the different polygons representing the different rock types were drawn. The strike and dip measurement sites were inserted on the map as well as the sampling sites. After the outcrops were mapped, the patterns along with structural data was used to extrapolate the geological boundaries over areas which could not be mapped because of for example vegetation.
Sample preparation
Six rocks were chosen for thin section preparation. The rocks were cut perpendicular to the foliation with a diamond saw. Rectangular pieces measuring 1x2x3.5 cm were prepared. The rock samples were then polished in a process called lapping were grains of silicon carbide placed on a rotating plate was used to polish the rocks. Two different grain sizes of silicon carbide were used in the lapping process. The coarser grain size of the silicon carbide was separated by a grid of 180 strings per square inch and the finer grain size was separated by 400 strings per square inch. The finer grain size was used for the more sensitive samples and also as a final stage in the lapping process. The samples were then sent to Vancouver Petrographics where they were cut to make thin sections with a thickness of 30 µm.

Thin section analysis
The thin sections were analyzed at Stockholm University with a petrographic microscope where the mineralogy and the textures were identified and documented. This enabled classification of some of the rocks that were too fine grained to classify in hand sample and more importantly a more accurate estimation of the mineralogy. Two samples which contained the most suitable mineralogy for geothermobarometry were chosen to have their mineral composition determined by the EMPA.

Electron Microprobe Analyzer (EMPA) preparation and analysis
Before the analysis by EMPA the samples were polished once more to create a flat smooth surface so that the surface imperfections would not interfere with the analysis. The samples were coated with carbon at a pressure of 1 Pa. The EMPA analysis took place at GeoCentrum at Uppsala University on the 14th of May 2015. The instrument used was a Jeol JXA 8530 hyperprobe which was run at 15 kV with a 10 nA beam. The sample was subjected to electron bombardment which produced X-rays. The X-rays were analyzed based on their intensity and wavelength and an estimation of the composition of the sample could be made. Depending on the minerals analyzed, varying width of the electron beam was used to achieve the most accurate results. This is because in order to determine composition quantitatively a comparison of a known standard is made and therefore standardizations has to be made for the desired elements that are to be measured. Harder minerals such as garnet were hit with a 1 µm beam and a 10 µm beam was used for softer and hydrous minerals like chlorite and biotite. Four analyses were made on two different thin sections. The analyses were made preferentially on minerals that were in contact with each other and that did not show signs of retrograde reactions. This increases the chances that they were once in equilibrium.
Geothermobarometry

Garnet-Biotite exchange geothermometer (GARB)

The GARB is a method developed by Ferry and Spear (1978) and was used in this study to estimate temperature. The method is based on experiments which were conducted at a pressure of 0.207 GPa and between temperatures of 500° to 800°. The experiments involved the exchange reaction seen in Equation 1.

\[
Fe_3Al_2Si_3O_{12} (\text{Almandine}) + KMg_3AlSi_5O_{10}(OH)_2 (\text{Phlogopite}) = Mg_3Al_2Si_3O_{12} (\text{Pyrope}) + KFe_3AlSi_3O_{10}(OH)_2 (\text{Annite})
\]  

(1)

This reaction was given time to reach equilibrium at different temperatures. Since only Fe and Mg are of interest, all components in the reaction except Fe and Mg are subtracted (see Equation 2).

\[
Fe_{(\text{garnet})} + Mg_{(\text{biotite})} = Mg_{(\text{garnet})} + Fe_{(\text{biotite})}
\]  

(2)

An ideal solution is assumed where the activity is defined in Equation 3.

\[
a_i^A = (X_i^A)^y
\]  

(3)

Where \( a \) is the activity of component \( i \) in phase \( A \) and \( X_i^A \) is the mole fraction of component \( i \) in phase \( A \). \( y \) is the number of crystallographic sites on which mixing is possible (\( y \) is in this case 3) (Winter, 2010). The equilibrium constant \( K \) is defined by Equation 4.

\[
K = \left( \frac{a_{Mg}^Gt a_{Fe}^Bt}{a_{Fe}^Gt a_{Mg}^Bt} \right) \approx \left( \frac{(X_{Mg}^Gt)^3 (X_{Fe}^Bt)^3}{(X_{Fe}^Gt)^3 (X_{Mg}^Bt)^3} \right) = \left( \frac{(Mg/Fe)^{Gt}}{(Mg/Fe)^{Bt}} \right)^3
\]  

(4)

The \( \ln(K) \) values from the experiments were plotted against \( 1/T \) where \( T \) is the temperature at which the reactions had equilibrated. Since this was a linear relationship, \( K \) could be used as a geothermometer (see Equation 5).

\[
\ln(K) = -6382.5 \times \frac{1}{T(K)} + 2.4539 = -6382.5 \times \frac{1}{T(K)} + 2.4539
\]  

(5)

Geothermometry is based on the thermodynamic relationship shown in Equation 6.

\[
T = \frac{\Delta H_{\text{reaction}} + dP \Delta V_{\text{reaction}}}{\Delta S_{\text{reaction}} - R \times \ln(K)}
\]  

(6)

This equation relates pressure, temperature and \( K \). \( \Delta S \) (change in entropy), \( \Delta V \) (change in volume) and \( \Delta H \) (change in enthalpy) are assumed constant. \( R \) is the gas constant which has the value 8.3144 J/K mol. The change in Gibb’s free energy is set to zero which means that the reaction is at equilibrium and can be represented by a univariant line in P-T space. \( dP \) is the
difference between $P_1$ and $P_2$ where $P_1$ is the pressure at a reference state at 0.1 MPa and $P_2$ lies on the univariant line for the reaction. Since $P_2 \gg P_1$, $dP = P$. Equation 6 can be rearranged to Equation 7 which puts it in the same format as the equation for a straight line.

\[ \ln K = \frac{-\Delta H - P \Delta V}{R} \times \left( \frac{1}{T(K)} \right) + \frac{\Delta S}{R} \]  

(7)

Note the similarities between Equation 5 and 7. According to Robbie and Hemingway (1995) cited in Winter (1995) $\Delta V$ for the exchange reaction is 2.494 J/MPa. Since Equation 5 equals Equation 7, by inserting values for the known constants, the unknown constants could be determined (see Equation 8 and 9).

\[ \Delta S = R \times 2.4539 = 8.3144 \times 2.4539 = 20.403 \text{ J/K mol} \]  

(8)

\[ \Delta H = -R \times (-6382.5) - 207 \times \Delta V = -8.3144 \times (-6382.5) - (207 \times 2.494) = 52550 \text{ kJ/mol} \]  

(9)

These experimentally determined values can be inserted in Equation 6 which relates $K$ to a temperature (see Equation 10).

\[ T(K) = \frac{52550 \text{ J/mol} + 2.494 \times P(\text{MPa})}{20.403 \text{ J/K} - 8.3144 \times \ln(K)} \]  

(10)

The EMPA data of MgO and FeO from the garnet and the biotite could be used to calculate $K$ by using Equation 4. When the value of $K$ is known it can be used in Equation 10 along with a pressure estimate to get a temperature (Winter, 2010).

**AX 2 and THERMOCALC**

The compositional data obtained with the EMPA was run in AX 2 and THERMOCALC 3.33. In AX 2 the activity of certain minerals in the sample was calculated. Activity is a number between 0 and 1 which determines how much an endmember will partake in a reaction at a specific pressure and temperature. In AX 2 this is calculated in different ways depending on the mineral phase and components present. The GARB for example assumed an ideal solution in which $a_i^A = (X_i^A)^\gamma$. AX 2 deals with non-ideal solutions. For solutions that are non-ideal activity coefficients ($\gamma_i$) are applied. Activity coefficients are determined experimentally or theoretically and may vary with the mole fraction. For non-ideal solutions Equation 11 applies (Winter, 2010).

\[ a_i^A = (\gamma_i X_i^A)^\gamma \]  

(11)

In AX 2 the activity models are kept quite simple but the errors of the simplifications are probably no greater than those of for example incomplete equilibrium in the measured mineral (Holland and Powell 1988).
To run AX 2 a file was first prepared with the compositions of the different sampling locations, in this case there were four minerals analyzed. For every sampling location 12 different oxides and their respective weight percentages were added. The oxides used by AX 2 are listed in Table 1. These were run in AX 2 at a standard pressure and temperature of 6 kbar and 550° C. AX 2 then generates a file with the activity of different mineral end members and also makes an estimation of the Fe₂O₃ content for each mineral as electron microscopes in general cannot distinguish between ferric and ferrous iron (Schumacher 1991). The file generated was first altered to add additional phases that AX did not produce activities for (quartz, H₂O, muscovite) and was then run in THERMOCALC. THERMOCALC uses these activities with a table of end members and their thermodynamical data to find an independent set of reactions in a specified P-T window. The average pressure and temperature is the point where these reactions intersect. The average pressure and temperature value calculated was then used to run AX 2 one more time. New mineral activities were obtained and THERMOCALC could be run once again with these values to get more accurate pressure and temperature. This was done two times in total, after which the calculated average pressure and temperature remained the same.
Figure 2 Map of study area with different rock types. The red dots are the sampling sites from which rocks have been taken for thin section preparation. Brighter colors refers to extrapolated data.
Lithological description

Carbonate rocks
The carbonate-bearing rocks found in the study area were skarn and marble. The marble contained coarse calcite crystals and reacted strongly with HCl. Large tremolite crystals often occurred and were exposed on weathered surfaces. The marble was often found interlayered with the metavolcanic rocks. The skarn rocks encountered contained varying amounts of carbonate. They were in general rich in amphibole which gave the rock a greenish color. The skarn rocks varied in composition over very short distances, a rock could have a strong reaction with acid and just a couple of meters away the same unit would not react at all. Since all the rocks in the study area were more or less metamorphosed, most contacts between siliceous and carbonate rocks could be classified as skarn. Skarn was therefore generalized for quite large areas. On Skaftängskullen on the other hand (see map in Figure 2), where there was a clear stratification of marble layers and volcanic ash-siltstone the rock unit was classified as interlayered carbonate and metavolcanic rock. These bedding planes were strongly folded and no representative measurement could be made.

Metagreywacke
The metagreywackes were located on the eastern shore of the study area. At sampling site 38 they were found bedded with lighter sandy layers and darker schistose pelitic layers with andalusite phenocrysts (see Figure 2). The layers were 10 to 30 cm thick with a dip direction towards SW. Andalusite phenocrysts were pink and stood out where the surrounding micas had been eroded.

At sampling site 8 there was a garnet bearing metagreywacke, here the beds were dipping 80° to the SW (see Figure 1). Four samples of the metagreywacke were prepared for thin section analysis, one from sampling site 8 and three from sampling site 38.

Figure 3 Andalusite-bearing metagreywacke from site 38. Pen for scale.
Quartz Porphyry
Gavelin et al (1976) classified this felsic schist as a quartz porphyry which in the field was not that obvious. A sample was selected for thin section analysis. In thin section, the porphyritic texture was more evident and for that reason the classification, quartz porphyry, will be used in this thesis. There was no reaction with HCl so calcite could be ruled out. The rock was quite dark for its composition due to biotite laminations and could almost be mistaken for a metapelite when encountered in the field. Between the biotite laminations there were elongated quartz aggregates. The rock broke along foliation planes.

Pegmatite
A few pegmatite dikes were found in the mapping area. These consisted of coarse K-feldspar and quartz crystals, sheets of biotite and muscovite were usually around 3 cm long. Also small pink tourmaline crystals were found. At margins, contact aureoles extended into the adjacent rocks.

EMPA analysis
The data in Table 1 is the part of the EMPA analysis on sample 8AUÖFY that was used for geothermobarometry. A typical error from analysis by EMPA in general can be estimated to about 1.5 wt%. Some of the oxides that the EMPA measured cannot be run in AX and were therefore removed from this table. See appendix for complete results.

Table 1. Table with the EMPA data from sample 8AUÖFY that was used in AX. Oxides are shown as wt %.

<table>
<thead>
<tr>
<th>Name</th>
<th>Na2O</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>MgO</th>
<th>MnO</th>
<th>TiO2</th>
<th>K2O</th>
<th>CaO</th>
<th>FeO</th>
<th>Cr2O3</th>
<th>Fe2O3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>8A grt-rim</td>
<td>0.05</td>
<td>36.87</td>
<td>21.27</td>
<td>2.82</td>
<td>1.04</td>
<td>0.00</td>
<td>0.014</td>
<td>2.00</td>
<td>36.34</td>
<td>0.00</td>
<td>0.00</td>
<td>100</td>
</tr>
<tr>
<td>8A chl</td>
<td>0.02</td>
<td>25.25</td>
<td>22.24</td>
<td>15.56</td>
<td>0.04</td>
<td>0.11</td>
<td>0.01</td>
<td>0.02</td>
<td>25.17</td>
<td>0.03</td>
<td>0.00</td>
<td>88</td>
</tr>
<tr>
<td>8A bio-contact</td>
<td>0.28</td>
<td>35.51</td>
<td>17.04</td>
<td>11.07</td>
<td>0.00</td>
<td>1.38</td>
<td>8.26</td>
<td>0.03</td>
<td>19.97</td>
<td>0.04</td>
<td>0.00</td>
<td>94</td>
</tr>
<tr>
<td>8A plag1</td>
<td>6.19</td>
<td>55.79</td>
<td>26.88</td>
<td>0.01</td>
<td>0.04</td>
<td>0.02</td>
<td>0.07</td>
<td>9.72</td>
<td>0.09</td>
<td>0.00</td>
<td>0.00</td>
<td>99</td>
</tr>
</tbody>
</table>

Hand sample and thin section analysis
The thin section analysis includes a mode estimation of the mineralogy and is based on visual observations in the microscope (see Table 2-7). The mode is not necessarily representative of the entire rock since the thin sections were made on areas of the rock which included a desired mineralogy. It also includes description of textures and reactions. A documentation of textures and mineral observations made of a hand sample of the rocks is also included for every sampling site. The sampling sites are pointed out on the map in Figure 1.
Sample 8AUÖFY Metagreywacke

Hand sample observations
This rock sample was taken from a sandy layer of the metagreywacke approximately 50 meter from the sea. The garnets which are more resistant to weathering stood out on the weathered surface of the rock. In hand sample the platy biotite minerals defined the schistose foliation which was not that obvious since the rock was poorly foliated. The grain size of the matrix was medium sand and the garnet porphyroblasts were up to 5 mm in diameter.

Thin section analysis
Table 2. Mode estimation for sample 8AUÖFY.

<table>
<thead>
<tr>
<th>Name</th>
<th>Garnet</th>
<th>Plagioclase</th>
<th>Quartz</th>
<th>Biotite</th>
<th>Muscovite</th>
<th>Chlorite</th>
</tr>
</thead>
<tbody>
<tr>
<td>8AUÖFY</td>
<td>5%</td>
<td>30%</td>
<td>30%</td>
<td>20%</td>
<td>10%</td>
<td>5%</td>
</tr>
</tbody>
</table>

This sample contained porphyroblasts of garnet in a matrix of quartz, biotite, muscovite and plagioclase. The biotite minerals showed a preferred orientation. Sericite occurred as a secondary mineral. Figure 4 is a picture of the thin section in microscope with cross polarized light (XPL) and plain polarized light (PPL).

![Image of a thin section 8AUÖFY in microscope with XPL (left) and CPL (right) with approximate EMPA sampling locations pointed out with red dots.](image)

19UÖFY - Skarn

Hand sample analysis
This was a light green rock found at site 19. In hand sample a reaction front was visible which extended about one centimeter from the surface into the rock. An acid test confirmed that the rock was rich in calcite. Light green tremolite appeared as elongated fans and white calcite veins filled cracks.
Thin section analysis

Table 3. Mode estimation for sample 19UÖFY.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Calcite</th>
<th>Amphibole (tremolite)</th>
<th>Quartz</th>
<th>Epidote</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 UÖ FY</td>
<td>20%</td>
<td>60%</td>
<td>15%</td>
<td>5%</td>
</tr>
</tbody>
</table>

The amphibole crystals were sub- to anhedral but could often be easily identified by its distinct 120°/60° cleavages as can be seen in Figure 5. The calcite minerals were twinned and displayed high order birefringence colors in XPL. A majority of the grains in the sample were anhedral. There were many relicts of amphibole which had completely retrograded.

Figure 5. Image of thin section 19UÖFY in microscope with XPL (left) and PPL (right)

38 A UÖ FY - Metagreywacke

Thin section analysis

Table 4. Mode estimation for sample 38AUÖFY

<table>
<thead>
<tr>
<th>Sample</th>
<th>Andalusite</th>
<th>Quartz</th>
<th>Biotite</th>
<th>Muscovite</th>
<th>Chlorite</th>
</tr>
</thead>
<tbody>
<tr>
<td>38AUÖFY</td>
<td>10%</td>
<td>40%</td>
<td>25%</td>
<td>15%</td>
<td>10%</td>
</tr>
</tbody>
</table>

The andalusites were highly fractured and contained inclusions of biotite and quartz, large parts of the andalusites were often retrograded to micas (see Figure 6). Euhedral shapes of andalusites could be seen as relicts as the andalusites had completely retrograded. Chlorite occurred separately and as a secondary mineral on biotite which is a retrograde reaction. The biotite and muscovite minerals were aligned with a preferred orientation and were “flowing” around the andalusite porphyroblasts. In between the biotite + muscovite laminations fine grained quartz occurred as elongated aggregates with 120° triple grain intersections.
38B UÖ FY- Metagreywacke

**Hand sample analysis**

This sample was taken from a pelitic layer of the metagreywacke. On a weathered surface it had a silky lustre. Pink approximately 5 mm grains of andalusite porphyroblast were visible between the layers of muscovite and quartz.

**Thin section analysis**

*Table 5 Mode estimation for sample 38BUÖFY.*

<table>
<thead>
<tr>
<th>Sample</th>
<th>Andalusite</th>
<th>Quartz</th>
<th>Biotite</th>
<th>Muscovite</th>
</tr>
</thead>
<tbody>
<tr>
<td>38B UÖFY</td>
<td>10%</td>
<td>60%</td>
<td>20%</td>
<td>10%</td>
</tr>
</tbody>
</table>

The sample consisted of 10% andalusite phenocrysts and 90% matrix. The muscovite and biotite formed laminations and the biotite crystals had halos from radioactive decay which could be seen in PPL (Figure 7) as circles with a dark brown pleochroism. There was also some chloritization of the biotite.
**38CUÖFY Metagreywacke/turbidite**

*Hand sample analysis*

This sample was taken just by the shore at sampling site 38 from a metagreywacke characterized by turbidites. The sample was taken from a fine grained pelitic sequence with a clear schistosity and an abundance of biotite minerals.

*Thin section analysis*

Table 6 Mode estimation for sample 38CUÖFY

<table>
<thead>
<tr>
<th>Sample</th>
<th>Andalusite</th>
<th>Muscovite</th>
<th>Bioite</th>
<th>Plag</th>
<th>Quartz</th>
<th>Accessory minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>38CUÖFY</td>
<td>20%</td>
<td>10%</td>
<td>40%</td>
<td>10%</td>
<td>20%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

The sample contained andalusite porphyroblasts in a matrix of quartz, muscovite and biotite. Garnet occurred as an accessory mineral and displayed disequilibrium textures. It had a corona of secondary minerals which probably was due to retrogression to micas (Figure 8). Also the andalusite porphyroblasts showed the same retrograde reactions. The andalusites were fractured and many of them were poikilitic and hosted fragments of biotite and quartz crystals.
25UÖFY - Quartz porphyry

**Hand sample**

This rock was taken from sampling site 25 and appeared dark in hand sample due to 2 mm thick biotite laminations. Between these laminations, fine grey quartz grains could be seen.

**Thin section**

Table 7 Mode estimation for sample 25UÖFY.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quartz</th>
<th>Biotite</th>
<th>K-Feldspar</th>
<th>Accessory mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td>25UÖFY</td>
<td>65%</td>
<td>20%</td>
<td>15%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

The biotite minerals were aligned with a preferred orientation (see Figure 9) and displayed decay halos and chloritization with a green pleochroism in PPL. Between the biotite laminations quartz occurred in aggregates, often as fine grains but at some places porphyritically as aggregates of large phenocrysts. Some of the K-feldspar found could be classified as microcline from their cross-hatched twinning. The K-feldspar was also subject to seritization alteration which is a hydrous reaction.
Discussion

EMPA
The total wt % obtained in the biotite and chlorite measurements were significantly lower than 100 (see Table 1). This is because these are hydrous minerals and the EMPA cannot measure the lighter elements like hydrogen and carbon. All the measurements presented in Table 1 were considered good and could be used for geothermobarometry. The results from the EMPA analysis (Table 1) shows that the measurement from the garnet sample contains 21.37 % Al$_2$O$_3$, 36.34 % FeO and 36.87. % SiO$_2$. That closely resembles the ideal composition of Almandine (Fe$_3$Al$_2$Si$_3$O$_{12}$) which is a reactant in the GARB.

GARB
The Fe and Mg weight percentages from the EMPA data (Table 1) for the garnet and the neighboring biotite was put into the Equation 4 which calculated the equilibrium constant for the reaction: $K = 0.00274$. The temperature for the $K = 0.00274$ could be determined by inserting pressures in Equation 10 and is plotted as an isopleth in Figure 9 below which suggests that the temperature of metamorphism was around 500°C. The reason that the isopleth is so steep is that the $\Delta V$ is small. This is because the mineral reaction only involves ion exchange, the reactants and the products are the same phases. The Clayperon equation states that $dP/dT = \Delta S/\Delta V$, the small $\Delta V$ makes the Kd isopleths sensitive to temperature changes which makes it a good geothermometer. An advantage with this method is that the constants: $\Delta S$ and $\Delta H$ for the reaction are experimentally determined at a pressure of 0.207 Ga. The alternative would have been to use values determined by calorimetry which would have had to be extrapolated to fit these kinds of pressures which might not work as well.
Using THERMOCALC, an average pressure of 5.3 kbars ± 0.9 kbars and an average temperature of 580° C ± 14° C was calculated. This is plotted as a green dot in Figure 9. THERMOCALC obtained these average values from an independent set of reactions. The univariant lines for each of these reactions were plotted in Figure 9. The average P-T is the best fit intersection for these lines that THERMOCALC finds. The lines represents pressures and temperatures where the change in Gibb’s free energy is zero, hence where both the reactants and the products are stable. These are the P-T conditions where all the minerals involved in the reaction are at equilibrium.

Reaction 6 (see Figure 9) has a very large error in pressure, 1.7 GPa (see vertical error bars), which might seem like something that could corrupt the data. Because of the steepness of the reaction this does not affect the average P-T measurement significantly. The reaction is not that sensitive to pressure because the ΔV of the reaction is relatively small even though it is not an exchange reaction. Some of the reactions end abruptly at 0.1 MPa and 0.3 MPa. This is because the reactions are calculated for a T-P window between 200 and 1000°C and between 0.1 and 1 MPa.
Figure 10. Reactions from THERMOCALC are plotted with an isopleth for the K value 0.00274 which was determined by Ferry and Spear’s (1978) biotite exchange geothermometer. Black lines define the stability fields for kyanite, sillimanite and andalusite determined by THERMOCALC and are only a visual aid for orientation in P-T space, they are not results derived from the EMPA. The green dot is the average P-T and the green box covers its uncertainty in pressure and temperature.
Figure 11 Metamorphic facies diagram with the average P-T of sample 8AUÖFY is shown as a green dot (Nelson 2011).

The average temperature and pressure from the THEMOCALC calculation was plotted in a facies diagram in Figure 10 and plots in the amphibolite facies. The temperature that was calculated for the sample 8AUÖFY, 580 ± 14°C coincides fairly well with the results attained by Rundberg (2015) on a skarn about 1 km to the north of sampling site 8. The metamorphic temperatures of the skarn was determined to be 551 ± 5°C. These results were produced by Annovitz and Essene’s (1987) calcite-dolomite solvus geothermometer.

The P-T conditions that was determined for sample 8AUÖFY puts the rock at sampling site 8 in the stability field of kyanite. However, only around 50 meters away (see map) at site 38 andalusites were found which should not have formed in the kyanite zone. In Figure 9 the error is displayed for the average P-T and it nearly reaches the stability field of andalusite. There are multiple sources of error which will be discussed below that could have affected the geothermobarometry results. The andalusite seen at site 38 could therefore have formed during the same metamorphic event as the garnet at site 8. According to Skelton et al. (in preparation) metamorphic conditions in the Svecofennian Province are generally close to the Al₂SiO₅ triple point.
Retrograde reactions found in thin sections from site 38 are indicative of that pressure and temperature of a late metamorphic event must have been lower than that of an earlier event. Multiple metamorphic events are a possibility since the rocks formed about 1900 Ma and the tectonic evolution of this area has gone through continental collision and intrusions since then. As stated above there are at least two generations, of andalusite. Also the rocks display secondary lineation and foliation structures which indicates that they have been exposed to differential pressure.

Sources of error

Mapping
The map produced in this thesis mainly based on rock classification done in the field. The extrapolated areas of the map are areas that could not be mapped because of vegetation. The extrapolations were based on rock classifications and structural measurements on outcrops and therefore these area classifications has an uncertainty.

THERMOCALC
THERMOCALC assumes that the minerals from the sample are in equilibrium. This however might not be the case and if so the calculated PT conditions will be wrong. This potential error source was countered by thorough thin section analysis in which only minerals without signs of disequilibrium textures were selected for analysis. Also the dataset that THERMOCALC uses with thermodynamical data for different phases is potentially a small error source since the data is experimentally determined and is being updated all the time as technical advances makes it possible to produce more reliable values. When running THERMOCALC H₂O was added as a fluid phase with the activity 1. It is likely that fluids were present but a composition can only be estimated. Fluids are probably dominated by H₂O, no calcite was found in thin section which reduces risk that CO₂ was a fluid component.

AX 2
None of the activity models used by AX 2 are perfect. They are experimentally determined and minerals in nature are more complex. AX 2 only takes 12 different oxides into consideration. The EMPA that was used obtained wt % data from 17 different oxides. The oxides that were neglected all had very small weight percentages so they probably did not alter the activities significantly.

GARB
According to Spear (1993), cited by Winter (2010), the experiments that GARB is based on were conducted at a pressure of 0.207 GPa and works for garnet biotite pairs down to mid crustal levels. At higher pressures than 0,207 GPa, ΔH which is a function of the P (see Equation 9) will not be constant (an assumption that Equation 6 is based on). Also Ca is usually incorporated at higher pressures. This geothermometer is based on measurements where there was no Ca involved. As can be seen in Table 1 both the biotite and the garnet have small concentration of CaO. To include Ca, a more complex activity model must be applied (Winter, 2010), however
since there was only 2.00 wt% CaO in the garnet sample it is likely not that influential on the calculated temperature.

**EMPA**
Each microprobe analysis has a small error which affects the final results. An important thing to bear in mind is that the minerals that are being probed might not be completely homogeneous. This error however can be reduced by taking several measurements and selecting the one with the best total. The garnet was probed three times from the core to the rim and the composition was similar. Experienced personnel operated the EMPA which increases precision of the measurements.

**Conclusion**

The metamorphism on the eastern shore of northern Utö occurred under a pressure of 5.3 ± 0.9 kbar and a temperature of 580 ± 14°C based on geothermobarometry executed on a garnet bearing metagreywacke. These pressure and temperature conditions are in the stability zone of kyanite, in amphibolite facies.

**Acknowledgment**

I would like to thank my supervisors Alasdair Skelton and Joakim Mansfeld. I would also like to thank Dan Zetterberg for helping me with the sample preparation.
References


Rundberg, 2015, THERMOCALC modelling calculations [conversation] (Personal communication, 1 June 2015).


Appendix

Thermocalc

Run 1

calcs use:

an independent set of reactions has been calculated

Activities and their uncertainties

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Independent set of reactions

1) py + 2gr + 3ames + 6q = 3clin + 6an
2) 3gr + 5ames + 11q = 4clin + 9an + 4H2O
3) py + clin + 2mu = ames + 2east + 6q
4) py + phl + 2mu = 3east + 6q
5) gr + alm + mu = ann + 3an
6) 5py + 3daph + 3east = 5alm + 3ames + 3phl

Calculations for the independent set of reactions

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Average PT (for x(H2O) = 1.0)

Single end-member diagnostic information

avP, avT, sd's, cor, fit are result of doubling the uncertainty on ln a:
a ln a suspect if any are v different from lsq values.
e* are ln a residuals normalised to ln a uncertainties:
large absolute values, say >2.5, point to suspect info.
hat are the diagonal elements of the hat matrix:
large values, say >0.46, point to influential data.
For 95% confidence, fit (= sd(fit)) < 1.54
however a larger value may be OK - look at the diagnostics!

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T = 579°C, sd = 14,
P = 5.3 kbars, sd = 0.9, cor = 0.481, sigfit = 0.70

===============================================
Run 2
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an independent set of reactions has been calculated
Activities and their uncertainties

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**Independent set of reactions**

1) py + 2gr + 3ames + 6q = 3clin + 6an
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4) py + phl + 2mu = 3east + 6q
5) gr + alm + mu = ann + 3an
6) 5py + 3daph + 3east = 5alm + 3ames + 3phl

**Calculations for the independent set of reactions**

(for x(H2O) = 1.0)

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T = 580°C, sd = 14,
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THERMOCALC phase diagram calculations
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non-unit activities:

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<td>py</td>
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</tr>
<tr>
<td>gr</td>
<td>0.000300</td>
</tr>
<tr>
<td>clin</td>
<td>0.0320</td>
</tr>
<tr>
<td>ames</td>
<td>0.0380</td>
</tr>
<tr>
<td>an</td>
<td>0.700</td>
</tr>
</tbody>
</table>

all phases involved
no excluded assemblages
no of reactions = 1, no of intersections = 0

1) \( \text{py} + 2\text{gr} + 3\text{ames} + 6\text{q} = 3\text{clin} + 6\text{an} \)

Thermodynamics of reactions \( 0 = a + bT + cP + RT \ln K \)
linearised at \( T = 550, P = 5.5 \)

\((a, b \text{ and } c \text{ includes fluid fugacities; } \ln K \text{ includes } x(\text{CO2}), x(\text{H2O}))\)

\[
\begin{array}{cccccc}
a & \text{sd}(a) & b & c & \ln K & \text{sd(ln}_K)
\end{array}
\]

\[
\begin{array}{cccccc}
1 & 6.09 & 1.89 & -0.24432 & 11.789 & 19.559 & 1.186
\end{array}
\]

Temperatures in the range 100 < \( T \) < 1000\(^\circ\)C;
uncertainties at or near 5.5 kbars

\[
\begin{array}{ccccccccccccccc}
T\text{C} & 1.00 & 2.00 & 3.00 & 4.00 & 5.00 & 6.00 & 7.00 & 8.00 & 9.00 & 10.00 & \text{sdT} & \text{sdP}
\end{array}
\]

1 \( - - 241.1 \ 381.3 \ 523.1 \ 670.2 \ 829.2 \ 987.4 \ + + 123 \ 0.81 \)

calcs use:
non-unit activities:

<table>
<thead>
<tr>
<th>name</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>gr</td>
<td>0.000300</td>
</tr>
<tr>
<td>clin</td>
<td>0.0320</td>
</tr>
<tr>
<td>ames</td>
<td>0.0380</td>
</tr>
<tr>
<td>an</td>
<td>0.700</td>
</tr>
</tbody>
</table>

all phases involved
no excluded assemblages

no of reactions = 1, no of intersections = 0

1) \( 3\text{gr} + 5\text{ames} + 11\text{q} = 4\text{clin} + 9\text{an} + 4\text{H2O} \)

Thermodynamics of reactions \( 0 = a + bT + cP + RT \ln K \)
linearised at \( T = 550, P = 5.5 \)

\((a, b \text{ and } c \text{ includes fluid fugacities; } \ln K \text{ includes } x(\text{CO2}), x(\text{H2O}))\)

\[
\begin{array}{cccccccc}
a & \text{sd}(a) & b & c & \ln K & \text{sd(ln}_K)
\end{array}
\]

\[
\begin{array}{ccccccccc}
1 & 260.80 & 2.94 & -0.61478 & 17.593 & 23.708 & 1.705
\end{array}
\]

Temperatures in the range 100 < \( T \) < 1000\(^\circ\)C;
uncertainties at or near 5.5 kbars

\[
\begin{array}{ccccccccccccccc}
T\text{C} & 1.00 & 2.00 & 3.00 & 4.00 & 5.00 & 6.00 & 7.00 & 8.00 & 9.00 & 10.00 & \text{sdT} & \text{sdP}
\end{array}
\]

1 \( - - 241.1 \ 381.3 \ 523.1 \ 670.2 \ 829.2 \ 987.4 \ + + 123 \ 0.81 \)
calcs use:

non-unit activities:

name a
py  0.00250
clin 0.0320
ames 0.0380
east 0.0490

all phases involved

no excluded assemblages

no of reactions = 1, no of intersections = 0

1) py + clin + 2mu = ames + 2east + 6q

Thermodynamics of reactions (0 = a + bT + cP + RT ln K)

linearised at T = 550, P = 5.5

(a, b and c includes fluid fugacities; ln K includes x(CO2), x(H2O))

<table>
<thead>
<tr>
<th>a</th>
<th>sd(a)</th>
<th>b</th>
<th>c</th>
<th>ln_K</th>
<th>sd(ln_K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-16.80</td>
<td>1.07</td>
<td>-0.00214</td>
<td>3.154</td>
<td>0.131</td>
</tr>
</tbody>
</table>

Temperatures in the range 100 < T < 1000°C;

uncertainties at or near 5.5 kbars

<table>
<thead>
<tr>
<th>T°C</th>
<th>1.00</th>
<th>2.00</th>
<th>3.00</th>
<th>4.00</th>
<th>5.00</th>
<th>6.00</th>
<th>7.00</th>
<th>8.00</th>
<th>9.00</th>
<th>10.00</th>
<th>sdT</th>
<th>sdP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

  147.8 * * * * 224 0.72
  + + + + + + + + +

calcs use:

non-unit activities:

name a
py  0.00250
phl 0.0480
east 0.0490

calcs use:

non-unit activities:
name        a
py  0.00250
pht  0.0480
east  0.0490
all phases involved
no excluded assemblages
no of reactions = 1, no of intersections = 0
1)  py + phl + 2mu = 3east + 6q
Thermodynamics of reactions (0 = a + bT + cP + RT ln K)
linearised at T = 550, P = 5.5
(a, b and c includes fluid fugacities; ln K includes x(CO2), x(H2O))

<table>
<thead>
<tr>
<th>a</th>
<th>sd(a)</th>
<th>b</th>
<th>c</th>
<th>ln_K</th>
<th>sd(ln_K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-13.81</td>
<td>1.23</td>
<td>-0.01260</td>
<td>3.499</td>
<td>-0.020</td>
</tr>
</tbody>
</table>

Temperatures in the range 100 \(\rightarrow\) 1000¡C;
uncertainties at or near 5.5 kbars

<table>
<thead>
<tr>
<th>T¡C</th>
<th>1.00</th>
<th>2.00</th>
<th>3.00</th>
<th>4.00</th>
<th>5.00</th>
<th>6.00</th>
<th>7.00</th>
<th>8.00</th>
<th>9.00</th>
<th>10.00</th>
<th>sdT</th>
<th>sdP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>*</td>
<td>*</td>
<td>208</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

calcs use:
non-unit activities :

name        a
gr  0.000300
alm   0.470
ann   0.0320
an    0.700
all phases involved
no excluded assemblages
no of reactions = 1, no of intersections = 0
1)  gr + alm + mu = ann + 3an
Thermodynamics of reactions (0 = a + bT + cP + RT ln K)
linearised at $T = 550$, $P = 5.5$

(a, b and c includes fluid fugacities; $\ln K$ includes $x$(CO2), $x$(H2O))

\[
\begin{array}{cccccc}
a & sd(a) & b & c & ln_K & sd(ln_K) \\
1 & 36.50 & 1.15 & -0.12659 & 7.414 & 4.355 & 0.454
\end{array}
\]

Temperatures in the range 100 <-> 1000°C;

uncertainties at or near 5.5 kbars

\[
\begin{array}{cccccccccccccc}
T\degree C & 1.00 & 2.00 & 3.00 & 4.00 & 5.00 & 6.00 & 7.00 & 8.00 & 9.00 & 10.00 & sdT & sdP \\
1 & 221.9 & 300.2 & 379.4 & 459.6 & 541.0 & 623.7 & 707.6 & 792.6 & 878.7 & 965.8 & 40 & 0.48
\end{array}
\]

calcs use:

non-unit activities:

- py 0.00250
- alm 0.470
- daph 0.0200
- ames 0.0380
- phl 0.0480
- east 0.0490

all phases involved

no excluded assemblages

no of reactions = 1, no of intersections = 0

1) 5py + 3daph + 3east = 5alm + 3ames + 3phl

Thermodynamics of reactions ($0 = a + bT + cP + RT \ln K$)

linearised at $T = 550$, $P = 5.5$

(a, b and c includes fluid fugacities; $\ln K$ includes $x$(CO2), $x$(H2O))

\[
\begin{array}{cccccccccccc}
a & sd(a) & b & c & ln_K & sd(ln_K) \\
1 & -228.57 & 5.75 & 0.05409 & -0.878 & 28.046 & 2.088
\end{array}
\]

Temperatures in the range 100 <-> 1000°C;

uncertainties at or near 5.5 kbars

\[
\begin{array}{cccccccccccccccc}
T\degree C & 1.00 & 2.00 & 3.00 & 4.00 & 5.00 & 6.00 & 7.00 & 8.00 & 9.00 & 10.00 & sdT & sdP \\
1 & 525.8 & 528.8 & 531.9 & 534.9 & 538.0 & 541.0 & 544.1 & 547.1 & 550.2 & 553.2 & 53 & 17
\end{array}
\]
### EMPA results

**Table 8 EMPA results for sample 8AUÖFY in weight %**

<table>
<thead>
<tr>
<th>Na2O</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>MgO</th>
<th>F</th>
<th>MnO</th>
<th>TiO2</th>
<th>K2O</th>
<th>CaO</th>
<th>Cl</th>
<th>NiO</th>
<th>FeO</th>
<th>Cr2O3</th>
<th>V2O3</th>
<th>SrO</th>
<th>BaO</th>
<th>CO2</th>
<th>Total</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>37.14</td>
<td>21.37</td>
<td>2.36</td>
<td>2.11</td>
<td>0</td>
<td>0.0132</td>
<td>3.02</td>
<td>0</td>
<td>0</td>
<td>34.75</td>
<td>0.0063</td>
<td>0.0071</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100.7766</td>
<td>8A-Grt-cor</td>
<td></td>
</tr>
<tr>
<td>0.0175</td>
<td>36.89</td>
<td>21.42</td>
<td>2.3</td>
<td>1.77</td>
<td>0.0282</td>
<td>0</td>
<td>2.32</td>
<td>0</td>
<td>0.0776</td>
<td>35.63</td>
<td>0.0211</td>
<td>0.0448</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100.537</td>
<td>8A-Grt-mix</td>
<td></td>
</tr>
<tr>
<td>0.0487</td>
<td>36.87</td>
<td>21.27</td>
<td>2.82</td>
<td>1.0375</td>
<td>0</td>
<td>0.0136</td>
<td>2</td>
<td>0</td>
<td>0.0616</td>
<td>36.34</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100.4613</td>
<td>8A-Grt-rir</td>
<td></td>
</tr>
<tr>
<td>0.0204</td>
<td>25.25</td>
<td>22.24</td>
<td>15.56</td>
<td>0</td>
<td>0.0389</td>
<td>0.1127</td>
<td>0.0141</td>
<td>0.0174</td>
<td>0.0245</td>
<td>0</td>
<td>25.17</td>
<td>0.0258</td>
<td>0.0168</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>88.4907</td>
<td>8A-Chl</td>
</tr>
<tr>
<td>0.4655</td>
<td>35.94</td>
<td>17.29</td>
<td>11.17</td>
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<td>0</td>
<td>1.469</td>
<td>8.04</td>
<td>0.0652</td>
<td>0.0599</td>
<td>0</td>
<td>20.13</td>
<td>0.0882</td>
<td>0.094</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>95.1626</td>
<td>8A-Bio-mix</td>
</tr>
<tr>
<td>0.2838</td>
<td>35.51</td>
<td>17.04</td>
<td>11.07</td>
<td>0.424</td>
<td>0</td>
<td>1.3803</td>
<td>8.26</td>
<td>0.0254</td>
<td>0.0721</td>
<td>0</td>
<td>19.97</td>
<td>0.0449</td>
<td>0.0372</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>94.3267</td>
<td>8A-Bio-cor</td>
</tr>
<tr>
<td>6.19</td>
<td>55.79</td>
<td>26.68</td>
<td>0.0075</td>
<td>0</td>
<td>0.0353</td>
<td>0.0242</td>
<td>0.0712</td>
<td>9.72</td>
<td>0</td>
<td>0</td>
<td>0.0922</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>98.8105</td>
<td>8A-P11</td>
</tr>
<tr>
<td>6.19</td>
<td>56.07</td>
<td>26.68</td>
<td>0.0078</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0739</td>
<td>9.48</td>
<td>0</td>
<td>0</td>
<td>0.0518</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>98.5611</td>
<td>8A-P12</td>
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</table>