GEO-3900

MASTER'S THESIS IN GEOLOGY

MICROSTRUCTURAL AND METAMOPRHIC STUDY ON ROCKS OF THE SEILAND IGNEOUS PROVINCE BETWEEN LANGFJORD AND ØKSFJORD, ALTA KOMMUNE, NORTHERN NORWAY.

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Tromsø, November, 2010

Faculty of Science

Department of Geology

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FORORD

Først og fremst vil jeg takke mine flotte veiledere Holger Stünitz og Erling J. Krogh Ravna for god veiledning og en interessant oppgave. Det har vært en fornøyelse å ha hatt dere som mine veiledere. Godt humør og god støtte har ikke vært mangelvare!

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Nå bærer det straks videre til Førde og jobb i NVE. Ett nytt kapittel er i gang!

Birgit K. Rustad

Tromsø, november 2010.

Abstract

The Seiland Igneous Province (SIP) is situated in western Finnmark, Northern Norway. The SIP comprises a suite of mainly gabbroic plutons, with ultramafic, syenitic and felsic intrusions. The origin of the region has been interpreted in different ways and several tectonic models have been proposed. Many different ideas have been suggested about the metamorphic, magmatic and deformation history. New age dates by Roberts (2008) fall within a narrow time range, from 555 Ma to 579 Ma, concluding that the main magmatism took place within ten million years. This is a much shorter period than previously estimated, and the deformation and metamorphic history of the province is therefore reconsidered. In order to better understand the metamorphic and deformation history of the SIP, studies on microstructures, deformation and metamorphism have been carried out in this thesis on a gabbroic pluton and a strongly sheared quartz-feldspathic xenolith of the Seiland Igneous province situated between Langfjord and Øksfjord. Observations from the field and thin sections indicate that the metamorphic and deformational history of these two rocks can be divided into the following stages: contact metamorphism of the country rock caused by the emplacement of the plutonic gabbro (stage I) with subsequent cooling (stage II) and following loading probably as a result of nappe emplacement during the Caledonian orogeny (stage III). Microstructures and metamorphic reactions observed in the rocks support pressure and-temperature estimates given by Elvevold *et al.* (1994). Both rock types show evidence of a cooling and subsequent solid state deformation. The cooling stage was followed by a higher-pressure metamorphism interpreted to be related to emplacement of a tectonic unit of cold thrust sheet over hot rock during the Caledonian orogeny. The nappe emplacement resulted in the formation of thin mylonitic zones recognized by a strong grain size reduction and a replacement of a pyroxene granulite assemblage to a garnet granulite assemblage.

The foliation seen in the Suborg-gabbro and the quartz-feldspathic gneiss is suggested to be a result of extension associated with continental rifting. The emplacement of the Suborg-gabbro is believed to have taken place during regional deformation. The foliation in the Suborg-gabbro shows evidence of magmatic flow overprinted by a solid state flow. Kinematic indictors observed in the quartz-feldspathic xenolith indicate normal faulting supporting extension and a rifting model for the SIP.

Keywords: Seiland Igneous Province, metamorphism, deformation, extension.

Table of Content

1. Introduction

1.1 Main Objective

The primary goals for this thesis are:

- Study fabric transitions between undeformed and deformed rock, and between different rock types in order to better understand the deformation and metamorphic history of the Seiland Igneous Province.
- Determine mineral assemblages for the studied rocks.
- Establish P-T conditions for the different mineral assemblages.

A distinction between potentially different deformations events can hopefully in the end be carried out on the basis of the microstructural analysis in conjunction with the pressure and temperature estimates.

1.2 Geographical Location of Study Area

The area of interest in this project, the Seiland Igneous Province (SIP), is situated in Western Finnmark, Northern Norway (figure 1.1). The SIP covers an area of 5000 km^2 and includes the Islands of Seiland, Stjernøya, parts of the island of Sørøya and parts of the Øksfjord peninsula together with the peninsulas situated in-between Kvænangen and Lopphavet (Reginiussen 1992). The investigated area in this thesis is situated in the south-eastern part of the Seiland Igneous Province (figure 1.2), between Øksfjorden and Langfjorden, Alta kommune. Map 1835 III Øksfjord (1:50000) covers the area.

Investigations have been performed close to the summit of Høgfjellet and along the ridge stretching south from the summit. The area is situated from 300-630 m.a.s.l. and is easily accessed from “riksvei” 882. Good outcrops are found in the area, though some are heavily weathered.

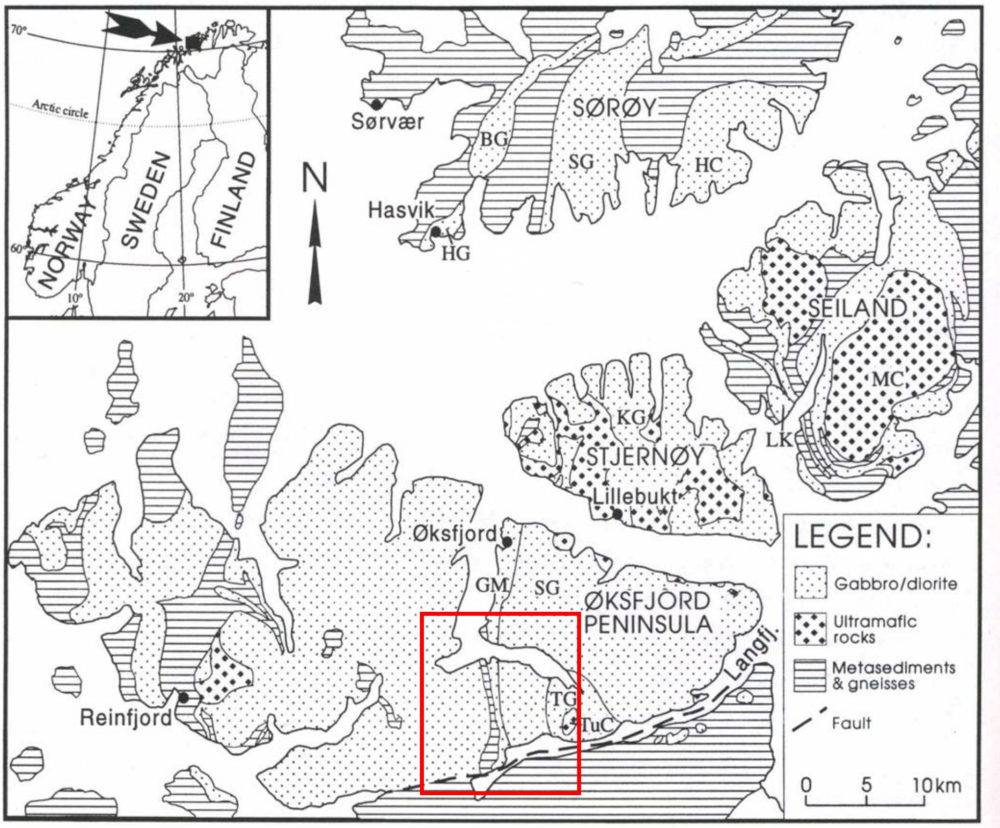


Fig. 1.1. Simplified geological map of the Seiland Igneous Province from Reginiussen & Elvevold (1994). The red box refers to the area studied in this thesis (figure 1.2). HG - Hasvik Gabbronorite, BG – Breivikbotn Gabbro, SG – Storelv gabbro, HC – Husfjord Complex, KG – Kvalfjord Gabbro, LK – Lille Kufjord Gabbro, MC – Melkevann Complex, GM – Gabbro Monzonite (Suborg Metagabbro), SG – Storvik Gabbro, TG – Tappeluft Gabbro, TuC – Tappeluft Ultramafic Complex.

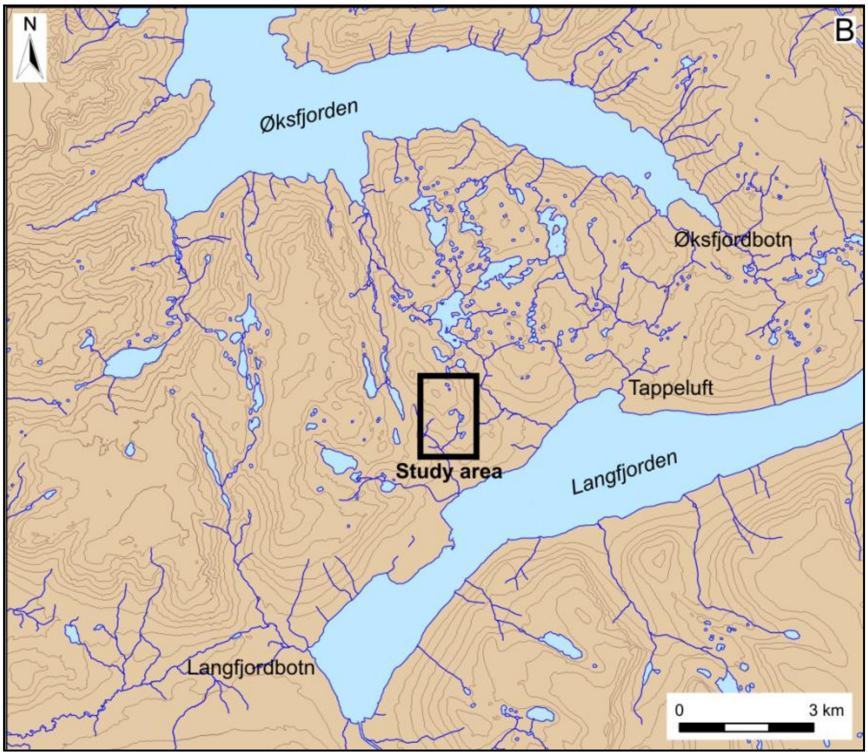


Fig. 1.2. Topographic map illustrating the locality of study area.

1.3 The geology of the Seiland Igneous Province

1.3.1 Introduction

A dominant feature of the Norwegian geology is the Scandinavian Caledonides stretching from the north-east coast of North America, across the northern part of the British Isles and along the length of Norway and northern Sweden. This fold and thrust belt was created during the collision between the Laurentian and Baltican cratons subsequent to the closure of the Iapetus Ocean. The collision took place during the Late Cambrium to Early Silurian periods, during the so-called Scandian event 420 Ma ago. The Norwegian part of the Caledonides consists of four distinct nappes: the lower, middle, upper and uppermost allochthon (Ramberg *et al.,* 2006, p. 199). The lower and middle allochthon is interpreted to originate from the Baltic margin, the upper is suggested to represent oceanic crust from the Iapetus Ocean and the uppermost allochthon is believed to be relict rocks from the Laurentian craton (Stephens, 1988). The nappes recognized in Finnmark, Northern Norway, from bottom to top are the Gaissa Nappe Complex, the Laksefjord Nappe Complex, the Kalak Nappe Complex and the Magerøy Nappe Complex. The Gaissa Nappe Complex belongs to the lower allochthon, the Laksefjord Nappe Complex is tectonostratigraphically placed above the Gaissa Nappe Complex and belongs to the middle allochthon, the Kalak Nappe Complex is considered as a part of the middle allochthon, whilst the Magerøy Nappe complex belongs to the upper allochthon.

The SIP lies within the Sørøy Succession classically considered as a part of the upper structural unit of the Kalak Nappe Complex (KNC). The SIP includes layered gabbros, syenites and nepheline syenites, ultramafics and carbonatites which are all characteristic of extensional environments. The magmatic event is considered to have occurred in an extensional stress regime, possibly during intracontinental rifting or back-arc spreading (Roberts 2008).

1.3.2 Tectonostratigraphy of the SIP

The KNC is made up of a series of major allochthonous thrust sheets of metasediments covering a Precambrian basement, mostly gneisses (Ramsey *et al.*, 1985). One of the most special and interesting stratigraphic packages within the Kalak Nappe Complex is the "Sørøy Succession" (or "Sørøy Group") (Roberts 1988). A strong correlation to the KNC is provided by the lithostratigraphy of the Sørøy Group on the Island of Sørøy (Roberts *et al.*, 2006). The basal member of the Sørøy group is named the Klubben Psammite and is widely distributed in Finnmark, whilst the younger sequences; the Storelv Formation schists, Falkenes Formation marbles and Hellefjord Formation schist is more limited in extent (Roberts 2008). Figure 1.3 illustrates the location of the Sørøy Succession within the Kalak Nappe Complex.

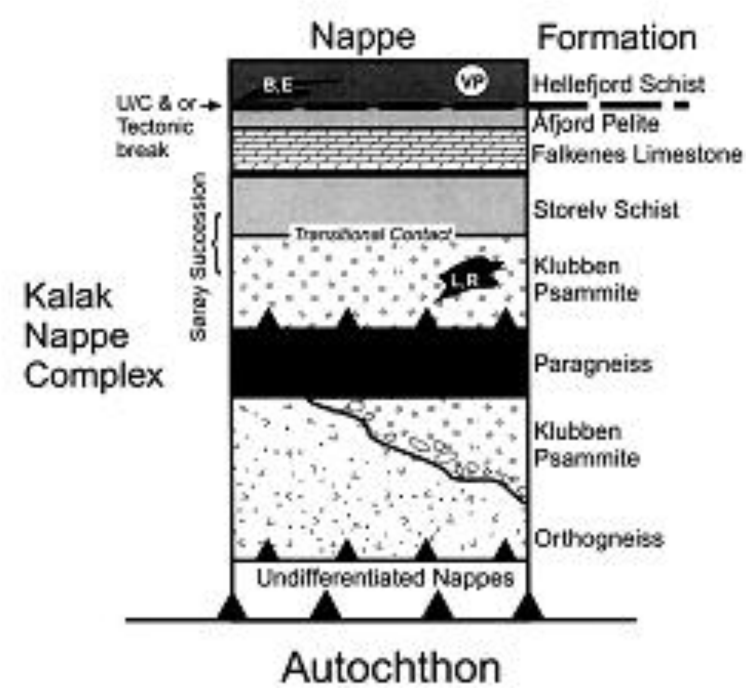


Fig. 1.3. Simplified tectonstratigraphy of the Kalak Nappe Complex from Kirkland *et* al. 2005. The figure schematically illustrates the location of the Sørøy Succession which, as proposed by Kirkland *et al.* (2005), to only refer to the Klubben Psammite and overlying Storelv Schist. VP: Volcaniclastic psammite; E: Engesfjellet Granite; B: Bakfjord Granite; L:Litlefjord Granite; R: Repvåg Granite. Figure from Kirkland *et al.* 2005.

The SIP is classically considered as a part of the Middle Allochthon. However, this is questioned by Andréasson *et al*. (1998) who suggested a stronger correlation for the Seiland Igneous Province to the Seve Nappes that belong to the lower part of the Upper Allochthon. The Upper Allochthon is mainly made up of exotic terrains containing marginal basin, magmatic arc and oceanic associations previously situated within the Iapetus Ocean (Stephens & Gee 1985; Stephens *et al*., 1985). Geochronological studies by Kirkland *et al.* (2005) suggest a more exotic origin for the entire KNC. Previously the Sørøy Succession has been used to refer to the entire stratigraphic package; from Klubben Psammite to Hellefjord Schist based on the idea that the sequence was conformable. Kirkland et al. (2005) proposed a new fundamental tectonostratigraphic revision of the entire Kalak Nappe Complex and they also suggested that the Sørøy Succession should only refer to the Klubben Psammite and overlying Storelv Schist (figure 1.3).

Recent work by Roberts (2008) supports the idea that the SIP can be considered a remnant of on an older geological terrane emplaced onto the margin of the Caledonian Orogeny. New age dating by Roberts (2008) on magmatic zircons from a range of intrusion in the SIP indicate that the bulk of the magmatism took place between 560-570 Ma and can therefore be regarded as pre-Caledonian.

The rocks investigated within the Seiland Igneous Province in this thesis are the Suborg-gabbro and an external paragneiss (Eidvågeid paragneiss) into which the Suborg-gabbro intruded. The Suborg-gabbro is considered to represent one of the first pulses of magmatic activity in the SIP. An Rb-Sr age of 829±18 Ma was given by Krogh & Elvevold (1990), though this age is no longer considered valid due to recent U-Pb zircon dating by Roberts (2008) which supports a short time interval of magmatic activity within 560-570 Ma. The Eidvågeid paragneiss is dated by Aitcheson (1990) to be older than 1000 Ma (Sm-Nd isotopic data).

1.4 Previous Work and Ideas on the Seiland Igneous Province

The Seiland Igneous Province (SIP) has been subject to different interpretations and several tectonic models have been proposed. The province is highly debated, and much has been suggested about its age, origin, metamorphic, magmatic and deformation history. The first geologist to visit and partly map the geology in western Finnmark was Karl Pettersen (1875). The province has since then been visited by several researchers and research groups who has tried to unravel its geological history. Early contributors include Barth (1927, 1953), Krauskopf (1954), Oosterom (1963), Roberts (1968), Robins & Gardner (1975), Sturt *et al.*, (1975, 1978) and Ramsay *et al.* (1985). Several isotopic dating works have also been carried out (Brueckner 1973; Sturt *et al.*, 1978; Aitcheson 1989; Mørk & Stabel 1990; Daly *et al.*, 1990; Krogh & Elvevold 1990; Roberts 2007).

In the earlier models (Robins & Gardner, 1975; Sturt *et al.*, 1978) the deformation, metamorphism and magmatism of the SIP were related to eastward subduction of oceanic crust beneath the Baltic plate during closure of the Iapetus Ocean. Krill & Zwaan (1987), on the other hand, related the intrusions to continental rifting prior to the opening of the Iapetus Ocean. More recent work by Reginiussen *et al.*, (1995), Reginiussen (1996) and Reginiussen & Elvevold (1996) support the idea that the SIP was formed in an extensional regime and that the magmatism was related to rifting. Reginiussen & Elvevold (1996) supported the work of Krill & Zwaan (1987) suggesting that the SIP represents the root zone of a palaeorift related to continental break-up and formation of the Iapetus Ocean. Elvevold & Reginiussen (1994) considered a rift related origin for all the intrusions based on the results that the rocks of the SIP have alkaline/transitional geochemical characteristics and within plate affinities. Reginiussen & Elvevold (1996) suggested that the magmatism could be related to a passive rift model where boundary layer instabilities between the lithosphere and the asthenosphere were potential plume sources. They also proposed that extension and rifting in the SIP occurred in several discrete episodes: failed rifting around 830 Ma and reactivating of rifting later at 700-520 Ma (associated with the opening of the Iapetus Ocean) responsible for the main magmatic activity. According to Aitcheson (1989) the magmatism of the SIP could be explained by extensional forces acting on the crust: She suggested that the Kalak Nappe Complex suffered ductile extension at a deep level in the crust along with the invasion of mafic and ultramafic intrusions, and that the peak magmatic activity was in the period 560-600 Ma (based on Nd, Sr and Pb istotopic study). She also suggested that the SIP could be associated with a "triple junction" meaning that the SIP could have formed where the Timan margin met the Baltoscandian margin together with a possible third margin north of Baltica. Such a "triple junction" can cause the mantle to bulge and result in large-scale magmatic activity (Ramberg *et al.*, 2006, p. 135).

Recent isotopic dating based on U-Pb analyses on magmatic zircons from a range of intrusions propose only one short time interval of magmatic activity associated with intra-continental rifting prior to the Caledonian Orogeny (Roberts 2008): Various intrusions on the Øksfjord peninsula give nearly identical U-Pb radiometric ages within 560-570 Ma. His studies invalidate previous models involving multiple rifting events over a period of 300 Ma. The oldest isotopic dating of the SIP was calculated by Rb/Sr isochrons resulting in an age of 612±17 for a suite of syenite-monzonite-gabbro and peridotite from the Øksdjord peninsula (Brueckner 1973). Later isotopic (Rb/Sr whole-rock) dating recorded by Sturt *et al.* (1978) proposed an age of 540-490 Ma for the intrusions in the SIP and they suggested that the magmatic activity was related to a orogenic event referred to as the Finnmarkian orogenic phase (pre-Caledonian). Later Sm-Nd isotopic dating by Mørk & Stabel (1990) supported a Cambrian thermotectonic event. Nd, Sr and Pb isotopic studies by Aitcheson (1989) suggested that the lithosphere under the SIP underwent incipient extension and partial melting from 700-520 Ma. Krogh & Elvevold (1990) proposed, from Rb-Sr isotopic whole rock studies, a very long time interval for the magmatic activity spanning over 300 Ma and that the P-T-t history of the Øksfjord area can be explained in term of a multicycle tectonic model involving different tectonic processes. The theory of Reginiussen (1996) on layer instabilities between the lithosphere and asthenosphere as potential mantle plumes could be an explanation to the long-lived magmatism. Aitcheson (1990) isotopic dating does also support such a long period of time for the magmatism.

An explanation to the wide range of age dating given on the SIP can be explained by magma mixing, assimilation of crustal material and fractional crystallization that all work to change the original magmatic composition and hence give inaccurate age dating. Studies by Aitcheson (1987), Mørk & Stabel (1990), Reginiussen *et al.* (1995) and Roberts (2008) all indicate that the rock of the SIP show considerable variation in their isotopic signatures which support crustal contamination.

The metamorphic history of the SIP is also a debated topic. Earlier ideas suggest that the metamorphism is related to the closure of the Iapetus Ocean (Robins & Gardener 1975; Sturt *et al.*, 1978). Elvevold *et al*. (1994) did studies on a suite of granulite facies rocks and suggested that the metamorphic evolution of the Øksfjord rocks is reflected in a sequence of mineral reactions that can be subdivided into M1-M3 (M1: related to contact metamorphism during emplacement of the intrusions, M2: related to the following cooling and crystallization after emplacement of the intrusions, M3: related to the Caledonian Orogeny and causing minor adjustment in host rocks and complete recrystallization in narrow mylonite zones). Elvevold *et al*. (1994) proposed a P-T-t- history that can be explained by tectonic processes such as rifting and extension followed by compression and crustal thickening, and that the paragneisses and the older intrusives have been subjected to strong deformation and recrystallization at granulite facies conditions. Roberts (2008) did not support the metamorphic history given by Elvevold *et al.* (1994). He suggested, based on U-Pb ID-TIMS dating of monazite from paragneisses from the Øksfjord area, that the metamorphism present in the paragneisses is much older (640-630 Ma) than the emplacement of the SIP. This means that the paragneiss has experienced metamorphism prior to the emplacement of the SIP and that metamorphism and magmatism related to the SIP, together with subsequent metamorphic events, has not been sufficient to reset the age given by the monazites in the paragneiss.

The most reasonable model for the SIP is that it represents the eroded root of an intercontinental rift similar to the East African Rift system where enormous quantities of magma intruded the sedimentary rocks towards the end of the Precambrian during a short time interval giving rise to the Seiland Igneous Province.

1.5 Abbreviations

The following symbols are used in this thesis (mineral symbols after Kretz 1983).

Minerals

Bt = biotite

Crd = cordierite

Cpx = clinopyroxene

Grt = garnet

Hbl = hornblende

Ilm = ilmenite

Kfs = K-feldspar

Ol = olivine

Opx = orthopyroxene

Pl = plagioclase

Qtz = quartz

Rt = rutile

Other

P = pressure

T = temperature

Sil = sillimanite

Spl = spinel

2. Field Relations & Rock Description

2.1 Introduction

The objective of this chapter is to give a description of the rocks observed in the field and in thin sections made of the rocks sampled. This chapter forms the base for later chapters.

The investigated rock-units are the following:

Suborg- gabbro: a plutonic rock, observed with a magmatic fabric and also with a solid-state overprint (section 2.3).

Magmatic lens: a plutonic rock with primary magmatic fabric preserved interpreted to represent an undeformed part of the Suborg-gabbro (section 2.3).

Quartz-feldspathic gneiss: a high-grade paragneiss (section 2.4).

Shear zones: found within the Suborg-gabbro and quartz-feldspathic gneiss (section 2.5).

The studied area is located within the central part of the Suborg-gabbro which is suggested to represent one of the first intrusions of the Seiland Igneous Province (Krogh & Elvevold 1990). The Suborg-gabbro is observed both as a strongly foliated and non- to weakly foliated gabbro. The summit of Høgfjellet represents a unit with a primary magmatic layering that displays an isotropic fabric. The gabbro surrounding the summit of Høgfjellet shows a more penetrative foliation interpreted to have formed by a solid state overprint. The difference between a magmatic to a more solid state fabric is in the field defined by the presence of elongated mafic grains or not.

2.2 Sampling & Methods

The main objective when sampling was to get an assortment representing the different fabrics (divided into different units) present in the field area. Samples representing the thin ductile shear zones were also collected. In all 16 samples were collected. The photographs from the field are taken with an Olympus Mju Digital 850 SW. Figure 2.1 illustrates where the samples were collected.

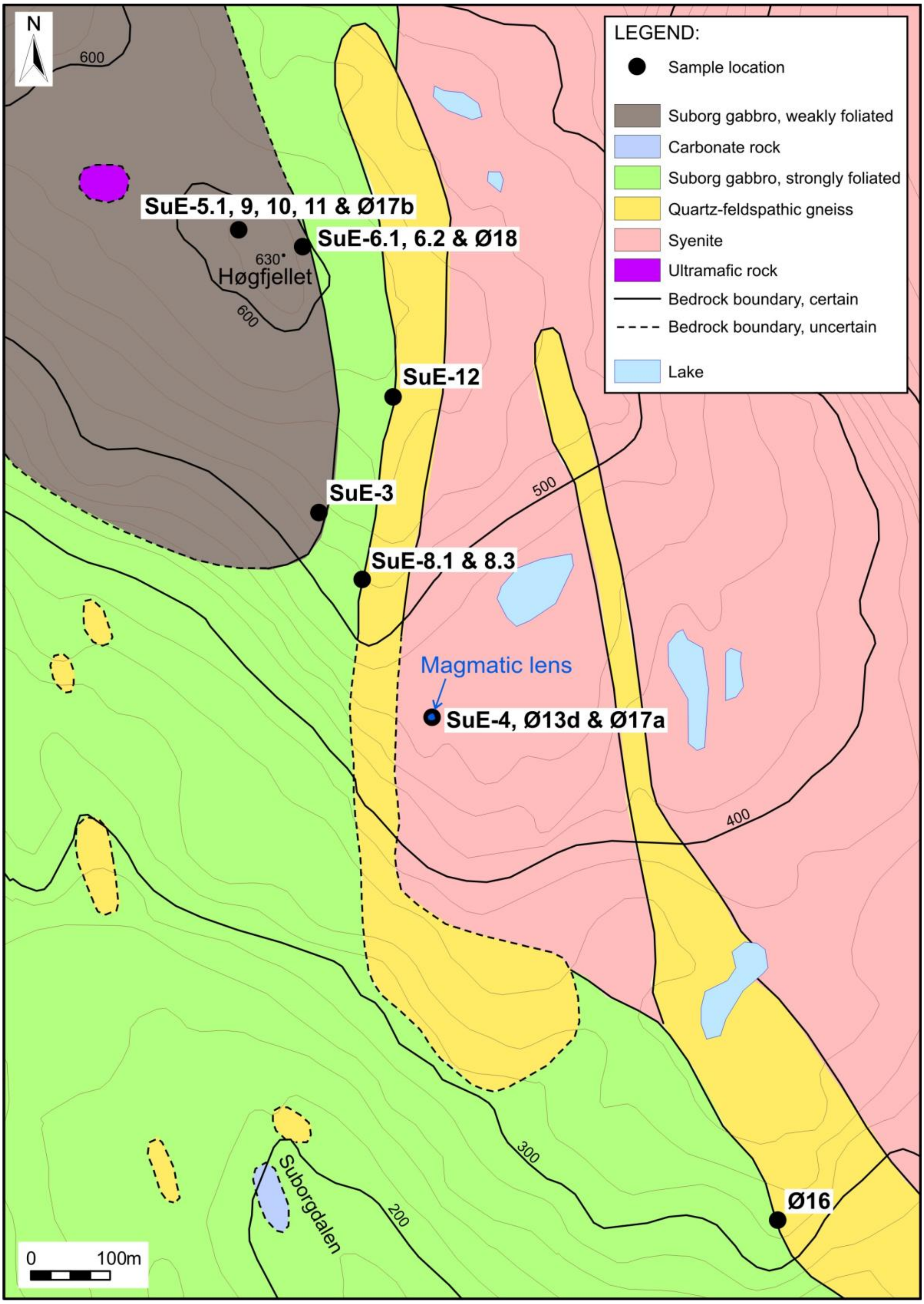


Fig. 2.1. Geological map of the Høgfjellet area with sample locations. Modified after Reginiussen (1992).

The samples were washed, cut into chips and handed in to the laboratory at the University of Tromsø for thin sectioning.

The thin sections were studied with the use of a Leitz Laborlux 11 pol s polarization microscope. The pictures of the thin sections are taken with a Canon 450DC mounted on a Leitz Orthoplan polarization-microscope.

The fabric nomenclatures used in the description of the thin sections is from Passchier & Trouw (2005).

2.3 Suborg-gabbro

The Suborg-gabbro studied covers the summit of Høgfjellet and is seen as an elongated pluton following the Suborg valley. The valley stretches approximately 8 km from the Langfjorden in the south to the Øksfjorden in the north. The Suborg-gabbro covers the summit of Høgfjellet (630 m.a.s.l.) and Sandfjellet (717 m.a.s.l.). The rock can be named a gabbroic gneiss due to its distinct penetrative layering where dark-colored layers alternate with bright-colored layers. The layering is interpreted to represent a primary magmatic layering. According to Reginiussen *et al*. (1995) can this compositional layering represent a primary modal layering which has been modified during metamorphic events.

For most of the area the Suborg-gabbro is seen as a strongly deformed rock with a distinct fabric. However, close to the summit of Høgfjellet the gabbro shows a less penetrative foliation. A larger lens (15m x 20 m) with a fabric suggested to be of magmatic origin is observed along the ridge stretching southwards from the summit of Høgfjellet.

Thin ductile shear zones cross-cutting the rock are observed close to the summit of Høgfjellet.

The Suborg-gabbro is often seen as a strongly weathered rock where it displays a brownish color.

Some of the samples of the Suborg-gabbro represent a transition zone from a magmatic fabric to a fabric with a solid-state overprint.

2.3.1 Unit with a magmatic fabric (locally with a weak solid state overprint)

The rock shows only locally the typical elongated/needle shaped mafic grains that define the foliation characteristic of the unit with a solid state overprint. The unit has a relatively isotropic fabric (figure 2.2). Locally the mafic grains have a preferred orientation that is more or less parallel to the foliation seen in the more deformed unit of the Suborg-gabbro. According to Reginiussen (1992) and my field observations, the fabric in the Sandfjellet and Høgfjellet area is slightly discordant with the fabric measured in the more deformed unit of the Suborg-gabbro. The weakly- to non-deformed gabbro appears as a large non-foliated lens sitting within the deformed unit. The gneissic foliation in the deformed unit wraps itself around the large lens (figure 2.1). The transition between the two units is seen as a progressive increase in deformation over a distance of 20-50 meters.

Fig. 2.2. Close-up of magmatic layering in the Suborg-gabbro. Some of the grains are elongated and define a layering, though the rock has a more isotropic fabric compared to the more deformed unit of the Suborg-gabbro.

In some parts of the non- to weakly deformed rock unit a weak layering is seen (light-colored layers alternate with dark-colored layers). The rock is medium grained and has grayish- beige color for the felsic layers, and brown to black color for the mafic parts (figure 2.3).Grains of plagioclase, biotite, pyroxene and amphibole can be seen with the aid of a hand lens.

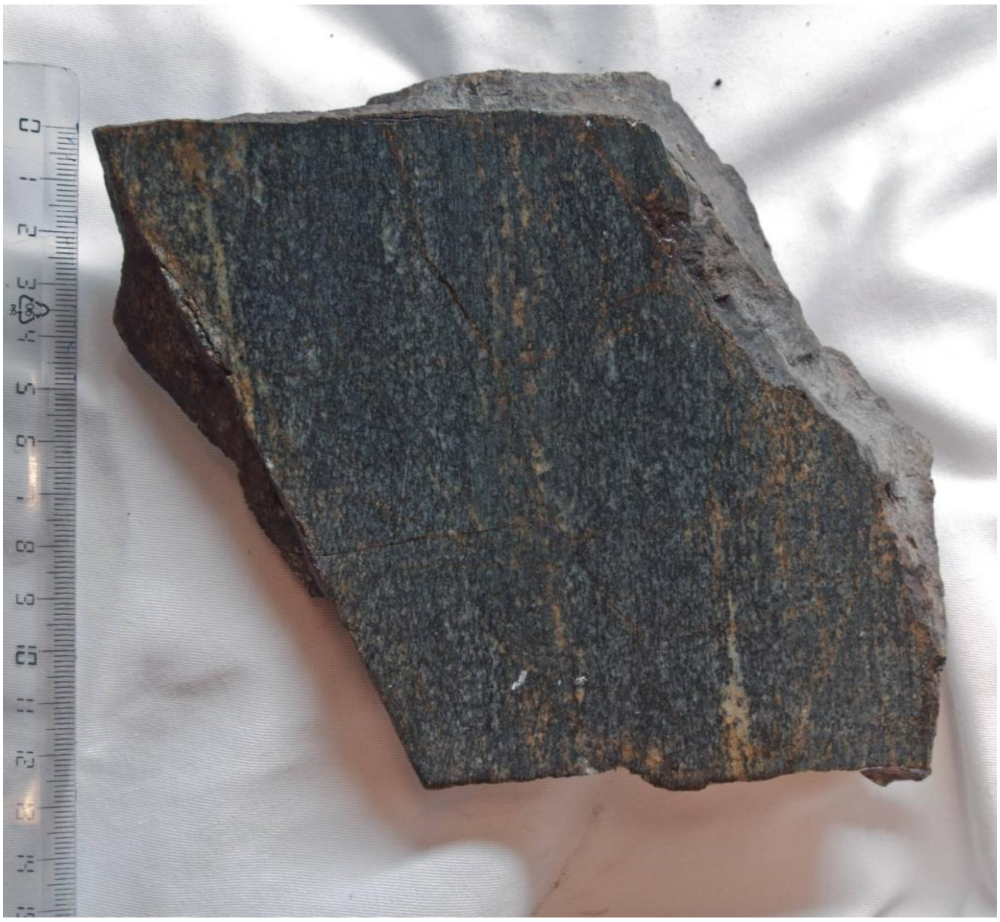


Fig. 2.3. A weak foliation defined by aggregates of felsic and mafic grain aggregates can be seen in sample SuE-5.1a.

Microscopic features

The unit of un-foliated Suborg-gabbro has a complete gradation of fine- to coarse-grained grain size distribution with polygonal grain boundaries. Many of the grain aggregates of amphibole and feldspars show triple junctions forming a foam structure. The individual grains have subhedral to anhedral grain, and locally the grains are elongated parallel to each other. Compared to the deformed Suborg-gabbro this unit has a higher amount of triple junctions, overall a larger grain size and more of the primary mineralogy preserved: olivine + clinopyroxene + orthopyroxene). Reaction rims (corona structure) are seen enclosing olivine grains (figure 2.4). Some of the feldspar-gains are present as inequant grains with locally a subophitic structure, or what can be interpreted to be a relict of a subophitic structure,common for igneous structures and characteristic of magmatic flow (Passchier & Trouw, 2005, p. 239, 2nd ed.).

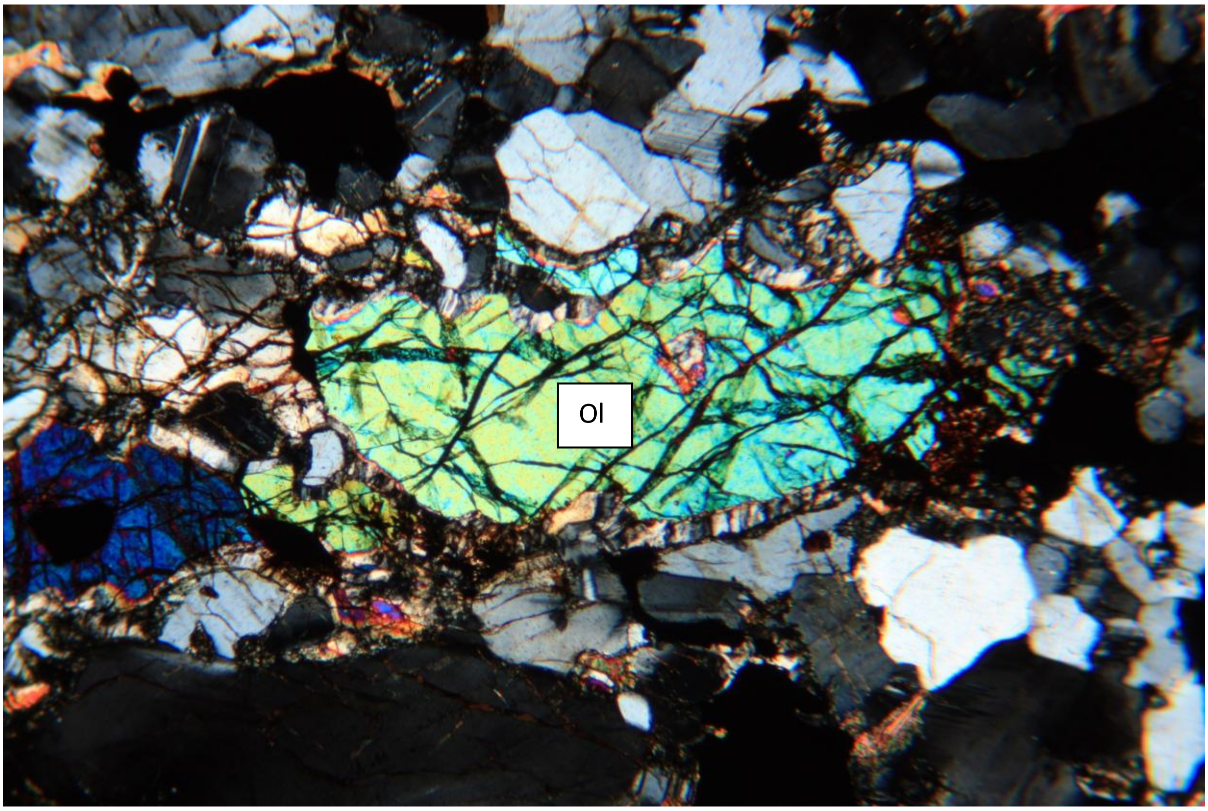


Fig. 2.4. An olivine grain with a reaction rim of orthopyroxene is seen in the centre of the picture. Crossed polars; base of photo 4 mm.

Plagioclase (40-60%, grain size 0.03-1mm, average grain size 0.1 mm) is seen as subhedral to anhedral recrystallized grains and as subhedral inequant grains penetrating pyroxene (figure 2.5). Subgrain formation occurs and a high amount of the plagioclase grains are present in granoblastic grain aggregates with a high abundance of triple junctions. Many grains show twinning; albite-, pericline- and contact-twinning.

Orthopyroxene (5-30%, grain size 0.15-0.75mm) is seen as anhedral grains with a weak pink pleocroism and δ = 0.012-0.015. Some of the grains have well developed cleavage at right angles to each other. The mineral is often seen in conjunction with amphibole and many of the grains have subgrain formation.

Clinopyroxene (5-20%, grain size 0.1-3mm) is colorless, δ = 0.018-0.025, has an inclined extinction and a high relief. Two cleavages at right angles to each other are seen in some grains. Contact twinning and a high abundance of lamellas is present. Locally the grain aggregates have “foam-structure” with triple junctions. The mineral is often seen close to orthopyroxene grains and is in many places overgrown by amphibole. Locally the grain forms granoblastic aggregates with triple junctions.

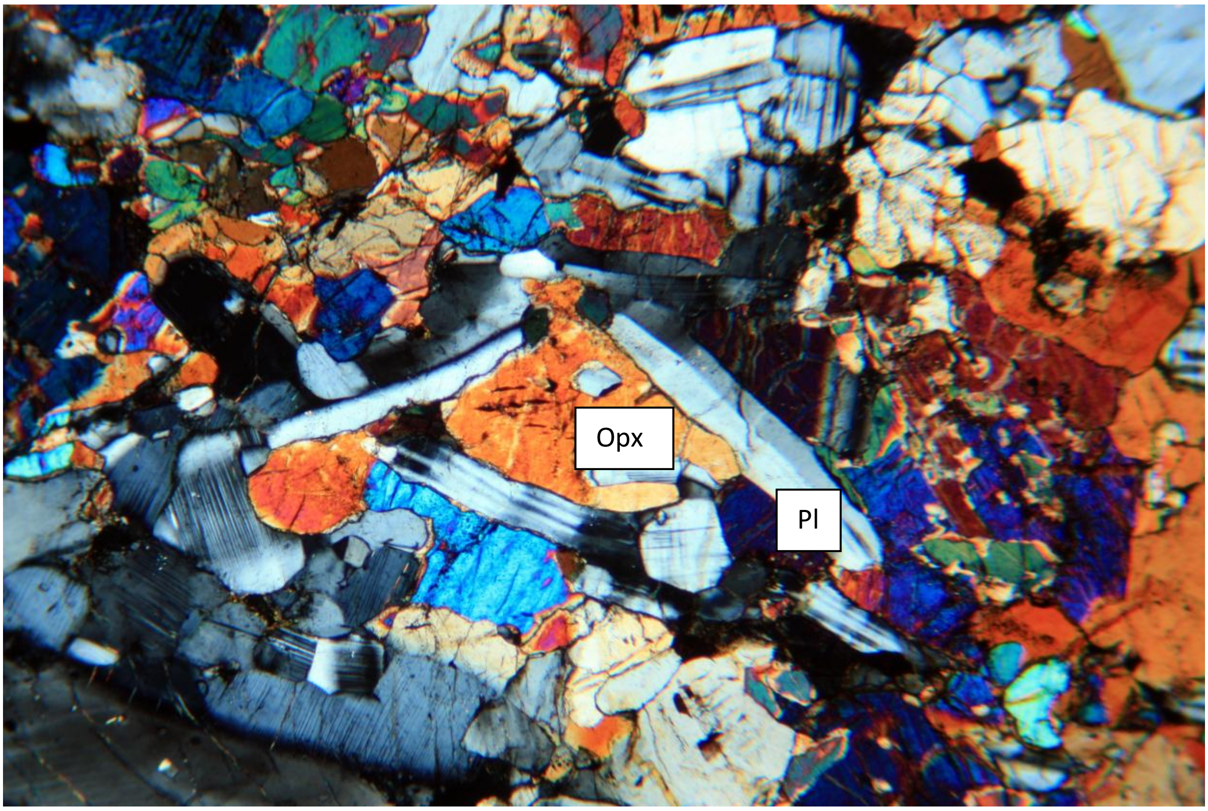


Fig. 2.5. Subophitic microstructure (or a relict of it) typical for magmatic crystallization. The elongated plagioclase grains are penetrating pyroxene (yellow grain in centre). Crossed polars; base of photo 4 mm.

Amphibole (10-20%, grain size 0.05-2.5mm) has a moderate to high relief and the two distinct cleavages are present in many of the grains. Large amounts of anhedral opaque grains and lamella of opaque minerals is seen within the larger amphibole grains. The mineral is found in two different settings: mostly as overgrowth on clinopyroxene, orthopyroxene and olivine, and as a few individual grains. Closer to the transition zone to the more deformed unit the rock show different mineralogical properties. Some of the grains show simple twinning.

1) Close to the deformed unit: variable green pleocroism, extinction angle = 14-32°. The individual grains appear mostly as anhedral recrystallized grains.

2) Høgfjellet-area: reddish-brown pleocroism, extinction angle = 15-18°. The grain aggregates have a granoblastic shape with triple junctions. The individual grains have a subhedral grain shape and only a few recrystallized grains can be seen.

Olivine (2-5%, grain size 0.05-1.5mm) is not observed close to the contact to the more deformed gabbro. The mineral is colorless, has a high relief, a very high birefringence

(>0.035) and has the irregular crack pattern typical for olivine. Corona structure of fine-grained orthopyroxene is seen enclosing olivine. Iddingsite, an alteration product of olivine (Shelley 1975, p. 100) is found as pseudomorphs of olivine (figure 2.6).

Spinel (accessional-2%, grain size 0.03-1.75mm) is dark green and isotropic with a moderate relief. The mineral has an anhedral grain shape and is mostly found between aggregates of plagioclase and orthopyroxene, and amphibole and opaque grains. It is often found in proximity to olivine and in-between plagioclase grains. Spinel is not found in the samples from the transition zone to the more deformed gabbro.

Biotite (accessional-2%, grain size 0.03-0.3mm) has a reddish-brown pleocroism, δ = 0.03-0.038 and relatively straight extinction. A perfect single cleavage is seen in some of the grains. The mineral is subhedral tabular and is mostly found between amphibole and clinopyroxene and as overgrowth on amphibole.

FeTi-oxides (accessional-10%, grain size 0.03-2.5mm) are found as subhedral to anhedral opaque grains. It occurs in conjunction with aggregates of amphibole ± orthopyroxene ± clinopyroxene ± spinel, and in-between triple points of amphibole. Locally opaque grains form the centre of some amphibole grains.

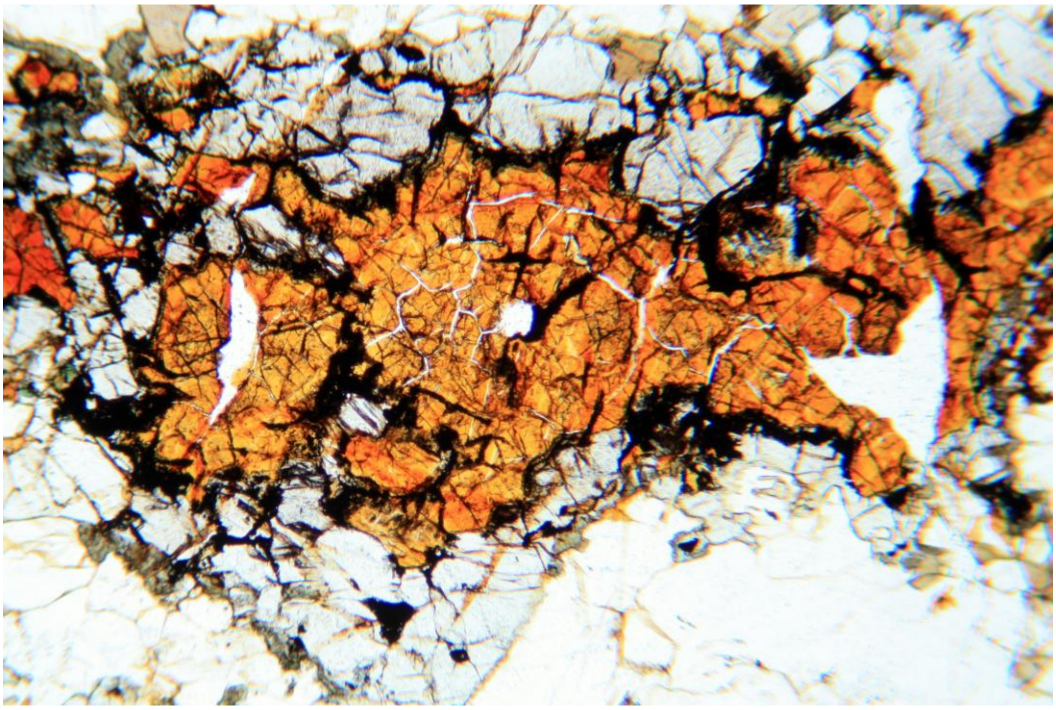


Fig. 2.6. Pseudomorph of olivine grain where olivine has been altered to iddingsite (centre). Base of photo 4 mm.

2.3.2 Unit with a solid-state fabric with relicts of magmatic fabric

The unit has a very strong fabric characterized by a penetrative gneissic foliation with alternating layers defined by needle shaped mafic minerals and mineral-aggregates (amphibole + biotite + pyroxene) (figure 2.7). The light-colored layers are 0.2-0.4 cm thick. A few grain aggregates (>1 cm in length) and porphyroclasts (>0.5 cm) of felsic composition are seen within the light-colored layers. The porphyroclasts have rims of recrystallized material indicating that deformation has taken place. The color of the rock varies between black-grey to black-greenish. The rock is inequigranular where the grain size distribution varies from fine- to medium-grained; less than 0.1 mm up to 3 mm in length. Mafic grains are on average larger compared to the felsic grains. Individual felsic grains are difficult to see with the aid of a hand lens, though some porphyroclasts of feldspar are present. Figure 2.8 is a picture of one of the hand samples collected. Hand samples may suggest a mylonitic fabric, though thin sections made of the rock reveal that this is not the fact.

Fig. 2.7. Picture illustrating the characteristic fabric seen in the deformed units of the Suborg-gabbro. The fabric is defined by alternating light- and dark-colored layers.

Fig. 2.8. Sample 8.1 representing Suborg-gabbro with a solid state overprint. A distinct layering is seen in this rock where alternating mafic- and felsic layers define a foliation.

Microscopic features

The Suborg-gabbro with a strong overprint of a solid-state fabric has a foliation defined by recrystallized elongated grains and grain-aggregates of amphibole + clinopyroxene ± orthopyroxene ± biotite (figure 2.9). Clinopyroxene is locally surrounded by biotite and amphibole. The rock has different domains: clinopyroxene rich areas and areas with a high abundance of amphibole. Most of the grains have cracks with a random orientation. Growth of biotite is localized within these cracks.

The individual grains seen in the rock are mainly subhedral to anhedral, whilst the average shape of the grain aggregates is inequigranular with core- and mantle structure with interlobate grain boundaries to polygonal grain boundaries.

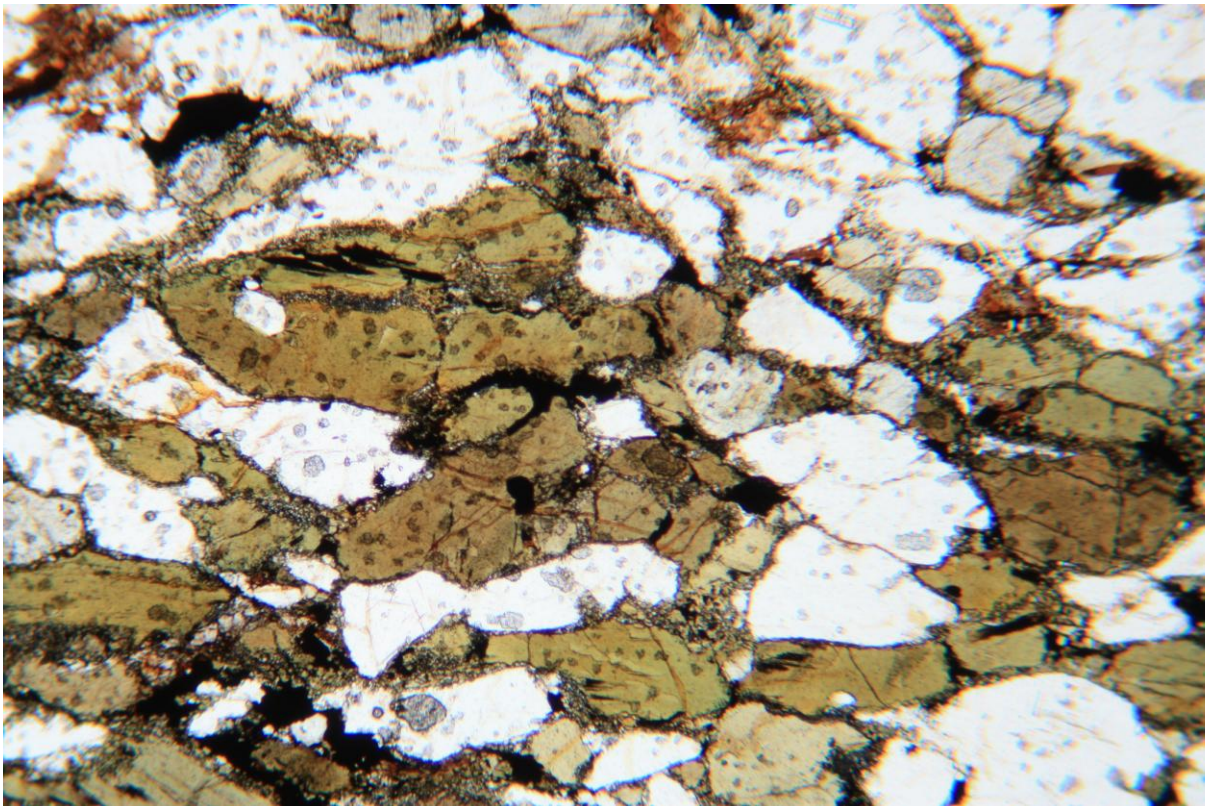


Fig. 2.9. Recrystallized elongated grains of amphibole and clinopyroxene where larger grains are surrounded by smaller garins. Base of photo 4 mm.

Plagioclase (25-40%, grain size 0.03-1.2 mm) is mostly seen as recrystallized subhedral to anhedrale grains with undulouse extinction. Some relict grains with subgrain boundaries are observed. The grains are elongated parallel to each other and parallel to the main foliation. The minerals exhibit a granoblastic fabric with an average grain size of 0.3mm. Deformation twinning, pericline and albite twinning are present in many of the grains.

Clinopyroxene (5-15%, grain size 0.03-0.25mm) is colorless to pale green with an inclined extinction angle and $\delta = 0.020$. A well developed cleavage is seen in some of the grains. The mineral is elongated in the same direction as the main foliation and has a subhedral to anhedral shape.

Orthopyroxene (15-25%, grain size 0.05-2mm) has a pale red pleocroism and a moderate relief. Well developed cleavages can be observed in some of the grains. The mineral has a straight extinction and $\delta = 0.012$-0.014. Many of the grains have non-oriented cracks with overgrowth of biotite. Some grains are present as recrystallized grains.

Biotite (2-5%, grain size 0.03-1.25mm) are found as subhedral and acicular grains elongated in the same direction as the main foliation. The mineral can also be seen as overgrowth in clinopyroxene, orthopyroxene and amphibole. The mineral has a brownish-red pleocroism and shows the typical bird's eye texture seen at extinction (common for some of the minerals belonging to the mica group), a moderate to high relief and a high birefringence.

Fe-Ti oxides (2-4%, grain size 0.015-0.3mm) are seen as anhedral to acicular grains randomly oriented. The opaque grains appear as inclusions within other grains and in the junction between other grains.

Amphibole (30-50%, grain size 0.03-1.5 mm) is seen as subhedral to anhedral grains forming locally a granoblastic fabric where many of the grains are elongated in the same direction as the foliation. Two distinct cleavages are developed in many of the grains. Amphibole is observed in two different settings:

I) A primary amphibole with a brownish green to dark green pleocroism and $\delta = 0.020$-0.025 where a textural equilibrium exist between amphibole and clinopyroxene.

II) A secondary amphibole with a green pleocroism. This mineral is only observed locally in-between biotite grains and as overgrowth on clinopyroxene (figure 2.10).

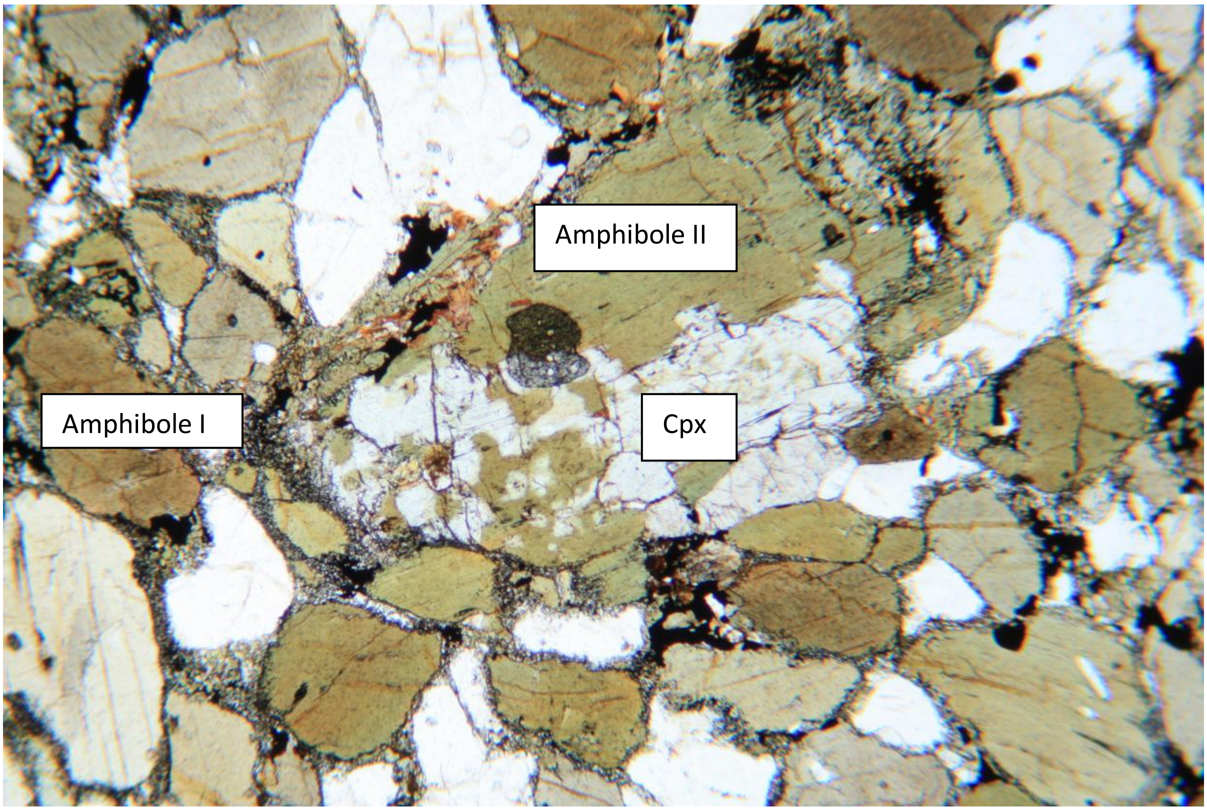


Fig. 2.10. Two different amphiboles are seen in the rock as illustrated by the picture. A clinopyroxene grain is overgrown by a green amphibole (type II), whilst more brownish-green amphiboles (type I) are seen as individual grains surrounding the clinopyroxene grain. Base of photo 4 mm.

Accessional grains: apatite appearing as inclusions within some of the mafic grains. The mineral is colorless with a straight extinction and has a low birefringence.

2.3.3 Magmatic lens

A large lens suggested to represent a primary magmatic fabric from the Suborg-gabbro (figure 2.11) is observed to the south of the summit. Elongated aggregates of mafic composition together with elongated aggregates of felsic material define a weak fabric in the rock which is relatively parallel to the main foliation seen in the gneissic Suborg-gabbro. The structure of the rock is massive and equigranular where larger felsic aggregates of felsic material (~1 cm) occur between mafic aggregates (~6 mm) (figure 2.12). The rock is medium-grained with an average grain size of 2 mm. Amphibole, pyrite, feldspar, biotite and grains of pyroxene are observed with the aid of a hand lens. Fine-grained veins of mafic composition rich in biotite crosscut the rock.

Fig. 2.11. Primary magmatic fabric seen in a magmatic lens.

Fig. 2.12. Hand sample SuE-4 from magmatic lens. Notice large grain aggregates of felsic and mafic material with a somewhat preferred orientation.

Microscopic features

The rock is characterized by patches of mafic (amphibole ± clinopyroxene ± orthopyroxene ± olivine) and felsic polygonal grain aggregates together with relicts of primary magmatic fabric. Locally the felsic aggregates have a granoblastic shape with foam structure, but some irregular, lobate grain boundaries are also seen. Smaller grains of relatively uniform size are found between larger grains of amphibole and feldspar indicating recrystallization. The larger individual grains have euhedral to subhedral shape.

Aggregates of amphibole define a fabric in the rock by shape preferred orientation of elongated aggregates of relatively equidimensional and slightly elongated individual grains. The individual grains show a less shape preferred orientation in this unit compared to the previous described units.

The larger subhedral to anhedral grains of plagioclase, clinopyroxene and olivine can be interpreted to represent igneous cumulates defined by ortho- and mesocumulate texture seen in the rock. Amphibole and plagioclase are interpreted as postcumulate minerals.

Overprint of biotite on amphibole and clinopyroxene, together with overprint of amphibole on clinopyroxene is found throughout the rock (figure 2.13).

Plagioclase (30-50%, grain size 0.03-2.5mm) is found as mainly larger grains surrounded by smaller grains. The larger grains are equigranular and forms granular aggregates displaying a foam structure. Some core-and mantle structure is seen for a few plagioclase grains. Locally clinopyroxene, orthopyroxene, amphibole and biotite fill the interstices in a random network of larger plagioclase grains. Replacement textures, such as pseudomorphs of large plagioclase grains, are present. Pericline, albite and contact twinning are present. Many of the plagioclase grains have inclusions of opaque minerals.

Orthopyroxene (3-5%, grain size 0.02-1.25mm) appear as anhedral locally recrystallized grains with a pale red pleochroism, straight extinction and $\delta = 0.010\text{-}0.020$. The mineral has two distinct cleavages at right angles to each other along with a high amount of non-oriented cracks. Orthopyroxene is found in feldspar- rich areas and has overprint of amphibole and is often seen in association with biotite aggregates. Overprint of amphibole is seen along the grain boundaries of the mineral.

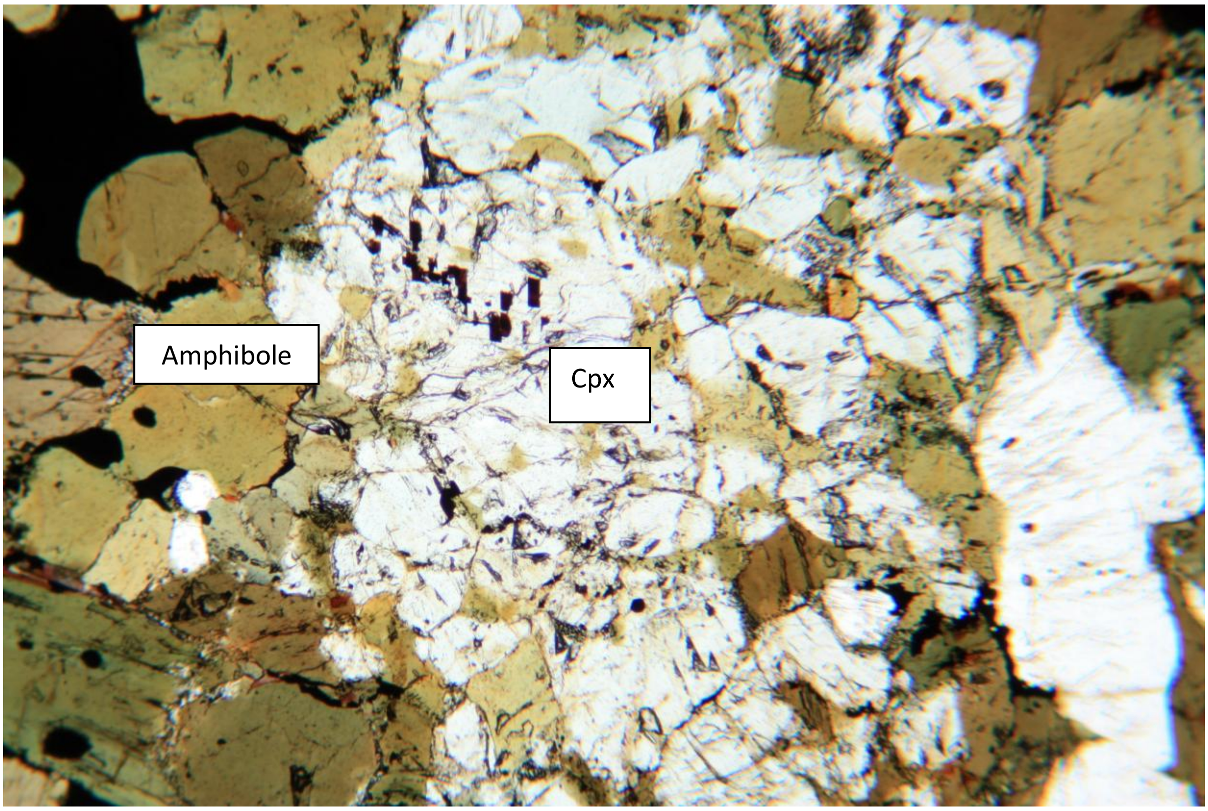


Fig. 2.13. Overprint of amphibole on a large clinopyroxene grain. The clinopyroxene grain displays a lamellar structure. Base of photo 4 mm.

Biotite (10-20%, grain size 0.01-1.75mm) is found as subhedral tabular grains concentrated in veins, and as individual recrystallized grains. The mineral has a mottled extinction, high birefringence, straight extinction and a strong pleochroism.

Biotite is present in three different settings:

I. As small (0.03mm) grains surrounding large clinopyroxene and amphibole grains displaying a strong reddish-brown pleochroism.

II. As individual grains forming fibrous/tabular grain aggregates.

III. As overprint on amphibole and pyroxene. Grain aggregates of biotite are oriented in the same direction as the veins.

Amphibole (20-40%, grain size 0.05-2.5mm) is present as subhedral to anhedral, locally elongated, grains. Amphibole is present as two different types:

I. For most parts of the rock the mineral forms granoblastic grain aggregates displaying a strong green-dark green pleochroism, $\delta \sim 0.020$, two distinct cleavages at around 60° and extinction angle between 26° and 32°. Locally the aggregates show foam-structure with triple junctions. Many of the grains have lamellas following a certain crystallographic plane.

II. Amphibole is found as overprint on recrystallized orthopyroxene grains where it displays a blue color and a blue-green pleochroism with an average grain size ~0.03mm (figure2.14). This type of amphibole is also found as overprint on green to dark green pleochroic amphibole.

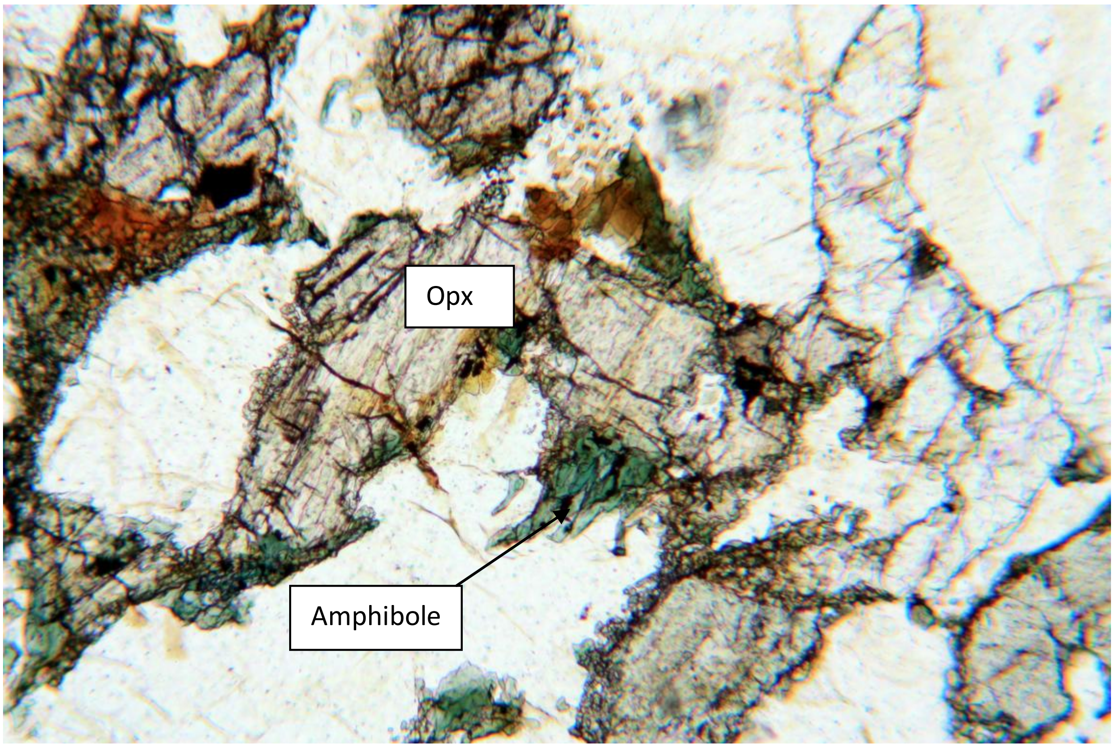


Fig. 2.14. Overprint of type II amphibole on clinopyroxene. Notice the blue-greenish color. Base of photo 1.5 mm.

Clinopyroxene (20-30%, grain size 0.03-3mm) displays a pale green color, two cleavages at right angles to each other and show an inclined extinction. Exsolution lamella is present in many of the grains. The larger grains of clinopyroxene have a subhedral shape, whereas the smaller grains are more anhedral. Clinopyroxene is found in feldspar-rich areas as individual subhedral grains, aggregates of non-oriented elongated grains and forming granoblastic aggregates. Some larger grains are surrounded by smaller grains indicating recrystallization. Locally the mineral is found as a part of granoblastic aggregates of olivine and amphibole. Overprint of a green-dark green pleochroic amphibole is found throughout the rock.

Olivine (accessional-2%, grain size 0.05-0.75mm) is recognized by its high relief, high δ and distinct crack pattern. The mineral is, as mentioned, found as a part of clinopyroxene and amphibole granoblastic aggregates. Recrystallized grains of olivine are locally altered to amphibole.

Fe-Ti-oxides (accessional-5%, grain size 0.01-1.5mm) are present as subhedral to anhedral opaque grains and as lamellas in amphiboles. Locally the mineral forms polygonal grain boundaries, and the mineral is often present between triple junctions of mafic grains.

2.4 Quartz-feldspathic Gneiss

Several xenoliths of quartz-feldspathic material are seen within the Suborg-gabbro. These xenoliths, which range from small xenoliths to larger rafts (several meters long), are interpreted to be derived from the quartz-feldspathic gneiss found on the western side of the Suborg-valley (Elvevold & Reginiussen 1996). The quartz-feldspathic gneiss observed in the field is a high-grade parageniss considered to be an external part (xenolith) of the Eidvågeid paragneiss into which the Suborg-gabbro intruded. Thin ductile shear zones are seen cross-cutting the rock (section 2.6).

The quartz-feldspathic gneiss described here forms a 50-100 m wide and 130 m long band situated to the southeast of the summit of Høgfjellet. The quartz-feldspathic gneiss is strongly sheared with a distinct layering (figure 2.15). None of the xenoliths, besides the large body of quartz-feldspathic gneiss close to the summit of Høgfjellet, will be described here. Local shearing within the quartz-feldspathic gneiss will be discussed later (section 2.5). The unit show textural and mineralogical variations. A sample from the transition zone between the quartz-feldspathic gneiss to the Suborg-gabbro was also sampled. This rock also represents a strongly sheared rock.

Fig. 2.15. Overview of the sheared quartz-feldspathic zone close to the summit of Høgfjellet.

The rock is fine-grained with aggregates (largest 1 cm) of quartz and feldspar and it has a grey-white-pinkish color. Red garnets make up a high percentage of the rock (figure 2.16). The sample from the transition zone is more mafic in composition (figure 2.17) and is more green in color.

Fig. 2.16. Hand sample SuE-12 from a sheared quartz-feldspathic zone. The rock has layers rich in feldspars, biotite and garnet. Notice the steep fabric in the rock (the hand sample is oriented back to the field).

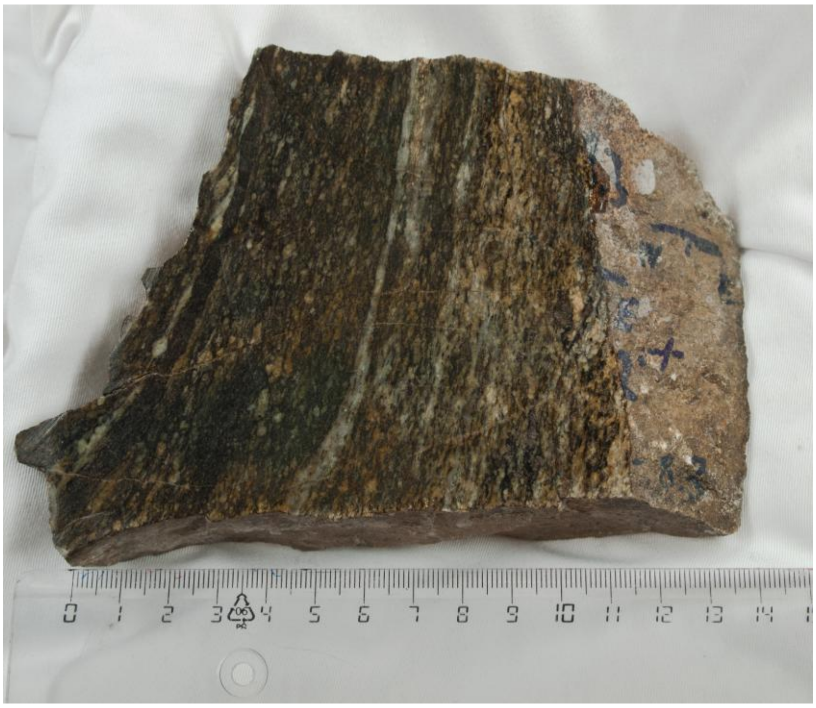


Fig 2.17. Picture of hand sample SuE-8.3. The rock has the same steep and sheared fabric as SuE-12. Porphyroclasts of felsic composition and layers of fine-grained material are recognized. Notice the difference in color between sample SuE-8.3 and SuE-12.

A gradual layering is defined by thin garnet- and biotite-rich layers (0.2-1cm). The felsic layers (>1cm) are coarser-grained. No individual grains can be seen with the aid of a hand lens. The gneissic rock has a penetrative foliation defined by its modal layering. Porphyroclasts are oriented parallel to the layering. The foliation in the quartz-feldspathic gneiss is oriented parallel to the foliation in the Suborg gabbro. The transition between the two rock types is relatively sharp (figure 2.18), but the sample from the transition zone indicates a locally gradual transition. Elvevold & Reginiussen (1994) state that the contact between the xenolithic rafts and the Suborg gabbro is gradual with development of a contaminated zone.

The oldest rocks recognized in the area are garnet-bearing parageniss (Elvevold *et al.*, 1994). Age of intruded sediments is dated by Aitcheson (1990) to be older than 1000 Ma. Sedimentary structures are not found in this unit, but isotopic studies done by Aitcheson (1989) indicate that the gneiss most likely has a sedimentary protolith.

Fig. 2.18. The transition zone between the Suborg-gabbro and the quartz-feldspathic gneiss (xenolith). The contact zone is relatively sharp and sheared. According to Elvevold & Reginiussen (1994) the contact zone is contaminated.

Microscopic features

The rock has an inequigranular grain size distribution with interlobate to amoeboid grain boundaries. Large grains of garnet + quartz + biotite + feldspars are sitting within a matrix of recrystallized feldspar, quartz and biotite. The foliation is defined by elongated grains of quartz, bands of recrystallized biotite and feldspar and also with aggregates of garnet. Locally the foliation bends around augen of K-feldspar and porphyroclasts of orthopyroxene and garnet (figure 2.19).

The contaminated contact zone displays many of the same features as mentioned above, but a lesser amount of garnet, quartz and porphyroclasts of orthopyroxene are found.

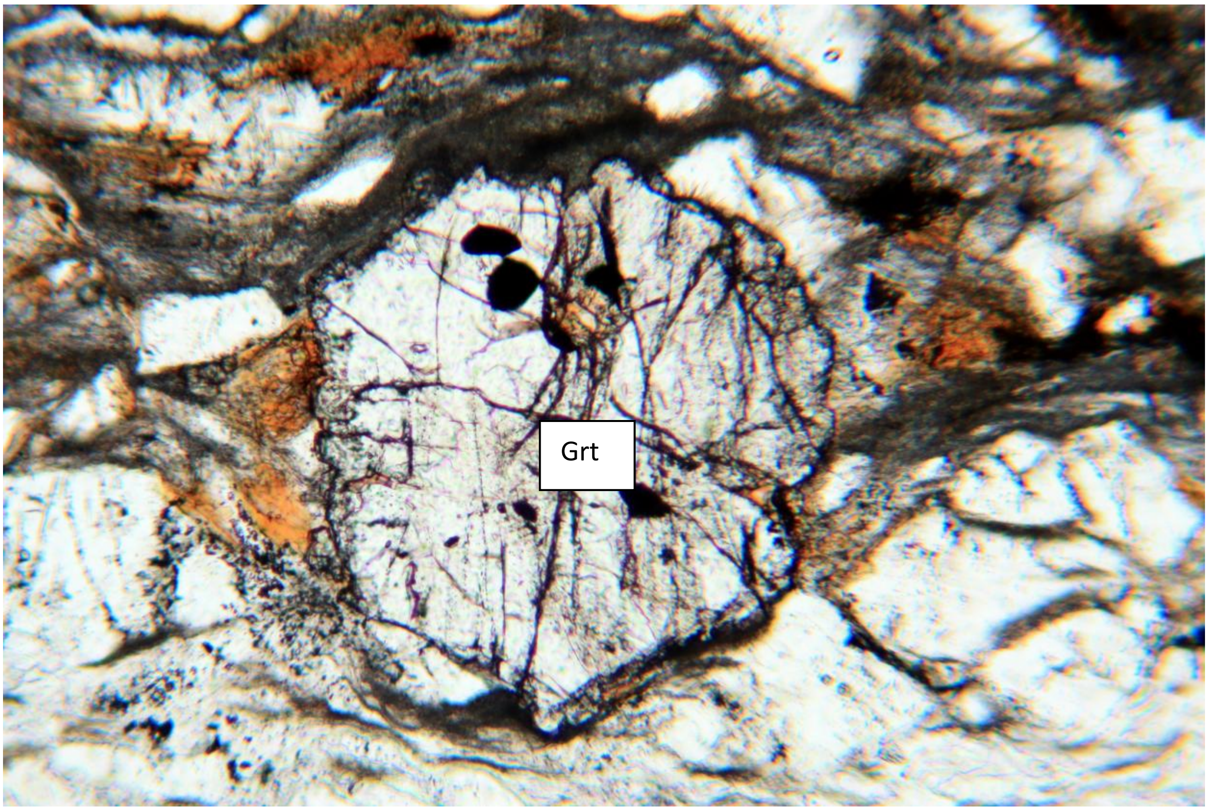


Fig. 2.19. Porphyroclast of garnet showing partial recrystallization along the rim in response to deformation. Fine-grained feldspar grains bends around the garnet grain. Base of photo 1.5 mm.

Quartz (10-30%, grain size 0.015-1 mm) has strong undulouse extinction, low relief and shows no sign of internal alteration or deformation. Quartz is found in three different setting:

I. As anhedral equigranular individual elongated grains (average size 0.3 mm) sitting within a matrix of feldspars.

II. As fine-grained recrystallized polygonal matrix material with interlobate grain boundaries.

III. As anhedral inclusions in garnet.

Plagioclase (20-40%, grain size 0.15-2mm) is found as equigranular recrystallized polygonal matrix material together with quartz and k-feldspar and as larger recrystallized anhedral grains (porphyroclasts). Secondary deformation albite (with tapering edges) and pericline twinning is seen in many of the grains. Alteration to white mica is very common. The seritization seems to follow internal cracks. The mineral shows a strong undulose extinction.

Biotite (5-10%, grain size <0.01-1 mm) is present as large subhedral elongated grains oriented parallel to foliation, and as small recrystallized grains in-between feldspar grains. The mineral is recognized by its straight extinction, reddish-brown pleocroism and high birefringence. Biotite is found within cracks in garnet and as overgrowth on orthopyroxene.

Orthopyroxene (15-25%) is only found in the contaminated contact zone as porphyroclasts. The mineral has a pale red pleocroism, two distinct cleavages, undulose extinction, straight extinction and a relatively low δ. Elongated sub- to anhedral recrystallized grains. The grains are heavily cracked with alteration along grain boundaries, cracks and cleavage planes. Many of the grains are overprinted by biotite.

K-feldspar (10-40%, grain size 0.03-3mm) is found as lens-shaped crystals (augen) surrounded by a reaction rim of fine-grained material. The mineral has inclusions of white mica, quartz and show locally perthite formation. Internal cracks with biotite are present in many of the grains.

Garnet (10-40%, grain size 0.1-3 mm) locally has inclusions of quartz and oxides. The mineral is present in two different settings:

I. Larger sub- to anhedral fragmented grains with inclusions of FeTi-oxides, biotite, zircon and feldspar. The mineral has a high amount of internal cracks, and forms locally domino-type and mosaic fragmented porphyroclasts (figure 2.20).

II. In elongated grain-aggregates parallel to the lineation within a matrix of feldspar and quartz. No inclusions could be found in this setting.

FeTi-oxides (3-5%, grain size 0.03-1 mm) are seen throughout the rock, and are very common as inclusions in garnet. The oxides are also found as elongated subhedral grains oriented parallel to the lineation as a part of the matrix. In the contaminated zone FeTi-oxides are present along the rims of porphyroclasts of orthopyroxene.

Cordierite (8-10%, grain size 0.15-0.5 mm) is only found in the non-contaminated zone. The mineral is recognized by its low relief, low to medium δ, and that it is often overprinted by sillimanite of fibrous nature (figure 2.21). Locally cordierite show simple twinning. The mineral is seen as individual subhedral grains with commonly overgrowth of sillimanite. Inclusions of zircon showing characteristic pleochroic haloes are present in many of the grains.

Accessional is zircon and white mica found as inclusions, sillimanite is present as overgrowth on cordierite.

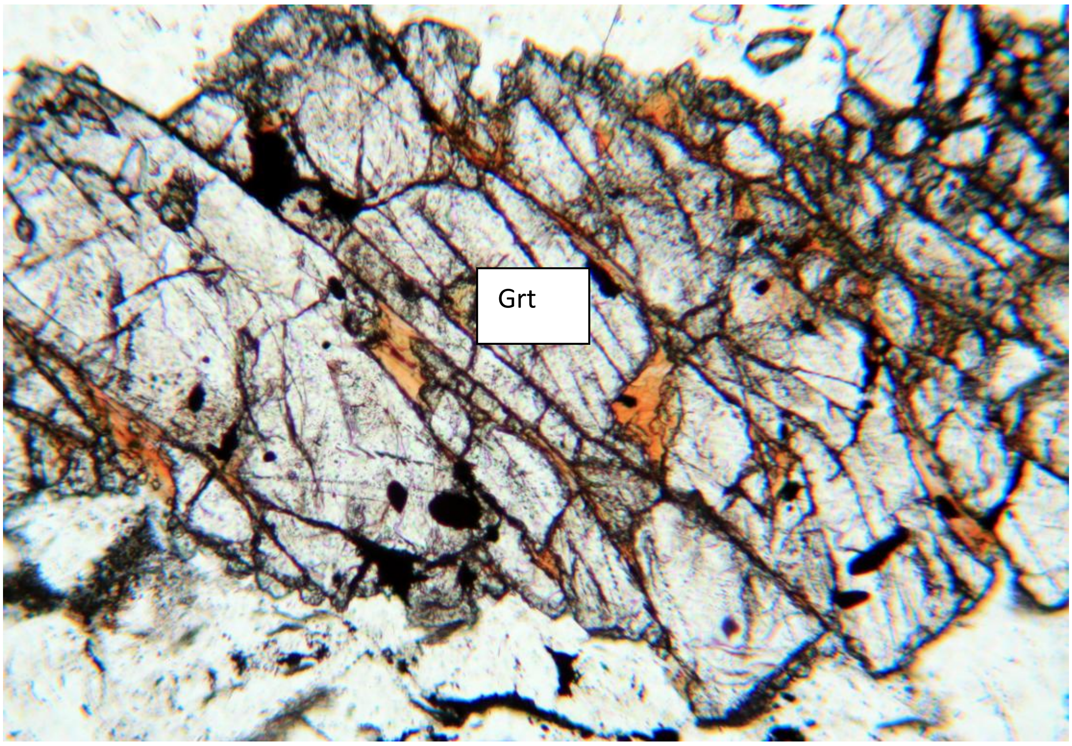


Fig. 2.20. Domino-type fragmented porphyroclast of garnet in a section parallel to the aggregate lineation and normal to the foliation. Sinistral sense of shear. Base of photo 1.5 mm.

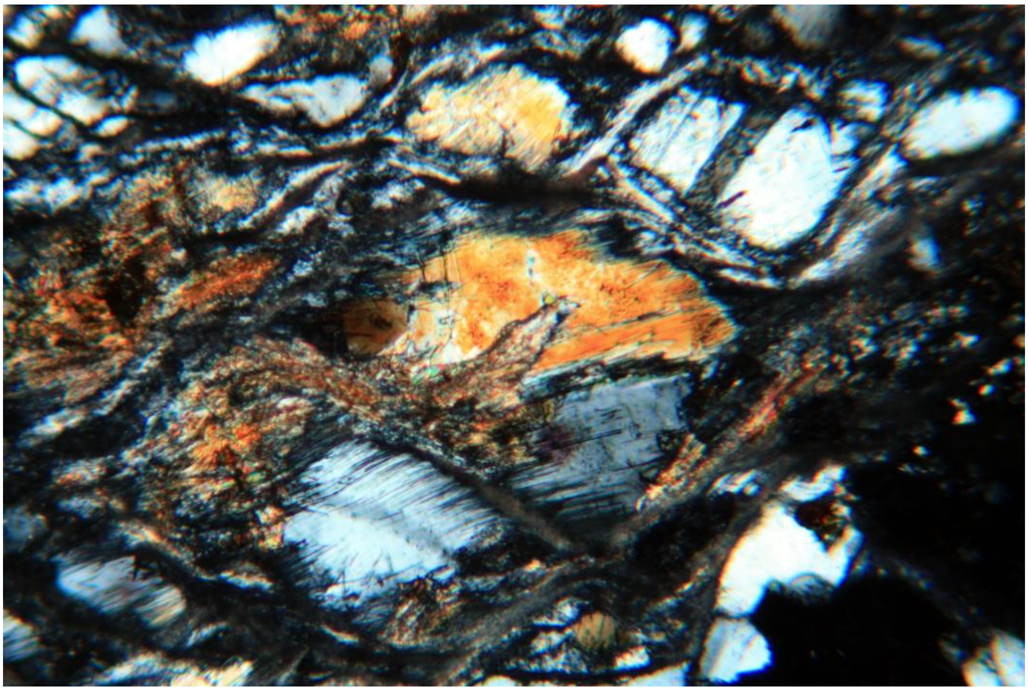


Fig. 2.21. Cordierite in the center of the picture with overgrowth of sillimanite. The cordierite grain show simple twinning. Crossed polars; base of photo 1.5 mm.

2.5 Ductile Shear Zones

Three different thin ductile shear zones were sampled: Two from the Suborg-gabbro with a magmatic fabric, and one is from a shear zone within the external quartz-feldspathic gneiss. Also, a shear zone suggested to be a pseudotachylyte fault rock was sampled close to the summit of Høgfjellet. The grain size in the shear zones is smaller compared to the wall rock and the shear zones (5-15 cm wide) display very regular and planar foliations together with straight lineations. The boundary to the wall rock is very sharp (figure 2.22). Porphyroclasts are not seen in the hand samples of the mylonitic zones, and no minerals could be identified with the aid of a hand lens.

Pseudotachylyte is a cohesive or very fine-grained fault-rock with a distinct fabric (Passchier & Trouw, 2005, p. 115, 2nd ed). The pseudotachylyte is observed as a planar main fault vein up to maximum few centimeters wide, and occurs as straight bands with connected injection veins (figure 2.23). Pseudotachylyte veins have distinct, sharp and straight boundaries with the wall rock. The matrix of pseudotachylyte is commonly black and relatively homogenous. Pseudotachylyte is suggested to be the result of local melting of rocks by frictional heating developed in a fault zone during periods of rapid displacement (Philpotts, 1964).

The orientation of the shear zones are commonly discordant to the main foliation seen in the Suborg-gabbro and the quartz-feldspathic gneiss. The foliation of the wall rock has been displaced in the shear zone; the wall rock is dragged into the foliation of the shear zone which could act as shear sense indicators.

Fig. 2.22. Shear zone seen close to the summit of Høgfjellet. The boundary to the wall rock is very sharp. Sample Ø18 and SuE-6.1 are from this locality.

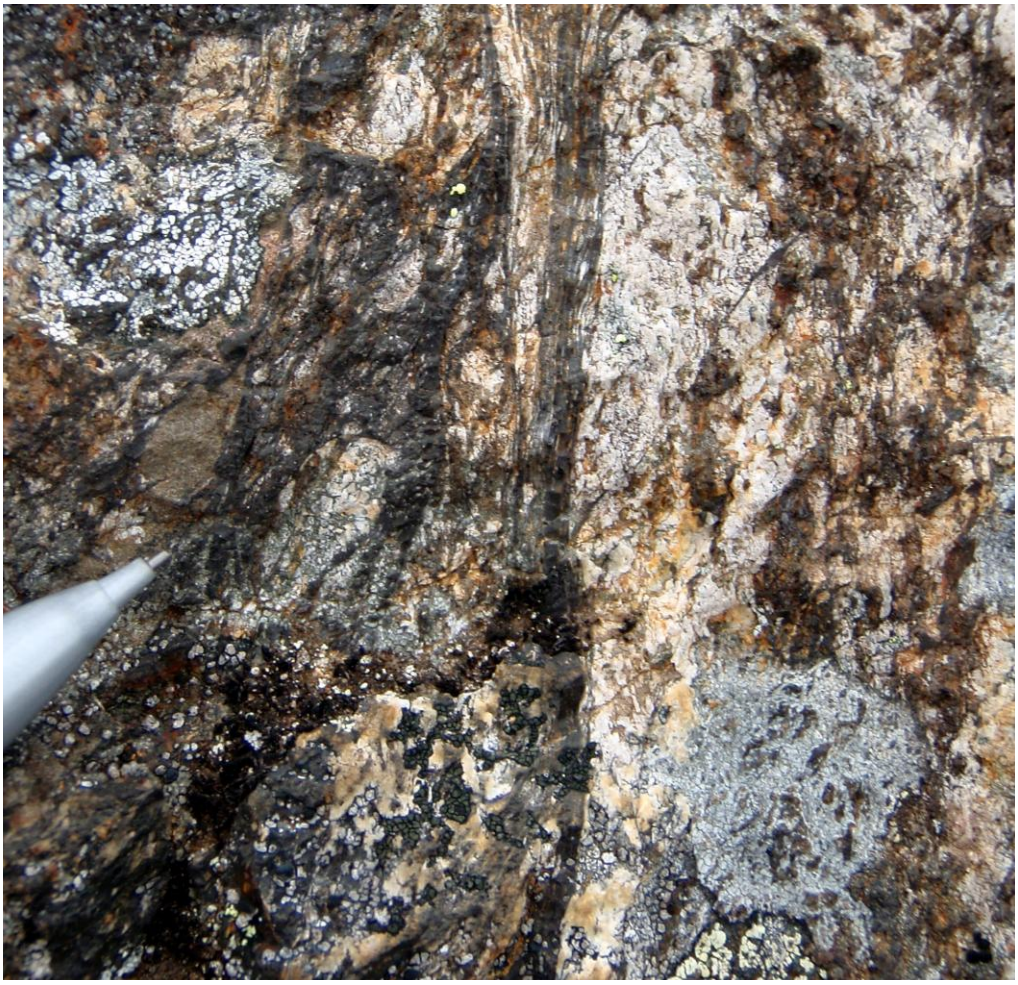


Fig. 2.23. Thin mylonitic zone suggested representing pseduotachylyte fault rock. Thin injection veins are connected to the straight black vertical band.

Microscopic features

The shear zones sampled can be classified into ultramylonites and as pseudotachylyte fault rock. Mineral growth in the shear zone is related to recrystallization, corona structure and presence of porphyroclasts in the matrix and formation of planar and regular foliation. Some of the clasts within the matrix show evidence of brittle deformation where internal fractures and fragments have moved relative to each other (figure 2.24). The shear zones are ductile, but some larger, single grains have been exposed to brittle deformation in a soft ductile matrix. White *et al.* (1980) argue for localized brittle deformation of hard minerals within ductility deforming mylonite matrix. It is reasonable to assume that the fabric seen in the shear zones are controlled by the mineralogical composition of the wall rock.

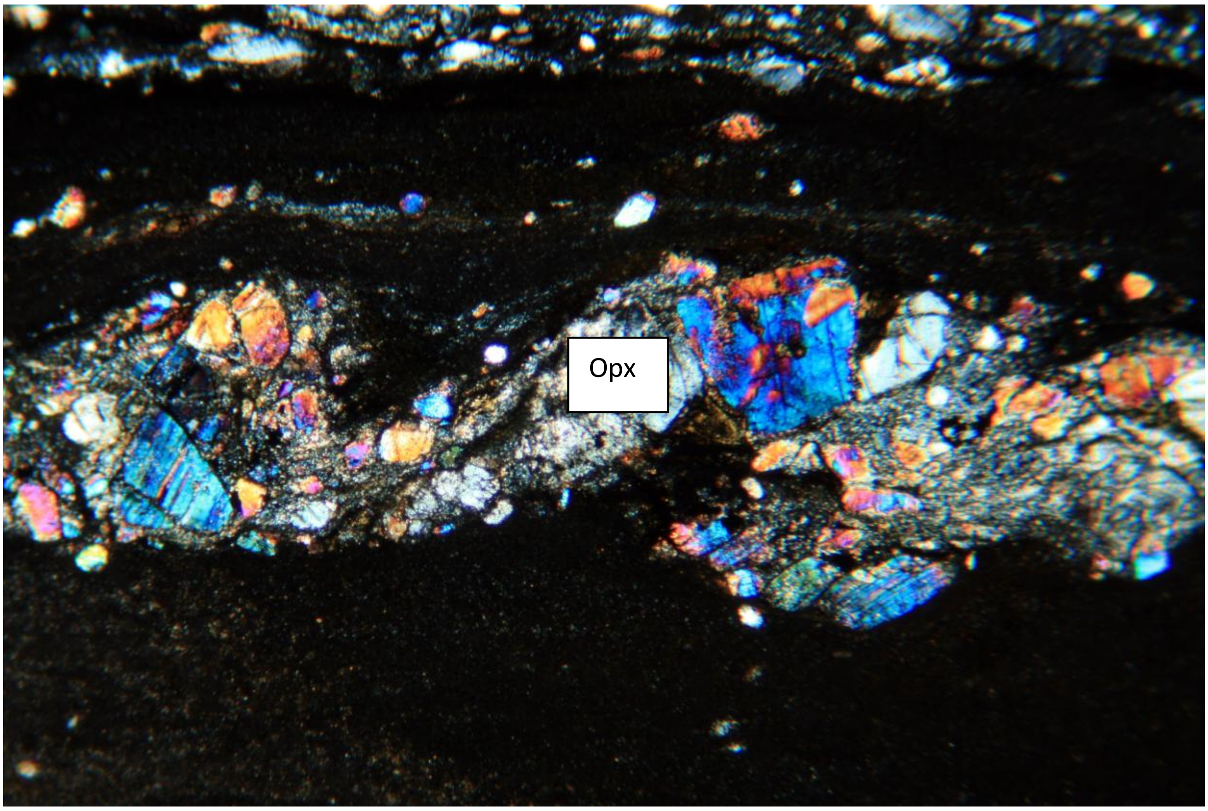


Fig. 2.24. Relict of porphyroclast of clinopyroxene exposed to brittle deformation in a soft ductile matrix. Picture is from thin section of the shear zone defining a contact between the Suborg-gabbro and the quartz feldspathic gneiss. Crossed polars; base of photo 4 mm.

Garnet is found as small euhedral to anhedral grains within the matrix of the shear zone sampled from the external quartz-feldspathic gneiss, and locally as porphyroclasts within the matrix of the shear zones sampled from the Suborg-gabbro.

Irregular injection veins, sharp boundaries to the wall rock and black matrix with minor rounded, isolated inclusions of plagioclase and amphibole are all features found in the shear zones characteristic of pseudotachylyte fault rock (figure 2.25).

The ultramylonitic zones could represent former pseudotachylyte fault rock by their fine-grained homogenous nature and the presence of injection vein relicts (Passchier and Trouw, 2005, p. 115-118, 2nd ed).

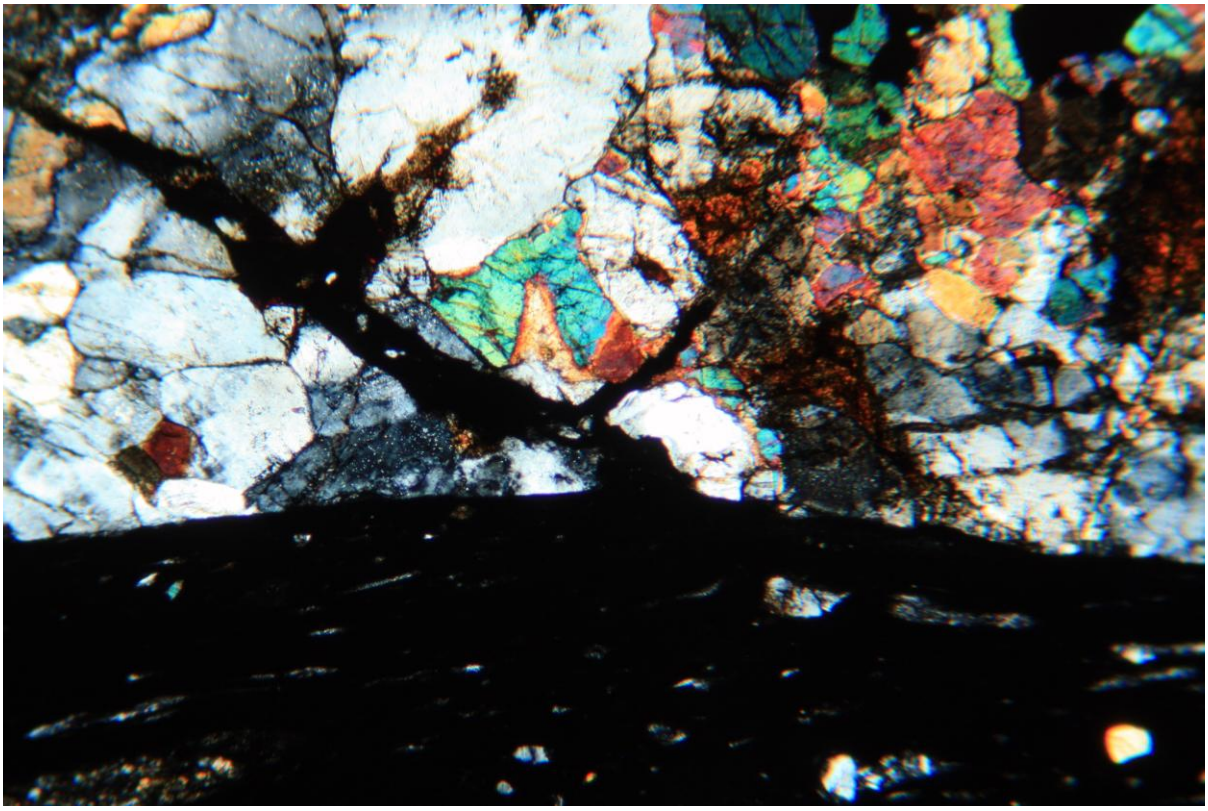


Fig. 2.25. Main fault veins transect the rock along the bottom of the picture. Isolated fragments lie in a dark pseudotachylyte matrix and an injection vein occurs at left. Boundaries between pseudotachylyte and wall rock are sharp. Crossed polars; base of photo 4 mm.

2.5.1 Shear zones in the Suborg-gabbro

The shear zones observed in the Suborg gabbro have the same mineral composition as the country rock. The only difference is the presence of euhedral to anhedral inclusion-free garnet (grain size 0.01-0.5mm). Garnet makes up about 20% of the shear zone.

According to Reginiussen (1992) the fine-grained matrix is composed of recrystallized biotite, plagioclase and FeTi-oxides. Porphyroclasts of pyroxene, garnet and feldspar are found within the matrix. Some of the porphyroclasts appear as winged mantled clasts (δ-type) indicating both a sinistral and dextral sense of shear. Some show stair stepping.

Many of the porphyroclasts of garnet and clinopyroxene show evidence of internal brittle deformation as shown in figure 2.24.

Amphibole is mostly found as overgrowth on pyroxene within the shear zone.

2.5.2 Shear zones in the Quartz-feldspathic gneiss

Garnet makes up about 60% of the shear zone. The mineral is euhedral to anhedral, inclusion free and is mostly found as elongated aggregates with a grain size 0.01-0.6 mm, (figure 2.26). Growth of small euhedral garnets are interpreted to have grown during shearing (Reginiussen1992).

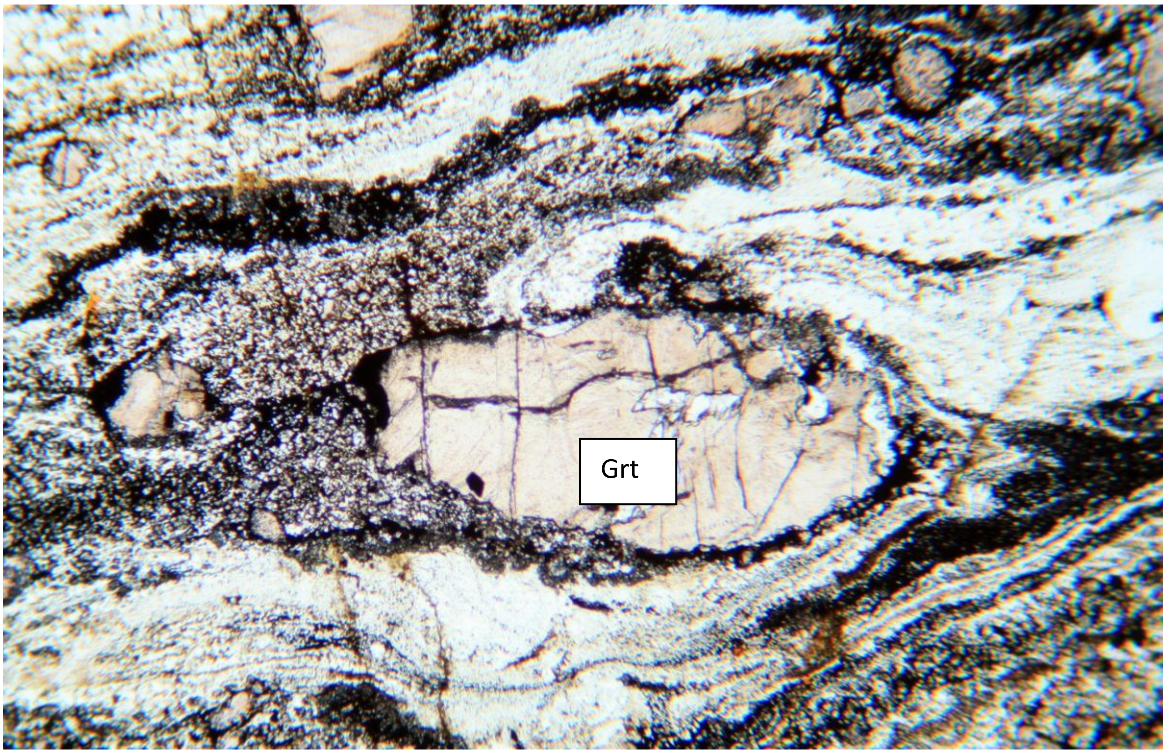


Fig. 2.26. Inclusion-free porphyroclasts of garnet from a ductile shear zone from the Suborg-gabbro. Base of photo 4 mm.

Quartz, garnet, zircon (sparsely) and feldspars are found as porphyroclasts within the matrix. Feldspar shows evidence of internal brittle deformation. Biotite is found as very fine-grained recrystallized grains as a part of the matrix. Recrystallized phases within the mylonitic shear zones seen in in the quartz-feldspathic gneiss include Grt + Qtz + Pl + Bt ± Ky ± Kfs ± Ru according to Elvevold *et al.* (1994).

3. Petrology

3.1 Introduction

A petrological description of the Suborg gabbro and the quartz-feldspathic gneiss will be given in this chapter. Some petrography from chapter 2 is included in this chapter for a better understanding of the metamorphic reactions. Observations and mineral analyses from Elvevold *et al.* (1994) will, together with my observations, give suggestions to the origin, composition and alteration of the mineral assemblages in the Suborg-gabbro and quartz-feldspathic gneiss. Suggestions for the original mineral assemblages and subsequent mineral assemblages in response to deformational and metamorphic event(s) are given for the Suborg-gabbro and the quartz-feldspathic gneiss in section 3.2. Three different metamorphic/deformation phases (phase I-III) are proposed for the two rock types and is represented by different mineral assemblages and reactions. Reaction sequences together with pressure and temperature are included in section 3.2. Mineral assemblages are given roman numerals I-VI and mineral reactions are given ordinary numbers 1-7.

Pressure- and temperature-estimates on a layered metagabbro from the SIP and the quartz-feldspathic gneiss is provided by Elvevold *et al.*, (1994). Their results contribute to a better understanding of metamorphic reactions and also different deformational events.

In all 18 thin sections were studied with the use of a Leitz Laborlux 11 pol s polarization microscope. Pictures of thin sections are taken with a Leica DC 300F camera mounted on a Leica DM LP polarization-microscope.

3.2 Mineral Textures and Reaction Phases

3.2.1 Stage I: Emplacement of the Suborg-gabbro and contact metamorphism

The Suborg-gabbro is observed both as a unit with a solid-state overprint with relics of a magmatic fabric, and as a unit with a magmatic fabric with only locally a weak solid state overprint. The main minerals found in the Suborg-gabbro with a magmatic fabric are plagioclase, orthopyroxene, clinopyroxene and olivine. This primary mineral assemblage

I. Pl + Opx + Cpx + Ol

is suggested to constitute a basic plutonic rock. Features typical for igneous microstructure are seen in the Suborg-gabbro with a non- to weak metamorphic/deformational overprint, for example: inequigranular grain size distribution, grain shape preferred orientation of inequant euhedral to anhedral plagioclase (figure 3.1), ophitic fabric, and uniformly distribution of mineral phases. Uralitization, a process where pyroxenes are altered to fibrous blue-green amphiboles (figure 2.14), is seen throughout the Suborg-gabbro. The process of uralitization is generally ascribed to be the action of hydrothermal solutions which may be associated with the late-stage crystallization of igneous rocks (Deer *et al.*, 1992) and therefore also support an igneous mineral assemblage for the Suborg-gabbro. Many bodies of igneous rocks contain structures of magmatic origin that are partially or completely overprinted by “solid state” deformation fabrics. But even where deformation and recrystallization at high temperature- and pressure levels have removed much of the primary igneous microstructure relicts of magmatic features can be preserved (Vernon 2004, p. 280). This could be the case for the Suborg-gabbro.

The quartz-feldspathic gneiss represents a contact metamorphosed pelitic xenolithic raft of the Eidvågeid gneiss. Xenoliths are bodies of external origin in an igneous rock that were plucked from the walls of the country rock by hot magma and remained partly solid (Vernon 2004, p. 480). The mineral assemblages in the rock represent a granulite facies metamorphism and indicate that the rock has been exposed to high temperatures. Textural relationships suggest an early stabilization of the mineral assemblage

II. Opx + Grt + Qtz + Pl + Kfs + Oxides ± Crd.

According to Elvevold *et al.* (1994), paragenesis II has been produced by the breakdown of biotite, quartz and sillimanite through successive dehydration and partial melting in response to high temperatures during the emplacement of the Suborg-pluton. A microstructure indicating high temperature deformation are lobate grain boundaries seen within the quartz assemblages (figure 3.2). Lobate grain boundaries are due to grain boundary migration recrystallization (GBM) and occur commonly at high temperatures (Passchier & Trouw 2005, p.57, 2nd ed). The exposure to high temperatures has also caused the rock to be plastically deformed as indicated by undulatory extinction observed for feldspars, orthopyroxene, cordierite, and quartz grains. Deformation twinning in plagioclase are also indicative of crystal plastic deformation. The reaction

1. Bt + Sil + Qtz = Crd + Opx + Kfs + H_2O

took place in response to higher temperatures and pressure (Bucher & Frey 1994, p.220, 6th ed.). The assemblages: orthopyroxene + sillimanite + quartz + K-feldspar and orthopyroxene + sillimanite + quartz + biotite + K-feldspar typically form at pressures greater than 8 kbar and temperatures above 800ºC ((Bucher & Frey 1994, p.220, 6th, ed.).

Elvevold *et al.* (1994) used garnet, orthopyroxene and plagioclase from the xenoliths to derive thermobarometric estimates of *P-T* conditions during the emplacement of the Seiland Igneous Province (Suborg-gabbro intrusion). Core compositions of garnet and orthopyroxene surrounded by quartz, plagioclase and K-feldspar were selected for temperature and pressure calculations for the contact metamorphism.

The result from Elvevold *et al.* (1994) on the *P-T* calculations on two samples of xenoliths is 925-960ºC and 4.8-6.5 kbar. The intrusion temperature of the gabbro magma was therefore probably in the range of 1000-1100ºC, and it is reasonable to assume that the xenoliths were heated to 930-960ºC during the emplacement (Elvevold *et al.,* 1994), and that the magmatic temperatures caused partial melting of the xenoliths (Elvevold & Reginiussen, 1996). Anatexis of a pelite may reduce the concentration of SiO_2, Na_2O, K_2O and H_2O in the restite such that its composition becomes silica-undersaturated and anhydrous (Elvevold & Reginiussen, 1996). Hence, it can be assumed that the xenoliths were dehydrated high-grade rocks before they were emplaced into the Suborg-gabbro (Elvevold *et al.,* 1994).

Figure 3.3 illustrates the proposed pressure-and-temperature conditions given by Elvevold *et al.* (1994) and from Bucher & Frey (1994) for the quartz-feldspathic gneiss due to contact metamorphism.

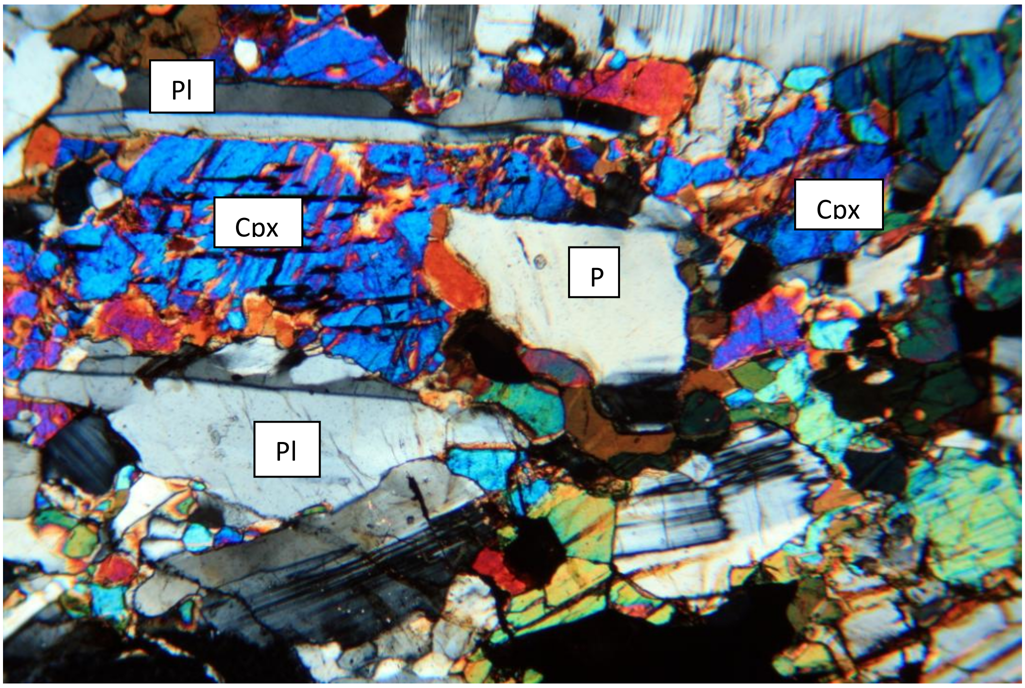


Fig.3.1. Inequant euhedral to subhedral plagioclase show a grain shape preferred orientation characteristic of an igneous microstructure for plagioclase. Crossed polars; base of photo 4 mm.

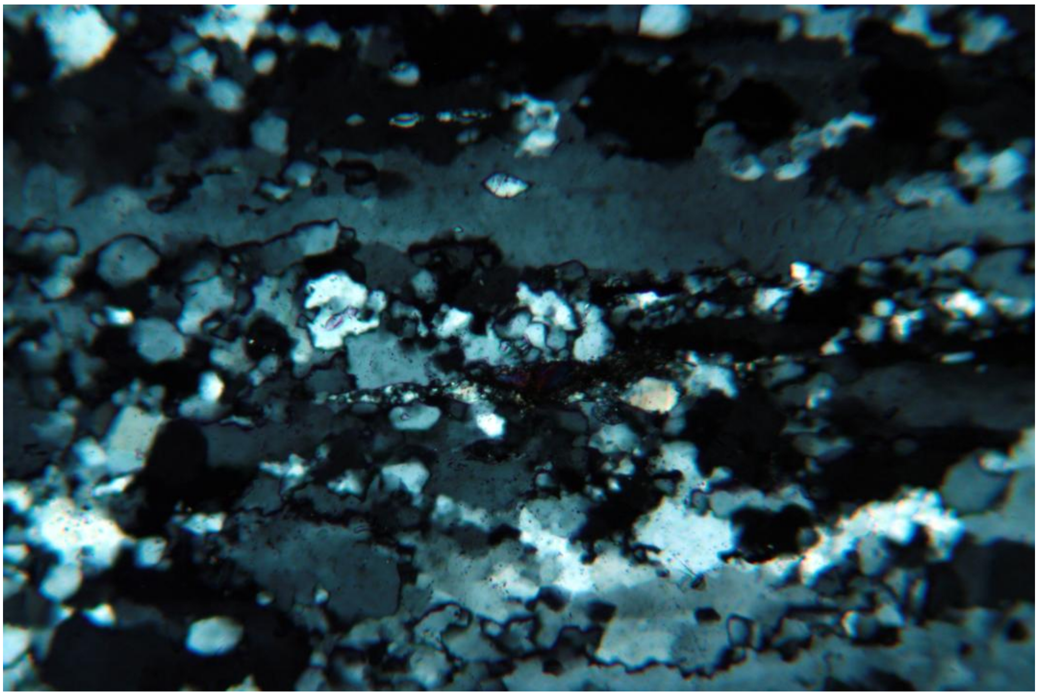


Fig. 3.2. Interlobate to amoeboid grain boundaries between quartz grains which is indicative of high temperature deformation. Crossed polars; base of photo 1.5 mm.

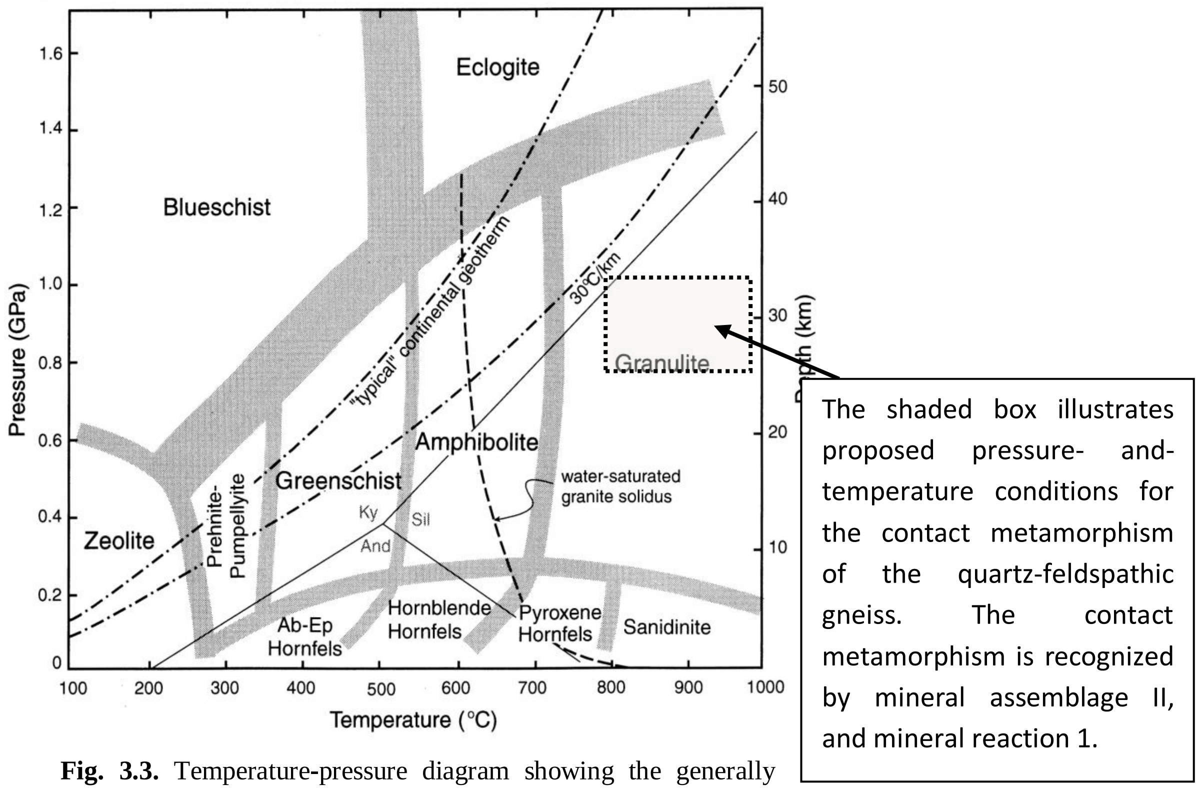


Fig. 3.3. Temperature-pressure diagram showing the generally accepted limits of the various facies. The proposed contact pressure-and-temperature conditions shows that the quartz-feldspathic gneiss was metamorphosed at granulite facies during the contact metamorphism. The figure is from Winter (2001, p. 498). 0.1 GPa = 1 kbar.

3.2.2 Stage II: Cooling

The Suborg-gabbro: Evidence for solid state deformation is present throughout the Suborg gabbro and is especially seen in the strongly foliated parts of the Suborg-gabbro. The high temperatures during final crystallization of mafic igneous rocks may have provided sufficient heat long enough for solid-state grain-boundary adjustment and/or metamorphic reactions. Lower-energy grain shapes and larger grain-sizes may be produced and thereby reduce the total interfacial energy of the aggregates. Polygonal grain aggregates of amphibole and feldspar in the Suborg-gabbro show triple junctions for solid-state (subsolidus) grain-boundary adjustment (figure 3.4a), and the larger subhedral to anhedral shapes of plagioclase, clinopyroxene and olivine grains with polygonal grain boundaries present in the magmatic lens could represent igneous cumulates. Many cumulate grains with polygonal grain shapes are interpreted to be due to solid-state interface adjustment.

The strongly foliated Suborg-gabbro shows many features indicative of metamorphism and deformation; reaction to hydrous minerals (amphibole and/or biotite in the rim zones of pyroxene grains) (figure 3.4b), recrystallized grains (also figure 3.4b), strong undulatory extinction seen in many grains, mineral phases concentrated in clusters, deformation twins in plagioclase and aggregates of pyroxene showing a strong shape preferred orientation. Solid-state microstructures observed in the Suborg-gabbro include: internal deformation of grains visible as undulatory extinction, formation of subgrains, recrystallization into smaller grains, recrystallized wings on porphyroclasts, reaction rims of orthopyroxene on olivine (figure 2.4) and symplectic intergrowth of orthopyroxene and spinel (figure 3.4c). All these features observed indicate that the rock has adjusted to different temperature and pressure conditions after it was emplaced. The development of corona textures (reaction rims) on olivine is suggested to have occurred during cooling from subsolidus igneous temperature at relatively high pressures (Deer *et al.*, 1992, p.13, 2nd ed.).

According to Elvevold *et al.* (1994), the development of corona on olivine textures could imply a direct transition from an unaltered igneous assemblage to an assemblage typical of high temperature and medium pressure suggesting that the magma crystallized at medium depth in the crust and while cooling, the magma entered the medium-*P* granulite field. The mineral assemblage and structural features seen in the Suborg-gabbro indicate that the rock has undergone metamorphic and deformation event(s). The primary olivine-bearing magmatic assemblage in the Suborg-gabbro recrystallized to the assemblage

III. Opx + Cpx + Pl + Hbl + Bt + FeTi-oxides

resulting in a pyroxene granulite assemblage. According to Bucher & Frey (1994, p. 282, 6th ed.), the typical lower pressure granulite facies is: plagioclase + clinopyroxene + orthopyroxene, and that one clear indication that granulite facies conditions are reached is the appearance of orthopyroxene (Bucher & Frey 1994, p. 281, 6th ed.).

In response to cooling, granulite facies rocks can undergo a transition to amphibolites facies rocks and resulting in a mineral assemblage richer in hydrous minerals. The breakdown of pyroxenes to amphibole and/or biotite can take place through the reaction

2. Pl + Cpx + Opx ± Grt = Pl + Hbl + Cpx ± Bt

according to Bucher & Frey (1994, p. 283, 6th ed.).

Another reaction (from Elvevold *et al.*, 1994) implying cooling from high temperatures is the symplectic intergrowth of spinel and orthopyroxene:

3. Pl + Ol = Spl + Opx

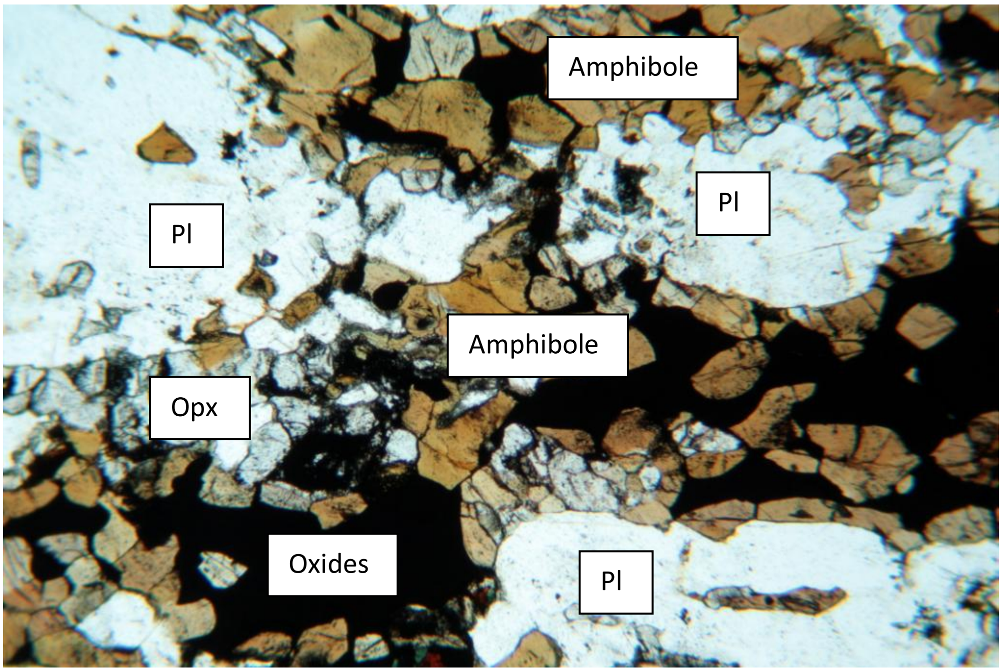


Fig. 3.4a. Base of photo 4 mm.

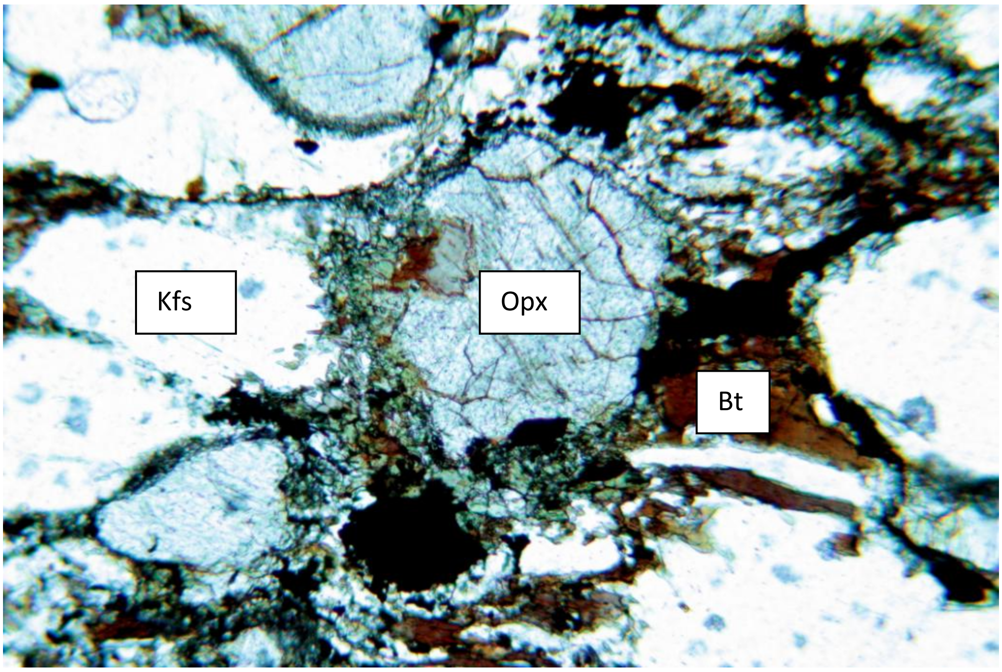


Fig. 3.4b. Base of photo 4 mm.

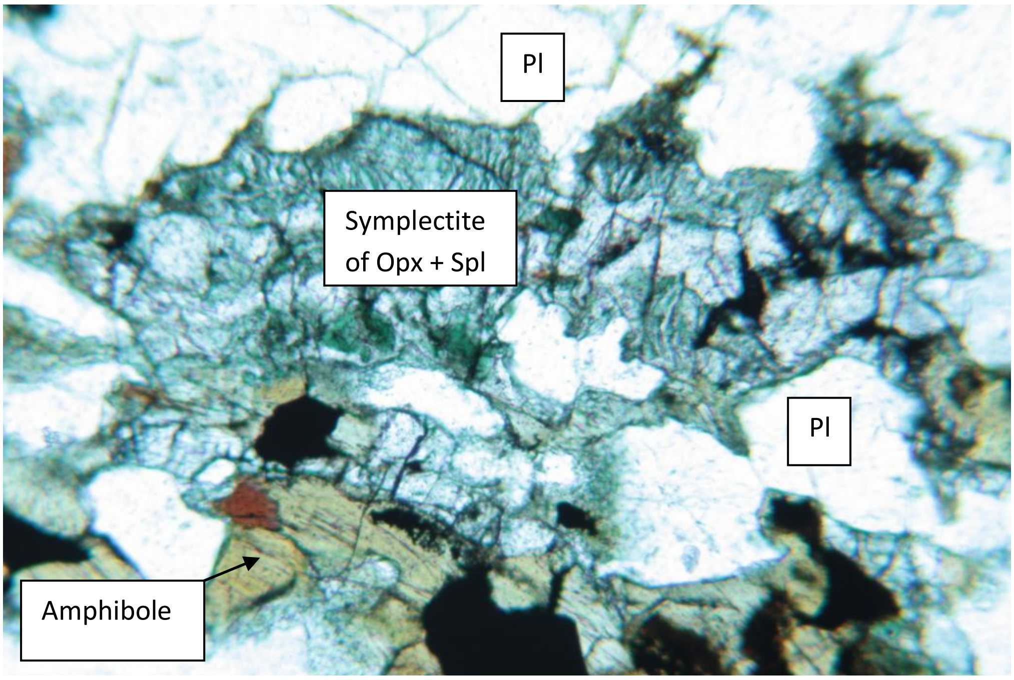


Fig. 3.4c. Base of photo 1.5 mm.

Fig. 3.4a-c: Microstructures observed in the Suborg-gabbro indicating that the rock has gone through a cooling stage. (a) Grain aggregates of amphiboles and pyroxenes exhibiting triple junctions indicative of grain boundary adjustment. (b) Recrystallized amphibole grain with overprint of biotite (c) Symplectic intergrowth of orthopyroxene and spinel produced in reaction 3.

The quartz-feldspathic gneiss shows microstructural and metamorphic reactions indicating cooling. Several features typical for solid state deformation in response to cooling from high temperatures are present in the rock; internal deformation seen as recrystallization to smaller grains, recrystallized wings on porphyroclasts (figure 3.5a), elongation of recrystallized aggregates and foliations anastomosing around less deformed porphyroclasts. The foliation in the quartz-feldspathic gneiss is defined by the parageneses

IV: Grt ± Sil ± Opx ± Crd + Kfs + Qtz + Pl ± Bt + FeTi-oxides

produced in response to the cooling of a high temperature rock. Aggregates of these secondary recrystallized grains show a grain-shape preferred orientation.

It can be assumed that cordierite and orthopyroxene may not have co-existed at the peak metamorphic conditions since the two minerals are not seen to be in mutual contact with each other. This implies that cordierite may have formed both as a prograde and retrograde reaction product according to reaction 1 and the following retrograde reaction

4. Opx + Spl + Qtz = Crd + Grt

proposed by Elvevold & Reginiussen (1996). I could not see spinel in the rock, but Elvevold & Reginiussen (1996) states that green spinel is found in three textural varieties in the quartz-feldspathic gneiss.

One important feature indicating cooling from high temperatures is the secondary growth of biotite within internal cracks of garnet (figure 3.5b) and overprint of metamorphic cordierite by sillimanite (figure 3.5c). Elvevold *et al.* (1994) proposes a breakdown of garnet to produce biotite. The reaction involves hydration and water is therefore necessary for the reaction to occur. Biotite and sillimanite were produced according to the reaction (Bucher & Frey 1994, p. 211, 6th ed.).

5. Grt + Kfs + Crd + H_20 = Bt + Qtz + Sil

The hydration of cordierite and garnet indicates an increase in water during cooling from high temperatures.

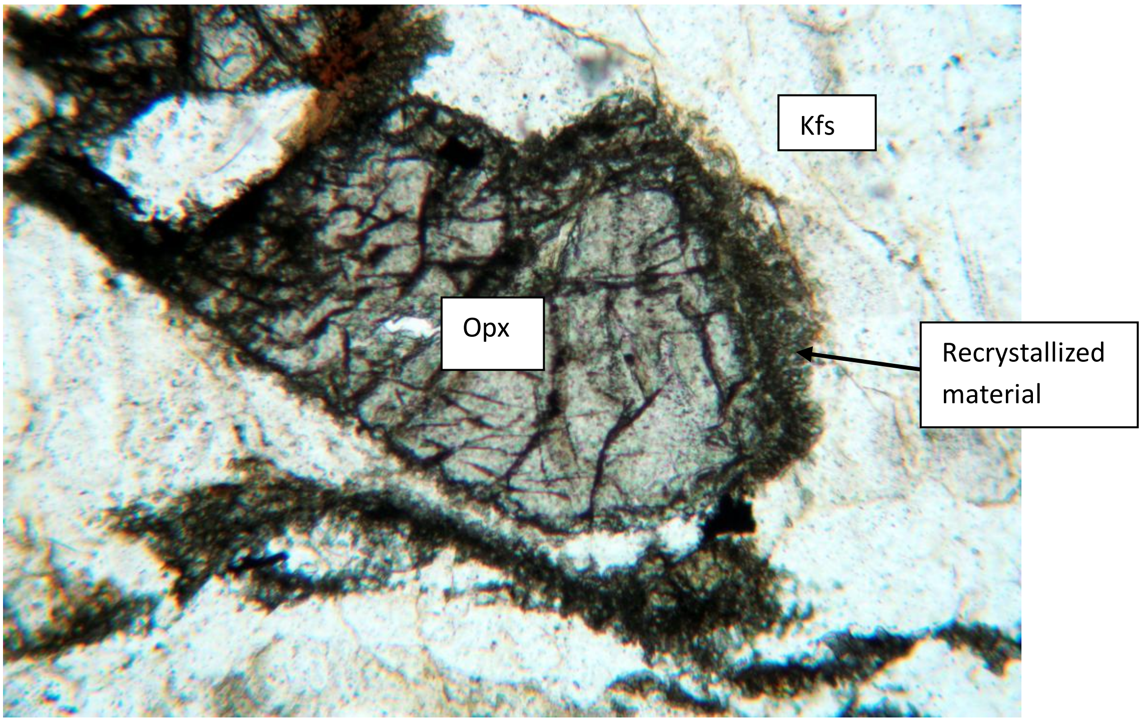


Fig. 3.5a. Base of photo 1.5 mm.

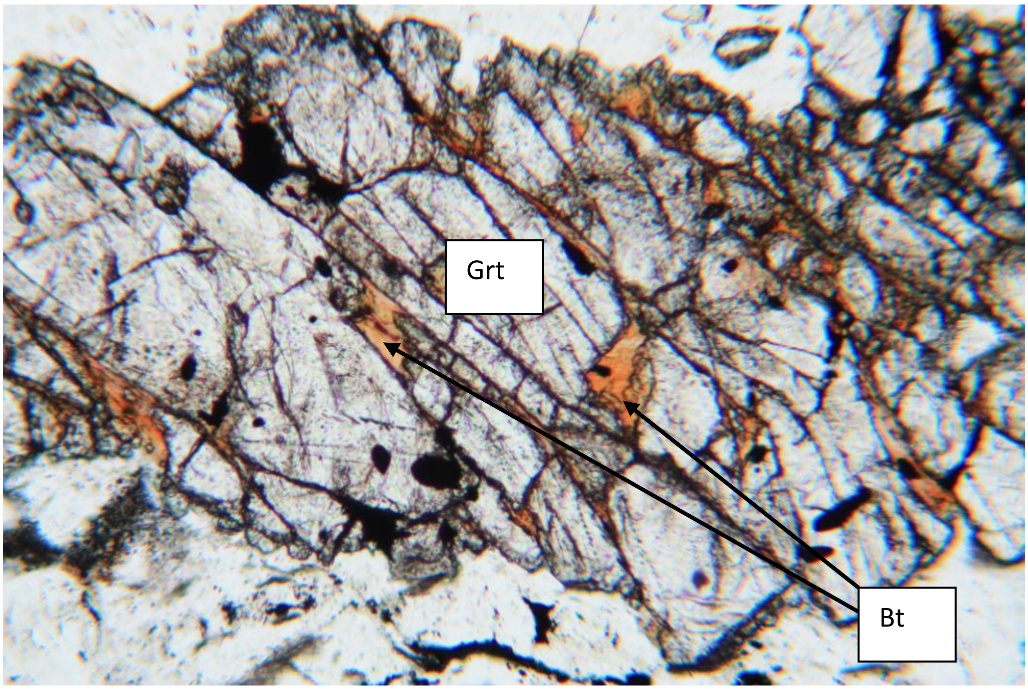


Fig. 3.5b. Base of photo 1.5 mm.

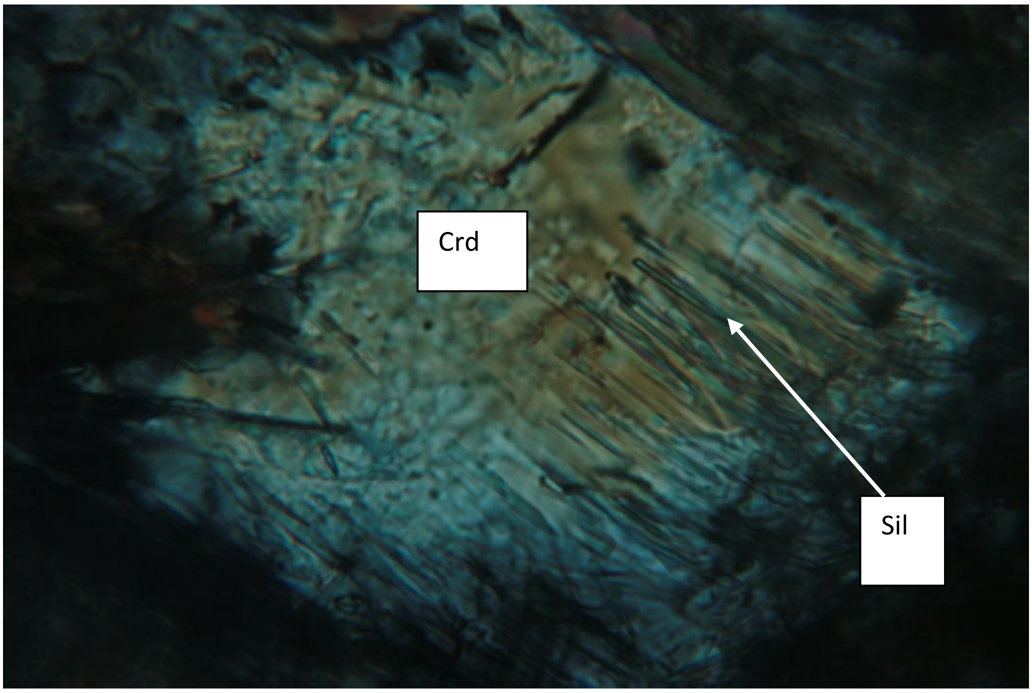
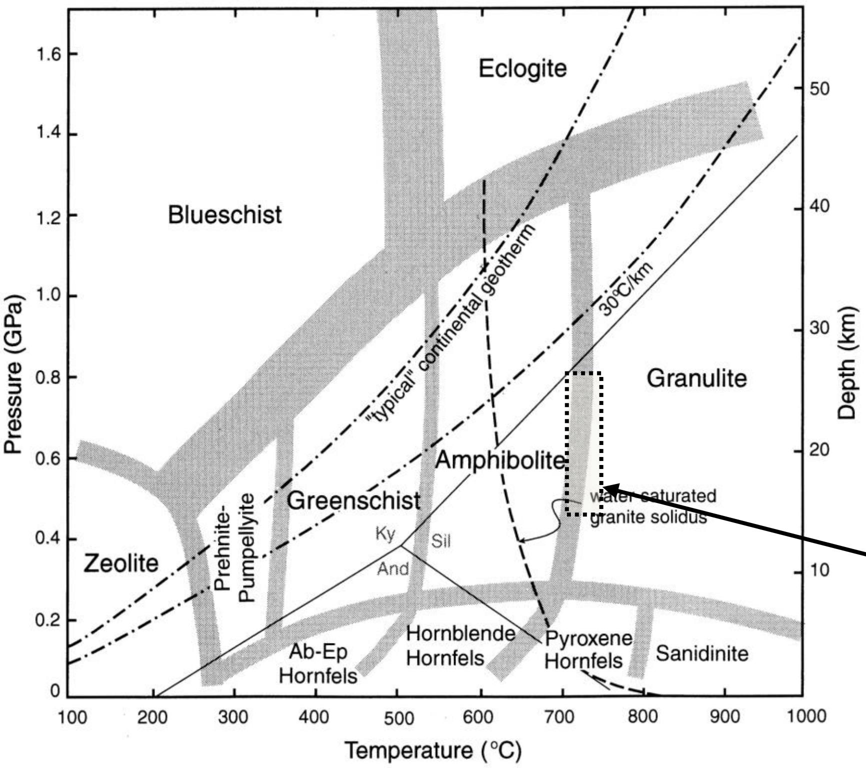


Fig. 3.5c. Crossed polars; base of photo 0.6 mm.

Fig. 3.5a-c: Microstructures observed in the quartz-feldspathic gneiss indicating that the rock has gone through a cooling stage. (a) Recrystallized wings on a porphyroclasts of orthopyroxene. (b) Overgrowth of biotite within cracks in garnet. (c) Overprint of sillimanite on cordierite.

Mineral zoning is of great importance in the interpretation of P-T evolution. Zoning can form in at least two different ways: as growth zoning reflecting changes in *P-T* conditions during growth, and as a reaction zoning in a pre-existing crystal by an ion-exchange reaction along the rim (Passchier & Trouw, 2005, p. 226-7, 2^{nd} ed.). Diffusion is the most important process producing mineral zoning in high-grade rocks, because diffusion is thermally activated and becomes exponentially more rapid with increasing *T*. The mineral zoning observed by Elvevold *et al.* (1994) for the quartz feldspathic gneiss is the interpreted to be the result of diffusion during retrograde net transfer reactions and diffusion driven by post-growth exchange reaction during cooling. The mineral zoning therefore supports a cooling stage following the contact metamorphic stage for the quartz-feldspathic gneiss and the Suborg-gabbro.

It can be assumed that a period of initial cooling from peak temperatures followed the contact metamorphism. Retrograde reaction products are seen in both the quartz-feldspathic xenoliths and the deformed Suborg-gabbro. The mineral parageneses indicate recrystallization and cooling to intermediate-*P* granulite facies with the formation of a penetrative foliation present in both the Suborg-gabbro and the quartz-feldspathic gneiss. Core analyses of garnet, plagioclase and orthopyroxene of the Eidvågeid paragneiss were used to derive thermobarometric estimates for the cooling stage and yielded temperatures in the range 700-750ºC and pressures in the range 4.6-7.9 kbar (Elvevold *et al.*, 1994). Figure 3.6 illustrates the proposed cooling pressure and-temperature estimates from peak temperatures given by Elvevold *et al.* (1994) for the quartz-feldspathic gneiss and the Suborg-gabbro.



The shaded box illustrates proposed cooling conditions from peak metamorphic conditions for the quartz-feldspathic gneiss and Suborg-gabbro. The cooling stage is recognized by mineral assemblages II and III, and mineral reactions 2-5.

Fig. 3.6. Temperature-pressure diagram showing the generally accepted limits of the various facies. Pressure and temperature estimates by Elvevold *et al.*(1994) yielded temperatures in the range 700-750ºC and pressures in the range 4.6-7.9 kbar for the cooling stage. The figure is from Winter (2001, p. 498,). 0.1 GPa = 1 kbar.

3.2.3 Stage III: Formation of thin ductile shear zones

The Suborg-gabbro: Both the penetrative layering in the gneissic Suborg-gabbro and the weak fabric seen in the non- to weakly deformed Suborg-gabbro is transected by younger 5-15cm wide ductile shear zones. The localized strain resulted in crystal plastic deformation and recrystallization in the shear zones. The mylonitization imparts a distinct foliation as shear and recrystallization causes elongated elements. The larger porphyroclasts in the matrix define a grain shape preferred orientation commonly developed by crystal plastic processes. Pyroxene granulite assemblages in the Suborg-gabbro are replaced by garnet granulite assemblages in the shear zones (figure 3.7a):

V: Grt + Cpx + Pl + Rt + Opx.

At higher pressures, the typical anhydrous granulite facies assemblage is Pl + Cpx + Grt ± Qtz (Bucher & Frey 1994, p. 281, 6th ed.). According to Elvevold *et al.* (1994) is quartz also present in the shear zones. The pyroxene granulite assemblage can therefore be assumed to have been replaced by the reaction:

6. Crd = Grt + Sil + Qtz

as suggested by Elvevold & Reginiussen (1996). Reaction 6 explains the presence of garnet; gabbros in the low pressure granulite facies lack garnet, whereas higher pressure granulite facies may loose orthopyroxene by reaction with plagioclase and produce garnet.

The quartz-feldspathic gneiss is, as the Suborg-gabbro, also transected by younger, 5-15 cm wide, ductile shear zones. The localized strain resulted in mylonitic zones with porphyroclasts of garnet, quartz, and feldspars where the matrix consists of recrystallized quartz, feldspars, and biotite. The mineral assemblage

VI: Grt + Qtz + Pl + Bt ± Kfs + FeTi-oxides

is recognized as recrystallized phases within the mylonitic zones present in the quartz-feldspathic gneiss.

The metamorphic event causing the formation of localized strains also resulted in overgrowths and reaction rims on minerals belonging to mineral assemblage IV. The overgrowths include small euhedral garnets along the margins of primary garnet (figure 3.7b) and symplectites of garnet and quartz on orthopyroxene (figure 3.7c) and on primary garnet (only found in the contaminated quartz-feldspathic gneiss). The mantling of orthopyroxene and garnet by a garnet-quartz symplectite can be explained by the reaction

7. Opx + Pl = Grt + Qtz.

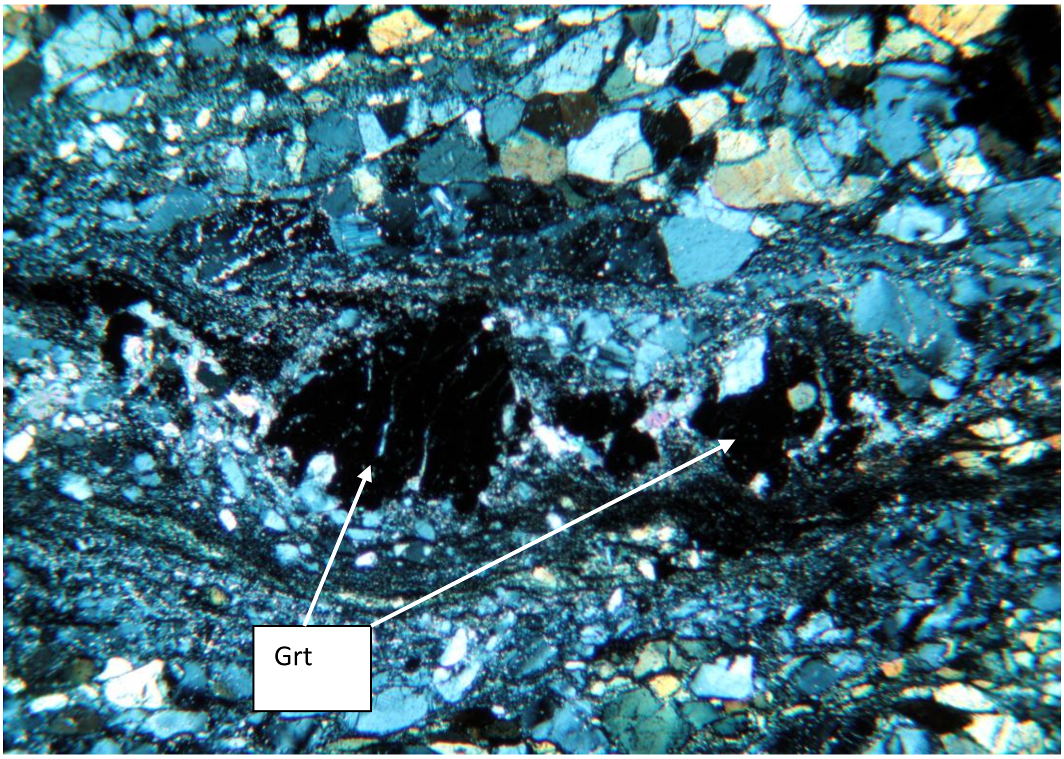


Fig. 3.7a. Crossed polars; base of photo 4 mm.

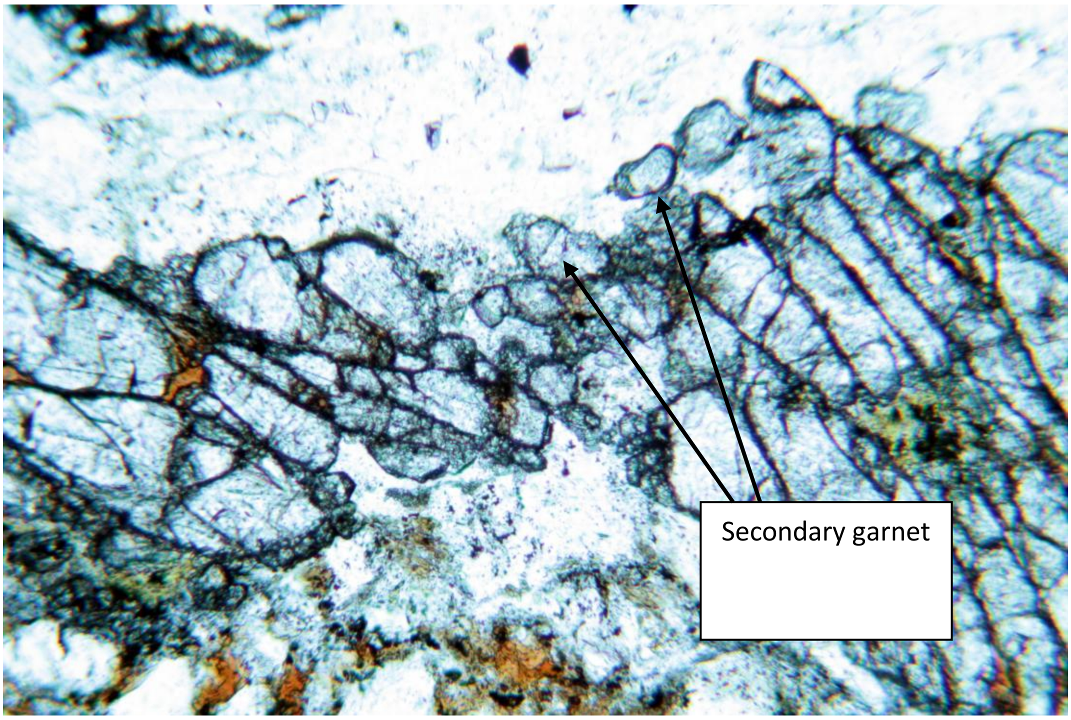


Fig. 3.7b. Base of photo 1.5 mm.

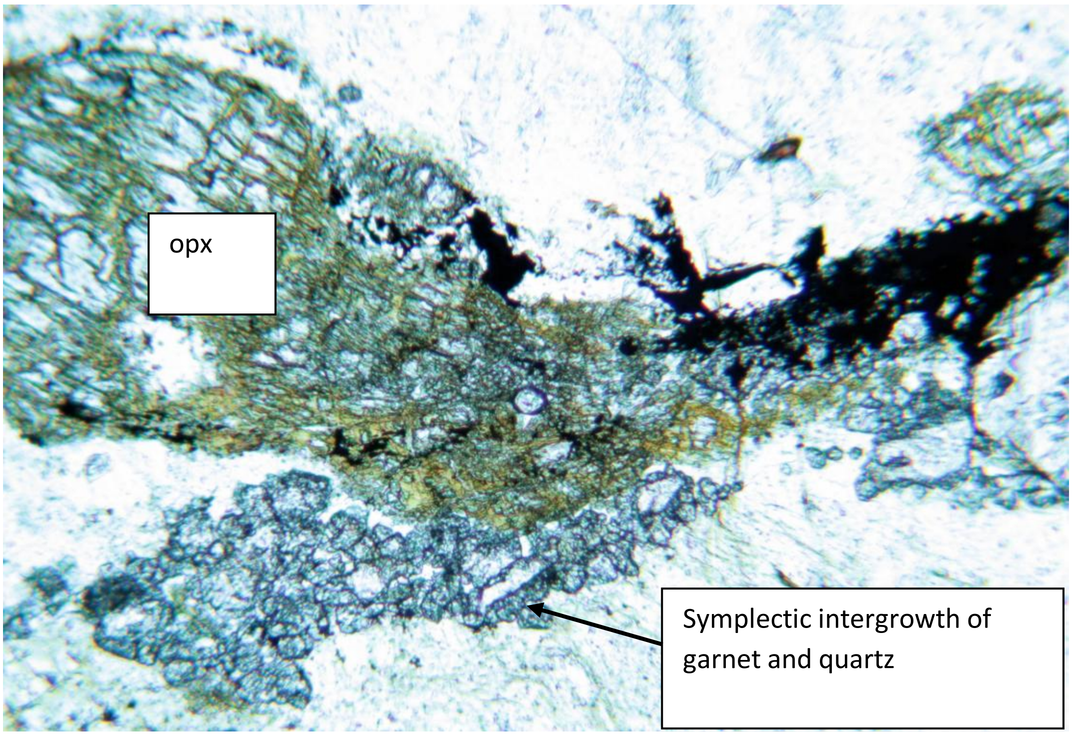
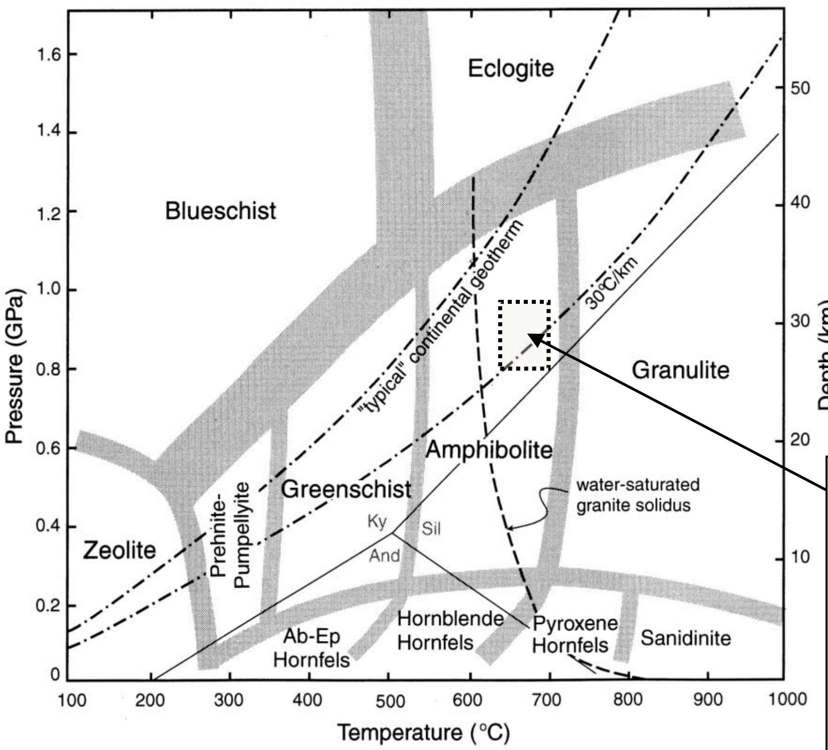


Fig. 3.7c. Base of photo.

Fig.3.7a-c. Microstructures present in the thin ductile shear zones. (a) Growth of garnet in a shear zone from the Suborg-gabbro. Fine-grained material anastomose around garnet. (b) Growth of secondary small euhedral garnets along the margins of primary garnet. (c) Symplectic overgrowth of garnet and quartz on orthopyroxene found in the contaminated quartz-feldspathic gneiss.

The retrograde cooling stage was accompanied by strong shearing and formation of a locally mylonitic foliation (which can also be referred to as localized shearing). The garnet granulite assemblage found in the thin ductile shear zones is characteristic of the higher pressure granulite facies (Winter 2001). A pressure increase of 3-4 kbar is indicated by secondary growth on primary garnets, symplectites of garnet and quartz on orthopyroxene and on primary garnet, and the fact that pyroxene granulite assemblages within the Suborg-gabbro are replaced by garnet granulite assemblages along the shear zones. The shear zone assemblage in the Eidvågeid gneiss and metagabbro allow the application of various geothermobarometric methods; temperature estimates are in the range 650-700°C and calculated pressure fall in the range 8-10kbar (Elvevold *et al.*, 1994). No evidence of a temperature increase related to the strong shearing exists according to Elvevold *et al.* (1994).

Figure 3.8 illustrates the proposed cooling pressure-and-temperature estimates from peak temperatures given by Elvevold *et a.l* (1994) for the quartz-feldspathic gneiss and the Suborg-gabbro.



The shaded box illustrates pressure and temperature conditions the rocks experienced during a compression event causing the formation of localized shearing. According to Elvevold *et al.* (1994), the rocks experienced a pressure increase of 3-4 kbar during this event. Stage III is recognized by mineral assemblages 5 & 6, and mineral reactions 6 & 7.

Fig. 3.8. Temperature-pressure diagram showing the generally accepted limits of the various facies. Pressure and temperature estimates by Elvevold *et al.*(1994) yielded temperatures in the range 650-700ºC and pressures in the range 8-10 during the metamorphic stage causing the formation of the thin ductile shear zones. The figure is from Winter (2001, p. 498). 0.1 GPa = 1 kbar.

4. Deformation Microstructures

4.1 Introduction

Rocks with a penetrative fabric are known as tectonites (Davis & Reynolds 1996, p. 476, 2nd ed.). Tectonites are defined as metamorphic deformed rocks whose fabric can reflect the rocks history. A fabric “includes all those components that make up a rock. It covers concepts such as *texture, structure* and crystallographic preferred orientation” (Hobbs *et al.*, 1976). At the microscopic level, the fabric consists of the grain shapes and arrangement (the microstructure) and the spatial orientation of the minerals (the preferred orientation) (Vernon 2004, p. 7). The development of a fabric is very important for the interpretation of the metamorphic and deformation history of the rock. Both the Suborg-gabbro and the quartz-feldspathic gneiss can be classified as tectonites; both rock units have a fabric displaying coordinated geometric features indicating flow in the solid state. Most tectonites, and thus most foliations and lineations, form in environments of elevated temperatures and confining pressure (Davis & Reynolds 1996, p. 477, 2nd ed.).

The primary goal for this chapter is to present data for the analysis of the deformation history of the Seiland Igneous Province. The microfabric observed in thin sections from the Suborg- gabbro and the quartz-feldspathic gneiss will be studied and the fabric transition between undeformed and deformed Suborg-gabbro and between different rock types (Suborg-gabbro and quartz-feldspathic gneiss) will be of great importance for better understanding the deformation and metamorphic history of the Seiland Igneous Province. The microstructural descriptions given here include foliation and lineation development, recovery and recrystallization processes, metamorphic reactions, deformation partitioning and porphyroclasts relationships (with regard to the relative timing of deformation and metamorphic reactions).

Only ductile and semi-ductile structures in the rock units are considered. Younger brittle deformation in the rocks is not described here.

Sections 4.2 will a give a general overview of the structural elements observed in the field. Further, deformation microstructures are described for the two rock types (Suborg-gabbro and the quartz-feldspathic gneiss) in section 4.3. Deformation fabric observed in the thin ductile shear zones present in the Suborg-gabbro and the quartz-feldspathic gneiss is described in section 4.4. Section 4.5 will provide a kinematic analysis of shear senses observed in the different samples.

4.2 General Overview of Structures and Macrostructures

The most characteristic structural element in the area is a steeply dipping (typically > 65º) gneissic foliation present in the quartz-feldspathic gneiss and large parts of the Suborg-gabbro. The foliation has a relatively constant orientation striking N-S. The fabric seen in the Suborg-gabbro is suggested to be of both magmatic and tectonic origin. Elvevold *et al.* (1994) propose that a syn-intrusive deformation of the pluton could have resulted in the parallelism of a magmatic foliation and a secondary foliation (suggested being a solid-state fabric). The fabric in the quartz-feldspathic gneiss is parallel to the foliation in the Suborg-gabbro. The penetrative foliation is truncated by steeply to low angle dipping ductile shear zones ranging in width from 5-15 cm wide.

The deformation in the area is heterogeneous, as indicated by strongly foliated, occasionally mylonitic fabric alternating with lesser deformed parts seen in the same outcrop. The Suborg-gabbro on the summit of Høgfjellet shows a less penetrative foliation compared to the Suborg-gabbro present below the summit of Høgfjellet and compared to the quartz-feldspathic rock. The variable degree of deformation is also recorded by microstructures observed in thin section from the two rock units; fine-grained bands of recrystallized material anastomose around less deformed parts of the rock. Inhomogeneous deformation patterns can be due to the mechanical heterogeneity of rocks (Williams, 1990). Some minerals are able to change their shapes in response to the local stress field more readily than others, and this can lead to localization of deformation into high-stress zones (Vernon, 2004, p. 349). Zones rich in weak minerals and/or fine-grained recrystallized aggregates may develop due to heterogeneous deformation.

Both rock units and the shear zones have fabrics indicating that deformation and metamorphic reactions have taken place. Metamorphic reactions typically accompany and affect deformation. They "(1) provide new strain free grains and so assist deformation, (2) may release or consume fluid, which affects mineral deformation, and (3) may produce stronger minerals ("reaction strengthening") or weaker minerals ("reaction weakening") (Vernon, 2004, p.353). Reaction weakening can operate by forming weaker minerals from strong minerals, grain size reduction and/or presence of water released in prograde dehydration reactions. Dehydration reactions generally produce stronger minerals. Examples of metamorphic reactions are evident in the rocks and will be described in the following sections.

Kinematic indicators present in both rock types and the ductile shear zones suggest simple-shear deformation has taken place in the area (more on this in section 4.5).

4.3 Deformation Microfabrics

4.3.1 Suborg-gabbro

Paterson *et al. (*1989) state that a distinction between foliations formed by magmatic and solid-state processes, as well as the distinction between foliations formed during different mechanisms of emplacement, are vital to achieve an understanding of both timing relationships and behavior of plutons during and after emplacement. Hence studies aimed at understanding the nature and timing of foliations in plutons should, according to Paterson *et al. (*1989), include a thorough examination of microstructures in the pluton and an examination of patterns of foliations in the pluton and surrounding wall rocks. Studies of microstructures observed in the pluton will be described in this section. Chapter 5 will give an interpretation to the parallel foliation observed in the external pluton contact.

The Suborg-gabbro is seen as an elongated pluton stretching N-S along the Suborg valley which is interpreted to have intruded the Eidvågeid paragneiss 570-560 Ma ago (Roberts 2008). The deformation in the Suborg-gabbro is, as mentioned, very heterogeneous as indicated by field observations and deformation microstructures present in thin sections. The Suborg-gabbro has a modal rhythmic layering defined by alternating felsic and mafic layers that constitutes a foliation. A primary foliation is evident in the plutonic rock by the preferred orientation of primary igneous grains and grain aggregates (figure 4.1); Inequant feldspar grains, primary orthopyroxene, clinopyroxene and olivine all show a shape preferred orientation occasionally recognized as a L-fabric in the field. The primary mineralogy in the non- to weakly deformed parts of the Suborg-gabbro show no- to little signs of recrystallization and only few grains show undulatory extinction. The igneous minerals show a shape preferred orientation, only locally crystal plastic deformation of grains and non- to weak signs of recrystallization indicate that the rock has a primary foliation formed by magmatic flow. The primary foliation can be classified as a continuous foliation.

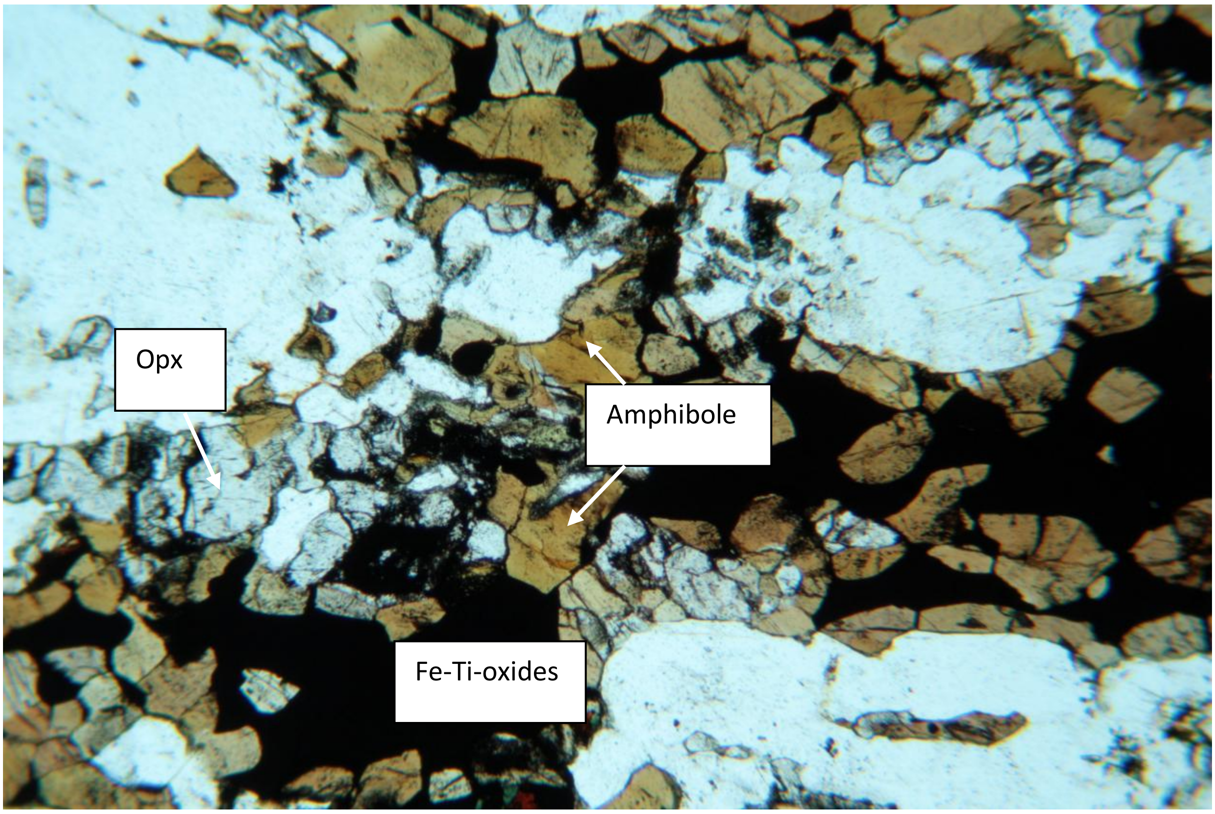


Fig. 4.1. Grain aggregates consisting of amphibole, clinopyroxene and FeTi-oxides show a shape preferred orientation in the non- to weakly deformed gabbro. Base of photo 4mm.

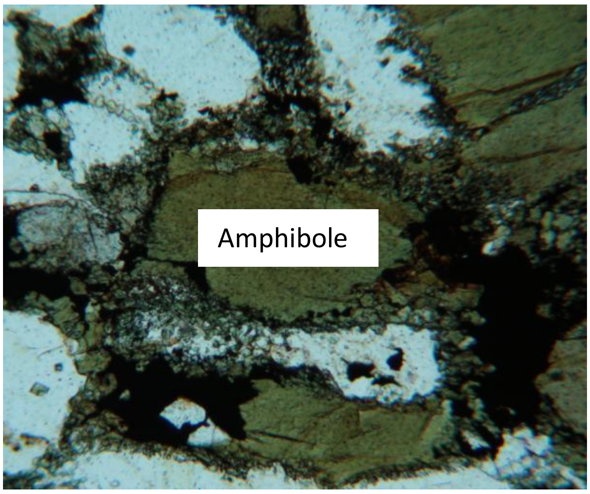
Many plutonic rocks show evidence of a super position of solid-state deformation on a magmatic foliation. This is also the case for the deformed Suborg-gabbro where a secondary mineral assemblage show microscopic evidence of crystal plastic deformation, recovery processes, presence of symplectites, metamorphism and recrystallization to finer-grained aggregates. It has been suggested that magmatic flow may pass continuously into solid-state flow, but this requires that deformation took place at temperatures near the solidus of the rock. The primary foliation for the Suborg-gabbro is overprinted by a secondary continuous foliation parallel to the primary foliation. The secondary foliation is generated as a result of deformation and metamorphism by recrystallization, crystal plastic deformation, orientation of new grains and static recrystallization and mimetic growth. The listed features are all important mechanisms contributing to development of a secondary fabric in rocks (Paterson *et al.*, 1989). Examples observed in the Suborg-gabbro are the following:

- *Neo/Recrystallization:* The igneous mineral assemblage re/neoreystallized to metamorphic orthopyroxene, clinopyroxene, plagioclase, hornblende, biotite and Fe-Ti oxides. The strongly deformed parts of the Suborg-gabbro have relicts of large grains of amphibole, orthopyroxene and feldspars enclosed by relatively small grains. This is referred to as a "core-and-mantle" structure indicating dynamic recrystallization (figure 4.2a).

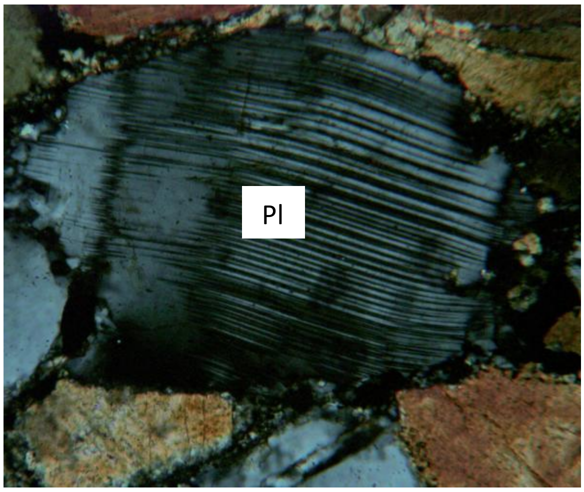
- *Crystal plastic deformation:* Amphibole, plagioclase and large relic grains of pyroxene show undulatory extinction in the more deformed Suborg-gabbro indicating dynamic recrystallization. Many of the grains obtained have an elongated shape resulting in shape preferred orientation of the grains. Undulatory extinction is only seen locally in large relics of pyroxenes and olivine in the less deformed Suborg-gabbro. Deformation twinning in plagioclase is found throughout the rock (figure 4.2b).

- *Orientation of new grains:* The recrystallized metamorphic mineral assemblage is elongated in the same direction as the minerals belonging to the original assemblage. Recrystallization to finer-grained aggregates of plagioclase is seen as elongated aggregates oriented in the same direction as the original foliation (figure 4.2c). The combination of grain size reduction and elongation of these finer-grained aggregates lead to the formation of a new foliation (Paterson *et al.*, 1989).

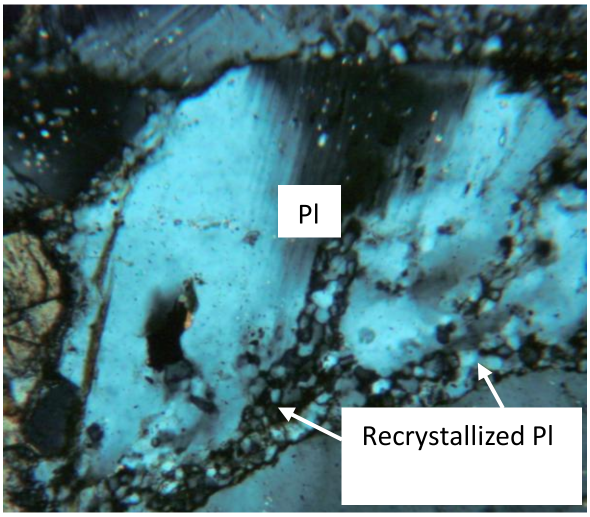
- *Static recrystallization and mimetic growth:* Foliations can be modified in several ways after deformation ceased (Passchier & Trouw, 2005, p. 86, 2nd ed.). Elongated hornblende (that seem to have grown within a fabric with strong preferred orientation, and following this orientation) and overprint of amphiboles on pyroxenes both help to define a secondary fabric that is parallel to the primary foliation. In some rocks, elongate crystals that help define a secondary foliation may actually have grown in the direction of the foliation after the deformation phase responsible for the primary foliation ceased. Elongated amphibole replacing existing minerals and inheriting their shape indicate growth of amphiboles after deformation ceased (figure 4.2d).



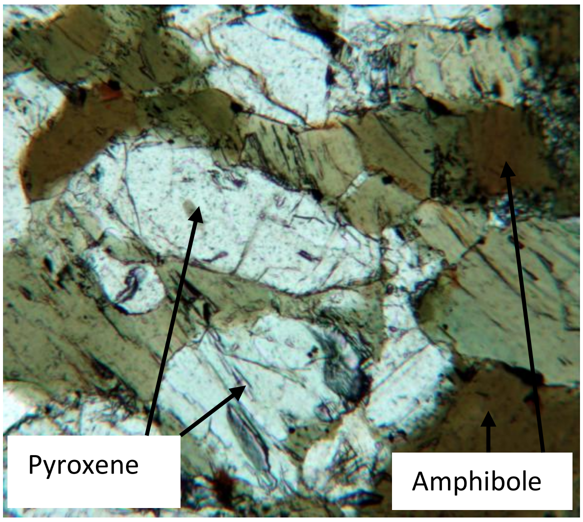
A. Base of photo 1 mm.



B. Base of photo 0.5mm.



C. Base of photo 1 mm.



D. Base of photo 1 mm.

Fig. 4.2. Deformation microstructures observed in the Suborg-gabbro exhibiting a penetrative foliation (a) Core-and-mantle structure for amphibole. Some of the recrystallized amphiboles show different color pleochorism indicating a chemical change taking place during recrystallization. (b) Deformation twinning in plagioclase. (c) Recrystallized aggregates of plagioclase surrounding a larger grain of plagioclase. (d) Growth of amphibole on pyroxene following the orientation of pyroxene.

The secondary foliation is, as mentioned, generated as a result of deformation and metamorphism. The distribution and properties of the minerals together with microstructures observed for the mineral assemblage present in the Suborg-gabbro support that the rock has been exposed to deformation and metamorphism:

- *Olivine:* A reaction rim of orthopyroxene ± hornblende is seen enclosing individual relic olivine grains in the non- to weakly deformed Suborg-gabbro. Olivine in metamorphosed gabbros may, as stated by Shelley (1975, p. 100) be surrounded by reaction rims usually composed of orthopyroxene and amphibole. Iddingsite, a mixture alteration product of olivine, is also found (figure 2.6). Olivine is also present as recrystallized grains with undulatory extinction and subgrain boundaries with overprint of pyroxenes and amphiboles (figure 4.3a).

- *Orthopyroxene:* Recrystallized finer-grained aggregates of orthopyroxene form "foam-structure" indicative of recovery after deformation (figure 4.3b). Larger individual grains show fine exsolution lamellae in the (100) plane of the host grain. These orthopyroxenes are referred to as orthopyroxenes of the Bushveld type and is a result of induced stress during cooling from high temperatures. (Deer *et al.,* 1992, p. 161, 2nd ed.). Smaller orthopyroxenes grains are seen altered to a pale green/blue amphibole, referred to as uralite (figure 2.14) (Deer *et al.*, 1992, p. 161, 2nd ed.), whilst larger orthopyroxene grains are overprinted by dark green-green amphiboles. These alteration products indicate a change in the temperature- and/or pressure conditions. A high amount of symplecitites of spinel and orthopyroxene are found in the non- to weakly deformed Suborg-gabbro. This is commonly found for larger grains with an inner zone of orthopyroxene surrounded by an outer rim composed of a symplectic intergrowth of orthopyroxene and spinel where spinel is present as distinct elongated droplets (figure 4.3c). Symplecitites are commonly formed in solid-state metamorphic reactions (Vernon, 2004, p. 234).

- *Clinopyroxene:* In the strongly foliated Suborg-gabbro clinopyroxene is seen as larger individual relict grains with overprint of amphiboles (figure 4.3d). Partial pseudomorphs of clinopyroxene are seen in the deformed parts of the Suborg-gabbro (figure 2.10). Locally the larger individual grains have exsolution lamellae indicating high temperature conditions. In the non-to weakly deformed Suborg-gabbro clinopyroxene is present in grain aggregates of olivine + orthopyroxene forming triple junctions. Triple junctions indicate recovery at the solid state.

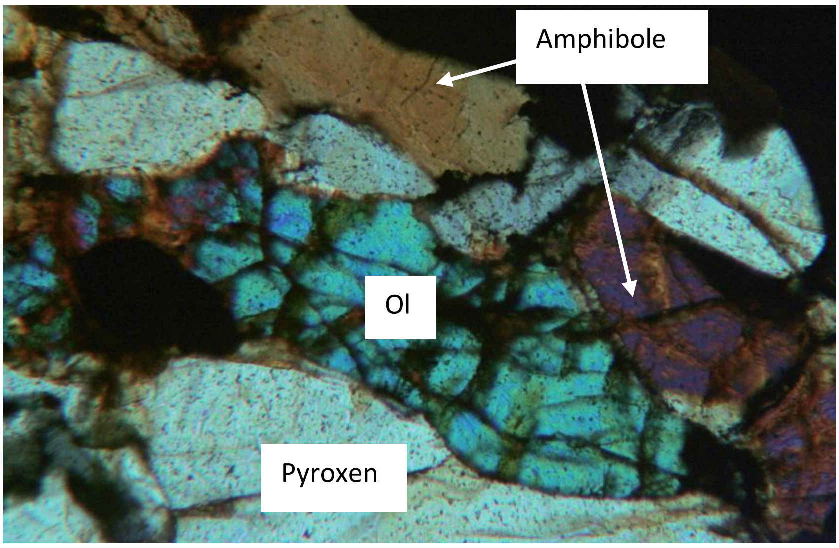
- *Amphiboles:* are mostly seen as overprint on pyroxenes (figure 4.3d) in the non- to weakly deformed Suborg-gabbro, and as recrystallized grain aggregates forming triple junctions. In the strongly foliated Suborg-gabbro amphiboles are present as larger individual grains indicating replacement of the original mineral assemblage. The hornblende is secondary in origin and suggested to derive from primary pyroxene. Two different types of amphibole are present in the Suborg-gabbro; uralite and hornblende. The alteration of pyroxenes to fibrous amphiboles is described as uralitization (Deer *et al.*, 1992, p. 257, 2nd ed.) and is, along with the overprint of pyroxenes by amphiboles, a result of change in metamorphic conditions. The metamorphic amphiboles have polygonal grain boundaries resulting in a "foam-structure" indicating that the temperature has been high enough for the movement of grain boundaries to reduce their internal energy to a minimum (figure 4.3e) (Vernon, 1994, p. 175-181).

- *Biotite:* Biotite occurs in a wide range of igneous rocks, but the most common occurrences are as metamorphic products (Deer *et al.*, 1992, p. 305, 2nd ed.). In the strongly foliated Suborg-gabbro and the magmatic lens, the appearance of biotite indicates a metamorphic origin. Biotite forms veins the magmatic lens, and is present as an alteration product/overprint on pyroxenes and hornblende in the strongly foliated Suborg-gabbro (figure 4.3f).

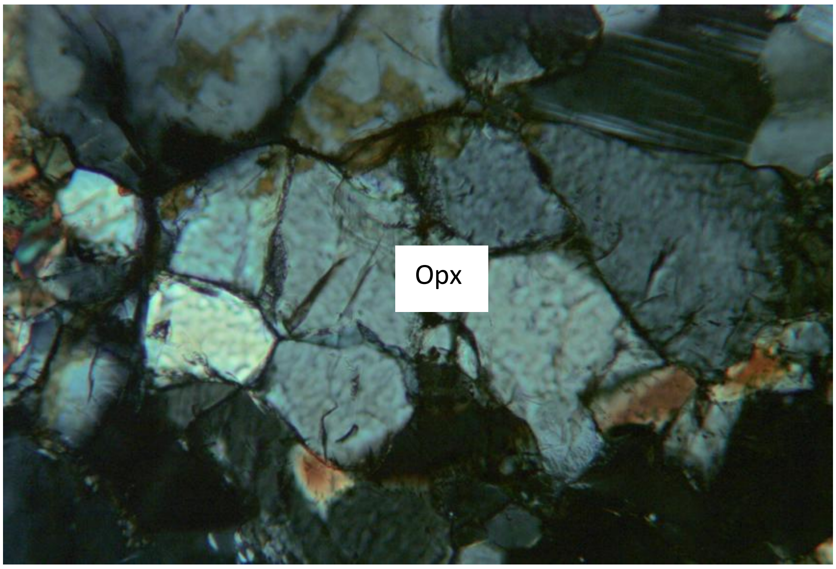
- *Ilmenite:* is a common accessory mineral in a wide range of igneous and metamorphic rocks (Shelley, 1975, p. 208). Ilmenite is found throughout the Suborg-gabbro as inclusions in mafic grains and in-between triple points of amphibole. Both occurrences indicate a metamorphic origin of ilmenite.

- *Spinel (hercynite):* is found as an accessional grain only in the non- to weakly deformed Suborg-gabbro in conjunction with aggregates of plagioclase and orthopyroxene, and aggregates of amphibole and ilmenite. Spinel is a common high-T mineral in metamorphic rocks (Deer *et al.,* 1992, p. 566, 2nd ed.). Spinel is also present in symplectic intergrowths with orthopyroxene.

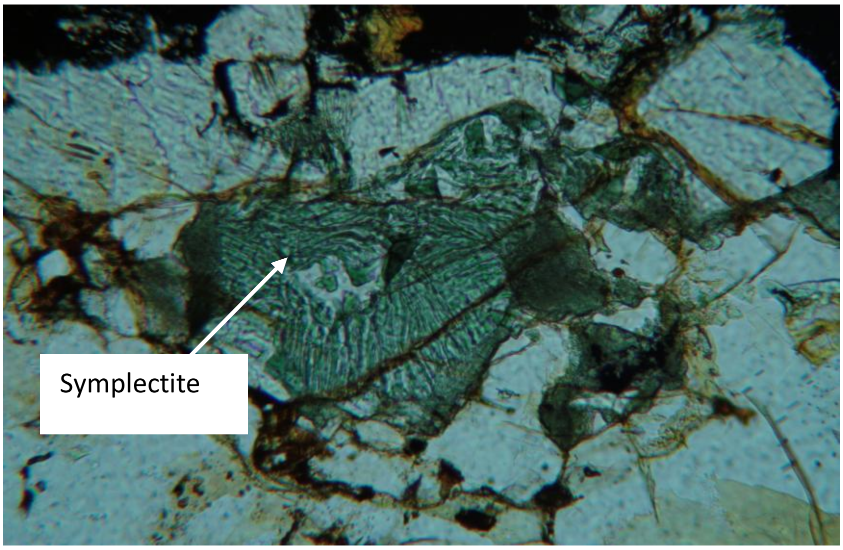
- *Plagioclase:* appears as a groundmass constituent, and is present in the non- to weakly deformed Suborg-gabbro in subophitic textures as inequant euhedral to subhedral grains. Plagioclase grains throughout the unit show deformation twinning indicating crystal plastic deformation. Plagioclase-grains in the strongly foliated Suborg-gabbro show core-and-mantle structure (due to BLG recrystallization) (figure 4.3g), and locally subgrain rotation recrystallization (SGR). The plagioclase in the lesser foliated Suborg-gabbro has, on average, a larger grain size, and recrystallized aggregates of plagioclase have polygonal grain boundaries exhibiting foam-structure (indicating low-energy shapes of the grains). The presence of BLG and SGR indicate that plagioclase has been deformed first at high temperatures with subsequent cooling reactions (Passchier & Trouw, 2004, p. 59, 2nd ed.).



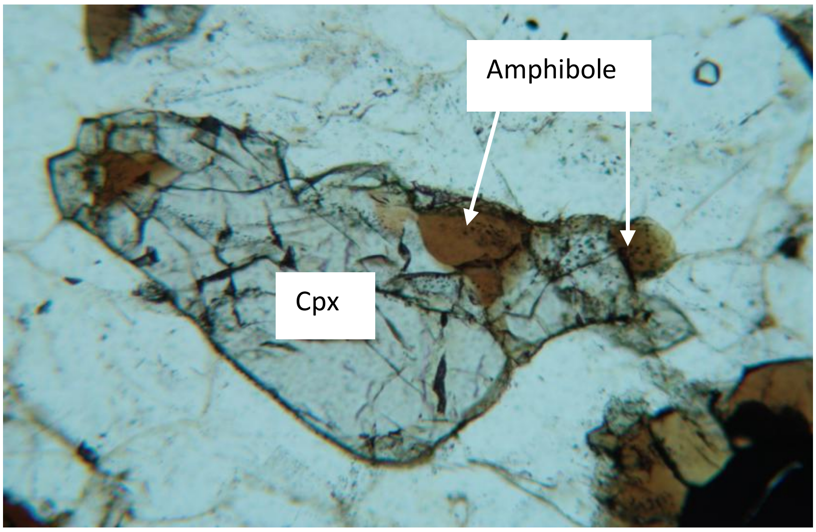
A. Crossed polars; base of photo 0.6 mm.



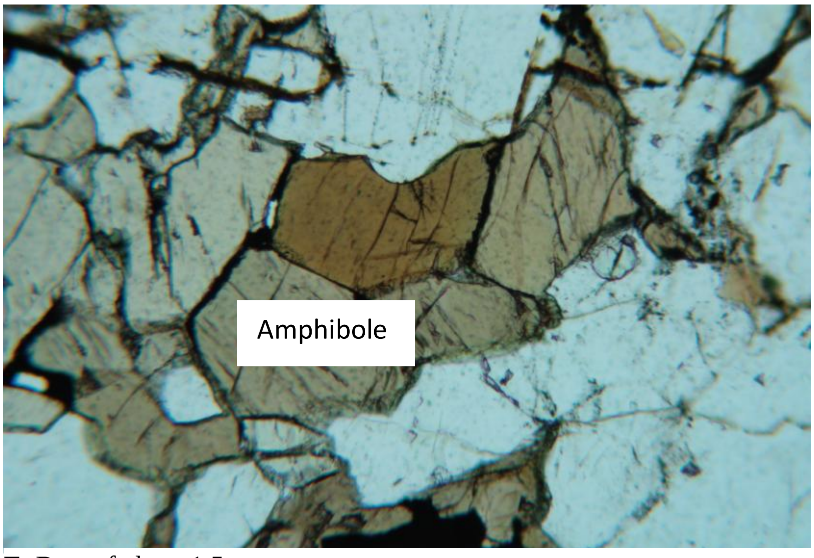
B. Crossed polars; base of photo 0.6 mn.



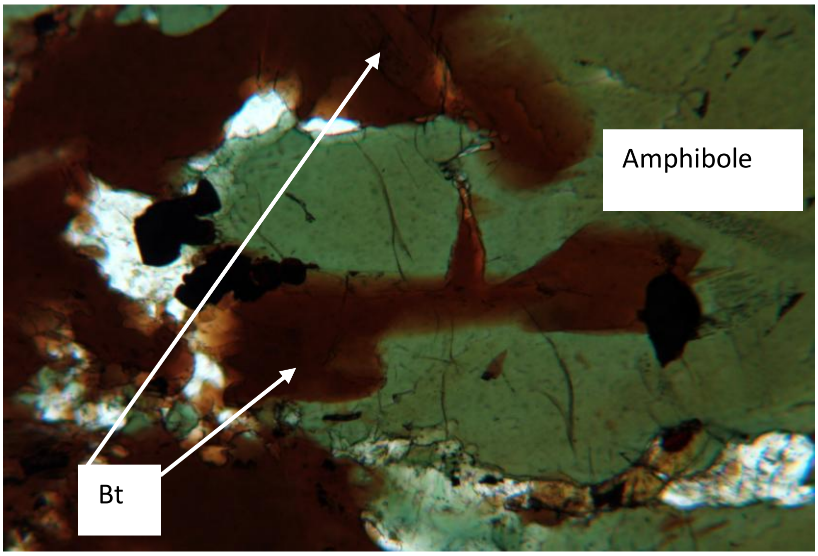
C. Base of photo 0.6 mm.



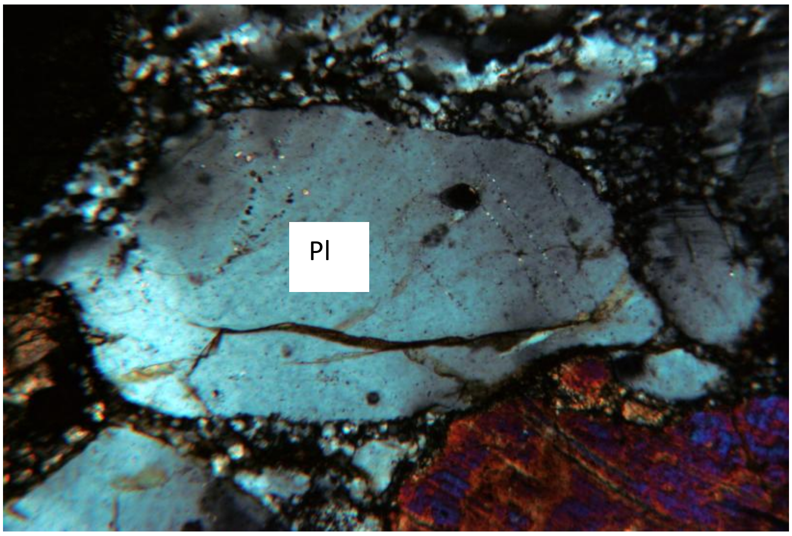
D. Base of photo 1.5 mm.



E. Base of photo 1.5 mm.



F. Base of photo 1.5 mm.



G. Crossed polars; base of photo 1.5 mm.

Fig. 4.3. Microstructures present in the Suborg-gabbro: (a) Olivine grain with overprint of pyroxenes and amphiboles. (b) Grain aggregate consisting of orthopyroxene exhibiting triple junctions. (c) Symplectic intergrowth of orthopyroxene and spinel. Spinel is seen as elongated droplets. (d) Overprint of amphiboles on clinopyroxene grain. (e) Amphibole grains in a “foam-structure” indicating recovery. (f) Overprint of biotite on amphibole. (g) Recrystallized plagioclase grain in a core-and-mantle structure.

The primary foliation is defined by an igneous mineral assemblage whose microfabric reflects magmatic flow. A secondary foliation (parallel to the primary foliation) overprints the magmatic flow with a metamorphic mineral assemblage. If the intrusion temperature of the gabbro magma was in the range of 1000-1100ºC (Elvevold *et al.*,1994) it can be assumed that the rock crystallized through transitional stages between the liquid and the solid state resulting in magmatic flow. The primary mineral assemblage is recognized as:

Pl + Opx + Cpx + Ol.

Deformation microstructures support the formation of a secondary foliation; The shape of individual grains and grain aggregates seen in the units, from a primary fabric (euhedral, subhedral and inequant grains sitting in a inequigranular grain size distribution with polygonal grain boundaries) to a secondary fabric (subhedral to anhedral grains in an equigranular grain size distribution with core- and mantle structure and interlobate grain boundaries), indicate that deformation has taken place by dislocation creep. The fabric, processes and mechanisms observed from the unit with a magmatic fabric to the unit with a secondary fabric suggest that deformation and metamorphism took place in response to cooling from high temperatures. It can therefore be assumed that a period of initial cooling from peak temperatures followed the emplacement of the gabbro magma. The mineral parageneses

Opx + Cpx + Pl + Hbl + Bt + FeTi-oxides

indicate recrystallization and cooling to intermediate-*P* granulite facies with the formation of a penetrative foliation locally present in the Suborg-gabbro.

The later formation of thin ductile shear zones in the Suborg-gabbro does not seem to have affected the country rock. The formation of locally strong shearing will be discussed in section 4.4.

4.3.2 Quartz-feldspathic gneiss

The quartz-feldspathic gneiss represents a high-grade sheared paragneiss. The rock does not show any indications of a primary foliation, but it has a penetrative secondary foliation defined by different compositional bimodal layers. The penetrative foliation present in the quartz-feldspathic gneiss is defined by a metamorphic mineral assemblage of elongated grains of plagioclase, K-feldspar, quartz and poikilitic clasts of garnet together with elongated grain aggregates of biotite, quartz, feldspar, cordierite and garnet. The recrystallized fine-grained and elongated aggregates of quartz (ribbons), feldspar, cordierite and biotite anastomose around deformed and elongated porphyroclasts of garnet (figure 4.4) and orthopyroxene (only in contaminated quartz-feldspathic gneiss). The secondary foliation can be classified as a spaced foliation with an anastomosing spatial relationship between the different cleavage domains. The spaced foliation shows compositional layering which most likely represents a transposed bedding and/or new compositional layering of tectonic origin in strongly deformed rocks (Vernon, 2004, p. 400).

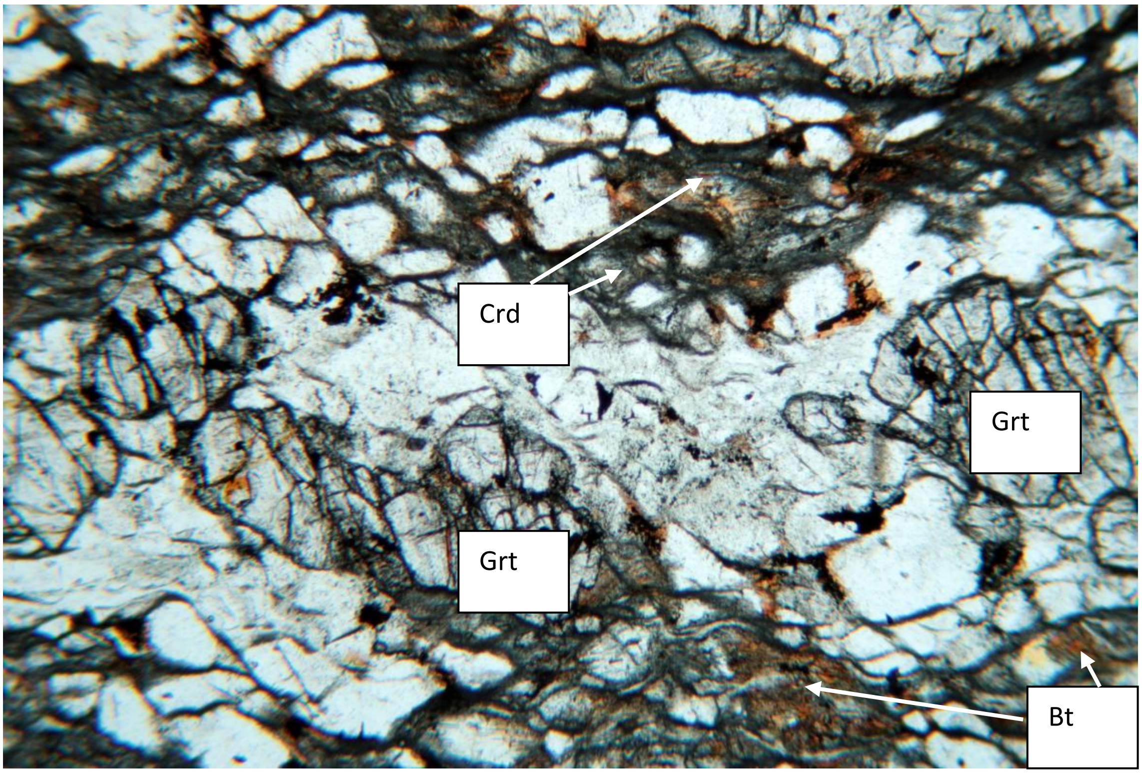


Fig. 4.4. Different domains consisting of a metamorphic mineral assemblage define a foliation in the quartz-feldspathic gneiss. Base of photo 4 mm.

The secondary foliation is a result of deformation and metamorphism and is defined by microstructures observed in the rock:

- *Recrystallization:* The rock shows evidence for partially dynamic recrystallization with a partially bimodal grain size distribution with aggregates of small new grains of relatively same size between large old grains with undulatory extinction. Features of different recrystallization mechanisms can be found together in the rock, from bulging (BLG) to subgrain rotation (SGR) to grain boundary migration (GBM): Porphyroclasts of orthopyroxene and garnet is locally seen as core- and-mantle structures (figure 4.5 a), ribbons of quartz show lobate and irregular grain boundaries (figure 4.5b) and larger feldspar grains show sweeping undulatory extinction and formation of subgrain boundaries,

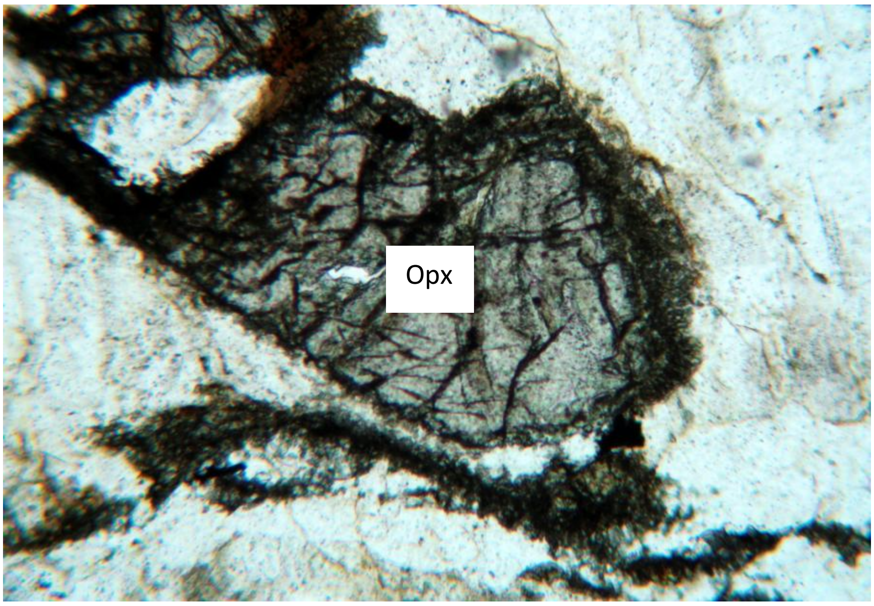
- *Crystal plastic deformation:* Many of the minerals recognized in the quartz-feldspathic gneiss exhibit a shape preferred orientation (SPO). The SPO could have formed due to crystal plastic deformation which is seen as undulatory extinction in quartz and feldspars and as stress-induced solution transfer resulting in "beards" (aligned intergrowths of dark material) adjacent to cordierite grains (figure 4.5c) and orthopyroxene grains. The formation of concentration of fine-grained material at high-strain sites adjacent to larger garnet grains could be due to solution and removal of quartz and feldspars (Vernon, 2004, p. 404).

- *Orientation of new grains:* Aggregates of parallel and sub-parallel fibrolitic sillimanite projects into cordierite grains. The secondary foliation is partly defined by fibrolitic sillimanite (figure 4.5d). Microstructural criteria indicate that the fibrous sillimanite postdates previous phases and therefore support sillimanite as a part of the new metamorphic mineral assemblage in the quartz-feldspathic gneiss. According to Vernon & Flood (1977) the following criteria can support fibrous sillimanite as a part of a new mineral assemblage:

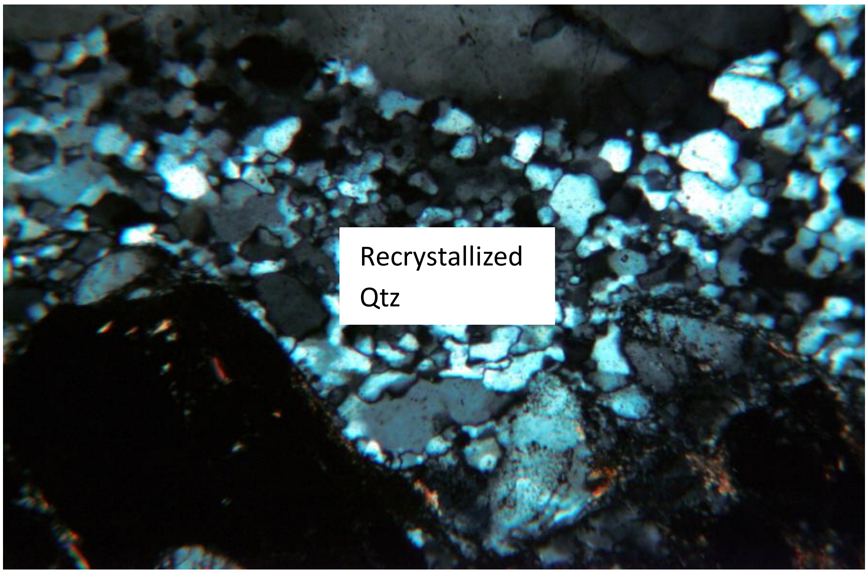
  - The fibrolitic sillimanite is concentrated along the grain boundaries of cordierite.
  - Grain boundaries of other minerals are not deflected by fibrolitic sillimanite.
  - Twin boundaries in cordierite are not deflected where they intersect with fibrolitic sillimanite indicating that the growth of the twin predates the sillimanite.
  - Polygonal grain boundaries are preserved despite growth of sillimanite.

- *Static recrystallization and mimetic growth:* Elongated crystals that help define the secondary foliation may have grown in the direction of the foliation after deformation ceased. The elongate grains may have replaced existing minerals inheriting their shape. The monomineralic quartz ribbons present in the quartz-feldspathic gneiss may have developed in this way.

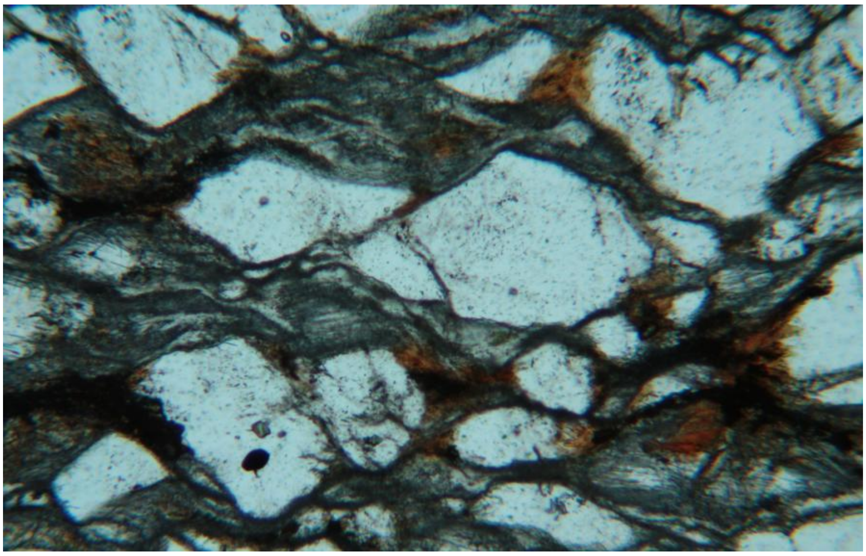
- *Development of spaced (compositional) foliation:* A strong compositional layering is observed in the quartz-feldspathic gneiss and is suggested to derive from the deformation and metamorphism of the rock. Elvevold *et al*. (1994) suggests that the quartz-feldspathic gneiss has been partial melted. The compositional layering could therefore have been produced as a result of anatexis during high-grade metamorphism resulting in leucosomes and neosomes (Vernon, 2004, p.402).



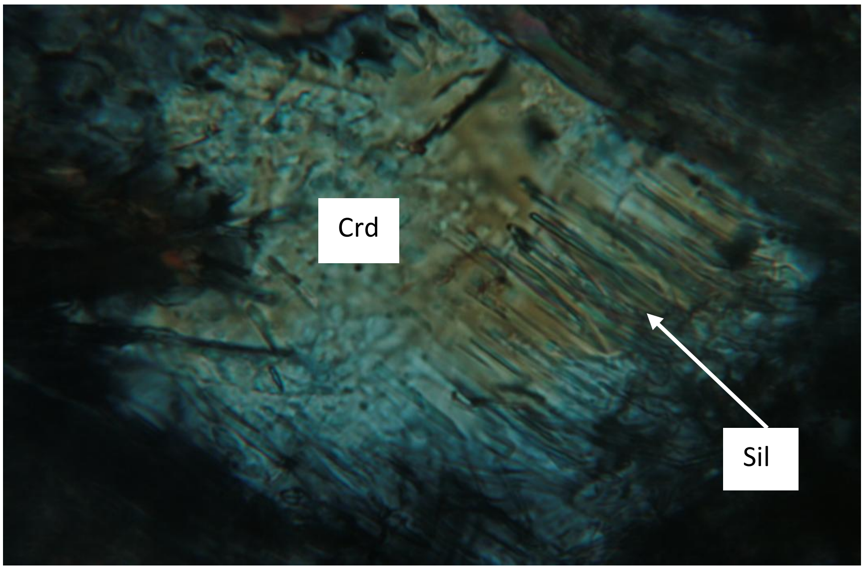
A. Base of photo 1.5 mm.



B. Crossed polars; base of photo 1.5 mm.



C. Base of photo 1.5 mm.



D. Crossed polars; base of photo 1.5 mm.

Fig. 4.5. (a) Recrystallized orthopyroxene in a core-and-mantle structure indicating dynamic recrystallization. (b) Recrystallized quartz seen as elongated ribbons with interlobate to amoeboid grain boundaries. (c) Beards of insoluble dark fine-grained material anastomosing around larger clasts. (d) Overgrowth of fibrolitic sillimanite exhibiting a shape preferred orientation on cordierite.

Properties and microstructures observed in the rock support that the rock has been exposed to both deformation and metamorphism. The following deformation and metamorphic indicators are observed for the different minerals:

- *Quartz:* appear as recrystallized aggregates of fine-grained quartz with irregular boundaries and as elongated isolated grains. The mineral show strong sweeping undulatory extinction and locally chessboard extinction (figure 4.6a). The rods of quartz can be explained as a result of deformation. High-grade rocks commonly contain layers or rods of quartz generally attributed to strong deformation, coupled with recrystallization, of primary quartz grains (Vernon, 2004, p. 401). The elongated grains can also be explained as a result of deformation at high metamorphic levels. Hippert *et al.* (2001) states that isolated quartz grains become elongated by crystal plastic flow that could later coalesce to form polycrystalline layers (ribbons).

- *Orthopyroxene:* is present as elongated recrystallized porphyroclasts. No exsolution lamella could be seen for the orthopyroxene grains. The lack of exsolution bodies in recrystallization products indicates that the deformation and metamorphism of the mineral occurred below the solvus temperatures of the mineral (Goode, 1978). This supports high temperatures and partial melting of the quartz-feldspathic gneiss during peak deformation and metamorphism. Alteration of orthopyroxene to biotite along grain boundaries and within cracks suggests hydration of orthopyroxene related to cooling. Symplectites of garnet and quartz is seen as overgrowth on orthopyroxene (figure 4.6b). Symplectites commonly grow in response to solid-state metamorphic reaction (Vernon, 2004, p. 243). Elvevold *et al.* (1994) propose that garnet-quartz symplectic intergrowths grew in response to an increase in pressure. The mineral does also show evidence for crystal plastic deformation seen as undulatory extinction.

- *K-feldspar:* A high abundance of feldspar-augen with recrystallized rims resulting in core-and-mantle structures is present in the rock. Perthite exsolution is observed in a few feldspar grains (figure 4.6c). Perthite exsolution is common in slowly cooled high-grade metamorphic rocks (Deer *et al.*,1992, p. 430, 2nd ed.). Alteration of feldspar to white mica is seen as very fine-grained inclusions (figure 4.6d). Feldspars are prone to extensive alteration and a typical alteration product in a reaction involving water is sericite (Shelley, 1975, p. 191). K-feldspar grains show sweeping undulatory extinction indicating intracrystalline deformation. Some of the K-feldspar porphyroclasts have conjugate shear bands that can be categorized as a C'type shear band cleavage (more on this in section 4.5).

- *Plagioclase:* large porphyroclasts of plagioclase show deformation twinning and sweeping undulatory extinction indicating intracrystalline deformation (figure 4.6e). The rim zones of porphyroclasts are recrystallized and show core-and-mantle structures. The porphyroclasts have inclusion of white mica suggesting a reaction involving water took place. The plagioclase grains present in the matrix form shear band cleavage (more on this in section 4.5) and thus show evidence of stress-induced solution transfer.

- *Garnet:* The garnet grains could be classified as porphyroblasts (formed due to metamorphic growth), but since the garnets have been deformed and metamorphosed at a later stage they are here classified as porphyroclasts. The mineral is present as elongated recrystallized grains and as symplectic intergrowth together with quartz. Garnet shows indicators for brittle deformation (high amount of internal cracking) and contains high amounts of inclusions indicating that an early mineral assemblage has been metamorphosed (figure 4.6f). The inclusions can be regarded as passive inclusions without being significantly displaced by the growing porphyroblasts

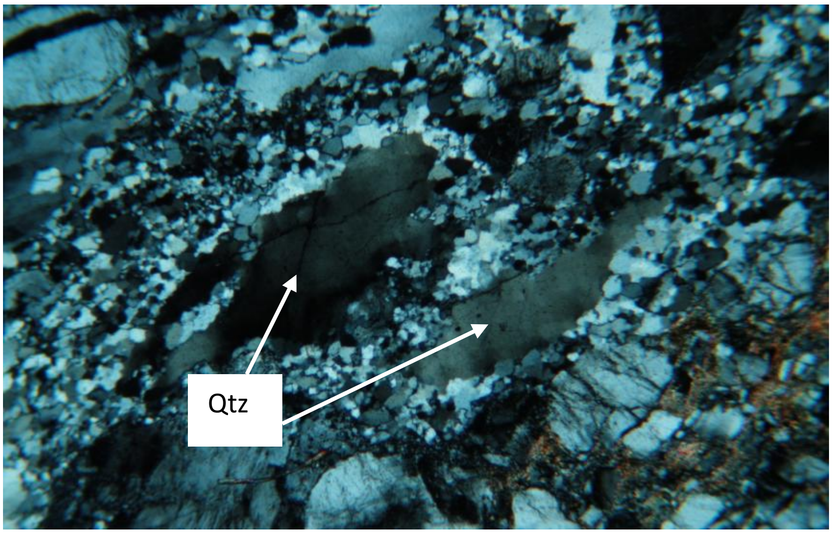
(Passchier & Trouw, 2005, p. 191, 2nd ed.). Garnet is found both as a part of an early mineral assemblage and as a metamorphic mineral. Secondary growth of euhedral garnets along the margins of porphyroclasts of garnet and garnet-quartz symplectite overgrowth indicate metamorphic reactions taking place due to increase in pressure.

- *Fe-Ti oxides:* The mineral is mostly found as inclusions in garnet and along rim zones of orthopyroxene (figure 4.6g). Both occurrences indicate overgrowth and growth in response to a change in temperature and/or pressure. Elvevold *et al.* (1994) suggest an alteration of ilmenite to rutile as a response to increase in temperature.

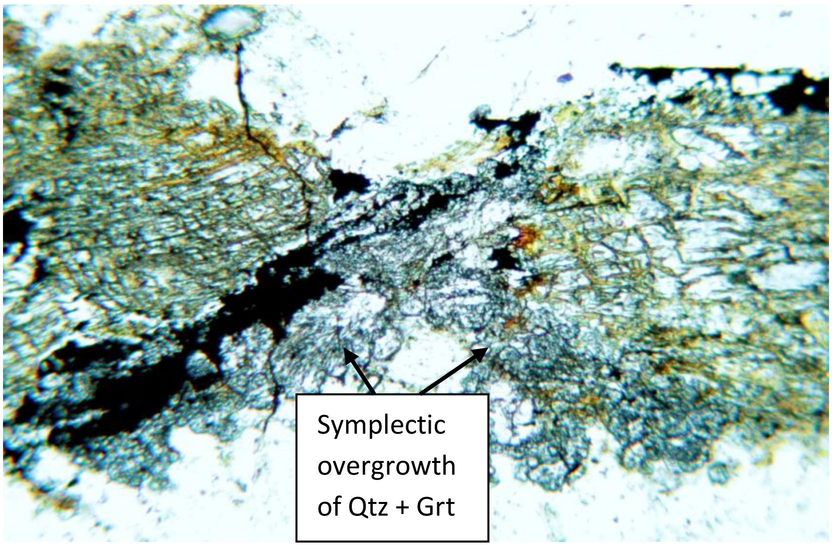
- *Cordierite:* Cordierite is a characteristic mineral in many granulite terrains occurring typically in a mineral assemblage containing garnet, orthopyroxene and quartz (Deer *et al.*, 1992, p. 129, 2nd ed.). Cordierite is found as elongated porphyroclasts. The mineral has a sweeping undulatory extinction and alteration to sillimanite along its grain boundaries. Cordierite is commonly altered to sillimanite in response to higher pressure.

- *Sillimanite:* Fibrolitic sillimanite helps define the strong foliation seen in the rock and is present as overgrowth on cordierite. Sillimanite is interpreted to have grown as a result of cooling and presence of water.

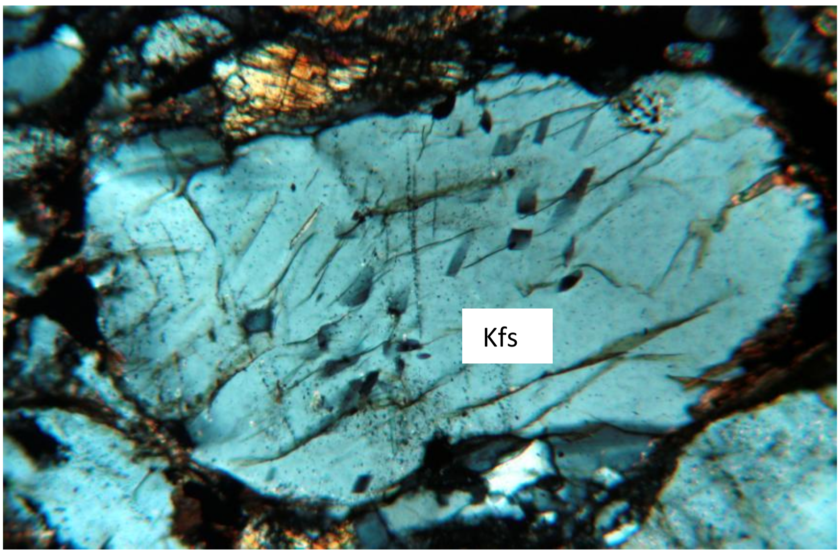
- *Biotite:* is mostly found as an alteration product within cracks of garnet (figure 4.6g) and along rims of orthopyroxene. Acicular grains have a shape preferred orientation parallel to the foliation. Biotite is suggested to have grown in response to cooling from high temperatures.



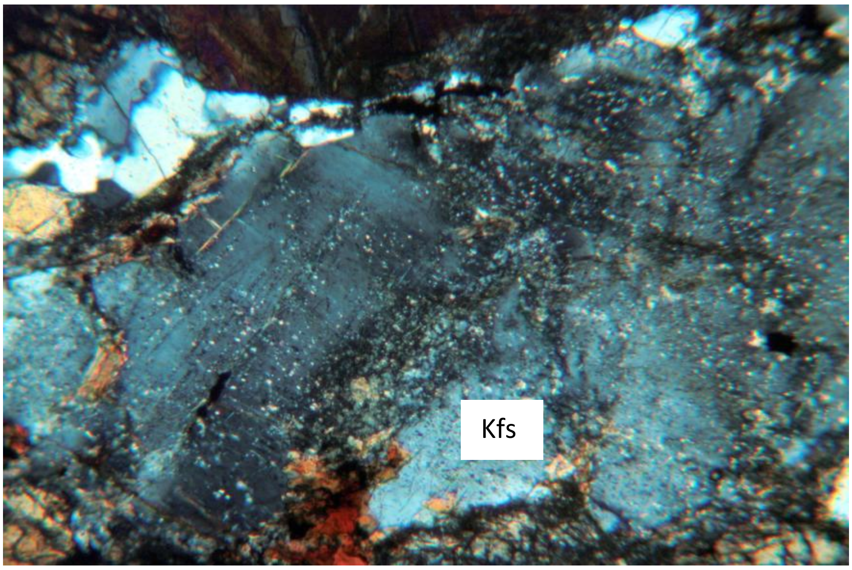
A. Crossed polars; base of photo 4 mm.



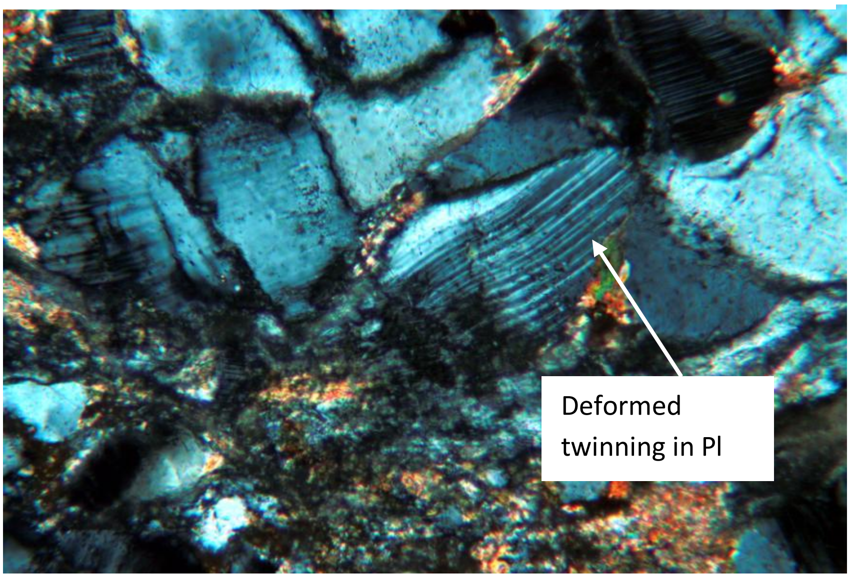
B. Base of photo 1.5 mm.



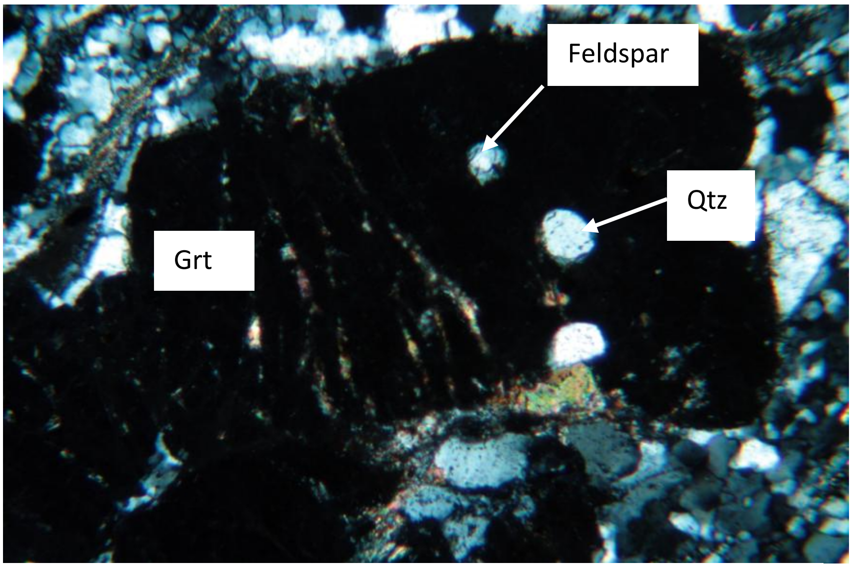
C. Crossed polars; base of photo 1.5 mm.



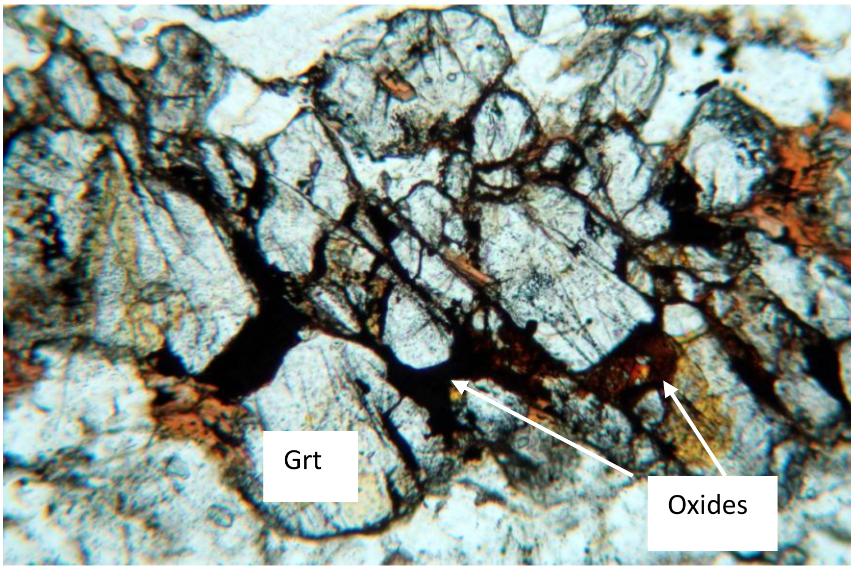
D. Crossed polars; base of photo 1.5 mm.



E. Crossed polars; base of photo 0.6 mm.



F. Crossed polars; base of photo 1.5 mm.



G. Base of photo 4 mm.

Fig. 4.6. (a) Elongated quartz grains with chessboard extinction. (b) Symplectic overgrowth of garnet and quartz on orthopyroxene. (c) Perthite exsolution lamella in K-feldspar. (d) Alteration to sericite in K-feldspar. (e) Deformation twinning in plagioclase indicating deformation. (f) Inclusion of quartz and feldspar in porphyroclasts of garnet. (g) Growth of Fe-Ti oxides within garnet.

The fabric, structures and reactions observed in the quartz-feldspathic gneiss indicate that the rock has been exposed to metamorphism and deformation. The rock has been partially recrystallized as indicated by a bimodal grain size distribution with aggregates of small new grains of approximately uniform size between large old grains with undulatory extinction (Passchier & Trouw, 2005, p. 50, 2nd ed.). The strong foliation is defined by a recrystallized mineral assemblage whose fabric indicates deformation and metamorphism taking place at high grade conditions. Fabric such as intracrystalline deformation seen as sweeping undulatory extinction and chessboard extinction in quartz, feldspars, orthopyroxene and cordierite, and the presence of interlobate to amoeboid grain boundaries are strong indicators of high-temperature deformation. During the emplacement of Suborg-gabbro, the quartz-feldspathic xenolith was heated to 930-960ºC (Elvevold *et al.*, 1994) resulting in the metamorphic mineral assemblage Opx + Grt + Qtz + Pl + Kfs + Oxides ± Crd.

The rock does also have a fabric indicating deformation and metamorphism taking place during a cooling stage; a period of initial cooling from peak temperatures followed the contact metamorphism. This is indicated by perthite exsolution in K-feldspar and reactions resulting in the formation of biotite and sillimanite, and resulted in the mineral assemblage:

Grt ± Sil ± Opx ± Crd + Kfs + Qtz + Pl ± Bt + FeTi-oxides where the production of fibrolitic sillimanite and its orientation can especially be regarded as a part of a synkinematic mineral assemblage.

The formation of thin ductile shear zones in the quartz-feldspathic gneiss did affect the country rock, and resulted in metamorphism and deformation taking place in response to an increase in pressure (3-4 kbar according to Elvevold *et al.*, 1994) as indicated by reaction rims, symplectic overgrowth with garnet and overgrowth of secondary euhedral garnet on primary garnet.

4.4 Thin Ductile Shear Zones

4.4.1 Shear zones in the Suborg-gabbro

Thin ductile mylonitic shear zones are locally present in the Suborg-gabbro. They occur in discrete zones and show higher strain accumulation and finer grain-size than the adjacent rocks. The mylonitic zones consist of relatively continuous, fine-grained, recrystallized folia anastomosing around porphyroclasts of garnet, feldspars and clinopyroxene (figure 4.7).

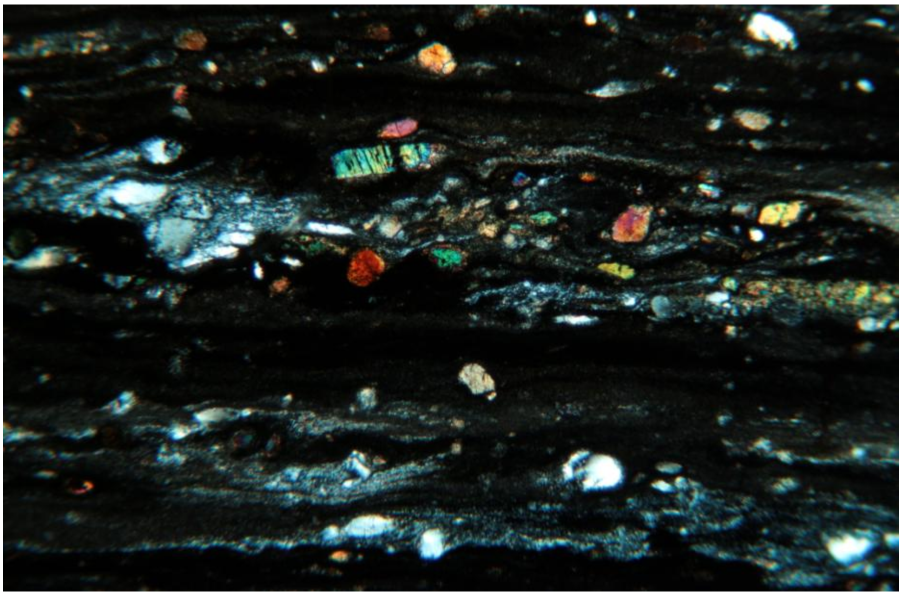


Fig. 4.7. Fine-grained material anastomosing around clasts of clinopyroxene, feldspars and garnet. Crossed polars; base of photo 4 mm.

The shear zones can be classified as ultramylonites. The mylonitic zones display a typical mylonitic foliation where alternating layers of different mineral composition contain embedded porphyroclasts. The development of porphyroclasts can be explained by a difference in rheology between constituent minerals: relatively “hard” minerals will form porphyroclasts, while relatively soft ones form part of the matrix (Passchier & Trouw, 2005,

p. 119, 2nd ed.). The high strain rate reached in the mylonitic zone must have exceeded that in the wall rock for some time, and it can therefore be assumed that the material constituting the shear zones must have been "softer" compared to the wall rock. However, the mylonites in the Suborg-gabbro have relatively the same chemical and mineral composition as the wall rock. This implies that a change in rheology of material occur after the ductile shear zone formed; this is known as "strain-softening" (Passchier & Trouw, 2005 p. 122, 2nd ed.). Strain softening occurs as a result of deformation and/or metamorphism which again cause ductile deformation and recrystallization as indicated by microfabric recognized in the thin ductile shear zones:

- *Deformed porphyroclasts indicating metamorphism:* The porphyroclasts of feldspars and clinopyroxene show undulatory extinction indicating intracrystalline deformation. The porphyroclasts of garnet appear as domino fragmented porphyroclasts indicating internal brittle deformation (figure 4.8a). The porphyroclasts are commonly mantled and have a rounded shape indicating strong deformation. Marginal recrystallization resulted in the development of tails or wings of fine-grained recrystallized aggregates (figure 4.8b). Subgrain rotation dynamic recrystallization is seen for porphyroclasts of orthopyroxene, whilst relicts of feldspars and quartz show bulging recrystallization. The porphyroclasts show a shape preferred orientation; some can be used as shear sense indicators (more on this in section 4.5).

- *Grain size reduction:* The grains constituting the matrix are strongly decreased in size. The mineral assemblages in the Suborg-gabbro reflect a dry high- temperature rock and when high-strains occur in these dry, high-grade rocks, they tend to be localized into mylonitic zones characterized by strong grain size reduction as a result of dynamic recrystallization (Vernon, 2004, p.362 and p. 373). A decrease in grain size causes grain size-sensitive deformation mechanisms (such as diffusion creep and grain boundary sliding) to occur and contribute to a strain softening which again promotes local shearing.

- *Growth of new "softer" minerals:* The pyroxene granulite assemblage is replaced by a garnet granulite assemblage. Garnet and quartz are present in the new mineral assemblage where the reaction Opx + Pl = Cpx + Grt + Qtz took place. The replacement of feldspars by aggregate of quartz is an example of reaction softening since quartz deforms more easily compared to plagioclase (Passchier & Trouw, 2005, p. 123, 2nd ed.).

- *Indications of solution-transfer:* Deformation may cause local solution of chemical components and the transfer of solutions to other sites where they may be deposited. This may change the shape if an aggregate since the material is dissolved from sites of high normal compressive stress and deposited at sites of low stress. Many of the porphyroclasts of orthopyroxene and plagioclase are enclosed by dark seams of insoluble material that were concentrated during dissolution (figure 4.8b).

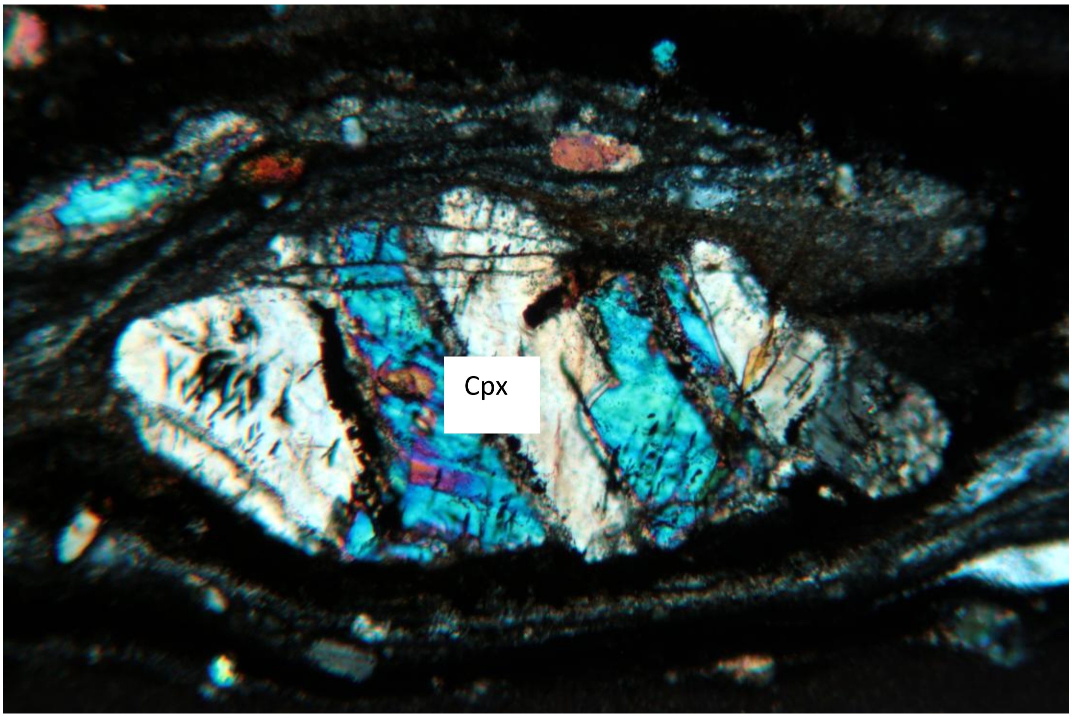


Fig. 4.8a. Domino-fragmented porphyroclast of clinopyroxene. Crossed polars; base of photo 1.5 mm.

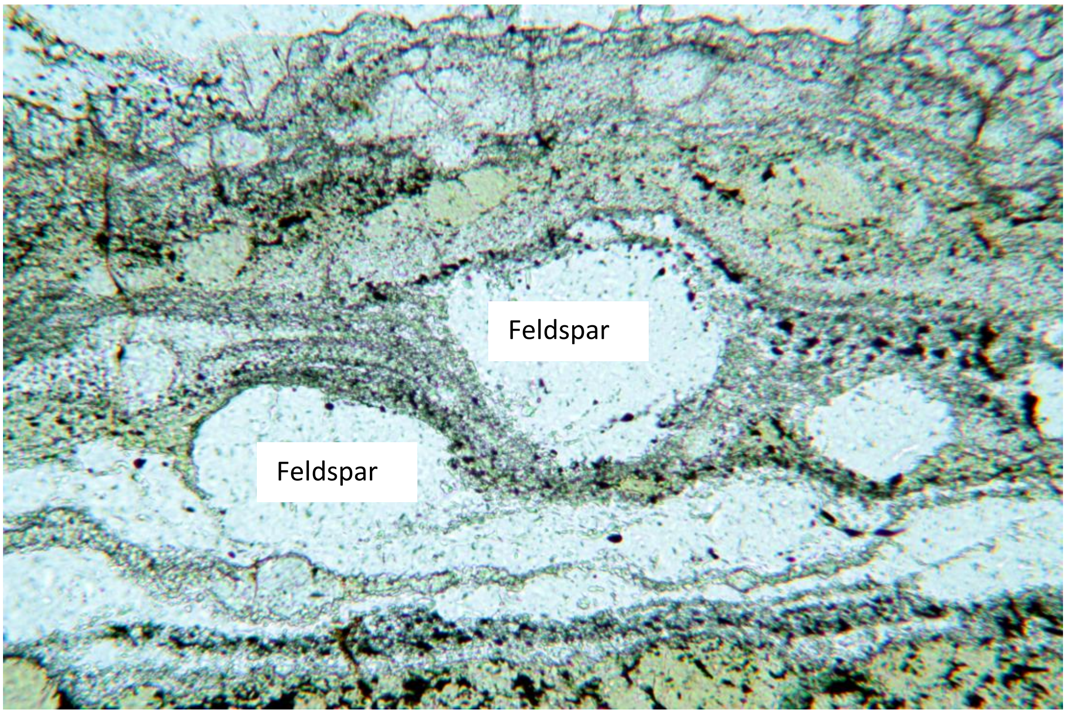


Fig. 4.8b. Mantled clasts of feldspars with tail/wings of dark seams. Base of photo 0.6mm.

The localized strain resulted in mostly ductile deformation and recrystallization. Grain size reduction has taken place by diffusion creep which involves change of grain shape by diffusion of chemical components. It is assumed that water was present in the formation of the shear zones, and the presence of water caused diffusion creep to occur in aqueous solution due to stress-induced solution transfer where material is removed from sites of high normal compressive stress and deposited at low-stress sites.

The structures and reactions observed indicate that a separate deformation event from the event causing the secondary foliation in the Suborg-gabbro has taken place. As mentioned in chapter 2 some of the mylonitic zones resemble relicts of pseudotachylyte fault rock. The main pseudotachylyte fault vein could have been reactivated as a mylonitic zone; the mylonite can be recognized as a former pseudotachylyte by its fine-grained homogenous nature and the presence of injection veins relict (figure 4.9). A pseudotachylyte fault rock is present in the Suborg-gabbro and indicates very fast strain rates in dry rocks producing so much frictional heat that melting occurs (Vernon, 2004, p. 363). The relics of pseudotachylyte in mylonite zones can be explained by pseudotachylyte veins acting as the preferred nucleation sites of mylonite zones (Sibson 1980). This suggests that deformation persisted and continued to be localized.

The mineral assemblage recognized in the shear zones indicates that prograde metamorphic reactions have taken place; from a pyroxene granulite assemblage to a garnet granulite assemblage. A prograde metamorphism could explain the localized strain since water is pervasively released at the grain scale by dehydration reactions during prograde metamorphism, and water can enhance weakening. An increase in pressure causing shearing and involving hydrous minerals from the country rock (biotite and amphiboles) could have acted as a source of water. The following synkinematic mineral assemblage was produced in the shear zones present in the Suborg-gabbro:

Grt + Cpx + Pl + Rt + Opx.

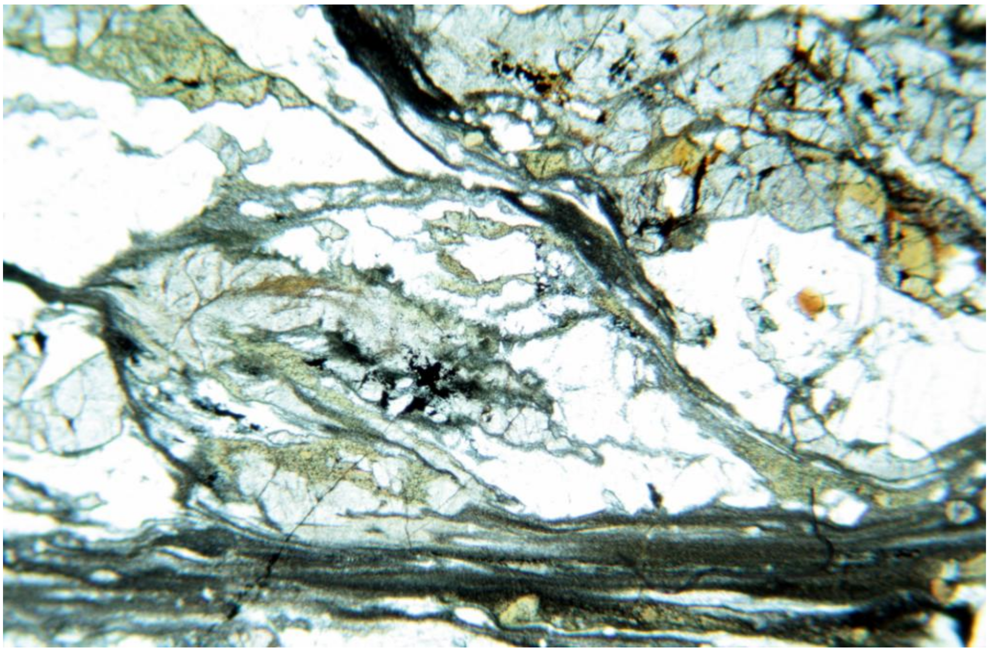


Fig. 4.9. Shear zone suggested being a relic of a pseudotachylyte fault vein. A pseudotachylyte fault vein could have been reactivated as a mylonitic zone. The mylonite can be recognized as a former pseudotachylyte (bottom) by its fine-grained homogenous nature and the presence of injection veins (from right to left) relicts. Base of photo 4 mm.

4.4.2 Shear zones in the quartz-feldspathic gneiss

Thin ductile shear zones appear in the same manner in the quartz-feldspathic gneiss as in the Suborg-gabbro; as thin ductile shear zones with higher strain accumulation and finer grain size compared to the country rocks. The mylonitic zones consist of relatively continuous, fine-grained, recrystallized folia anastomosing around porphyroclasts of garnet, quartz, feldspars and sparsely zircon. The mylonitic zones display a typical mylonitic foliation where a fine-grained matrix contains embedded porphyroclasts. The shear zone studied here is recognized by elongate recrystallized ribbons of matrix material and a few large porphyroclasts of quartz, garnet and feldspar.

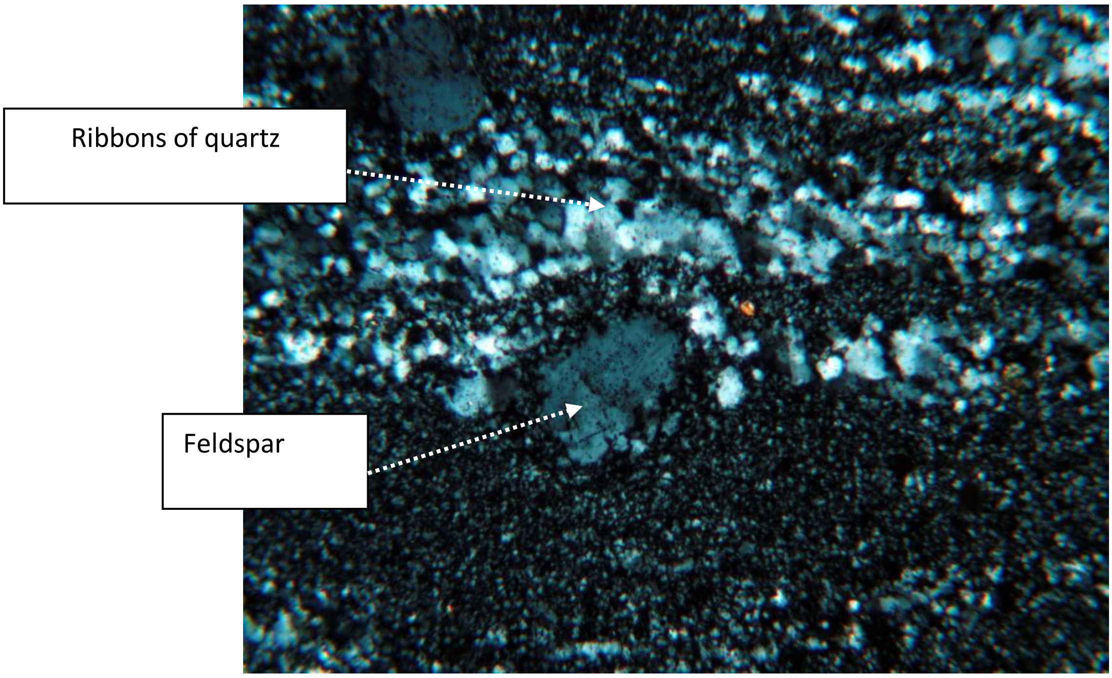
It is assumed that the shear zone in the quartz-feldspathic gneiss developed due to strain-softening, as explained for the development of thin ductile shear zones found in the Suborg-gabbro. The localized strain resulted in deformation and recrystallization as indicated by microfabric present in the thin ductile shear zone and country rock:

- *Deformed porphyroclasts*: Porphyroclasts of quartz show strong undulatory extinction and have a strong preferred orientation. Porphyroclasts of garnet have inclusion of quartz and are often found mantled with fine-grained aggregates of garnet. Thin folia (ribbons) of quartz anastomose around porphyroclasts of feldspars (figure 4.10a). Porphyroclasts of feldspars have inclusions of white mica. Many of the clasts have "tails" reflecting sense of shear. Interlobate to amoeboid grain boundaries between some of the clasts and the matrix indicate that new grains formed by dynamic recrystallization (figure 4.10b).

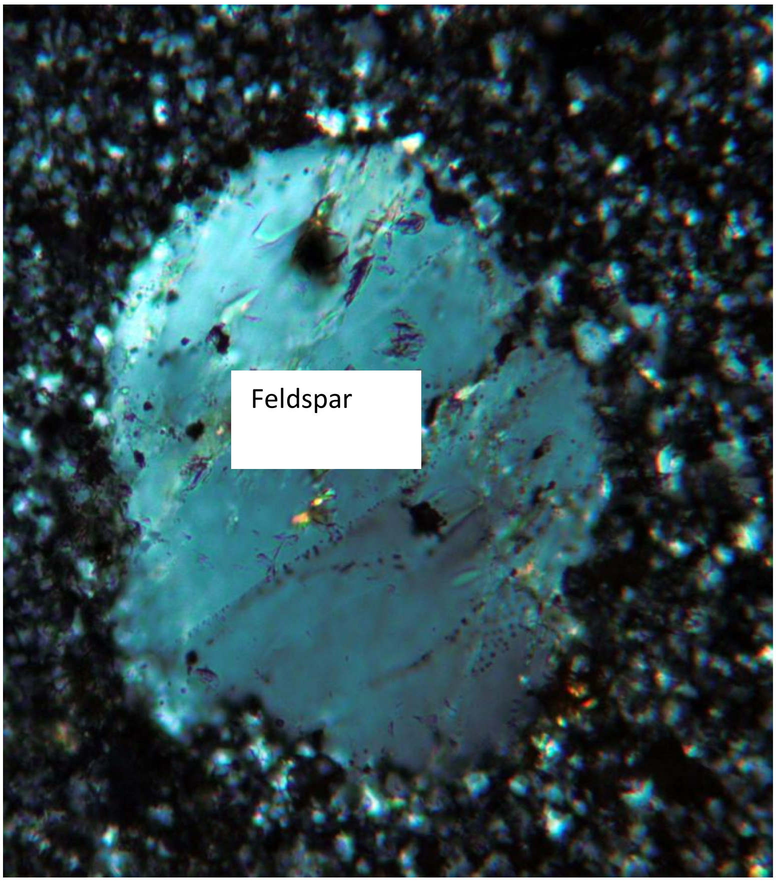
- *Grain size reduction:* the grains constituting the matrix are strongly reduced in size. The grain size reduction has taken place in response to diffusion creep. This can, as mentioned, promote "fabric softening". The matrix consists mostly of quartz, garnet, plagioclase and biotite. Quartz and feldspar grains are seen with lobate to amoeboid grain boundaries which is a typical deformation structure developed at high temperatures. Some of the garnet grains have fractures indicating brittle deformation, but subgrain formation is also observed acting as an indicator for crystalplastic deformation.

- *Growth of new minerals:* Fine-grained euhedral garnets are present throughout the mylonitic zone (figure 4.10c) and are interpreted to have grown due to strain increase. Growth of garnet has taken place in response to an increase in the pressure gradient.

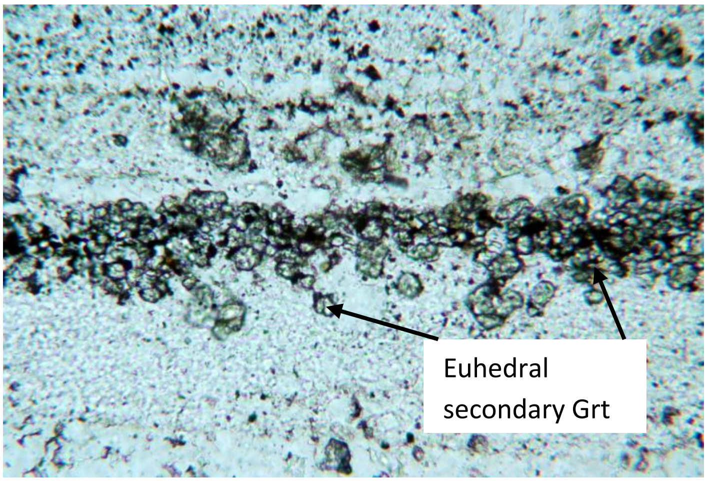
- *Indications of solution-transfer:* Dark seam of fine-grained new minerals are seen enclosing porphyroclasts of feldspars and forming beard structures (figure 4.10d). Many of the porphyroclasts of feldspars and quartz have tail or wings of dark folia. The nucleation of fine-grained new minerals indicates a metamorphic reaction taking place.



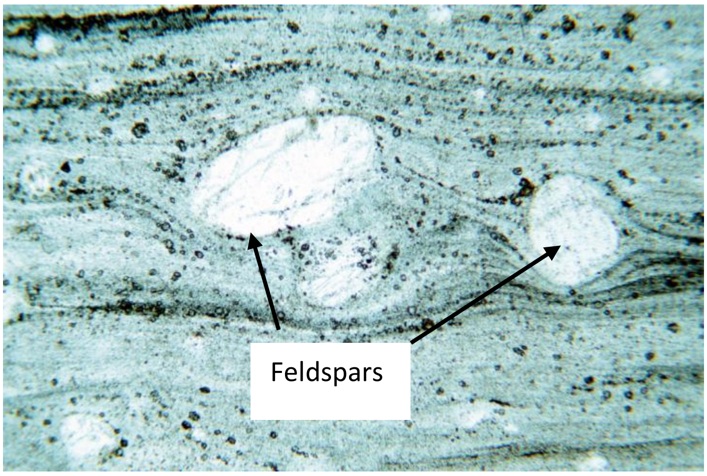
A.Crossed polars; base of photo 1.5 mm.



B. Crossed polars; base of photo 1 mm.



C. Base of photo 0.6 mm.



D. Base of photo 4 mm.

Fig. 4.10. Microstructures observed in a thin ductile shear zone in the quartz-feldspathic gneiss. (a) Ribbons of fine-grained quartz anastomose around a porphyroclasts of feldspar. (b) Interlobate to amoeboid grain boundaries between a feldspar clasts and the matrix. (c) Band of fine-grained euhedral garnet in matrix. (d) Dark seams of nucleated new minerals enclosing clasts of feldspar.

The localized strain in the quartz-feldspathic gneiss is a result of (mostly) ductile deformation and recrystallization. The shear zone has overall deformed ductilely, but the appearance of porphyroclasts of garnet can be considered to have deformed by brittle deformation. Subsidiary brittle deformation can occur during mylonitization according to White *et al.* (1980). They also propose that brittle deformation of isolated grains can take place after a ductilely deformation of the minerals. The formation of strong minerals (in response to high-grade metamorphic conditions) such as garnet is an example of reaction strengthening. Later deformation of these strong minerals may result in brittle deformation mechanisms.

Secondary growth of garnet and symplectites of garnet and quartz on orthopyroxene and primary garnet indicate that a prograde metamorphic event has taken place. The fact that the mylonitic zone is discontinuous to the main foliation proposes that the formation of localized strain can be regarded as a result of a separate deformation and metamorphic event. The following mineral paragenesis

VI: Grt + Qtz + Pl + Bt ± Kfs + FeTi-oxides

is recognized as recrystallized phases within the mylonitic quartz-feldspathic gneiss.

4.5 Kinematic Analysis

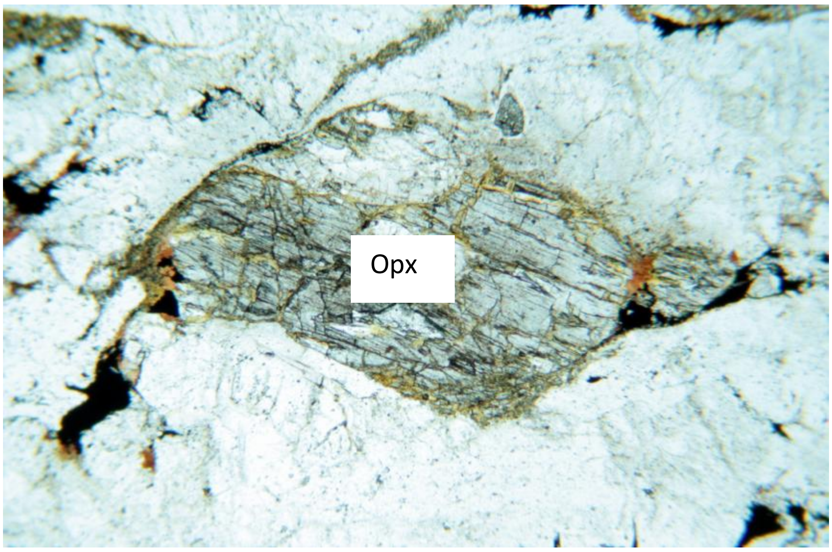
Kinematic indicators observed in rocks allow the sense of shear to be determined. Shear sense indicators are observed in thin sections from the quartz-feldspathic gneiss and the thin ductile shear zones. The presence of mylonites and sheared rock provides the possibility of finding the movement direction during shear formation. In all 5 samples were studied for kinematic analysis. The results of kinematic analysis of the samples are given in table 4.1. The following kinematic indicators have been used to establish the movement directions:

σ-clasts: Porphyroclasts systems can have a number of characteristic shapes that can be used to determine shear sense. A description of different σ-shapes is described by Passchier & Trouw (2005, 2nd ed.). Asymmetric clasts with tail/ wings acting as shear sense indicators are present in the quartz-feldspathic gneiss and in the localized ductile shear zones (figure 4.11a-c). The quartz-feldspathic gneiss has clasts with reaction rims and strain shadows. Clasts in the ductile shear zones commonly show reaction rims.

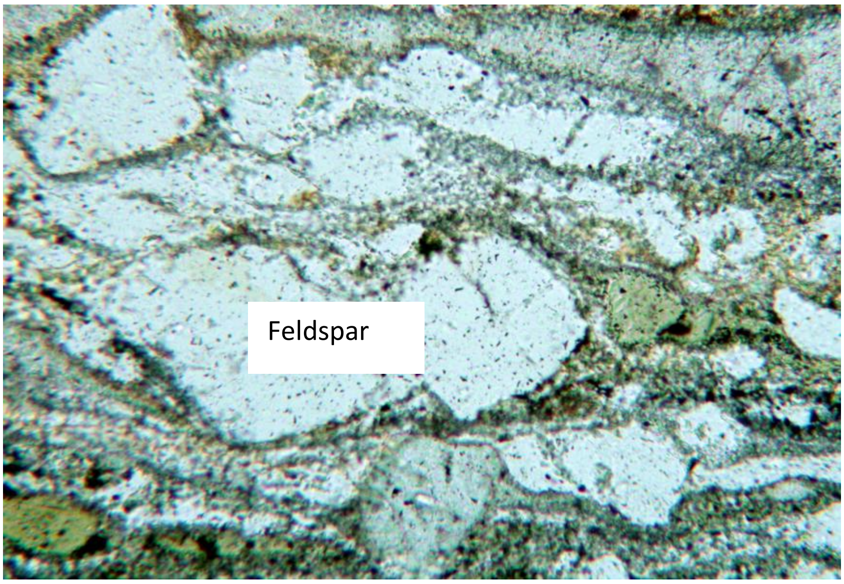
Drag folds: can be used to determine the direction and sense of slip during faulting provided that they all have the same asymmetry on the width of the shear zone. Tight asymmetrical drag folds commonly occur in the interior of fault zones. A drag fold is observed in a thin ductile shear zone from the Suborg-gabbro (figure 4.11d).

Quartz-shape fabric: Asymmetric quartz shape fabric can be used as reliable kinematic indicators. Quartz aggregates and elongated isolated quartz grains showing asymmetric shape fabric are present in the quartz-feldspathic gneiss (figure 4.12).

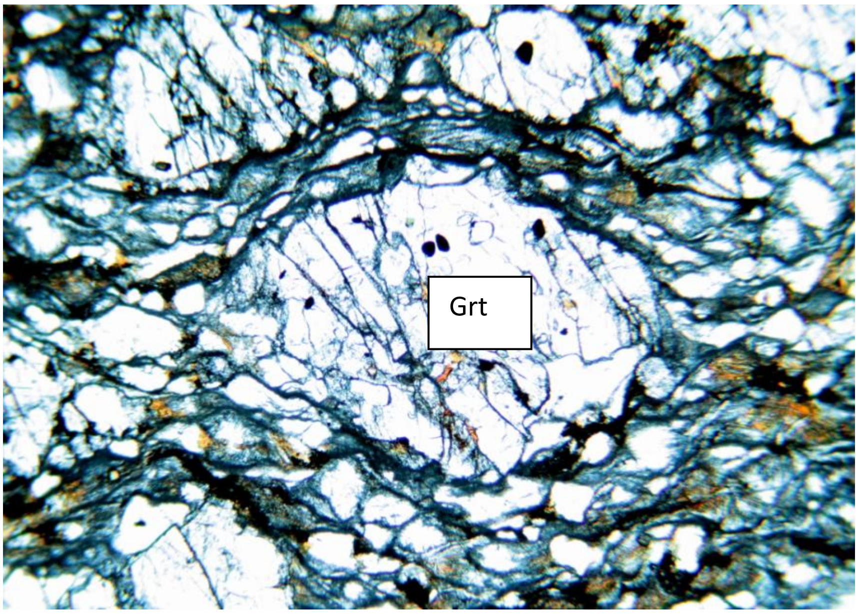
Shear bands: C' type shear bands are found in the quartz-feldspathic gneiss (figure 4.13). Shear bands are also referred to as "extensional crenulation cleavage" which are suggested to represents ductile faults with a synthetic normal fault displacement sense (Stünitz, 1989). But since the shear bands are only present locally in the thin sections and not observed as a penetrative fabric feature the C’ shear bands are only indicative of local extension.



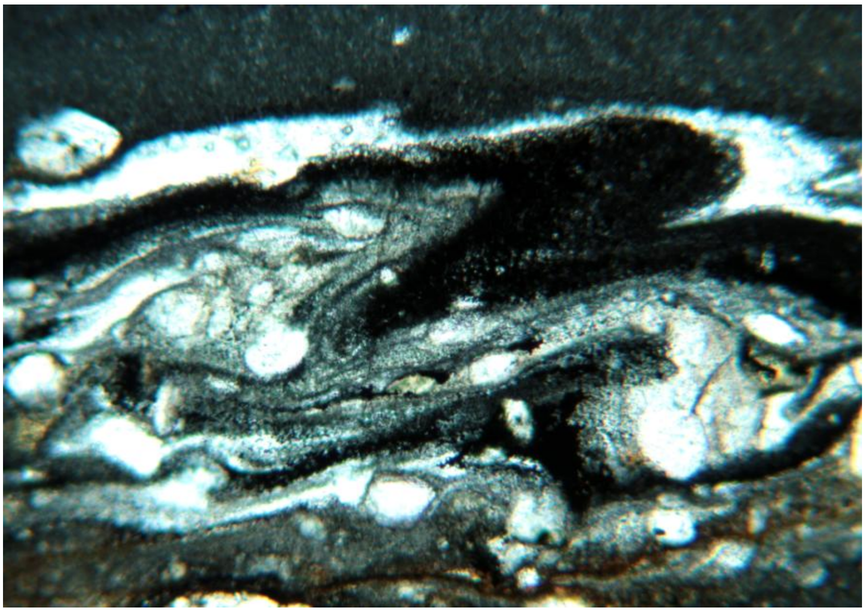
A. Base of photo 4 mm.



B. Base of photo 0.6mm.



C. Base of photo 4 mm.



D. Base of photo 1.5 mm.

Fig. 4.11. Examples of kinematic indicators present in the quartz-feldspathic gneiss and in the thin ductile shear zones. (a) Porphyroclasts of orthopyroxene with wings of recrystallized material present in the contaminated quartz-feldspathic gneiss indicating a sinistral sense of shear. (b) Clasts of feldspars with rims/tails of dark material present in thin ductile shear zone from the quartz feldspathic gneiss indicating a sinistral sense of shear. (c) Porphyroclasts of garnet in quartz-feldspathic gneiss indicating a sinistral sense of shear. (d) Tight asymmetrical drag fold present in a ductile shear zone indicating a dextral sense of shear. The fold can be classified as a Z-shaped fold.

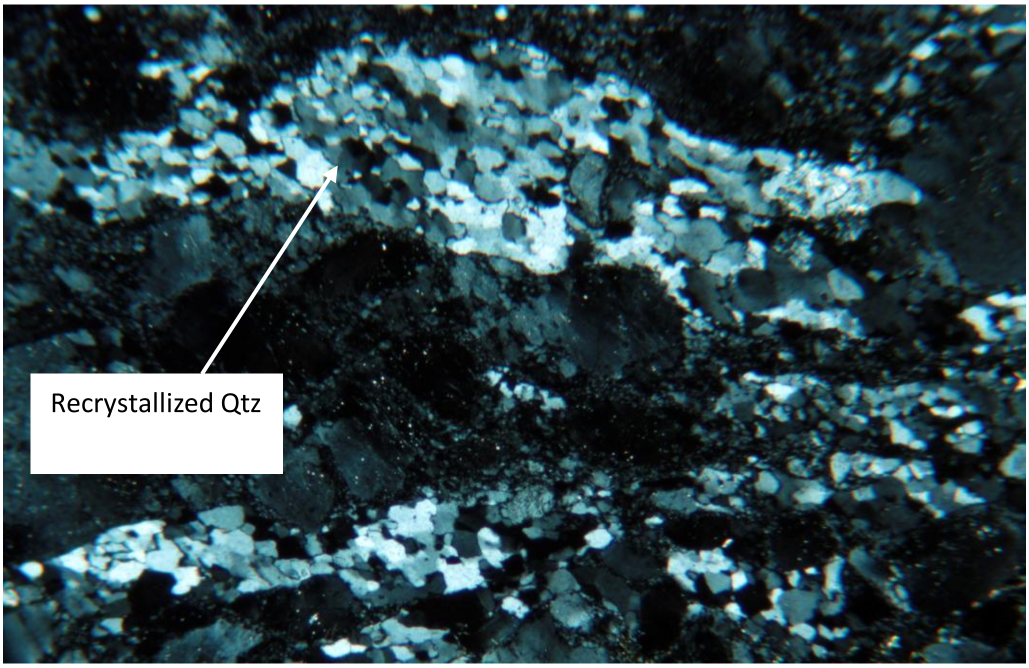


Fig. 4.12. Asymmetric quartz shape fabric present in the quartz-feldspathic gneiss indicating a sinistral sense of shear. Crossed polars; base of photo 2.5 mm.

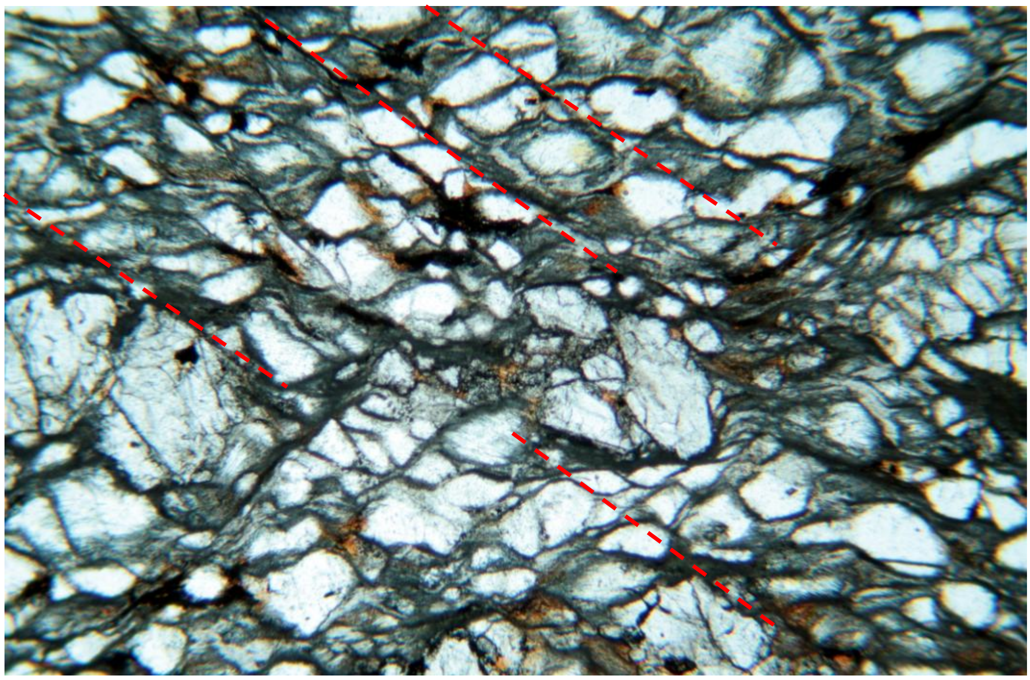


Fig. 4.13. C'-type shear bands (marked with red) indicating a dextral sense of shear observed in the quartz-feldspathic gneiss. Base of photo 4mm.

Table 4.1. Shear sense determinations.

Sample No.	Rock Type	σ-Clasts	Shear Band Cleavage	Quartz Shape Fabric	Drag folds	Movement vector
SuE-12	Quartz-feldspathic Gneiss	x	x	x		W block down
SuE-8.3	Quartz-feldspathic Gneiss	x		x		W block down
SuE-6.1	Ductile shear zone in Suborg-gabbro	x				NW block down
Ø18	Ductile shear zone in Suborg-gabbro	x			x	W block down
Ø16	Ductile shear zone in Quartz-feldspathic gneiss	x				E block down

The results of the kinematic analysis (table 4.1) are represented in figure 4.14. The two samples representing the quartz-feldspathic gneiss indicate the western block moving downwards. The samples from a thin ductile shear zone in the Suborg-gabbro indicate western block moving down. The thin ductile shear zone in the quartz feldspathic gneiss indicates a down movement of eastern block.

The kinematic indicators suggest a simple shear deformation in the area. Although no unique movement of the upper block can be given, it appears to have been normal faulting for the quartz feldspathic gneiss where the western block has moved down. The thin ductile shear zones indicate both the western and eastern block moving down. Both sinistral and dextral shear sense indicators are observed in the thin section representing the thin ductile shear zones.

Figure 4.15 illustrates the parallelism seen in the foliation for both rock types. One very interesting feature is how the foliation bends around the summit of Høgfjellet. This characteristic deflection in the foliation will be discussed in chapter 5.

A discussion of the kinematic analysis will be given in chapter 5.

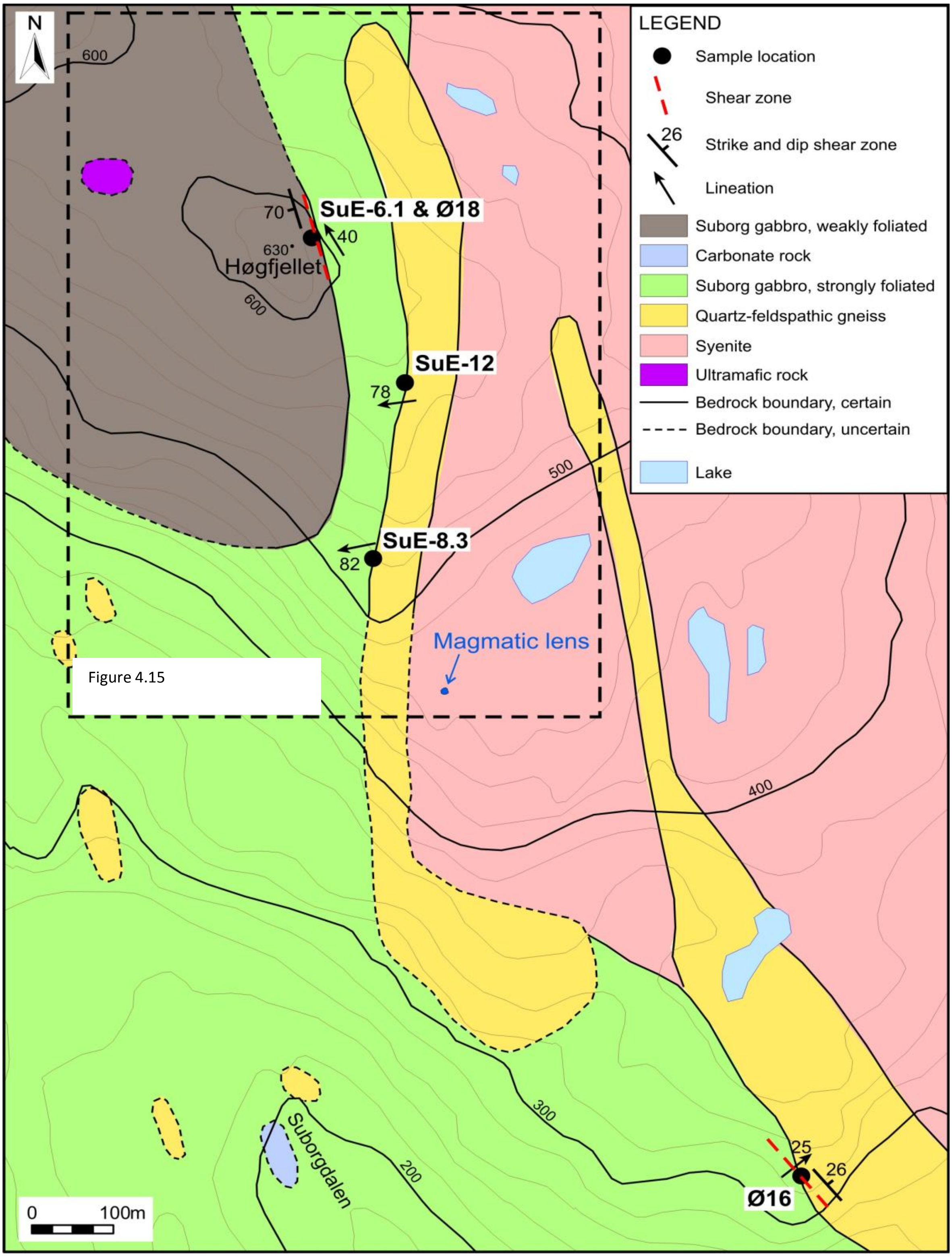


Fig. 4.14. Map of the determined shear senses of table 4.1. Arrows indicate the movement direction of the lower block. The area of figure 4.1.5 is marked on the map. Mapping after Reginiussen (1992).

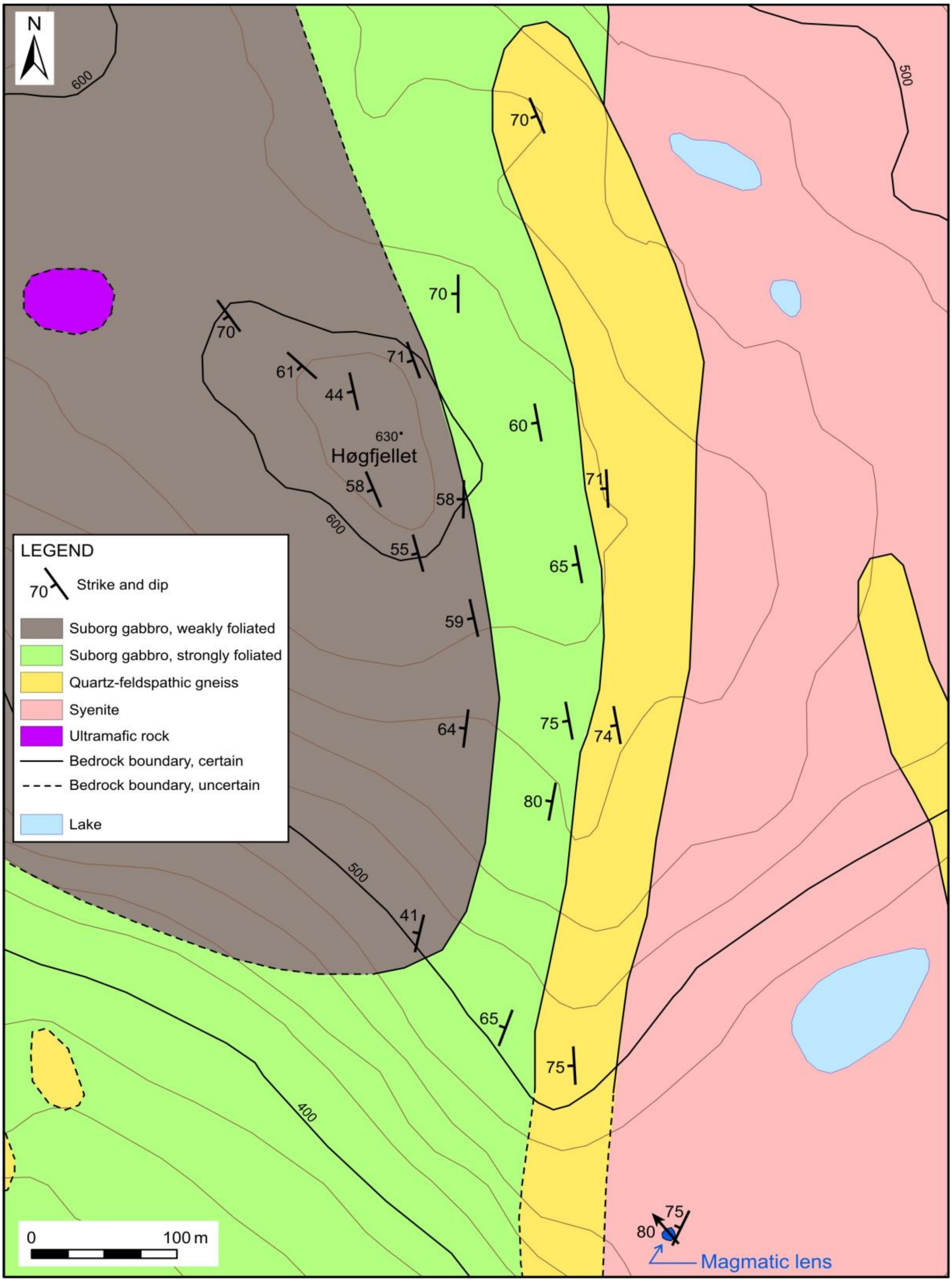


Fig. 4.15. Map illustrating how the foliation deflects around the summit of Høgfjellet. Mapping after Reginiussen (1992).

5. Discussion

5.1 Introduction

In this chapter the deformation events will be discussed for the Seiland Igneous Province based on descriptions from chapter 2 and 4 together with the pressure and temperature estimates from chapter 3. The metamorphic and deformation evolution of the area will be discussed in section 5.2. An interpretation of the kinematic analysis, in context with the metamorphic and deformational evolution of the SIP, will be given in section 5.3.

5.2 Metamorphic and Deformation Evolution of the SIP

Microstructures in the Suborg-gabbro and the quartz-feldspathic gneiss show evidence of recrystallization and recovery. The microstructures present in the Suborg-gabbro and the quartz-feldspathic gneiss suggest that the rocks have gone through the following stages:

I. Emplacement of the Suborg-gabbro causing contact metamorphism and partial melting of the quartz-feldspathic gneiss.

II. Cooling of both rock types resulting in retrograde metamorphic reactions.

III. Increase in pressure causing formation of thin ductile shear zones in the Suborg-gabbro and the quartz-feldspathic gneiss, and also resulting in prograde metamorphic reactions in the quartz-feldspathic gneiss.

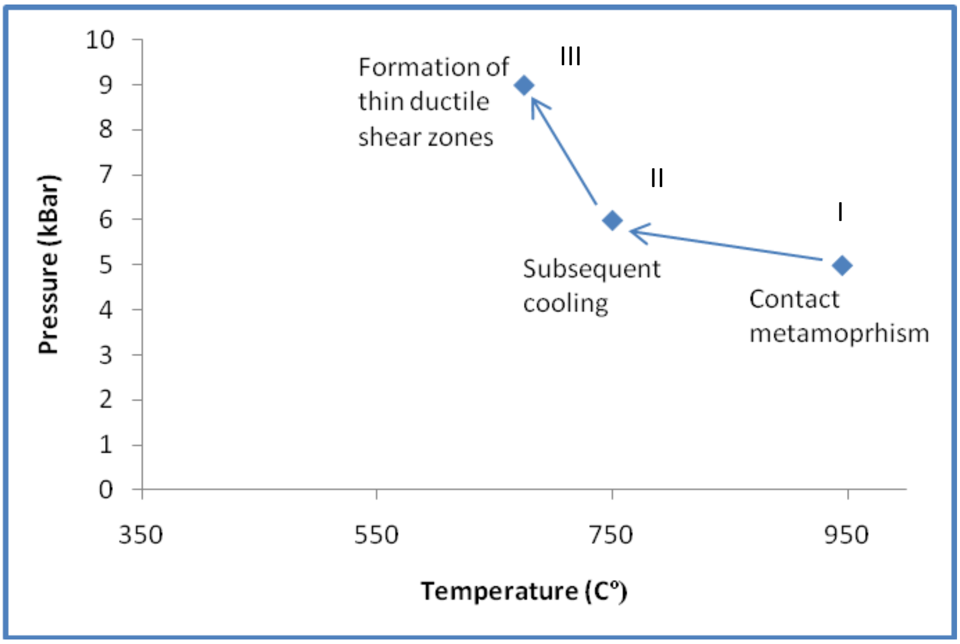


Fig. 5.1. Possible P-T path for the metamorphic and deformational evolution of the Suborg-gabbro and the quartz-feldspathic gneiss. Pressure and temperature estimates are given by Elvevold *et al.* (1994).

Microstructural evidences support the possible P-T path for the Suborg-gabbro and the quartz-feldspathic gneiss given in figure 5.1. The following observations in the two rock types support a metamorphic and deformation evolution as represented by stage I to III:

I. *Suborg-gabbro:* Residual igneous microstructures are found even though deformation and recrystallization/neocrystallization have removed much of the primary igneous microstructure. Igneous microstructures and an igneous mineral assemblage (chapter 3, assemblage I) support that the Suborg-gabbro is a plutonic rock and that the foliation present in the rock is partly of magmatic origin.

   Quartz-feldspathic gneiss: The emplacement of the Suborg-gabbro caused partial melting and high-T contact metamorphism of the quartz-feldspathic gneiss resulting in paragenesis II (see chapter 3). The formation of cordierite is diagnostic for high-grade gneisses, and the lobate grain boundaries seen for the quartz assemblages support high-T deformation.

   Both rock types show evidence of crystal plastic deformation as indicated by deformation twinning in plagioclase. The mineral assemblages present in both rock types represent high T- conditions and dry mineral assemblages.

II. *Suborg-gabbro:* Several features indicate a cooling stage for the Suborg-gabbro. Reaction rims of orthopyroxene on olivine are interpreted to form during cooling from subsolidus igneous temperature (Deer *et al.*, 1992, p. 13, 2nd ed.).

Symplectic intergrowths of orthopyroxene and spinel are present in the Suborg-gabbro (regarded as breakdown products of olivine and plagioclase). Symplectic intergrowths are particularly observed in granulite facies terrains where isobaric cooling can cause olivine and plagioclase to become unstable (Gardner & Robins 1974). Gardner & Robins (1994) did a study on olivine-plagioclase reaction from a series of plutons from the SIP and they claim that the reactions rims are produced during cooling of individual intrusions from solidus temperature to those of the regional metamorphism.

Amphibole has locally replaced pyroxene indicating a transition from granulite facies towards amphibolite facies conditions. Partial pseudomorphism is one of the most reliable criteria of a metamorphic reaction taking place (Vernon 1996) and therefore acts as a strong indicator for a change in the metamorphic conditions for the Suborg-gabbro.

Exsolution lamellae seen in orthopyroxene result from stresses induced during cooling from original magmatic temperature and supports deformation coexisting with stage II (Deer *et al.*, 1992, p. 257, 2nd ed.).

Formation of triple junctions (foam-structure), indicating grain boundary area reduction (GBAR), is seen for pyroxene and amphibole aggregates in the Suborg-gabbro. GBAR takes place in response to deformation, but its effect is more obvious and may become dominant after deformation ceased, especially at high temperatures since GBAR can continue in absence of deformation towards a lower internal energy configuration (Passchier & Trouw 2005, p. 51 & 56, 2nd ed.). The presence of GBAR therefore supports cooling from high temperatures for the Suborg-gabbro.

Microstructures present in the Suborg-gabbro support solid-state deformation seen as internal deformation (undulatory extinction), recrystallized wings on deformed grains and symplectic intergrowth.

Quart-feldspathic gneiss: The quartz-feldspathic gneiss, as with the Suborg-gabbro, shows evidence of solid-state deformation taking place in response to cooling from high temperatures. The mineral assemblage defining the foliation in the quartz-feldspathic gneiss is interpreted to be of metamorphic origin and the minerals show evidences of solid-state deformation. This is indicated by, for example, recrystallized wings on porphyroclasts, elongation of recrystallized aggregates (ribbons of quartz), fine-grained foliations anastomosing around less deformed lenses and crystal plastic deformation seen as undulatory extinction. Growth of biotite and sillimanite due to the hydration of cordierite and garnet (chapter 3, reaction 5) is an example of a reaction taking place in response to cooling. The metamorphic sillimanite present as overgrowth on porphyroclasts of cordierite is interpreted to postdate previous phases and therefore support sillimanite being a part of a new metamorphic mineral assemblage defining the foliation. The foliation in the quartz-feldspathic gneiss is parallel to the Suborg-gabbro. According to Paterson *et al.* (1989) where magmatic foliations increase in intensity near the margins of plutons (the foliation in the Suborg-gabbro is stronger near its margins, see figure 2.1), foliations in the country rock are commonly rotated into parallelism with the margin, and thus explain the parallelism seen in the foliation for the two rock types.

III. In response to an increase in the pressure the pyroxene granulite assemblage was replaced by a garnet granulite mineral assemblage in narrow ductile shear zones in the quartz-feldspathic gneiss and the Suborg-gabbro. The formation of the thin ductile shear zones affected the wall rock of the quartz-feldspathic gneiss, but not the Suborg-gabbro. The mylonitic zones consist of relatively continuous, fine-grained recrystallized folia anastomosing around porphyroclasts and the mylonites in the two rock types have relatively the same chemical and mineral composition as the wall rock meaning that a change in rheology of material must have taken place. Introduction of water is one way of initiating mylonites in rock; The presence of pore fluids can significantly reduce the strength of a rock, and according to Rutter (1972) the presence of fluids can increase the ductility of the rock. The presence of water could be e a result of chemical reactions taking place during the solid state deformation of the Suborg-gabbro and the quartz-feldspathic gneiss. Chemical reactions typically accompany and affect deformation, and may release or consume fluid which affects mineral deformation (Vernon 2004, p. 353). Zones of strong deformation may act as fluid channels which can be very important for metamorphic reactions within the shear zone. Vernon (2004, p. 354) states that for retrograde regional metamorphism water is available locally, mainly in shear zones. Once the deformation has begun, the localization of the mylonitic zones could be maintained and intensified by "strain softening" which is promoted by processes such as grain size reduction caused by dynamic recrystallization. According to White *et al.* (1990) once ductile strain increase in discrete zones, fluid activity and associated strain-softening will promote continued deformation. Grain size reduction caused by diffusion creep and grain boundary sliding is very evident in the mylonitic zones in the Suborg-gabbro and the quartz-feldspathic gneiss. Jin *et al.* (1998) conclude that grain-size reduction due to dynamic recrystallization at relatively high stresses and moderate temperature is a probable mechanism of shear localization. The formation of mylonitic zones in the two rock types occurred according to Elvevold *et al.* (1994) at higher pressure and relatively low temperature (figure 5.1).

The increase in pressure during stage III indicates tectonic thickening and that the rocks were buried to a depth of approximately 30 km (Winter 2001, p. 498). Narrow ductile shear zones with mylonitic fabric indicate strong deformation at middle to lower crust (Passchier & Trouw, 2005). Some of the thin ductile shear zones in the Suborg-gabbro can be recognized as pseudotachylyte fault rock and/or relicts of pseudotachylyte fault rock. Most pseudotachylytes form in the upper to middle crust. However, some occurrences from the deep crust, at apparently granulite or eclogite facies, have been reported by Austrheim & Boundy (1994). They claim that fluids play an active role in deep crustal processes causing metamorphic reactions that dramatically change the rheology and density of the rock and that these changes may be the indirect reason for pseudotachylytes. The presence of pseudotachylyte in the Suborg-gabbro supports the rock representing a relatively dry rock which is also supported by a dry mineral assemblage recognized in the Suborg-gabbro. Pseudotachylytes are formed due to very fast strain rates in a dry rock that may produce so much frictional heat that melting occurs, forming pseudotachylyte (Vernon 2004). Some of the mylonitic zones might resemble relicts of pseudotachylyte fault rocks. This proposes that the pseudotachylytes were exposed to continued deformation, and that strain-softening processes allowed for continued deformation in these thin localized zones.

The metamorphic stages I to III recorded in the Suborg-gabbro and the quartz-feldspathic gneiss define a pressure and temperature path given in figure 5.1. The peak conditions were followed by a period of cooling towards amphibolite facies which was again followed by prograde metamorphism resulting in garnet granulite facies. It is reasonable to assume that the heating of the xenolithic quartz-feldspathic gneiss by the Suborg-gabbro was rapid with only a modest increase in pressure (Elvevold & Reginiussen 1996). According to Bucher & Frey (1994, p. 284, 6th ed.), the geological cause of granulite facies metamorphism at low pressures are commonly attributed to intrusions of mafic magma into the continental crust. The large volumes of hot magma from the mantle or lower crust serves as heat source for extensive high temperatures, and after heating to high temperatures the rocks cool essentially isobarically. Many granulite facies terrains are characterized by isobaric cooling paths, which is also the case for the Suborg-gabbro and the quartz-feldspathic gneiss. If water becomes available during slow cooling, the high-grade assemblages may be completely erased and metamorphosed to a lower-grade facies rock (Bucher & Frey 1994, p. 284, 6th ed.). The presence of amphibole and biotite in the rocks indicate that the peak conditions were followed by retrograde reactions. Stage III is interpreted to be related to emplacement of a tectonic unit of cold thrust sheet over hot rocks during the Caledonian orogeny.

New monazite data by Roberts (2008) suggests that the paragneiss in the Øksfjord area records metamorphism that is much older than the emplacement of the SIP. Roberts (2008) claimed that it is therefore inappropriate to use metamorphic petrology from the paragneiss in conjunction with metamorphic data from metamorphosed mafic rocks of the SIP. Excluding the data observed in the quartz-feldspathic gneiss will result in a completely different view of the metamorphic history of the SIP. The following metamorphic history is suggested by Roberts (2008):

1. The paragneiss in the Øksfjord area were deposited, deformed and metamorphosed at least once, at 630-640 Ma.
2. Contact metamorphism accompanied the emplacement of the SIP.
3. Subsequent to the emplacement of the SIP, the Kalak Nappes were involved in the Caldonian Orogeny, and during this event the rocks experienced a pressure increase.

The metamorphic history proposed by Roberts (2008) does not correspond with the metamorphic history given by Elvevold *et al.* (1994). According to Roberts (2008) the early mineral assemblages recognized in the quartz-feldspathic gneiss could be a result of a metamorphic event predating the emplacement of the SIP, and not a result of contact metamorphism as proposed by Elvevold *et al.* (1994). If the pressure and- temperature estimates given by Elvevold *et al.* (1994) are re-evaluated without including any data from the Øksfjord paragneisses, Roberts (2008) states that a completely different view of the metamorphic history of the SIP is needed. He also suggested, when excluding the paragneiss data, the necessity to consider metamorphic stage II as a metamorphic event separate from either stage I and III.

The microstructures and metamorphic reactions observed in the rocks studied in this thesis support the metamorphic model proposed by Elvevold *et al.* (1994) involving a metamorphic history from stage I to stage III. Though, it could be that the early mineral assemblage recognized in the quartz-feldspathic gneiss predates the emplacement of the SIP as proposed by Roberts (2008). Stage II is supported by the fact that the foliation observed in the quartz-feldspathic gneiss is parallel to the foliation observed in the Suborg-gabbro. This means that the emplacement of the Suborg-gabbro most likely affected the quartz-feldspathic gneiss. The presence of stage III is strongly supported by the formation of the thin ductile shear zones (in both rock types) taking place in response to a pressure increase.

5.3 Kinematics in a Deformational Context

Age dating by Roberts (2008) suggests the Seiland Igneous Province represents the remains of a short-lived, late Precambrian, igneous intrusive event. The rock association proposes that the Seiland Igneous Province is the eroded roots of an intracontinental rift, similar to the East African Rift system (Roberts *et al.*, 2006). Elvevold *et al.* (1994) supports a rifting model for the magmatism in the SIP to be very likely. If the pressure estimates (4.8-6.5 kbar) of Elvevold *et al.* (1994) are correct it can be assumed that the magma was emplaced into the middle crust under ductile conditions.

The emplacement of the Suborg-gabbro is believed to have taken place during regional deformation, which again is responsible for the formation of the foliation. The Suborg-gabbro shows evidence of a primary magmatic flow overprinted by a solid-state flow parallel to the magmatic flow. Paterson *et al.* (1989) propose that many plutonic rocks show evidence of superposition of solid-state deformation on a magmatic foliation, and that a magmatic origin for the foliation is favored for foliations parallel to internal or external pluton contacts. Plutons suggested to have been emplaced during regional deformation presumably should have foliations formed by processes ranging from magmatic flow to solid-state deformation according to Paterson *et al.* (1989). They suggest that the strongest evidence for syntectonic emplacement is; a pluton showing parallel or subparallel magmatic and high-temperature solid-state foliations and that the solid-state foliation is continuous with a regionally developed foliation in the wall rocks. Microstructural observation in the Suborg-gabbro support a transition from magmatic to solid-state flow.

A syntectonic emplacement for the Suborg-gabbro is strongly supported by the fact that the solid-state foliation in the Suborg-gabbro is continuous with a regionally developed foliation in the wall rock (the quartz-feldspathic gneiss), and that the Suborg-gabbro shows parallel magmatic and high-temperature solid-state foliation. An asymmetric extension model with deep crustal shearing and syntectonic intrusions may explain the parallelism of the magmatic rhythmic layering and the solid-state foliation and the elongated pluton geometry seen for the Suborg-gabbro. Extension associated with continental rifting has been proposed as a mechanism for the generation of the fabric present in the Suborg-gabbro and the quartz-feldspathic gneiss (Elvevold *et al.*, 1994; Roberts *et al.*, 2006; Roberts 2008). The fabric seen in the Suborg-gabbro and the quartz-feldspathic gneiss is interpreted by Elvevold *et al.* (1994) as synorogenic, and produced as a result of simple shear deformation caused by shear zone evolution during lithopsheric extension. The quartz-feldspathic xenolith studied here is strongly sheared, and the kinematic indicators observed in the rock indicates that the main movement appears to have been normal faulting. A normal slip-fault is one in which the hanging wall moves down with respect to the footwall and where the dip of the fault averages around 60º. The dip seen for the kinematic indicators in the quartz-feldspathic gneiss is on average around 80º (figure 4.14), and the hanging wall has moved downwards towards the west. The kinematic indicators seen in the quartz-feldspathic gneiss support extension and rifting for the Seiland Igneous Province.

The deformation recorded in the studied rocks in this thesis can be considered extremely heterogeneous based on the assumption that the undeformed rocks and heavily foliated and metamorphosed rocks in the Seiland Igneous Province are all the same age. The Suborg-gabbro is very heterogeneous in appearance; it is found as a unit with a strong fabric and as a unit weakly to un-foliated. Figure 2.1 illustrates how the Suborg-gabbro is stronger foliated closer to the quartz-feldspathic xenolith. An explanation for this could be that the intensity of magmatic foliations commonly increases towards the external margin of the pluton (Frost & Mahood 1987). The foliation in the Suborg-gabbro is also seen deflected around the quartz-feldspathic gneiss (figure 4.15). Magmatic flow foliations are often seen deflected around large meatsedimentary xenoliths (Hurlbut 1935). Both the deflection and the stronger foliation closer to the xenolith can therefore support magmatic flow forming the foliation seen in the Suborg-gabbro.

Extension associated with continental rifting has been proposed as a mechanism for the generation of high-T and low-P metamorphic terrains (Wickham & Oxburgh 1985). Granulite facies metamorphism in the lower levels of continental crust which is undergoing extension is indicated by unusually high heat flow. According to Sandiford & Powell (1986), a certain metamorphic path can be recognized in extensions involving crustal-penetrative detachment zones; the metamorphism could occur on a regional scale causing heating into the granulite facies at constant or decreasing pressure during extension, followed by cooling at constant or increasing pressure after extension stops. Many terrains, as with the area studied in this thesis, preserve a pressure-temperature path which involves substantial, essentially isobaric cooling. Sandiford & Powell (1986) also propose that simple shear deformation may take place along a detachment zone associated with asymmetric extension.

The pressure and temperature path seen in figure 5.1 from stage II to stage III involves loading seen as a pressure increase with no increase in temperature which resulted in the formation of thin ductile shear zones. The loading can be explained by emplacement of a tectonic unit of cold thrust sheet over hotter rock (Karabinos & Ketcham 1988). The high pressure metamorphism (stage III) causing the formation of the thin ductile shear zones in the Øksfjord area is interpreted to be related to thrusting and nappe emplacement during the Caledonian orogeny. Field relations indicate that the compression post-dates the magmatic activity (Mørk & Stabel 1990) could support the formation of the thin ductile shear zones to be related to the Caledonian orogeny. The Caledonian thrust sheets are believed to have been transported eastwards onto the Baltoscndian craton during the closure of the Iapetus ocean (Elvevold & Reginiussen 1996). The kinematic indicators observed in the thin ductile shear zones sampled in the quartz-feldspathic gneiss indicate a down movement of the western block, whilst the kinematic indicators observed in thin ductile shear zones sampled from the Suborg-gabbro show down movement of the eastern and the northwestern to western block (for the thin ductile shear zone in the Suborg-gabbro). Further structural investigations are needed in order to constrain a better structural interpretation of the formation of the thin ductile shear zones. However, Reginiussen (1992) prepared a plot of 93 ductile shear zones from the area. He concluded two dominating orientations for the ductile shear zones dipping 40-60º SW and 70-90º ESE. This could suggest that the main movement of the Caledonian thrust sheets have been transported from the NW to NE.

6. Conclusion

1. The metamorphic history of the two rock types studied in this thesis could be summed up according to the following:

   - *The Suborg-gabbro* has, after emplacement, gone through a cooling stage and later a pressure increase resulting in the formation of thin ductile shear zones.

   - *The quartz-feldspathic gneiss* has been exposed to three different metamorphic events; contact metamorphism, subsequent cooling and later a pressure increase resulting in the formation of thin ductile shear zones.

2. The foliation in the Suborg-gabbro and the quartz-feldspathic gneiss is parallel to each other. The foliation seen in the Suborg-gabbro is suggested to be a primary magmatic foliation overprinted by a solid-state foliation parallel to the magmatic foliation. The secondary foliation is believed to have formed in response to solid-state deformation. The solid state deformation affected both the Suborg-gabbro and the quartz-feldspathic gneiss and is suggested taking place during the cooling stage. A solid state deformation is supported by the fact that the foliation in the quartz-feldspathic gneiss and the Suborg-gabbro are parallel to each other and the foliation is continuous with a regionally developed foliation.

3. An asymmetric extension model with deep crustal shearing and syntectonic intrusions can explain the parallelism of the magmatic rhythmic layering and the solid-state foliation seen for the Suborg-gabbro. Extension associated with continental rifting is proposed as a mechanism for the generation of the fabric present in the Suborg-gabbro and the quartz-feldspathic gneiss.

4. The early mineral assemblages present in the quartz-feldspathic gneiss and the Suborg-gabbro represents dry rocks. Very fast strain rates in dry rocks may produce so much frictional heat that melting occurs forming pseudotachylytes. The presence of pseudotachylytes and/or relicts of pseudotachylytes in the Suborg-gabbro support a dry rock assemblage of the SIP, and that deformation took place at middle to lower levels of the crust. The presence of dry rocks follows the idea of Elvevold *et al*, (1994) stating that the shearing took place at lower level of the crust, and hence an asymmetric extension model with deep crustal shearing.

5. The quartz-feldspathic gneiss is strongly sheared and its kinematic indicators indicate normal faulting supporting extension and a rifting model for the SIP.

6. The mineral assemblage present in the thin ductile shear zones supports an increase in pressure. The pressure increase is interpreted to be related to loading due to nappe emplacement during the Caledonian orogeny.

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